Born in 1564, Galileo Galilei once contemplated a career in the priesthood. It’s perhaps fortunate for science that upon the urging of his father, he instead decided to enroll at the University of Pisa. His career in science began with medicine and from there he subsequently went on to become a philosopher, physicist, mathematician, and astronomer, for which he is perhaps best known. His astronomical observations and subsequent improvements to telescopes built his reputation as a leading scientist of his time, but also led him to probe subject matter counter to prevailing dogma. His expressed views on the Earth’s movement around the sun caused him to be declared suspect of heresy, which for some time led to a ban on the reprinting of his works.

Galileo’s career changed science for all of us and he was without doubt a leading light in the scientific revolution, which is perhaps why Albert Einstein called him the father of modern science.

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On October 25, 2012 Beihang University, originally known as the Beijing Institute of Aeronautics when it was founded in 1952, will celebrate her 60th anniversary. To mark this occasion, the university plans to launch a yearlong series of programs and activities denoting Heritage, Openness, and Excellence. This special issue, published and sponsored by Beihang University, is part of that celebration.

It highlights the university’s research developments in science and technology, with an emphasis on the most significant accomplishments in the past as well as current and future research priorities and plans. This booklet intends to present to the world a clear and comprehensive picture of teaching and research activities at Beihang University.

Since its founding, Beihang University’s motto, “Ability, together with Integrity; Practice, in conformity with Truth and Morality” has inspired generations of students, faculty, and alumni to contribute to the well-being of China and the development of the world. Through the persistent effort of several generations, Beihang University has become a top-ranked comprehensive national university that not only excels in aeronautics, astronautics, and informatics, but is also known for multiple other disciplines within science, engineering, economics, humanities, law, philosophy, management, foreign language, education, and art. The fruitful and extensive international collaborations established under the UPS Program (a three-level hierarchy of dialogue: University-to-University, Professor-to-Professor, and Student-to-Student) has substantially consolidated and raised the international profile of Beihang University.

Throughout her 60-year history, Beihang University has laid a solid foundation of research and teaching excellence. To build upon these strengths and to meet current challenges, Beihang University has implemented a series of innovative reforms and strategic plans. For example, 2012 was named “The Year of Talent” at Beihang University. Projects such as the “Blue Sky Program” and “Great Wall Program” are under way to reform the human resource system, attract world-class scholars, establish international top-notch research groups (“Dream Teams”), further improve teaching quality, emphasize an international perspective for undergraduate and graduate students, and extend interdisciplinary cooperation among science, engineering, and humanity. Landmark buildings such as the Beihang University History Museum, the Technology Museum of Innovation, the Concert Hall, and the Beijing Air and Space Museum are also being utilized.

The Chinese calendar is measured in 60-year cycles. The 60-year anniversary of Beihang University gives us an opportunity not only to survey her accomplishments in science, technology, and culture over the past six decades, but also to plan for her future to meet the challenges of the next 60 years. At this historic juncture of another cycle, Beihang University is committed to further promoting international collaborations in all disciplines as well as fostering interdisciplinary research. The university is also determined to train and cultivate first-tier scholars and researchers, by encouraging joint training of students in collaboration with institutions in other countries.

I strongly believe that with the wisdom, strength, and support from students, faculty, and staff, Beihang University will accomplish its mission of building a world-class university through innovation. At this historical moment for our university, I would like to invite, on behalf of Beihang University, scholars and students from all over the world to visit, study, and work at our university. Beihang University is well positioned to engage in cross-cultural communication and globalization.

I would like to thank my colleagues for their hard work and contributions. I am also indebted to the publishing and production teams in the Science Custom Publishing Office for their assistance in the preparation and timely publication of this booklet.

Professor Jinpeng Huai, Ph.D.
President, Beihang University
Member of the Chinese Academy of Sciences
Onwards and Upwards

The Lebanese-born poet, writer, and artist Khalil Gibran once said, “Progress lies not in enhancing what is, but in advancing toward what will be.” This is perhaps truer nowhere more than in the fields of aeronautics and astronautics. Not only have humans flown to increasingly greater heights, moved faster than ever before, and plumbed greater oceans depths, but they have also escaped the confines of this planet to colonize space and visit the moon. It seems inevitable that manned journeys to other destinations in the solar system are not far behind. It is just our nature to continually push the boundaries of possibility, toward an imagined future.

On this, the 60th anniversary of Beihang University (formerly known as the Beijing University of Aeronautics and Astronautics, or BUAA), we visit some of the achievements of this prestigious Chinese institution in all manner of research fields related to air, land, sea, and space travel. Each of the schools featured in this booklet showcases their latest innovations, discoveries, and research in many and varied science and engineering disciplines. The cover depicts a multidisciplinary, multi-school effort in which researchers from across the Beihang University campus are using advanced engineering principles to design the so-called aero-levitation wheel-rail train, a high-speed and highly efficient transportation system of the future. These scientists and engineers are particularly adept at generating designs that are biologically inspired, borrowing the best systems from nature and applying them to create more effective technologies for human use.

Groundbreaking advances have been made at Beihang University in robotics and advanced manufacturing technologies. Researchers at the School of Mechanical Engineering and Automation have created state-of-the-art robots that aid in aircraft assembly as well as micromanipulation robots that can aid doctors in delicate brain surgery, while at the School of Biological Science and Medical Engineering novel nanomaterials are being applied in unique medical treatment regimens.

Also in the School of Biological Science and Medical Engineering, in the Laboratory of Environmental Biology and Life Support Technology, bioregenerative life support systems are being developed that may one day allow astronauts to live in space for prolonged periods of time, either on a space station or on an extended mission to distant planets.

From the nanoscale to the macroscale, advances being made at Beihang University are pushing the boundaries of what we can achieve, moving us toward what will be. No doubt much of the accomplishments over the next 60 years we have not even imagined today, a concept that is both exciting and humbling in its potential.

Sean Sanders, Ph.D.
Editor, Custom Publishing
Science
Beihang University (previously known as Beijing University of Aeronautics and Astronautics) was founded in 1952, following the merger of the aeronautical departments from eight top Chinese universities including Tsinghua University, Peiyang University (now Tianjin University), Xiamen University, and Sichuan University. With this, it became the first university of aeronautical and astronautical engineering in China.

Not long after it was founded, Beihang University was recognised as one of China’s 16 key universities and it has since received priority support from the Chinese government. Today, Beihang University is one of China’s leading research universities with preeminent science and engineering programs and is among a few top Chinese universities supported by the National Education Excellence Initiative (“211” and “985” Projects), aimed at developing world-class universities in China.

Beihang University is situated in Beijing within the Zhongguancun Science Park. The main, 120 hectare campus is adjacent to China’s National Olympic Centre, while a new campus of a similar size is located approximately 25 km to the north, in the city’s suburbs.

Since its foundation, Beihang has gained nationwide acclaim for its teaching, research, and scholarly achievement. The university currently has more than 2,200 full-time faculty members, including over 500 professors. The faculty includes 17 members of the Chinese Academy of Sciences and the Chinese Academy Engineering.

The university offers 57 undergraduate programs, 144 Master’s programs, and 63 doctoral programs across its 27 schools, which include engineering, sciences, medicine, economics, management, law, humanities and social sciences, education, and art. At present, Beihang University has 26,385 students, of whom 13,939 are undergraduates and 12,446 postgraduates. Over the past 60 years, the university has produced more than 120,000 graduates. A number of outstanding alumni have become members of the Chinese Academy of Sciences or the Chinese Academy of Engineering. Nearly a third of the top designers and directors in the Chinese Manned Space Program and Lunar Exploration Program studied at Beihang University.

As a leading university in science and technology innovation, Beihang has received more than 1,130 awards at the national or ministerial level for achievements in basic research, technological innovation, and engineering developments. During recent years, research funding at Beihang has been increasing at an annual rate of over 20 percent, with the research expenditures totalling 1.93 billion yuan (US$304.3 million) in 2011. The total amount of external research funding received is among the highest of all universities in China. Beihang also has strong links with industry, with more than 50 percent of its research projects originating from the industrial sector.

Beihang University has long made international networking a priority for its development. To maintain and extend its collaborative networks, the university has developed a strong strategy of internationalization called Vision Plan UPS (U, university to university; P, professor to professor; S, student to student). The university has developed partnerships and cooperative agreements with over 185 universities, research institutions, and companies in 32 countries. These multilevel partnerships cover faculty and student exchanges, joint workshops and conferences, joint educational programs, joint research endeavors, and collaborative publication. Beihang has established a number of ambitious international educational projects, such as the Beihang Sino-French Engineer School (also known as École Centrale de Pékin), a successful, internationally recognized joint project established in 2005 by Beihang and Le Groupe des Écoles Centrales.

In 1993, Beihang University, the first university in China to offer all Master’s and Ph.D. programs in English for international students, launched its international education programs. Now, with a total of over 200 courses offered in the English language by some of China’s most published faculty and international professors, the university has 1,200 international students from 80 countries, including one of the largest international graduate student populations in engineering studies in China.

Beihang University is celebrating its 60th anniversary this year and it has reaffirmed its commitment to build a world-class research university rooted in China. As an integral part of this goal it aims to provide high-quality education that links theory with practice to better foster innovation and creativity and to develop leaders and citizens who will contribute to the development of the nation and the world.

For more news and information on Beihang University, please visit www.buaa.edu.cn.
Material Science and Engineering Research at Beihang University

The School of Materials Science and Engineering at Beihang University provides cutting-edge research and education in advanced structural and functional materials, nanomaterials, new materials for clean energy, polymers and composites, nonequilibrium fabrication, corrosion science, and failure analysis.

There are 75 full-time teachers in the school, which annually graduates 150 undergraduates, 180 postgraduates, 50 Ph.D.s, and 10 students from abroad.

The School of Materials Science and Engineering (SMSE) at Beihang University grew out of the Aviation and Metallurgy Department, built in 1954. Now it ranks among 16 national key first-class disciplines of materials science and engineering, launching the earliest nationwide reform experiment on “the education of professionals of the general discipline of materials,” and earning itself a spot on the list of Beijing Laboratory Education Model Centers for materials science and engineering. There are 75 full-time teachers in the school, which annually graduates 150 undergraduates, 180 postgraduates, 50 Ph.D.s, and 10 students from abroad. The school employs a broad pedagogical mode, based on the first-class discipline of materials science and engineering. Accordingly, specialized basic courses and comprehensive laboratory courses have been established, with students receiving specific instruction in metal and ceramic materials, functional materials and devices, polymer and composite materials, materials process engineering and automation, corrosion and protection, nanoscience, and nanotechnology. At present, the school is undertaking a “graduate-postgraduate integration” pilot project spanning from graduate to doctoral courses.

The school carries out education and scientific research in materials structure, properties, manufacturing, service, and representation as well as applied basic research on the application of materials to the fields of aerospace, machinery manufacturing, energy, and the environment. Building upon the strong history of research—including high-temperature structural materials and coating technology, light alloy and laser rapid manufacturing, polymer and resin matrix composites, metallic corrosion science and protection technology, and failure analysis, prediction, and prevention—the school has continued to develop along new research directions such as special functional materials and intelligent materials, high-performance and nonequilibrium material science and technology, and new energy materials and nanomaterials.

Failure Analysis

Failure is intrinsically inevitable for every material. The failure analysis group led by Qunpeng Zhong, an member of the Chinese Academy of Engineering, has focused on failure analysis—the process of collecting and analyzing data to determine the cause of a failure and forecast future failures—for more than 40 years. It is an important discipline in many branches of manufacturing, particularly the materials industry, where it is vital tool for the development of new products and the improvement of existing products.

Zhong and his group have successfully proposed several mathematical models and controlling mechanisms of materials that describe the ductile-brittle transition. He organized and attended the academic committee for the analysis of more than 500 worldwide major disasters in the fields of electromechanics, aviation, and aerospace. On these committees, Zhong provided scientific, accurate, and convincing conclusions for the effective prevention and forecast of failures. In 2005, the group’s pressure pipe safety testing and evaluation technology was awarded the 2nd Prize National Science and Technology Progress Award.

Special Functional Materials

Metals and their alloys possess high structural strength per unit mass. One of the research groups directed by Huibin Xu, a member of the Chinese Academy of Engineering and vice president of Beihang University, focuses on the research of special functional materials, such as thermal barrier coatings (TBCs) and giant magnetostrictive materials (GMMs). The gas turbine engine is considered to be the heart of many aircraft. As highly advanced material systems, TBCs are usually applied to metallic surfaces, such as gas turbine or aeroengine parts, serving to provide oxidation resistance, corrosion resistance, and to insulate components from large and prolonged heat loads. New TBCs are needed for advanced gas turbine engine applications and have potential application value for the armaments, aerospace, and marine science fields. Since traditional TBCs failed to fully meet the demands of advanced turbine engines, Xu’s group has investigated new TBCs with better performance than the commonly used yttria-stabilized zirconia (YSZ) TBC. A graded bondcoat TBC (GB-TBC) with lower thermal conductivity and greatly improved durability than traditional TBCs was developed and applied in gas turbine engines. Due to their outstanding contributions, Xu and his coworkers were awarded the 2nd Prize National Technology Innovation Award in 2006.

GMMs are smart materials with strategic importance. Terfenol-D GMMs, traditionally employed in the fields of aeronautics and astronautics, are limited by a narrow operational temperature range of -20°C to 60°C. Xu and his colleagues undertook a rigorous study to reveal the
Direct Laser Manufacturing by Powder Deposition

The Beihang University Laboratory of Laser Materials Processing and Manufacturing (LMPM) studies the manufacture of metallic materials such as titanium alloys. Direct laser manufacturing of metallic components based on powder deposition has had a long history. Its applications over the past three decades have been confined to the fabrication of small metallic components. The biggest challenge is to manufacture large metallic components and push the technique into industrial applications. After more than 17 years of intensive study, investigators at the LMPM overcome this challenge. Large titanium airframe and key landing gear structures have been fabricated by a proprietary laser-melting–deposition process and successfully applied in the aerospace industry. Due to this exceptional contribution, LMPM scientists were invited to give a plenary speech at the Pacific International Conference on Applications of Lasers and Optics 2010.

Development of Alloys and Composites

Besides crystalline alloys, advanced amorphous alloys and related materials with novel physical and chemical properties—such as superhigh specific strength, large elasticity, and good biocompatibility—are also important research subjects at SMSE. The research focus emphasizes understanding the nature of glass formation and deformation behavior; establishing the relationship among alloy composition, disorder structure, and advanced properties; and developing new techniques. These nonequilibrium materials show wide potential applications, such as in electronic device casings, advanced sporting equipment, medical instrumentation, and military parts.

In addition to the excellent properties and common applications of steel, aluminum, magnesium, and titanium alloys, corrosion and its prevention are important research fields. Researchers are studying the development of high corrosion-resistant composite coatings, functional composite coatings for wear resistance, photocatalysis, antifouling, wax-proofing, and hydrophobicity as well as micro-arc oxidation techniques for application to aluminum, magnesium, and titanium alloys.

Composites are engineered or naturally occurring materials made from two or more constituent materials with significantly different physical or chemical properties, which remain separate and distinct within the finished structure. Investigators in the Advanced Polymer Matrix Composite group aim to contribute to the scientific understanding of the relationship between composite components and the nano-, micro-, and macrostructures of composite materials, based on knowledge of the manufacturing process. Innovative studies were conducted using a combination of experimental, theoretical, and advanced numerical analysis to understand multiscale structure formation and to develop novel composites with high performance that are useful across multiple platforms such as aircrafts, automobiles, and wind energy technologies.

Recently, the school has seen growth in the area of renewable energy research. Beihang University investigators are focused on energy-saving and renewable technologies such as lithium-ion batteries, fuel cells, and capacitors. They have proposed and successfully developed a series of rational strategies to prepare 3-D porous electrodes, including electrochemistry-oriented plating, electropolymerization, dealloying, hydrogen bubbles, and an approach involving metal foam templates. The resulting electrodes showed meaningfully improved performance in electrochemical energy storage and conversion applications.

Over the past 60 years, the Materials Science and Engineering school has made great strides in teaching and research. Students graduating from the school are engaged in a number of fields at home and abroad. As it looks to the future, the school will fully implement the educational development plan of the university, cultivate innovative talent with the global vision to lead and support the development of materials science and engineering, and contribute to the realization of Beihang University’s vision of building a “world-class university with the characteristics of integrating aeronautics, astronautics, and information science.”
New Thermal Barrier Coatings for Advanced Gas Turbine Engines

Hongbo Guo1,2*, Hui Peng1,2, Shengkai Gong1,2, Huibin Xu1,2

n the past few decades, thermal barrier coatings (TBCs) have seen increasing applications in gas turbine components such as vanes, blades, throats, and combustion walls (1, 2). The use of TBCs, along with internal cooling, enables the underlying superalloy to operate at temperatures exceeding the normal melting point of that superalloy, thus improving the efficiency and performance of engines. A TBC typically consists of a low thermal conductive ceramic topcoat to withstand hot gas, erosion, corrosion, and foreign objective damage, and a metallic bond coating to protect the superalloy against high-temperature corrosion. Yttria-stabilized zirconia (YSZ, 7% to 8% by weight) is the material most widely studied and used for TBCs, because it provides the best performance at temperatures below 1,200°C. However, YSZ cannot be operated above 1,200°C for long periods due to the transformation of its metastable tetragonal phase to a monoclinic phase. Excessive YSZ volumetric changes resulting from this phase transformation, together with accelerated sintering of YSZ at high temperature, tends to cause early spallation failure of TBC. Recently, the increased turbine inlet temperature (TIT) in advanced turbine engines has instigated the development of TBCs with higher temperature capability and lower thermal conductivity. Considerable effort is being invested in seeking new TBCs with better performance than YSZ. The new materials utilize, in particular, rare earth-doped zirconia (3), pyrochlores (4), perovskites (5), and aluminates (6). Recently, we investigated new TBC materials, including new ceramic topcoat materials with low thermal conductivity for ultrahigh-temperature application and new bond coat materials suitable for advanced single crystal superalloys.

Lanthanum cerium oxide (La₃CeO₇; LCO) is a solid solution of La₂O₃ in CeO₂ with a defective fluorite structure, in which La⁺ and Ce³⁺ can be substituted by other elements with similar ionic radii when the electrical neutrality is satisfied, thus providing the possibility of tailoring its thermal properties (7). The main advantage of LCO as a TBC material is its lower thermal conductivity and high-temperature capability. However, LCO showed a sudden drop in thermal expansion coefficients (TECs) over the temperature range of 200°C to 400°C (7), possibly due to crystal lattice contraction, which is undesirable for TBCs. To improve the TEC of LCO in the low-temperature range, we have investigated high-melting point oxides such as tantalum oxide-(Ta₂O₅) or tungsten oxide-(WO₃)-doped LCO (8). Ta₂O₅-doped LCO (LCT) effectively improved the TECs between 200°C and 400°C, revealing large TECs of 11 to 14×10⁻⁶ K⁻¹ over a broad temperature range (Figure 1A). The thermal conductivity increased below 1,000°C and then becomes stable up to 1,400°C with a value of ~0.7 watts per meter Kelvin (W/mK) at 1,400°C, which is only one-third that of the YSZ form of YSZ (bulk, 2.2–2.4 W/mK, 1,000°C). Also, no phase transformation occurred when LCT was examined between room temperature and 1,600°C. However, we also found that LCO reacted with aluminum oxide growing on the bond coat during thermal exposure, resulting in poor bonding between the LCO ceramic layer and the bond coat. As a result, the thermal cy-
REFERENCES


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High-Performance TbDyFe/Epoxy Magnetostrictive Composite

Chengbao Jiang*, Hao Meng, Tianli Zhang, Jingmin Wang, Jinghua Liu, Huibin Xu

Terbium-dysprosium-iron (TbDyFe) giant magnetostrictive materials are promising “intelligent” compounds for application in transducers, damping systems, and deep-sea measurements, among others (1–3). The magnetostriction properties of TbDyFe alloys exhibit strong anisotropy, with the optimum along the <111> direction (i.e., the easy magnetization direction) (4). However, it currently is a significant challenge to obtain <111>-oriented TbDyFe alloys. Moreover, the large eddy currents losses presented above a few kilohertz (kHz) and intrinsic brittleness are also severe obstacles to the synthesis of bulk TbDyFe alloys. One possible solution is to develop TbDyFe magnetostrictive composites by integrating TbDyFe particles in a nonmetallic binder (4). But the problem of obtaining <111> orientation for optimal magnetostriction value from the embedded TbDyFe unit remains unsolved.

Figure 1. X-ray diffraction patterns for the composites with a volume fraction of 20% TbDyFe particles cured under an 8,000 Oe dynamic magnetic field for different magnetostrictive anisotropies of TbDyFe alloys, Tb$_{0.2}$Dy$_{0.5}$Fe$_{1.75}$ (A) and Tb$_{0.2}$Dy$_{0.5}$Fe$_{1.75}$ (B). The characteristic diffraction peaks of (111), (222), and (333) were observed, demonstrating the highly preferred <111> orientation was successfully achieved in the TbDyFe/epoxy composites with high magnetostrictive anisotropy. (C) An exciting layer structure and highly fibrous alignment not previously reported was observed from the longitudinal section microstructure photographs of the composites, prepared by dynamic magnetic field orientation. (D) For comparison, the microstructure of incompletely aligned chains using static magnetic orientation. (E) The magnetostrictive properties for composite oriented by static or dynamic magnetic fields, for the particle composition Tb$_{0.2}$Dy$_{0.5}$Fe$_{1.75}$.

Current approaches for preparing particle orientation can be subdivided into three categories. The first approach relies on the particle shape anisotropy in which needle-shaped [112]-oriented TbDyFe particles serve as master materials for fabricating [112]-oriented magnetostrictive composites with magnetostriiction at 1,600 ppm (5). The second technique is to remove the eutectic phase from a <112>-aligned TbDyFe rod and infiltrating the epoxy into the vacated sites with magnetostriction at 1,013 ppm (6). Both of these abovementioned approaches involve complicated processes. The third approach is a simple and low-cost process involving curing epoxy resin with crushed particles using magnetic force. Utilizing bimodal particle distribution, the magnetostriction was increased to 1,170 ppm, an increase of 15% over other widely and narrowly dispersed distributions (7). A magnetostriction of 1,360 ppm was obtained by curing the epoxy under a moderate magnetic field as described in previous work (8). Other researchers, using another matrix system, have reported that the highest possible value is 1,390 ppm (9). However, the unsatisfactory particle orientation resulted in low strain levels which are far below the monolithic TbDyFe alloys. It thus makes sense to continue pursuing the <111> preferred orientation in the magnetostrictive composites, despite the challenges mentioned in previous reports.

How can we induce this preferred orientation? The goal is to orient the easy <111> axis of the particles in a longitudinal direction by magnetic force before curing and fixing this state. In monolithic TbDyFe, conventional wisdom suggests that low magnetostrictive anisotropy is amenable to magnetostriction at low magnetic field strengths. Unfortunately, in the composite, if the magnetostrictive anisotropy energy is low, the viscous resistance of the resin could not be overcome by static magnetic energy. In this case, particle rotation does not occur; rather, the domains rotate by the reorientation of electron orbits. In this work, it is suggested that if the magnetostrictive anisotropy energy is high enough, the particle rotation can be induced by magnetostrictive anisotropy to align the easy <111> axis of the particles parallel to the applied magnetic field direction.

We exploit an innovative protocol for preparing high-performance magnetostrictive composites based on high magnetostrictive TbDyFe alloys to obtain desirable <111> orientation. Particles ranging from about 200 μm to 300 μm in diameter were crushed from annealed TbDyFe alloys with series Tb$_x$Dy$_{0.2}$Fe$_{1.75}$ (x=0.27–0.5) composition, which corresponds to magnetostrictive anisotropy. Mixed with epoxy resin, the sealed mold was rotated in an 8,000 Oersted (Oe) magnetic field at a specific frequency before curing, which then maintains the magnetic field until curing is completed. The characteristic diffraction peaks of (111), (222), and (333) are observed, demonstrating that the highly preferred <111> orientation has been successfully achieved in the TbDyFe/epoxy composites. Diffraction peaks at (220), (311), and (440) are not seen, but do appear in the TbDyFe/epoxy composites with low magnetostrictive anisotropy, as shown in Figure 1B. The

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Figure 2. Dynamic hysteresis loops at frequencies ranging from 0.2 kHz to 10 kHz at 10 mT peak magnetic induction for (A) TbDyFe alloy and (B) TbDyFe/epoxy composite. With increasing frequency, the complex permeability of the TbDyFe alloy decreases rapidly, while the value is independent of frequency for the TbDyFe/epoxy composite. The total loss for the composite is just 4.3% of that for the monolithic TbDyFe alloy at 10 kHz under peak magnetic induction of 10 mT. The complex permeability spectra of the two magnetostrictive materials are also shown (10). The permeability μ’ and μ” represent the stored energy and the dissipated energy of the composites, respectively. The intersection points of the permeability graphs can be considered as the cut-off frequencies. The cut-off frequency of TbDyFe/epoxy composite is up to 6,800 kHz, three orders of magnitude larger than that of the TbDyFe alloy. mT, millitesla.

highly preferred <111> orientation achieved in our work with high magnetocrystalline anisotropy indicates that the particles’ rotation is aligned with its easy <111> axis. Surprisingly, the microstructure of the composites displays an exciting layer structure and highly fibrous alignment (Figure 1C), an observation not previously reported to our knowledge. The magnetostriiction might potentially have been enhanced by the magnetostriiction delivered to the adjacent particles. In recent research, the highly preferred <111> orientation and the noticeable layer structure of the composites led to an even greater enhancement in magnetostriiction. The magnetostriiction increased significantly to 1,900 ppm at 14,000 Oe and 21 MPa prestress. The strain level exhibits an obvious improvement compared with the previously reported highest value of 1,390 ppm. More specifically, the magnetostriiction is 700 ppm in a 2,000 Oe (low) magnetic field and 10 MPa prestress as shown in Figure 1E, which is more than twice that seen compared with the sample prepared using a static magnetic field.

Interestingly, the epoxy resin creates an insulating layer between the particles, which increases resistivity and strongly reduces eddy current losses at high frequencies. Further analysis demonstrated that the resistivity of the composites is six orders of magnitude greater than the TbDyFe alloys, which we attribute to the high-resistivity epoxy resin. As a result, the conduction of the eddy current could only exist in the particles of the composite. To quantitatively evaluate this loss, we examined a dynamical hysteresis loop over a broad frequency range (Figure 2). The total loss for the composite is just 3.7% of that for the monolithic TbDyFe alloy at 100 kHz under peak magnetic induction of 10 militesla (mT). Importantly, the cut-off frequency of TbDyFe/epoxy composite is up to 6,800 kHz, three orders of magnitude larger than that of TbDyFe alloys (10). We believe that the improved cut-off frequency with low eddy current loss achieved in the composite will open new applications at broad frequency ranges, including high-power actuators, ultrasonic field, and high-frequency transducers.

In summary, we have developed a novel and versatile method for controlling orientation and alignment of TbDyFe/epoxy composite by enhancing magnetocrystalline anisotropy and using a dynamic magnetic field. A highly preferred <111> orientation and unique layer structure is achieved with the magnetostriiction of 1,900 ppm. This work opens a new avenue to explore other high orientation magnetic materials and has potential applications at high-frequency ranges.

REFERENCES

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The School of Electronic and Information Engineering

The School of Electronic and Information Engineering (SEIE) at Beihang University is the oldest in China to offer an avionics major, with roots going back to 1958 with the establishment of the Department of Avionic Radio Engineering. The school has played a pivotal role not only in the development of avionic engineering in China but also in the development of electronic and information engineering in general. It started its Master’s program in Communication and Information Systems and Ph.D. program in Information and Communication Engineering in 1978 and 1986, respectively. The SEIE came into being in 2002 and now ranks sixth in the list of top national electronic engineering programs, because of its high quality of research and education.

With more than 50 years of development, the SEIE has evolved into a multidisciplinary school of engineering covering the areas of information and communication engineering, electronic science and technology, transportation engineering, optical engineering, and biomedical engineering. At present, it comprises three departments: the Department of Information and Communication Engineering, the Department of Electronic Science and Technology, and the Department of Photonics and Information Engineering—along with the Teaching Laboratory Center.

The school has a total of more than 130 faculty and staff, including one member of the Chinese Academy of Engineering (Professor Yanzhong Zhang), one National Outstanding Lecturer (Professor Xiaolin Zhang), two Chang Jiang Scholar Endowed Professors (Professors Jun Zhang and Jungang Miao), 33 full professors, and 53 associate professors. The school has a total enrollment of over 2,500 students, including more than 280 doctoral candidates, over 1,000 Master’s candidates, and over 1,000 undergraduates.

Research

In the 50 years since its foundation, the SEIE has made comprehensive progress in many fields, such as communication and information systems; signal and information processing; information networks; integrated circuit design; remote sensing and processing; avionic and satellite navigation; electromagnetic and microwave technology; circuits and systems; microelectronics and solid-state electronics; physical electronics; electromagnetic compatibility and electromagnetic environment; transportation information engineering and control; optical engineering; and biomedical engineering.

Now the school has become one of the most important innovation centers for information technology in China. It has received over 600 million yuan (US$94 million) in research funds in the past four years, and has established two major research and development centers at the state level—the National Industrial Technology Center of Satellite Navigation Application and the National Industrial Technology Laboratory of Digital Television—and four major laboratories at the ministerial level—the National Key Laboratory of Communications, Navigation, Surveillance/Air Traffic Management (CNS/ATM); the CNS/ATM Laboratory of the Civil Aviation Administration of China; the Advanced Avionic Navigation and Air-Control Key Laboratory of the Ministry of Education; and the Avionics Key Laboratory of the Ministry of Aviation.

The school is making pivotal breakthroughs in its scientific research. About 200 journal papers have been published in the last five years and included in the Science Citation Index (SCI). More than 160 patents have been granted in the past three years, 66 of which have been translated into actual applications in industry. In addition, the school has filled scientific and technological gaps nationwide by making significant contributions to meet the country’s most urgent needs in many areas. As a result of its achievements and contributions, the school has received more than 30 awards at the ministerial level or above, including one 1st Prize National Technology Innovation Award for the project entitled, “New Technologies and Apparatus of Air-Ground Collaborated Civil Aviation Airspace Surveillance,” three 1st Prize National Science and Technology Progress Awards, including one on “Service, Technology and Applications of New Generation Air Traffic,” and two 2nd Prize National Science and Technology Progress Awards for the projects “Key Technologies and Applications in the Monitoring System of China’s Civil Aviation” and “Key Technologies of System-Level Electromagnetic Compatibility Test System.”

Education

As one of China’s most important centers for innovation in—and teaching of—electronic and information engineering, the SEIE has fostered over 10,000 students. A great number of the alumni have made prominent advances in various fields including information technology, aeronautics, astronautics, business, and other fields.

The school explores innovative methods in science and technology teaching and mentoring of exceptional students. Education reform and innovation has yielded fruitful results, including one National Outstanding Lecturer Award, and two 2nd Prize National Teaching Achievement Awards. The lecture team responsible for the course on Electronic and Information Engineering has been recognized as a National Level Teaching Team. After years of trial and error, the school has now established its own unique curriculum system, which it continues to improve. The classes on Electronic Circuit I and Advanced Air Traffic Management have been listed as National Quality Courses. Five textbooks have been published as National Official Textbooks of the 11th Five-Year Project, including Electronic and Circuit Foundation, Network Security Theory and Practice, Introduction to Network Security, The Principle of Automatic Control, and Electromagnetic Fields and Waves.

The school’s laboratory facilities are among the best in China. It boasts the National Training Center of Integrated Circuit Design and two National Teaching Bases for Engineering Practice. The Joint
Teaching Laboratory for Undergraduates and Graduates, established with a total investment of 16.9 million yuan (US$2.65 million), provides all university students with 56 experimental courses in electronic information technology and has become an electronic engineering innovation base for undergraduate students.

The SEIE is well known for its lively and vigorous student activities in science and technology. The school has won 20 1st prize awards in both the National Undergraduate Electronic Design Contest and the National Undergraduate Information Security Contest. It won a special class award in the National Challenge Cup Contest, a nationwide academic Olympic contest for all tertiary institutions in China. And the school received 17 1st prize awards in the Fengru Cup, a competition showcasing extracurricular inventions in science and technology organized by Beihang University, and as a result it kept the cup permanently.

International Cooperation
In recent years, the SEIE has actively and intensively developed its international academic exchange and cooperation programs. Long-term academic exchanges, joint laboratories, and contracted projects have been established with more than 30 universities, research institutes, and industries from about 20 countries, including the United States, United Kingdom, Sweden, Canada, Germany, France, Singapore, Japan, Australia, and Russia. Every year, dozens of foreign experts and scholars come to the school to give lectures, visit with colleagues, carry out joint research, and/or take part in international conferences. The school has hosted several international conferences including ISAPE2008, APEMC2010, and ChinaCom2010. Several joint research centers have been established through cooperation between SEIE and such prestigious international research institutions and companies as the European Space Agency and Honeywell International Inc., and many joint research projects have been conducted. The Kungliga Tekniska högskolan (KTH)-BUAA center for wireless communications has been created with the support of the European Union’s Asia-Link program. The purpose of the center is to facilitate research collaboration on wireless technology between the SEIE and the School of Electrical Engineering, at KTH, Sweden’s Royal Institute of Technology. The school has conducted collaborations in teaching and training, even cotutelle programs with the Universities of Edinburgh, Sydney, and Nottingham. A total of 67 students have participated in these collaborative teaching and training projects. Additionally, 37 students have studied abroad, sponsored either by the Chinese government under the Graduate Student Overseas Study Program, or by BUAA under the Exchange Student Program. Meanwhile over 100 international students from more than 10 countries and regions are studying in the SEIE, including about 20 undergraduates, 30 Master’s students, and more than 50 Ph.D. candidates.

Looking to the Future
“Now, SEIE is drawing its roadmap for the next 10 years,” says Professor Zhulin Wang, dean of the SEIE. “We set our goal to become an internationally recognized, high-level, research-oriented electrical engineering school in the next decade. We aim to be a cradle for preparing innovative talent with leadership potential, while being an important source for technology innovation and transfer. We will focus on the construction of influential and specialized disciplines. We will carefully develop core competitiveness and promote the comprehensive, coordinated, and sustainable development of our school. We sincerely welcome scholars and students from around the world to join us in this worthwhile endeavor.”
Department of Information and Communication Engineering

The Department of Information and Communication Engineering (ICE) is one of the largest departments in the School of Electronic and Information Engineering (SEIE). It consists of two principal fields of second-level disciplines, namely communication and information systems, and signal and information processing. ICE’s nearly 70 faculty, including 19 full professors, find their research homes in 10 major affiliate laboratories. The cutting-edge research in these labs continues to have a significant impact on aerospace information technology, and each year it attracts approximately US$10 million in funding from governmental agencies and industry.

The goal of the High Dynamic Wireless Communications (HDWC) laboratory is to develop state-of-the-art practical techniques for real communication systems under extreme conditions (e.g., high dynamic range, supersonic speed, long latency, and weak signal power). “We not only focus on distinguished theoretical approaches, but also aim to provide efficient hardware solutions,” says Professor Zulin Wang, leader of HDWC. Indeed, after one decade of hard work, the laboratory has made several outstanding advances in error-correcting codes, Ramanujan Fourier transforms, spread spectrum receivers, and video transmission systems. Two theoretical results have been published in IEEE Transactions on Information Theory, one of the top journals in this field. A number of the techniques developed in HDWC have been applied in Chinese communication systems. Moreover, the laboratory is an open and diverse group: its faculty and students have education and travel experience all over the world, including in the United States, England, France, Italy, Sweden, Malaysia, and Bolivia.

The Digital Video Broadcasting (DVB) group focuses on the research and development of popular digital television technology and the evolution of Chinese Digital Terrestrial Multimedia Broadcast (DTMB) standard core technology. The DVB group leads the technical workgroup that sets national DTMB standards. In 2006, the joint working groups formulated the policy for compulsory national DTMB standards, which was supported and implemented by the State Administration of Radio Film and Television. The laboratory has successfully developed a compatible baseband Application Specific Integrated Circuit (ASIC) transmitter that complies with the 2006 national DTMB Standards. The ASIC chip was built using a 0.18 μm die process and supports three low-density parity-check (LDPC) modes, five mapping modes, two interleaving modes, two carrier modes, three frame types, and two pilot frequencies. It features an efficient LDPC coding module, pseudo-number based padding, double pilot frequency, and spread spectrum broadcasting of system information.

The Laboratory of Information and Network Security (LINS) was established in November 2006 under the supervision of Professor Jianwei Liu. LINS aims to become internationally recognized not only for providing the theoretical foundations for information security and cryptographic technologies related to communication, but also for its excellent research staff. Currently, LINS is involved in a variety of studies, including cryptography and information security, network coding, information theory, and channel coding. To date it has been involved in more than 20 national and provincial projects, including the National Basic Research Program of China (“973” program), the National High-Tech R&D Program (“863” program), and the National Natural Science Foundation of China. LINS has developed a series of software and experimental platforms such as firewalls, intrusion detection systems, virtual private networks, and dynamic password authentication systems. The corresponding products have been successfully applied in many enterprise networks and universities.

Built 55 years ago, the Navigation and Positioning (NP) laboratory developed the first radio altimeter, Doppler navigation systems, satellite navigation receivers, and other aviation equipment in China. The current research interests of NP include satellite navigation systems and integrated navigation as well as application technologies. Platforms developed over the past decade include a navigation signal test evaluation platform, a ground navigation signal monitoring network, and integrated aircraft navigation equipment. The key technical obstacles in satellite navigation and communication systems—interoperability, integrity, interference, antijamming, and reflected signal characteristics of satellite navigation systems—have been overcome. Such technologies have been deployed in the BeiDou Satellite Navigation System, the Shenzhou spacecraft rendezvous and docking system, the integrity monitoring systems for the Chinese global navigation satellite system (GNSS), and in autonomous integrity prediction systems for civil aviation applications in China. Several products in the area of satellite navigation, including multiconstellation navigation signal simulators, high-performance receivers, multimode chipsets, antijamming receivers, and software receivers have been developed and applied in some specific areas. Additionally, the equipment that was developed based on the GNSS reflected signal has also been applied in the field of meteorology.

The Avionics and Bus Communication (ABC) laboratory was established in the 1970s to study integrated avionics systems in China. Through their efforts, a MIL-STD-1553B–linked data bus was created from locally developed components and implemented on Chinese aircraft. At the end of the 1980s, a book entitled Avionics Integration was published and is regarded as the first academic literature from China in this area. In the 1990s, ABC made advances in high-speed, media-shared local area networks, such as Liner Token Passing Bus (LTPB) and Fibre Channel (FC) technology. During the past six years, ABC studies have included advanced interconnection technologies, real-time performance evaluations, avionics system design methodologies, integrated simulations, and ad hoc networking technologies. From 2009 to 2012, two books, Advanced Avionics Integration Technologies and Modern Aeronautical Communication Technologies, were published from the laboratory.

The Integrated Test and Simulation (ITS) laboratory, which was founded in 2003, has for a long time engaged in the research, simulation, equipment development, and system integration of test equipment and systems for satellite communication and onboard data handling. Under the leadership of Professor Wenquan Feng, ITS focuses on many research fields including rapid satellite testing technology, satellite fault detection and location technology, integrated satellite electronic testing technology, and satellite simulators. Over the years, the laboratory has undertaken a number of research tasks and collaborative research projects. Research results have been applied in many collaborative projects with other CAS institutes. The products, such as the integrated satellite testing system, have played a key role in satellite design and development, and greatly improved the quality of China’s satellite program.

The Remote Sensing Signatures (RSS) laboratory has recently concentrated on radar scattering phenomenology modeling for ships on time-evolving sea surfaces. The sea state is affected by a number of factors, including atmospheric conditions, geophysical location, wind direction, and speed, amongst others. The interactions between the complex geometric structures and scattering elements, as well as the time-variant and random characteristics of sea waves, play important roles in the electromagnetic (EM) scattering from a time-evolving sea
CHAPTER 2

surface. Even for the smallest ship cruising on the sea surface, with its large electrical size and complex structures, the EM scattering calculation is a challenge. The radar scattering phenomena become extremely complicated when the six degrees of freedom motion driven by sea hydrodynamics and the EM coupling between the ship and the sea surface are considered, which serves to modulate the radar returns in subtle ways. First principle or computational models and advanced signal processing algorithms have been integrated into a software tool, which generates high-fidelity signatures for modeling radar scattering from ships on a time-evolving sea surface, as illustrated in Figure 1B.

The Radar Signal Processing (RSP) Group has taken a state-space based approach to extracting target motion parameters, and proposed a micromotion parameter estimation method for free rigid targets using micro-Doppler radar. Modeling and theoretical analysis for rigid target motion were conducted based on inertial parameters, as well as target dynamic states under different inertial parameters and initial conditions. Conclusions can then be drawn about the effects of inertial parameters on dynamic states of rigid target and radar echoes.

The Radar Satellite System Simulation (RSSS) laboratory started research on spaceborne synthetic aperture radar (SAR) techniques in 1988. By applying SAR image formation software developed on-site, RSSS first acquired high-quality spaceborne SAR images in China using SEASAT SAR raw data in 1990 (Figure 1D). A joint laboratory studying radar satellite systems and simulation techniques was established with the Shanghai Aerospace Science and Technology Corporation in 2005, aiming to develop cutting-edge technology on SAR satellite systems. The main research fields of RSSS focus on innovative spaceborne and airborne SAR techniques, for example, high-resolution wide-swath spaceborne SAR systems, Earth observation with collaborative aerospace radar technology, and multisource remote sensing data fusion and high-speed, high-dynamic remote sensing data transmission and compression. Over the past 20 years, RSSS has been deeply involved in state-of-the-art spaceborne SAR projects supported by the National High-Tech R&D Program (“863” program) of China and the State Key Development Program for Basic Research of China.

Figure 1. (A) Software-defined radio-based platform for simulation, development, and testing of Global Navigation Satellite Systems (GNSS), which provides real-time processing for GNSS signal acquisition, capturing, tracking, and positioning. (B) 2-D Synthetic Aperture Radar (SAR) refined image chips using an advanced image processing algorithm. (C) Integrated GNSS-reflected signal receiving and processing platform for meteorological applications. (D) First spaceborne SAR image generated in China employing domestically developed image formation software to process raw data acquainted by the SEASAT SAR satellite.
Department of Electronic Science and Technology Research

The Department of Electronic Science and Technology at Beijing University is involved in two research areas, electronic science and technology, and biomedical engineering. It covers five domains including electromagnetic field and microwave technologies, circuits and systems, physical electronics, microelectronics and solid-state electronics, and electromagnetic environments. Major research fields in the department include compact field technology and electromagnetic (EM) scattering theory and measurement technologies, aeronautic antenna design, electromagnetic compatibility (EMC), electromagnetic environmental effects, microwave and millimeter-wave imaging, electronic circuit design automation, high-speed integrated circuit signal integrity, and biomedical information.

After 20 years of work at the compact antenna test range (CATR), the Microwave Engineering Laboratory team developed several core technologies, including the design theory and technology of large CATR reflectors (relative to EM wavelengths), the formation and manufacture of a large curved high-precision reflector, and antenna radiation and target scattering measuring techniques. Based on our research into electromagnetic wave scattering, we have been able to control the background scattering and to design an ultralow scattering target supporter. Along with all these efforts and achievements, we have designed and built many CATRs across China, providing first-class facilities for research into antenna measurements and target scattering analysis.

These days, remote sensing is receiving greater attention in China, with increasing demands for weather observation and forecasting. A subgroup of the Microwave Engineering Laboratory, headed by Professor JunGang Miao, is devoted to millimeter/submillimeter-wave remote sensing methods and detection instruments. Theoretical work involves using a vector transfer model to analyze and interpret space-borne millimeter/submillimeter radiometer polarization measurements of the physical parameters of ice clouds, such as ice particle size and the quantitative relationship between particle shape and orientation. A prototype submillimeter, quasi-optical demultiplexer is being designed and built in our laboratory. Integrating many state-of-the-art submillimeter devices through careful engineering, the prototype will be a core part of next generation meteorological satellite development. A microwave imaging radiometer that utilizes aperture synthesis is also being developed. This instrument measures spontaneous microwave radiation and is an important sensor on spaceborne earth observation platforms, including satellites for monitoring the soil moisture, ocean salinity, and atmosphere temperature. Several prototypes have been designed (Figure 1C), implemented, and tested to provide validation and generate improvements. This work will greatly advance the research and application of remote microwave sensing in China.

The Institute of Electromagnetic Compatibility Technology (IEMCT) was established in 2011 by Professor Donglin Su, following over 20 years of continuous research on system-level EMC. Dr. Su pioneered innovative ideas in the system-level quantitative design of EMC and top-level EMC testing for large and complex electronic information systems, supported by the Chinese National Science Fund Committee. Theoretical and technical studies have been initiated at the IEMCT to realize a top-level quantitative EMC design to mitigate electromagnetic environmental effects on an entire aircraft. Quantitative analyses of the effects of the electromagnetic environment in entire aircraft have been successfully achieved for all radio frequency (RF) and microwave frequency bands. The electromagnetic environment characteristic model, the equivalent electromagnetic interference source model, and mathematical models for interference paths were developed by using unified numerical analysis methods based on the combination of field and circuit. Notable areas covered by the IEMCT include system-level EMC design and prediction/evaluation, system EMC test methodology, integration of EMC test systems, and signal integrity. Plans for the future include a major effort on the appraisal criterion and algorithms for entire aircraft electromagnetic integrity.

A method known as “top-down quantificational predesign and behavioral level simulation of system-level EMC” has been proposed for analyzing large and complex electronic information systems such as aircraft. Using this method, which assigns quantitative EMC parameters, good EMC performance of a system has been achieved. In addition, the effect of changes in subsystem parameters on EMC performance can be analyzed. Potential EMC problems can be revealed and resolved earlier in the design process. Examples of models developed using this method include the Numerical Airplane Model (NAM) and the Performance Simulation Model (PSM) of electronic equipment, which were based on the structure of the airplane and equipment, the relative location of the equipment, the specifications and operation principles of the electronic equipment, and the inputs and outputs of the electronic equipment.

A different type of model, the electromagnetic interference matrix (EIM), was built using a novel method called the “field-circuit hybrid method” (ECHM). EIM is a function of the bandwidth, sensitivity, polarization, signal characteristics, front-end nonlinearity, receiving antenna, radiation power, off-bandwidth characteristics, harmonics, intermodulation, transmitting antenna, location, and attenuation of cables. Based on ECHM and EIM, the EMC performance of entire aircraft can be predicted, evaluated, and quantitatively controlled. This method has been applied in the EMC design of several planes, validating its application.

The Integrated Circuit Laboratory investigates several research areas, including integrated circuits; genetic circuits; embedded chip and microsystem design; implementation and testing of security processors; medical devices; dynamically reconfigurable systems; nanoscale device modeling; design of 60 GHz radio frequency circuit systems; and electromagnetic interference design of analog/mixed-signal circuits. In recent years, custom-made hardware for medical devices and microsystems has been developed. Current developments include the recording and detection system-on-chip (SoC) systems for electrocorticograms (ECogs)/spike signals under different experimental conditions and for extended periods of time. In addition, the laboratory aims to develop new fault-tolerant, dynamic reconfiguration systems including new technologies such as ultralow power, reconfigurable architecture, and...
Based on our research into electromagnetic wave scattering, we have been able to control the background scattering and to design an ultralow scattering target supporter.

Professor Xia Mao’s group at Beihang University investigates affective interfaces for human-computer interaction. The team’s research portfolio includes work on lifelike agent design, vocal prosody recognition, facial expression recognition and generation, and the detection of emotion in human speech. Recently, an Emotional Eye Movement Markup Language (EEMML) was proposed, which is an emotional eye movement animation-scripting tool that enables authors to describe and generate emotional eye movement in virtual agents. The group also proposed a computational framework for generating emotional gaze behavior in a virtual agent, concentrating on analysis and synthesis of primary and intermediate emotions through gaze behavior. To recognize emotional states contained in speech, a new method that employs two novel features, correlation density and fractal dimension, was put forward. For facial analysis, a nonlinearity shape-texture model was introduced to improve the performance of active appearance models. Additionally, to achieve intelligent and comprehensive facial-expression generation in a virtual agent, a novel model of layered fuzzy facial-expression generation was proposed. In affective tutoring systems, critical factors influencing a learner’s satisfaction were identified and an integrated model consisting of 10 factors in three dimensions was developed. The group also proposed an intelligent e-learning system featuring an affective agent tutor and has been committed to developing technologies for harmonious and affective multimodal human-computer interaction.

Professor Mao also investigates pattern recognition in infrared images. To evaluate the performance of preprocessing algorithms, two performance metrics, namely PFTN (potential false targets number) decline ratio and BRI (background relative intensity) decline ratio have been developed. A novel criterion of detectability of infrared small targets (DIST) was also proposed to measure the difficulty in distinguishing small targets in infrared images.
Air transport in China has experienced extremely rapid growth over the past 30 years and is now the second busiest system worldwide. The average annualized growth rate in the total volume of scheduled air transport (including both passengers carried and freight tons flown) is approximately 18%. The Boeing Company predicts strong growth in air travel in China over the next 20 years, with an average annualized rate of increase of 9%. In the same period, the Chinese fleet size is expected to surpass 4,600 aircraft, tripling the current number. In order to meet fast-growing demands from the market, China’s civil aviation industry has experienced several system reforms in recent years, in which the capacity of the air traffic management system has been enhanced.

In order to integrate communication, navigation, and surveillance (CNS) systems, a networked collaborative air traffic management (NC-ATM) has been developed to provide improved operations for satellites, aircraft, and ground-based subsystems. The NC-ATM provides an all-airspace, all-weather capacity for coordinating air traffic control (ATC) and air traffic service (ATS). As a forward-looking air transportation system, the NC-ATM represents a significant advance for the next-generation national air traffic management system.

Two significant achievements of the NC-ATM are highlighted below:

**Real-time flight status monitoring.** It is known that the surveillance of aircraft flight statuses over their full journey is important for the management and operation of civil aviation in China. Technology that enables real-time surveillance of aircraft has been a breakthrough and has allowed a new generation of ATS platforms to be developed (see Figure 1A). Providing integrated flight information services in real time from heterogeneous and distant ATS networks is an ongoing challenge. A general solution that uses gateway clustering has been proposed to replace traditional technologies originally employed in Europe and the United States, where data is exchanged through the so-called media layers. A mechanism for resolving conflicts between clustered service data streams and multiple network routing policies has been developed, using grouping policies for service networks and restraining algorithms for routing oscillation. The next generation ATS platform has been developed to overcome the “blind spot” in air traffic management caused by heterogeneous, disparate, and outmoded ATS networks in China. Moreover, a system to dynamically collect and correlate flight status information from multiple heterogeneous sources has been established. Diverse operations services, including real-time flight status surveillance and global flight freight service systems, have been created to build a foundation for transitioning from passive control to an active ATM system in China.

**More accurate flight path monitoring.** In order to decrease flight times and increase airspace utilization, while faced with the difficulties of maintaining safe flight boundaries in high-density airspace due to numerous and continually shifting variables in flight paths, a new basic theory for reliable flight monitoring has been developed, together with new air-ground cooperative facilities for use in civil aviation airspace surveillance (see Figure 1B). In particular, technology has been developed to overcome uncertainty created by satellite positioning errors as well as improve satellite-based aircraft detection. Additionally, the Ground-Based Regional Integrity Monitoring System (GRIMS)
has been developed, which is able to monitor 13 important variables that influence civil flight navigation. GRIMS overcomes the difficulties of accurately monitoring satellite navigation with a limited number of monitoring stations (seven stations, which is one-fifth that of the U.S. system). Moreover, the means for detecting deviations in flight paths caused by satellite positioning errors has been studied, resulting in the creation of more reliable monitoring facilities. Thanks to these monitoring systems, the confidence limit of flight paths could be reduced three-fold, from 0.3 nautical miles (the average level for similar international systems) to 0.1 nautical miles. Furthermore, the distribution of lateral and vertical flight paths has been studied, allowing the development of better safety criteria for all aircraft. Based on this work, a schema to more accurately monitor and maintain the flight paths of aircraft has been proposed, together with flight-path safety surveillance facilities that can effectively detect flight safety boundaries even under low visibility conditions, satisfying the flight safety requirements of the international civil aviation organization (ICAO). As a result, the first airspace surveillance platform has been successfully equipped with trajectory based autonomous operation (TBO) in China (see Figure 1C), which can make use of the facilities for air-ground cooperative testing for airspace surveillance. The performance of equipment in various Western-China airports has been evaluated using the airspace surveillance platform.

The Optical Engineering Group

As one of the pioneering groups in China venturing into the then cutting-edge, optical-fiber related technologies in the late 1970’s, the Optical Engineering Group of EIE at BUAA is now looking beyond its heritage and, in the past decade, has been devoting more effort toward two areas in photonics: ultrafast optics and nanophotonics. Led by a faculty team with extensive international research experience and collaborative networks, the group places greater emphasis than ever on innovation, international collaboration, and interdisciplinary research.

In the area of ultrafast optics and its applications, we have studied ultrafast lasers based on such emerging nanomaterials as carbon nanotubes and graphene. We have experimentally demonstrated a switchable, dual-wavelength, carbon nanotube mode-locked fiber laser based on the intracavity loss control mechanism (1). Femtosecond pulses at two center wavelengths can be generated simultaneously from one laser cavity, which opens various potential applications that currently require more complicated dual-laser, dual-comb systems. Other types of mode-locking mechanisms and regimes have also been investigated. We built a research platform based on compact ultrafast fiber lasers to study the generation, manipulation, and characterization of ultrashort optical pulses. Further applications including optical frequency comb, terahertz time-domain spectroscopy, all-optical signal processing in high-band-
width digital and radio-frequency optical communications, and optical imaging and ranging are under investigation.

Nanophotonic devices are having an ever-increasing impact in shaping current and future photonic technologies. Our research efforts in this area have focused on two aspects: the design and analysis of nanophotonic structures, and their applications in biosensing and communications.

Novel photonic crystal fibers (2), plasmonic waveguides (3), and sensing devices with nanostructures have been studied. They have been shown through numerical simulations to improve either the optical nonlinearity or the transmission loss and mode confinement of the device. Plasmonic and photonic devices have been implemented in such real-world sensing schemes as surface plasmon resonance (SPR), fluorescence, and surface enhanced Raman scattering. We have extensively investigated, both theoretically and experimentally, associated optical phenomena such as the enhanced Goos-Hanchen effect by the optical surface wave (the surface plasmon wave or the Bloch surface wave in photonic crystals) (4–5). We achieved an unprecedented submillimeter Goos-Hanchen shift with great potential to enable high-sensitivity sensing. In addition, novel optical interrogation schemes have been explored for these sensing systems, for example, to dramatically increase SPR measurement speed (6). Advanced fluorescence and SPR instruments have been developed, with potential applications in proteomics, drug discovery, environmental monitoring, food safety, and other areas.

REFERENCES
Real-Time Transcale Linear-Quadratic-Gaussian Control for a Class of Multirate Multisensor Systems

Yingmin Jia* and Lin Zhao

Multiscale processing algorithms have attracted increasing attention in the signal processing community with the development of the wavelet transform (WT). Among the reasons for this are the apparent or claimed computational advantages of such methods and the fact that representing signals or dynamic systems at multiple scales seems like a natural thing to do (1). There are three basic reasons for using multiscale models: First, the phenomenon under investigation may possess features and physically significant effects at multiple scales; Second, whether the underlying phenomenon has multiscale features or not, it may be that the observation occurs at several different scales; Finally, whether the phenomenon or observation has multiscale features or not, using the multiscale processing algorithm often provides greater confidence, which can reduce the uncertainty and complexity of the problems being analyzed (2). Based on these reasons, the multiscale dynamic models described in terms of scale-recursive state-space equations on a dyadic tree were introduced (3). Lang Hong (4) introduced a nearly optimal multiscale distributed filtering algorithm for a class of multirate multisensor systems. However, most of these approaches have relied on the multiscale (or equivalently, multiresolution) representation of measured signals through WT, but few have attempted to use multiscale models in the setting of engineering tasks operating at various scales. Stephanopoulos et al. (5) introduced an alternative philosophy of multiscale modeling for linear dynamic systems, which is based on the multiscale facets of a single model. The general multiscale models were described by using the Haar WT and conditions governing their stability, controllability, and observability were developed. Furthermore, the same group used these developments to establish the formulation of the multiscale model predictive control (6). Although the optimal control problem of multiscale systems was studied, their algorithm was based on quadratic programming and failed to consider stochastic control systems.

The linear-quadratic-Gaussian (LQG) control problem is the most fundamental optimal control problem for stochastic systems, where the state variables are not all measured and available for feedback (7). Unfortunately, the discrete stochastic control systems all assume the output data only contain features with fixed contributions over time and frequency (8). In practice, however, output data usually contain multiscale or multirate features (9). On the other hand, only limited effort has been devoted, with limited success, toward improving the computational efficiency of the conventional LQG control scheme.

It is well known that there exists one fundamental approach for achieving computational efficiency in engineering applications: parallel processing. Parallel processing divides a computational task into multiple subtasks, which can then be executed simultaneously with multiple processors. WT is an effective tool to implement many engineering tasks in parallel (10).

Yingmin Jia and colleagues (11) proposed a real-time transcale LQG control algorithm for the following discrete stochastic control system (DSCS) to be observed by several sensors of different scales

\[
\begin{align*}
x_{0,k0} + 1 &= Ax_{0,k0} + Bu_{0,k0} + Dw_{0,k0} \\
y_{j,k} &= C_j x_{j,k} + v_{j,k}
\end{align*}
\]

where the system state was modeled at the finest scale 0 (the highest sampling rate), \( x_{0,k0} \), \( u_{0,k0} \) are the state and control input vectors; \( y_{j,k} \) is the measurement at scale \( j \); \( A, B, \) and \( D \) are the system matrices; \( C_j \) is the output matrix; and \( w_{0,k0}, v_{j,k} \) are mutually independent Gaussian white noise. Note that the term transcale control was used (11) to emphasize that such a control system was capable of designing the control law at one scale but providing desired performance at each scale level. The resolution and sampling frequencies of the sensors were supposed to decrease by a factor of two (Figure 1). By using the Haar WT, the conventional LQG control problem was transformed into a suboptimal LQG control problem, in which the control law was designed to ensure that the stochastic performance indexes of all the decomposition systems of the DSCS were minimized. Jia (11) demonstrated that a design philosophy based on (i) transcale control, (ii) parallel processing, (iii) distributed fusion, and (iv) real-time, led to an effective control algorithm. The real-time transcale

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Figure 2. The simulation results of the RTTLQG-Case 1, the RTTLQG-Case 2, and the LQG-Case 2 in terms of the root mean square error in state, where the true state was directly obtained from the linear-quadratic regulator.

Figure 3. The simulation results of the state after the RTTLQG-Case 1 and the LQG-Case 2 at the last Monte Carlo run.

Figure 4. The simulation results of the state after the RTTLQG-Case 2 and the LQG-Case 2 at the last Monte Carlo run.
It is well known that there exists one fundamental approach for achieving computational efficiency in engineering applications: parallel processing.

LQG control algorithm proceeded in three steps. Step 1 established the state-space models of the scaling and wavelet coefficients of the DSCS by using the Haar WT. Based on these models, Step 2 designed the LQG control laws such that the stochastic performance indexes of the scaling coefficients model at the coarsest scale and the wavelet coefficients models at each coarser scale were minimized, in which the state estimates were obtained by using the distributed fusion with feedback (12). Step 3 was to successively compute the control laws of the scaling coefficients models at each finer scale using the controllers solved from step 1. The term real-time was meant in the sense that when a single new measurement was acquired at the finest scale, new fused estimate information at each coarser scale could be derived based upon all measurements available at all scales at the present sampling time (11). The parallel processing occurred in step 2, where the \( J+1 \) Riccati-type matrix difference equations could run in parallel. The complexity of each computation depended on the structures of \( A \), and for moderately dense matrix \( A \), remained approximately the same as in the DSCS. The maximum computational amount of the \( J+1 \) Riccati-type matrix difference equation was one half of the conventional LQG control approach. The control law solved from step 3 at the finest scale also guaranteed the desired performance in the first step. Moreover, the real-time transcale LQG control algorithm was applied to the stochastic control system with the single measurement at the finest scale.

Consider a 2nd-order DSCS with measurements at three different scales, where

\[
\begin{align*}
    x_{0,k_0+1} &= \begin{bmatrix} 1.1 & 0 \\ -0.6 & 1 \end{bmatrix} x_{0,k_0} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} u_{0,k_0} + \begin{bmatrix} 1 \\ -0.5 \end{bmatrix} w_{0,k_0} \\
y_{j,k_j} &= \begin{bmatrix} 1 & 0 \end{bmatrix} x_{j,k_j} + v_{j,k_j}, j = 0, 1, 2
\end{align*}
\]

For comparison, the real-time transcale LQG control and the conventional LQG control were also applied to the DSCS with the single measurement at the finest scale (11). For the sake of simplicity, we denote “RTTLQG-Case 1,” “RTTLQG-Case 2,” and “LQG-Case 2” for the real-time transcale LQG control for the DSCS with three measurements, the real-time transcale LQG control, and the LQG control for DSCS with the single measurement, respectively. The simulation results averaged over 100 Monte Carlo runs (11) are shown (Figures 2 through 4). It can be seen that the LQG-Case 2 slightly outperforms the RTTLQG-Case 1 and the RTTLQG-Case 2, since the LQG-Case 1 can guarantee optimal performance at the finest scale, but the proposed algorithm can guarantee optimal performance at each coarser scale. The average performance indexes are 6.5116, 6.5901, and 6.5992, respectively. However, by measuring the computational expense, it appears that the average CPU-time for the RTTLQG-Case 1 is about 0.4344 seconds, the RTTLQG-Case 2 is about 0.3634 seconds and that for the LQG-Case 2 is about 1.343 seconds. Thus we conclude that the RTTLQG proposed in reference 11 provides a good compromise between performance and computational cost.

The control algorithm combines the WT and conventional control approaches by establishing reasonable models and designing the algorithm to solve the control law. It should yield computational advantages and reduce the uncertainty and complexity of the problems based on the multiscale features of phenomenon or systems.

REFERENCES

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Scale-Free Networks, Fragile or Robust?

Chen Hong, Xian-Bin Cao, Wen-Bo Du, Jun Zhang

A network, which is a set of vertices or nodes with connections between them, is widely adopted to represent many real-world systems (1–9). Obviously, most real networks are neither simple random networks (10) nor regular lattices. Since the small-world property (11) and the scale-free network phenomenon (12) were put forward at the end of the last century, it has been found that many real networks are actually complex systems with small distance and power-law degree distribution (13). Over the past decade, the study of complex networks has advanced in many fields (14–16), and researchers have begun to realize that there must be a deep connection between the function and structure of networked systems. Since system reliability is of critical importance in many aspects of modern society, network robustness is an area of active investigation.

Network robustness is the ability of a network to maintain its topology connectivity when a portion of its nodes or edges are removed. The pioneering work of Albert et al. (17) found that complex scale-free networks would be robust with random errors (the random removal strategy, RRS), but fragile under intentional attacks (the high-degree removal strategy, HDRS). Since then it has been widely accepted that the “fragile” scale-free network will soon collapse if a few hub nodes are removed. Cohen et al. (18) investigated RRS in the Internet and introduced an analytical approach to find the percolation critical threshold of random networks. Holme et al. (19) further discussed the effect of four different attack strategies and found that the most effective strategy is to remove nodes according to the recalculated “betweenness.” Most previous studies assumed that the cost to remove any given node or edge would be the same (17–19). But in actuality, this cost can vary widely in many real-world networks. In the Internet, for example, the main servers are usually more secure such that attack on these servers should be more difficult than on other smaller, peripheral servers. Very recently, Zheng et al. (20) discussed the behaviors of the scale-free network under the selective node attack strategy with attack cost. They found that the scale-free network appears to be robust under intentional attacks.

The well-known Barabási-Albert (BA) model (12) is adopted in the cost-based model. The BA network model, which is generated using the growth and preferential attachment rules, is widely accepted as a suitable model for representing the structure of many realistic systems. Starting from a small core of nodes, the number of nodes increases throughout the lifetime of the network by the subsequent addition of new nodes exhibiting preferential attachment, i.e., the likelihood of connecting to an existing node depends on the node’s degree (12). The network robustness is quantified by the relative size of the largest connected component (LCC) $G=N’/N$, where $N’$ is the number of nodes in the LCC after attack, and $N$ is the number of nodes in the initial scale-free network. The larger the value of $G$, the more robust the network is.

Because the practical property of nodes or edges is usually heterogeneous, the cost of attacking them may vary. In the cost-based model, the nodes’ degree is used to measure the attack cost. Nodes and related links are removed until the value of total cost reaches a fixed fraction and the current relative size of LCC can be calculated.

Figure 1 shows the performance of RRS and HDRS on BA scale-free networks. It is found that HDRS is the best attack strategy when the attack cost is ignored (Figure 1A), which corresponds well with the work of Albert et al. However, when the attack cost is introduced, HDRS is no longer the best attack strategy unless the total attack cost is high (Figure 1B).

This interesting phenomenon can be explained approximately based on the experimental comparison of the network structures before and after attack. Figure 2A shows a small BA network ($N=100$ and $m_0 = m = 2$) and the top five hub nodes are marked. When the total attack cost is low, 26 nodes are directly removed under RRS (Figure 2B) and the LCC comprises 73 connected nodes. Both the average clustering coefficient $C$ and the average degree $<k>$ are lower, reflecting that the LCC is sparser than the initial network. Under HDRS, only six nodes (including four hub nodes and two non-hub nodes) are directly removed when the total attack cost is low (Figure 2C), resulting in six nodes that are jointly isolated from the LCC and 88 that are loosely connected. Compared with the LCC in Figure 2B, the LCC of the HDRS is larger but sparser. As $\rho$ increases for the RRS (Figure 2D), 46 nodes are directly removed and the LCC increases to 33. The average clustering coefficient $C$ is 0.04, the average path length $L$ is 5.17, and the average degree $<k>$ is 2.06. For the HDRS (Figure 2E), only 22 nodes are directly removed, but the main

Figure 1. (A) $G$ as a function of the fraction of removed nodes $f = N'/N$, where $N_i$ is the number of removed nodes and $N$ is the size of the initial network. (B) $G$ as a function of the total attack cost $\rho = \sum_{i=1}^{N} k_i / \sum_{i=1}^{N} k_i$, where $k_i$ is the degree of node $i$, and $Z$ is the set of removed nodes. Here $N=5,000$, $m_0 = m = 2$. Each datum is averaged over 20 independent realizations.

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framework is completely destroyed. The network splits into many small fragments, and the size of the LCC is only 10. The average clustering coefficient $C$ is zero, indicating that LCC exhibits a tree-like structure. For the BA scale-free network, there is a core of interconnected high-degree nodes that ensures the main framework of the network and the numerous low-degree nodes are likely to form a sparse out-core part. When the total attack cost is low, HDRS mainly attack the core and the out-core part is relatively safe. When the total attack cost is high, the core is completely destroyed and the sparse out-core part is also involved. Thus an intentional attack on a BA scale-free network is more effective when the total cost is high, and less effective when the cost is low.

It is well accepted that network heterogeneity plays a crucial role in network dynamics. From recent research advances, we know that the heterogeneous cost factor also has an important influence on the network robustness and that HDRS is no longer the best attack strategy unless the total attack cost is high. Such insights will be useful in further studies in the field of network robustness and optimal network design.

REFERENCES

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The School of Automation Science and Electrical Engineering (SASEE) at Beihang University, originally established in 1954 as the Aircraft Equipment Department, was the first department in China to focus on flight control systems. Over the past 58 years, SASEE has achieved national acclaim in scientific research and education. As the chief design organization, SASEE developed “Beijing No. 1,” the first flight passenger aircraft in China, the first coaxial twin rotor helicopter, and the first flight simulator in China. SASEE pioneers Shie Lin, Chuanyuan Wen, Xinfu Xu, Junqin Huang, and Weibing Gao, and their colleagues, made exceptional contributions to the foundation of several disciplines, including guidance, navigation and control, measurement technology and automatic devices, mechatronic engineering, and simulation.

SASEE now comprises five departments, three education centers, and two national research laboratories. These include the departments of Intelligent System and Control Engineering, Detection Technology and Automation Engineering, Mechatronic Engineering, Electrical Engineering, and Automatic Control; The Automatic Control and Measurement Education Center, Electrical and Electronic Education Center, and The Advanced Simulation Education Center; and the National Key Laboratory of Science and Technology on Flight Control, plus the Ministry of Education Engineering Research Center of Complex Product Advanced Manufacturing Systems.

Faculty
SASEE has 158 full-time faculty and staff, including 37 professors, 75 associate professors, and 40 assistant professors. Its faculty includes a member of the Chinese Academy of Engineering, a National Outstanding Contribution Expert, four Yangtze Fund Scholars, three winners of the National Outstanding Youth Fund, a Yangtze Fund Scholar Innovation Team winner, an Outstanding Teacher of Beijing, six winners of the New Century Excellent Talents in support of the Ministry of Education, and five Excellent Teachers of Beihang. Seventy percent of the faculty have Ph.D. degrees and many have international educational, teaching, or collaborative research experience.

Research Direction
SASEE research funding comes from the National Natural Science Foundation (NSFC), National High-Tech R&D Program (“863” program), National Basic Research Program (“973” program), and other national support programs as well as some industry/company collaborations. In recent years, SASEE has received a number of Key Projects from national support programs, such as a US$0.45 million grant from the NSFC for the development of a flight actuation system and a US$2.2 million from the “863” program for a Key Project on Cloud Manufacturing. SASEE receives about US$15 million per year.

SASEE is recognized as a premier institution for automation science and engineering, and mechatronics engineering research. SASEE research directions include:

Guidance, Navigation and Control
• Advanced flight vehicle guidance, navigation, and control
• Modeling, simulation, and virtual reality
• Precise navigation and guidance
• System reliability and safety
• Intelligent control and complex system control.

Measurement technique and automatic devices
• Health management of complex systems

SASEE is recognized as a premier institution for automation science and engineering, and mechatronics engineering research.

• Large measurement system development techniques
• Automatic testing under special environments
• New techniques for measurement and automatic devices
• Aeronautical and astronomic devices and electrical measurement.

Control theory and control engineering
• Modern control theory and applications
• Fault diagnosis and redundant control
• Intelligent transport system and information control
• Robotic control and navigation.

Pattern recognition and intelligent systems
• Intelligent pattern recognition and applications
• Biological feature information processing and recognition
• Intelligent optimization control and decision-making
• Intelligent automation under networked environments
• High-speed, real-time image processing and target recognition.

Electrical engineering and application
• Electrical system computer monitoring management systems for aircraft
• Rare-earth permanent magnet motors and redundant actuators
• Motors and control
• Electromagnetic field theory and noninvasive inspection
• Intelligent electric appliances.

Mechatronics engineering
• Design, control, and real-time simulation of mechatronic systems
• Fault tolerant control, redundancy, and reliability
• New actuation systems based on novel materials and structures
• Pneumatic and energy-saving technology
• Robotics.

Modeling and simulation theory and technology
• Modeling and simulation for complex systems
• Synthetic natural environments (SNE)
• Simulator and computer vision technology
• High-level architecture (HLA) and run-time infrastructure (RTI).

Complex product advanced manufacturing systems
• Cloud manufacturing
• Service science and technology
• Virtual prototype and integrated platforms
• High-efficiency computing.

Research Achievements
Five SASEE projects received National Science and Technology Awards:
(i) “High Reliable Aerial Hydraulic System and Application” won the 2nd Prize National Science and Technology Progress Award in 2010. The project presented a new type of active vibration control structure to decrease hydraulic system pulsation based on new vibration theory. This project designed a new type of water evaporator for aircraft to maintain the temperature within fixed limits. In order to extend system lifetime and reliability, the project presented a rapid robust fault diagnosis algorithm and accumulative damage model for prognostics. Results demonstrated that the hydraulic system could achieve high reliability and safety.
(ii) “Air Force Load Simulator Series” took the 2nd Prize National Technology Innovation Award in 2006. The project presented a new velocity synchronous control law to reduce extraneous force caused by actuation system operation. With the intelligent control law, low friction motor, and piezoelectric ceramic servo valve, the load simulator could
realize high-precision loading under a range of random loadings.

(iii) “The Redundant Flight Control System” received the 2nd Prize National Science and Technology Progress Award in 2001. The project presented a new type of redundancy structure with redundant sensors, computers, and actuators. Through designing appropriate monitoring and reconfiguration algorithms, the new type of redundant flight control system can guarantee higher reliability under failure condition.

(iv) “High Pressure Hydraulic System of Aircraft” took the 2nd Prize National Science and Technology Progress Award in 1999. This project designed a hydraulic pump and its accessories with 28 MPa pressure, adopting the active vibration control method to eliminate the pulsation and maintain good performance and fuel economy.

(v) “Flight Simulator” took the 1st Prize National Science and Technology Progress Award in 1985. It was the first flight simulator in China and provided actual flight training equipment for pilots. With the flight simulator, the researchers could verify the design of control systems and carried out flight simulation experiments on the ground.

In addition, SASEE has also won more than 40 Scientific Achievement Awards at or above the Provincial/Ministerial Level.

International Cooperation
Supported by Beihang University and the Chinese Ministry of Education and Ministry of Foreign Affairs, SASEE has established effective and long-term international collaborations with many world-class universities and institutes from Europe, the United States, Japan, and Russia, among others, and has signed reciprocal exchange agreements with these universities and institutes. Every year, the school sends more than 20 undergraduate and graduate exchange students abroad for joint training and research, and invites more than 20 top professors and experts to visit the school for collaborative research, curriculum discussion, and classroom lectures. The school has sponsored and hosted many important international conferences including the Asia Simulation Conference, the International Conference on Advanced Manufacturing, the IEEE Conference on Industrial Electronics and Applications, and the IEEE International Conference on Industrial Informatics. The school also founded the Chinese Guidance, Navigation and Control (GNC) Conference, which has extensive influence on the GNC field in China. Two international journals, published by Emerald Group Publishing and the World Scientific Publishing Co., have been founded.

Student Training
SASEE provides high-level education, from undergraduate to Ph.D. programs. Bachelor’s degree programs include two subjects: automation and electrical engineering. Master’s programs consist of nine subjects: navigation guidance and control, control theory and engineering, measurement techniques and automation, pattern recognition and intelligent systems, modeling simulation and techniques, mechatronic engineering, electrical engines and appliances, power electronics and electrical transmission, and electrician theory and new technology. Doctoral programs cover seven main areas: navigation guidance and control, control theory and engineering, measurement techniques and automation, pattern recognition and intelligent systems, modeling simulation and techniques, mechatronic engineering, and electrical engines and appliances. The school also provides international student education programs with such international partners as Superlec, France; Czech Technical University in Prague; University of Toronto, Canada; University of Tokushima, Japan;
Research Advances in Automation

Control Theory
The discipline of Control Theory and Control Engineering at Beihang University was established by Professor Weibing Gao (1925–1994), a member of the Chinese Academy of Sciences and a well-known specialist in control theory. The discipline was among the earliest in China to confer Ph.D. degrees approved by the Academic Degrees Committee of the State Council. Its research fields cover nonlinear control systems, robust control, intelligent control, adaptive control, robotic control, and unmanned vehicle control.

One of Gao’s most outstanding achievements is the introduction of a new design method in variable structure control research. The variable structure control strategy with sliding modes was first proposed and studied during the 1950s by scholars in the former Soviet Union. Due to its robustness for modeling uncertainties and external disturbances—and its simplicity in design and implementation—the variable structure control strategy has been applied to a wide variety of engineering systems. However, in the first iteration of the variable control theory, the lack of systematic design procedures for multi-input systems, as well as few methods to reduce chattering in variable structure control systems, greatly affected its use for practical applications.

In order to overcome these problems, Gao developed the “reaching law method” for variable structure control design. Using this method, variable structure controller design is simplified to algebraic equation; by properly choosing the function and parameters in the equation, variable structure controllers with different dynamic performances can be obtained. Therefore, the “reaching law method” is an effective means for reducing chattering in variable structure control systems and guaranteeing control process quality. This design method is easy to use and can be applied to many complex systems. Today, the “reaching law method” has become a fundamental approach to designing variable structure controllers and has been widely used in China and abroad. Two monographs written by Gao, Fundamentals of Variable Structure Control Theory and Theory and Design Methods of Variable Structure Control, won the 1st Prize National Excellent Science and Technology Books Award and greatly promoted variable structure control research in China.

Additional research on variable structure control theory have led faculty within the discipline of Control Theory and Control Engineering at Beihang University to establish the variable structure control theory of stochastic systems, which solved some fundamental theoretical problems in variable structure control theory of discrete, time-delay, and nonlinear systems.

Other research achievements include: adaptive stabilization and tracking control of uncertain nonholonomic systems with applications in mobile robot control; underactuated mechanical system control based on energy shaping; high-precision intelligent modeling and control of systems with dynamic delay nonlinearity as well as applications to active vibration control of intelligent structures; robust fuzzy controller and reliable fuzzy controller design of nonlinear systems, distributed parameter, time-delay, and stochastic jump systems; variable structure model reference adaptive control, backstepping adaptive control, and adaptive dynamic surface control of uncertain systems; modeling and control of city intelligent transportation systems; and high precision attitude control of spacecrafts.

Virtual Reality and Flight Simulation
The Virtual Reality and Flight Simulation Technology Research Group, part of the School of Automation Science and Electrical Engineering at Beihang University, is now part of the State Key Laboratory of Virtual Reality Technology and Systems (VR Lab), and also an important participant in the National Key Laboratory of Aircraft Control Integration Technology. This research group belongs to Navigation, Guidance and Control, a national key discipline.

The research group, formerly known as the Advanced Simulation Technology Lab (AST Lab), is one of the earliest research units in China to work on simulation systems and technology. The AST Lab developed China’s first Civil Aviation Flight Simulator, the Y7 Simulator, which won the 1st Prize Department of Aviation and Technology Progress Award in 1994.

The flight simulation is the most common application for virtual reality technology and the majority of flight simulators are used for pilot training. Flight simulation also plays an important role in aircraft design. In some aircraft development programs, particularly for new aircraft, the engineering flight simulator provides the basis of the software for developing subsequent training flight simulator models. With the increasing levels of systems integration in modern aircraft, the avionics design teams may require an airframe model and an engine model and similarly, the engine design teams require avionics systems models. Many systems have been developed during the past decade. Examples include:

(i) The Virtual Cockpit System, which was developed based on head-mounted displays (HMDs), data gloves, and motion tracking devices. It was used to design next generation military aircraft and carrier-based aircraft take-off and landing simulations.

(ii) A multi projector tiled-display system that has been successfully implemented in the aviation, aerospace, shipbuilding, and automobile industries as well as engineering education. In this system, some novel algorithms were proposed, including geometric distortion correction, edge blending, color correction, and parallel pipelined synchronous rendering.

(iii) Participation in a demonstration study of China’s ‘Shenzhou’ series of spacecraft and elements such as astronaut extravehicular, manual rendezvous, and docking methods. The group also has taken
part in lunar soft landing demonstrations, simulations, and verification.
(iv) Since 2009, the group has been developing a full mission flight simulator system based on a large aircraft. The goal is to supply the first level D flight simulator in China. To date, breakthroughs in several key technologies have been made, such as large aircraft dynamics, kinematics, control logic modeling and simulation, multichannel imaging geometry correction and edge blending, electric control loading system, a full-electrical six degrees of freedom motion platform, an off-axis virtual image display system, photorealistic scene rendering, sound rendering, weather modeling, and an instructor station. Now the group is working on engineering improvement, standardization, and qualification test guide (QTG) certification specification research.

Flight simulation is at the leading edge of several technologies, particularly in virtual reality, computer graphics, distributed computing, and mechanical actuation.

Cloud Manufacturing
In the manufacturing industry, service, agility, knowledge-based innovation, and environmental considerations, have become the key elements of enterprise competitiveness and a developing trend of IT applications. Fostering a new mode of manufacturing service to improve TQCSEK (i.e., fastest Time-to-market, highest Quality, lowest Cost, best Service, cleanest Environment, and most Knowledgeable), is emerging as a major challenge for the manufacturing industry in the next generation. At the same time, some new technologies have emerged and been applied in various fields, such as cloud computing, internet of things (IoT), and service-oriented technologies (SoT), which are enabling the above issues in manufacturing to be effectively addressed. By combining these technologies with existing theories and technologies of manufacturing informationization, Professors Bo Hu Li and Lin Zhang and their team proposed a new manufacturing paradigm in 2009: Cloud Manufacturing (CMfg).

In CMfg, manufacturing resources and capabilities are transformed into manufacturing services, which can be managed and operated in an intelligent and unified way to enable the full sharing and circulation of manufacturing resources and capabilities. Compared with cloud computing, the types of resources to be shared and ways of providing services are enriched and expanded, and more technologies are involved in CMfg. As illustrated in the CMfg concept model, the cloud manufacturing system consists of three factors: manufacturing resources and capabilities, the manufacturing cloud, and the whole manufacturing lifecycle; one core support: knowledge; two processes: import and export; and three types of stakeholders: providers, cloud operators, and customers.

Manufacturing resources and capabilities can be intelligently detected and connected into the network, and are automatically managed and controlled. They are then virtualized and encapsulated into manufacturing cloud services that can be accessed, invoked, and deployed. This process is called “import,” and several such cloud services combine to form a manufacturing cloud. In a manufacturing cloud, many types of services involved in the whole manufacturing lifecycle are included, such as design as a service (DaasS), machining as a service (MaasS), simulation as a service (SIMaaS), management as a service (MANaaS), maintenance as a service (MTaaS), and so on. The “export” process is activated when the customer takes advantage of man-machine interface technologies to obtain on-demand services from the cloud to complete their required manufacturing tasks. The cloud operator deals with flexible and dynamic management and operation of the manufacturing cloud to support the cloud service platform for both providers and customers, which can match the most suitable services to different customers and provide a virtual collaborative environment or solution for complex tasks.

Knowledge plays a central role in the operation of a manufacturing cloud. In a CMfg system, knowledge-based aggregation and integration through the whole manufacturing lifecycle is possible. Conversely, knowledge in the cloud will give support to the whole lifecycle of services, including service description, deployment, matching, composition, configuration, collaboration, and maintenance.

In 2011, the National High-Tech R&D Program (“863” program) launched a key project named “Research on key technologies of cloud manufacturing service platform.” There are over 300 researchers from 28 universities, enterprises, and institutes involved in the project, and Professor Lin Zhang from Beihang University was appointed as the Principle Investigator.

The manufacturing cloud research team has published over 50 papers on cloud manufacturing to date—a number of which have contributed to special issues in journals—both in Chinese and English. Several workshops and sessions on cloud manufacturing have also been organized at important international conferences, as more and more researchers from both China and other countries are now paying attention to cloud manufacturing.
The School of Energy and Power Engineering

The School of Energy and Power Engineering, while recognizing its mission and goals under the national core strategies, continuously works to meet challenges from scientific, industrial, and societal advances through optimizing higher education and research in relevant subjects.

The School of Energy and Power Engineering (SEPE) at Beihang University, which was originally established in 1952 as a department of aero-engine research and education, has played a unique role in the area of Aerospace Science and Engineering in China. Over the years, the research and educational activities have continually been adjusted to address the range of disciplines necessary for leadership in the evolving aerospace power and energy industry of today and tomorrow. All students at SEPE are educated and trained to function as professionals who can formulate, analyze, and solve a wide array of problems. Thus far, more than 8,000 undergraduates and over 2,000 postgraduate students, including more than 300 doctoral students, have graduated from the school. These graduates have made significant contributions in aerospace and other industrial fields, and have held positions of high responsibility in government, industry, and education. In fact, there are only five members with aero-engine design and research backgrounds in the Chinese Academy of Engineering and all are SEPE alumni.

Over the past six decades, the school has grown into a multidisciplinary institute comprising the departments of Aviation Propulsion, Fluid Machinery, Engineering Thermophysics, and Thermal Engineering. The school offers both undergraduate and postgraduate programs with Ph.D., Master's, and Bachelor's degrees. Current Ph.D. programs include Aerospace Propulsion Theory and Engineering, Fluid Machinery, Engineering Thermophysics, Thermal Engineering, and Turbomachinery and Engineering. Aerospace Propulsion Theory and Engineering was appointed as a national key discipline by the Ministry of Education, and has been ranked first in the national discipline evaluation of this field. Among them are two members of the Chinese Academy of Engineering, Professors Maozhang Chen and Daxiang Liu, both praised by the Chinese Central Government and relevant ministries for their outstanding contributions to gas turbine aerodynamics, viscous fluid dynamics, high-altitude simulation test technologies, and complicated numerical simulations of aero-engine operation and performance. Professors Xiaofeng Sun and Liping Xu have been granted Outstanding Youth Funds, and Yangtze River Scholarships have been awarded to Professors Xiaofeng Sun and Zhi Tao. Professor Ge Gao also earned a 1st Prize National Technology Innovation Award and a National Aviation Golden Award.

Current Research

SEPE faculty conduct research over a broad range of topics organized into one National Key Laboratory and two research centers with five specialist sections. The National Key Laboratory on Aero-Engines has a leading position in the aerodynamics of fans and compressors and the design of a compressor cascade with splitter vanes. The Aero-Engine Numerical Simulation Research Center (ASRC) possesses excellent computing capabilities and an experimental database. The Energy and Environment International Center (EEIC) provides a collaborative environment where a worldwide team of researchers and educators can work together to find innovative solutions to national and global energy and environmental issues, and provide students with the training and vision necessary for a clean and sustainable future.

The Turbomachinery Aerodynamics and Aeroacoustics (TAA)
research section has conducted various experimental studies and numerical simulations to identify mechanisms of complicated airflows. A new stereoscopic particle-image velocimetry (SPIV) method with high-resolution velocity results was developed and can be easily carried out in multistage turbomachinery flow studies. In fundamental turbulence research, a high-fidelity flow solver (ASTR) with high-accuracy numerical schemes for compressible complex turbulent flows were developed for the study of the dynamics of turbulence motions. In the area of turbomachine computational fluid dynamics (CFD), a new technique taking in the unsteady blade row interactions was developed that provides significant predictive improvements compared with the conventional method. Different levels of prediction tools have been developed for aeroacoustics, especially for jet noise, duct acoustics, turbomachinery noise, airframe noise, and wind turbine noise. In particular, a set of high-order computational aeroacoustic solvers for the understanding of sound generation from complex flows and a unified model for studying the effects of acoustic liners on the sound radiation generated by rotating fan blades have been developed.

The Engineering Thermophysics (ET) research section has two main research areas: heat transfer and energy. Efforts in heat transfer research have been devoted over the past 20 years to the complex fluid flow and heat transfer under rotating frames. Various experimental apparatuses have been developed, including a multifunctional rotating heat transfer test rig and a rotating film cooling test rig, and extensive experiments were carried out on flow and heat transfer through serpentine passages, impingement cooling, and film cooling. Research has focused mostly on the interaction between inertial and noninertial forces such as the Coriolis and buoyancy forces. Several in-house algorithms have been developed, including traditional simple-class codes, as well as the Arbitrary Lagrange-Euler (ALE) and Large Eddy Simulation (LES) codes. Many standard turbulence models were modified according to new experimental data and then embedded into algorithms. For energy research, special attention has been paid to the development of small-scale distributed power systems with solar-fuel complementary under the organic Rankine cycle (ORC), Stirling cycle, or Brayton cycle. An 18-kW ORC power system is being tested to investigate the influences of the working fluid, pressure, and temperature on efficiency.

The High-Efficient and Low-Emission Combustion (HELEC) research section focuses on the mechanism of improving atomization, fuel/air mixing, ignition, flameholding, turbulent combustion, emissions, and temperature distribution. Some innovative advances in liquid jet breakup, predictive modeling of the Lean Blowout limit of combustors, reaction mechanisms, fuel/air mixing, flame evolution process, and numerical simulations have been achieved. Some of the achievements of this group include: the setup of high temperature and pressure combustion test rigs for visualization and nonintrusive measurement; the design of high-temperature combustors with tri-swirlers, and low-emission combustors with central staged configuration, lean direct multi-injection, and rich quench lean configurations; the development and testing of high-intensity combustors that are shorter in length than previous models; the detailed analysis of the process of combustion in complex combustors; the proposal of new theories for predicting the bag breakup regime and the lean blow out limits of combustors, and of innovative criterion for the optimization of mixing in quench configurations; and the generation of new models for computational simulation of fuel droplet evaporation and combustion in relatively large grids.

The Structural Strength, Vibration and Control (SSVC) research section focuses on aeronautical engine performance, structural strength, vibration and reliability, and engine control. In the area of structural strength and reliability, fundamental and applied research in multidamage mechanisms has been developed, including thermo-mechanical fatigue (TMF), low cycle fatigue coupled creep (L-CF-creep), low-high cycle fatigue (L-HCCF), life prediction based on aerodynamic-thermal-structural coupling analysis through experimental and numerical methods, and probabilistic design on hot sections of the aero-engine. In particular, a probabilistic design system for turbine disk (T-PDS) has been established that takes into consideration random uncertainties such as loadings, material properties, and geometries. Innovative research facilities have been established, including a Ferris Wheel L-HCCF tester, a TMF facility for turbine blades and a LCF-creep facility for testing standard specimens, as well as actual turbine components, at elevated temperature. In the area of structural vibration, metal rubber (MR) made of shape memory alloy (SMA) wires has been proposed that may actively control an aero-engine’s vibration. Additionally, a novel MR with a negative Poisson ratio was proposed that possessed much higher damping and tremendous load resistance. New studies into engine design, lifetime, and structural reliability based on new materials and manufacturing processing are ongoing.

The Energy and Environment (EE) research section is conducting cutting-edge research in key areas of global interest, including development of alternative aviation fuels, green aviation engines, as well as solar energy, wind energy, hydrogen fuel production and utilization, biomass, distributed energy systems, and heat engines for polygeneration. The section is also an active participant in domestic and international policy research related to climate change and clean energy development. The development of new aviation fuels includes algae-based fuels, Fischer-Tropsch synthesis fuel, and will oil-based fuel. The main objective is to develop the use of alternative aviation fuels with a long-term outlook, to help improve energy independence, lessen global-warming effects, and to help mitigate the economic uncertainty of crude oil prices. New approaches and new alternative fuels to power aircraft will be investigated, at the same time reevaluating fuel specifications and reconsidering safety concerns throughout the aircraft.
Recent Advances at SEPE
Over the past five years, researchers at SEPE have published more than 600 scientific papers in high-impact international journals and have been awarded over 60 critical research grants including four from National Key Scientific Projects, three from the Chinese National High Technology Research and Development Program, and 50 from the Chinese Natural Science Foundation. Financial support has also been provided by such global companies as Boeing, Airbus, Rolls-Royce, and General Electric. In terms of international collaborations with academic institutions, SEPE has established solid links with the Massachusetts Institute of Technology in the United States, Aachen University in Germany, École Centrale de Lyon in France, and other partners. SEPE has also hosted and organized the biennial International Symposium on Jet Propulsion and Power Engineering since 2006.

Looking to the Future
With the above work as a foundation, SEPE has defined six research areas that represent great challenges and grand opportunities. These include heat transfer, structure strength, aero-engine control, dynamics, aeroacoustics, and sustainable energy application in aviation. More importantly, emphasis will be put on the substantive collaborations and active interactions across multidisciplinary research areas in order to tackle the most challenging problems from aerospace power and energy engineering. Currently, the research around sustainable aviation and green energy has been reorganized into a new team, significantly expanding the efforts in the enhancement of engine safety and reliability, and the reduction of various emissions (such as carbon dioxide and nitrogen oxides) and engine noise through innovative ideas in a variety of areas. In addition, the educational program will be gradually reformed to adopt modern aerospace propulsion and energy systems engineering practices as the context for the curriculum and pedagogy.

Now, SEPE has plans to enhance its scientific research output with the core goal of developing high-efficiency, low-emission, and low-noise gas turbine engines, while continuing to ensure that national strategic requirements of aircraft development are met. With SEPE laboratories enjoying recent enhancements in its diagnostic equipment and numerical simulation facilities, scholars from all of world are invited to join us in advancing higher education and research achievement in all of our research areas.
From Migratory Bird Flight to Internal Compressor Flow

Sheng Zhou and Anping Hou*

The axial flow compressor is a key component of modern turbofan engines. There are several rotor and stator rows in the axial flow compressor (Figure 1A), analogous to hundreds of “wings” in the flow field. Moreover, some are rotating and some are static, so the unsteady property of the flow field is obvious. Yet current aerodynamic designs are based on simplified assumptions of steady flow (1), meaning there is a large difference between the anticipated flow in an axial flow compressor and what happens in reality.

The difference between assumed and real conditions means that the potential exists for improving performance in axial flow compressors. In order to tap this potential, we turned our attention to the flight formation of migratory birds (Figure 1B). The record of migrating birds flying in a “V” formation can be traced back to China’s pre-Qin period. The first papers to quantify the energy savings achieved by migratory birds flying in formation were published in Nature in October 2001 (2, 3). Inspired by these studies, we compared the energy savings of migratory birds when flying in formation with the flow in an axial flow compressor in order to improve the space-time structure and unsteady vorticity fields of the compressor to improve its efficiency and flow stability, and to decrease its operational failure rate (6, 7).

We have conducted several successful studies using theoretical modeling, numerical simulations by Computational Fluid Dynamics, and experimental work. We proposed the theory of unsteady cooperative flow type in multibodies with relative motion in the flow field of an axial compressor. The study indicated that an unsteady flow structure form such as an inlet guide vane’s wake frequency and phase will be beneficial to the compressor’s aerodynamic performance. For example, experiments carried out in a single-stage transonic compressor at its designed rotation speed showed that the surge margin, which reflects the flow stability, increased from 8% to 24% (8).

Additional work on this problem is ongoing in the authors’ research group.

Figure 1. (A) The inside of a compressor is composed of rows of rotating rotors and stators, and the flow field is unsteady. A rational organization of the interaction between the cascade wake and the cascade flow field downstream can significantly improve the aerodynamic performance of the compressor flow field. (B) Observations published in October 2001 by French scientists showed that in comparison with flying individually, white pelicans have a lower frequency of wing-beating when flying in formation, and their heart rate could thus be reduced by 11.4% to 14.5%. This figure was also of the same order as the energy saving gained by the white pelicans.

REFERENCES

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The record of migrating birds flying in a “V” formation can be traced back to China’s pre-Qin period.
of aggregation and the Big Bang, are thought to have created all the larger particles subsequently discovered and further aggregated to form stars, and the gravitational space of the matter-state.

Singularitons exist in two states, meaning they continuously are in the process of transforming from a particle state into an imaginary state, and vice versa. The absolute time of each conversion is predicted to be $1 \times 10^{-15}$ s. The singulariton’s particle state has a diameter of $1 \times 10^{-40}$ m, and mass of $2.1 \times 10^{-72}$ atomic mass units ($\text{amu}$); the singulariton’s imaginary energy space has a diameter of $10^{-78}$ m, but has zero mass. We therefore conclude that the singulariton is responsible for matter’s mass!

**Dark energy and Dark matter**
The dark energy particle is hypothesized to consist of a Zhao particle and two sub-energy particles that constitute the cosmic gamma ray (Figure 1). The particle’s energy is $1.3 \times 10^9$ eV and its mass is $2.25 \times 10^{-13}$ times that of an electron ($\text{e}$).

We believe the dark energy particle to be the unique particle that transfers information energy from virtual information space to real matter space (Figure 2). It can form a high-speed rotating vortex inside the particle, which can attract the energy of virtual space or vacuum energy in the form of a macro-scale black hole, and then inject a singulariton flow into the real matter space via a white hole. The concept of a white hole is the opposite of a black hole, which sends energy or mass flow out of the center of a singulariton. The jet stream of the singulariton flow has a repulsive property that is theorized to be the root cause of our ever-expanding universe (2).

Dark energy particles can polymerize into dark matter once the rotation rate declines (Figure 3). Dark matter and dark energy account for 95.6% of the total mass of the universe, yet do not react with light and are nonmagnetic (2). Usually, dark matter exists as clouds surrounding solid stars. Meanwhile, dense dark matter may develop into quasars. The energy of quasar arises from the explosion of dark matter, which far exceeds the energy of nuclear fusion (1).

**REFERENCES**
Unsteady Vortex Lift: From Drosophila to Man-Made Fluid Machines

Xiaofeng Sun*, Lin Du, Xiaodong Jin

The seemingly magical flight ability of some insect species such as Drosophila has long interested experts of fluid mechanics (1–3). Figure 1A captures the instant when a hovering Drosophila is flapping its wings. It has been found that Drosophila cleverly utilizes the unsteady vortex effect to produce lift, which is known as the Weis-Fogh mechanism. The time-average lift coefficient due to the Weis-Fogh mechanism can be up to two to three, so a pair of small wings is enough for the insect to hover and maneuver in the air. In contrast, as far as we know, only the steady circulation effect has been exploited to produce blade lift in man-made fluid machines, with the useful lift coefficient seldom exceeding 1.3.

We set out to answer the question: is there any commonality between the underlying flow physics of Drosophila flight and man-made fluid machines? In our recent studies (4, 5), the flow details of both insect wings and the cascade blades of a turbomachine as illustrated in Figure 2A are simulated using the immersed boundary method with a global treatment of discontinuous boundary conditions, and the results are presented in Figures 1B and 1C, and 2B and 2C. Although there seems little resemblance between the clap-and-fling motion of Drosophila wings and the rotary motion of turbomachine blades, it is shown that, as the axial spacing between adjacent blade rows is reduced, the interaction between the blade rows can generate unsteady vortices around the leading and trailing edges of the blades and thus increase the average pressure loading of the cascade. Inspired initially by the Weis-Fogh mechanism, our findings raise the possibility of utilizing a novel mechanism—the unsteady vortex lift through the blade row interaction—to enhance the performance of fluid machines.

REFERENCES

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The School of Aeronautic Science and Engineering

The School of Aeronautic Science and Engineering, has distinct aeronautic and astronomic characteristics. It is dedicated to research and education in fundamental engineering problems as well as to new concepts, theories, and methods of general design, aerodynamics, structure, strength, flight dynamics, human-machine environments, and control of all kinds of aircraft including airplanes, helicopters and airships, near-space vehicles, and miniature aircraft.

The School of Aeronautic Science and Engineering (SASE), formerly the Department of Aeronautics of Tsinghua University, is one of only two departments that existed when the Beijing University of Aeronautics and Astronautics (now Beihang University) was first established. Originally named the Department of Aircraft, it offered two majors, Aircraft Design and Aircraft Technology. The Department has been renamed many times since then: the Department of Aeronautics and Engineering Mechanics in 1958, the Fifth Brigade in 1972, and the Department of Aircraft Design and Applied Mechanics in 1989, but has been known as the School of Aeronautic Science and Engineering since 2003.

SASE’s faculty has included many well-known experts in the fields of aircraft design and mechanics, including Shoue Tu, Derong Wang, Shijia Lu, Yuan Shen, Junkuai Wang, Liyi Wu, Guilian Zhang, Xingfu Xu, Huafang Xu, Qinzh He, Ronglin Wu, Chaoli Shi, and Fengpei Ye. These researchers have laid a solid foundation for SASE’s future development, and Shoue Tu was the first head of the department. SASE has consistently produced excellent graduates, many of whom have remained at Beihang University. SASE participated in the establishment of the Seventh, Third, and Fourteenth departments, the School of Aeronautics, the School of Pilots, The Institute of Unmanned Aerial Vehicles, the Department of Civil Engineering, and the School of Transportation Science and Engineering.

Over more than half a century of operation, SASE has trained some 1,696 Master’s students and 725 Doctorates, many of whom have made outstanding contributions in both national aeronautics and astronautics, as well as defense science and technology. Our school has provided a number of talented individuals to the aeronautics and astronautics industry, including Yong-zhi Wang, chief engineer of the manned astronautic project; Faren Qi, chief engineer of the “Shenzhen” spacecraft; and other eight members of the Chinese Academy of Sciences and the Chinese Academy of Engineering. Included in SASE’s alumni is Jia-jun Yuan, who was included among the 11th Annual “Top Ten Outstanding Youth in China” and the chief commander of the “Shenzhou” spacecraft, the first of its kind in China.

SASE has filled many scientific and technological gaps nationwide by making and launching aircrafts such as Beijing-1, the first light aircraft in China; the first high-altitude and high-speed unmanned aerial vehicle (UAV) in China; target drones; the first coaxial rotor helicopter; and the Honeybee series light aircraft (Honeybee-3c, Honeybee-4, and Honeybee-11), which at one time represented 70% of the national light aircraft market. SASE has taken part in research work for national key aeronautic projects, and has won hundreds of national, provincial, and ministerial level teaching and research awards, including more than 20 national prizes.

SASE has 169 faculty members, including 56 professors, 57 associate professors, and 52 doctoral supervisors. Full-time teachers account for 73% of all faculty, and 83% of our instructors have a doctoral degree. There are five CAS members among SASE faculty, including Yuan Shen, Zhenpiong Gao, Chunxuan Li, Jun Wang, and Tian Li, as well as seven Yangtze River Scholars (Huimin Fu, Mao Sun, Jialing Yang, Yitian Gao, Zhe Wu, Jijin Wang, and Jinwu Xiang), who influence the field of aeronautics both at home and abroad. Our faculty is characterized by integrity, persistence in academic pursuits, and patience in teaching, and also includes a National Teaching Master, three National Outstanding Youth Fund winners, and eight New Century Excellent Talents.

There are six departments within SASE, including the departments of Aircraft, Human-Machine and Environmental Engineering, Aerodynamics (formerly the Institute of Fluidics), Aircraft Structure and Strength (formerly the Institute of Solids), Flight Mechanics and Flight Safety, and Dynamics and Control. SASE also houses the Institute of Miniature Aircraft Design and the Research Center of Aviation Development Strategy.

SASE has three first-class disciplines and 10 second-class disciplines, and also has three undergraduate programs including Aircraft Design and Engineering, Aircraft Environment and Life Protection Engineering, and Engineering Mechanics. The discipline of Aeronautical and Astronautical Science and Technology ranks first and Mechanics ranks second in China, and both are the first-class national key disciplines. SASE also has 10 doctoral programs, eight Master’s programs and three postdoctoral positions. Aeronautical and Astronautical Science and Technology, and Mechanics are first-class doctoral disciplines, and Fluid Mechanics, Solid Mechanics, Aircraft Design, Human-Machine and Environment Engineering, Engineering Mechanics, and General and Fundamental Mechanics are national key disciplines.

There are many laboratories, centers, and bases in SASE including the National Laboratory of Computational Fluid Dynamics, the State School in Mechanics Course Teaching Base, the National Aeronautical and Astronautical Teaching Demonstration Center, the Key Laboratory of Fluid Mechanics of the Ministry of Education, the Key Discipline Laboratory of the Ergonomic and Environmental Control of National Defense, the Beijing Key Laboratory of Powder Technology, and the Beijing Mechanical Demonstration Center, as well as the Aviation Innovation and Practice Base, Plane Showroom, Teaching Experiment Center of Fluid Mechanics, Teaching Experiment Center of Solid Mechanics, the Laboratory of Flight Mechanics, and the Laboratory of Environment Modeling and Simulation. The Beijing Aviation Museum is also housed at SASE, and is one of the most famous aeronautical teaching and popular science bases in China.

SASE’s teaching achievements under the 10th National Five-Year Plan are numerous, including two National Teaching Achievement.
The Research Center of Solid Mechanics

The Research Center of Solid Mechanics (RCSM) at Beihang University was founded in 1980. Solid mechanics was among the first disciplines at Beihang University authorized to award Ph.D. degrees in 1981 and qualified to accept postdoctoral researchers in 1987. The scientific research projects completed by RCSM faculty have led to important theoretical findings and results with significant application value to aerospace engineering. Some of these findings have been directly applied to aircraft, missiles, satellites, and manned space flight, with significant economic and social benefits. Below are some of the research groups at RCSM.

Small Sample Technology

The Research Center of Small Sample Technology at Beihang University focuses on Reliability, Lifetime Prediction and Control, and Small Sample Statistics. Professor Huimin Fu is director of the research center. He discovered the fatigue strength distribution function, for which he was awarded the National Natural Science Award. Moreover, three of his other scientific achievements, “The Method of Reliability Life Prediction for Aircraft Structures,” “Aeronautical Material Database,” and “Research on Fatigue and Fracture of Aerospace Polymers,” have won National Science and Technology Progress Awards from the Aerospace Industry Ministry. In statistics, Professor Fu established a method for interval estimation and a hypothesis test for percentiles and percentages of continuous distributions, discovered the rank distributions of incomplete data, and developed the 2-D tolerance factor method, which can raise the precision of forecasts and controls. He founded the statistics of percentiles and percentages, and contributed heavily to the development of mathematical statistics and reliability. In fatigue and fracture analysis, he developed the concept and practice for controlling structural lifetime through nondestructive inspection. According to actual inspection requirements, the crack growth duration and inspection intervals of structures can be effectively controlled by this method. This has moved traditional lifetime predictions toward lifetime control, and the research on structural lives from passive to active.

Crashworthiness Design of Aircrafts

This research group is interested mainly in the crashworthiness design of aircraft, plastic deformation and failure of deformable structures under intense impulsive loads, stress wave propagation in solids, lightweight composite material designs, and impact experiments. The research team has developed novel ideas and methods for the analysis of impact dynamics and plasticity of deformable structures, including the dynamic plastic failure of a space free-free slender shell under intense dynamic loading, the three-stage plastic failure modes for deformable structures with consideration of large deformation, plastic dissipation and softening, the viscous plastic failure criteria for large deflection dynamic plastic response of structures with initial cracks, a series of dynamic experiments on elastic plastic flexural wave propagation and transient deformation prediction, and the relations between the deformation modes and loadings based on the rigid plastic model and elastic plastic model.

Lightweight Composite Materials and Porous Materials

This group, led by Professor Zixing Lu, studies lightweight composite materials and porous materials in the following major areas: (i) Exploring, characterizing, and understanding the structures, behaviors, and functional properties of fiber-reinforced composites across macro- and microlength scales; (ii) Quantifying fundamentals such as the constitutive relationship, damage evolution, and energy adsorption mechanisms of polymer and ceramic matrix composites in order to predict their mechanical behaviors over a wide variety of timescales and loading conditions; and (iii) Constitutive and multiscale modeling of conventional and auxetic foams to explore and predict the mechanical properties and...
provide a foundation for the application of porous materials with a negative Poisson’s ratio.

To date, Professor Lu’s group has made an in-depth study of the mechanical behaviors of 3-D braided composites as well as advancing a multiscale method for modeling the damage evolution of fiber-reinforced composites from the macro- to the microlength scale. In addition, to overcome the drawbacks of previous models for auxetic foams, Lu and his colleagues developed a quasi-3-D model for auxetic foams based on the model of Choi and Lakes, and provided a more precise description of the volumetric compression ratio.

Structural Dynamics
In the past, the exact solutions for the free vibration of a rectangular thin plate could be obtained using the semi-inverse method only for the case where at least two opposite edges are simply supported. Methods for obtaining exact solutions in other cases have proved to be a bottleneck in elastic mechanics for over a century. In 2009, Yufeng Xing and Bo Liu (1–2) made an important breakthrough and provided solutions for free vibration of isotropic and orthotropic thin rectangular plates with any combinations of simply supported and clamped boundary conditions by direct separation of the variable method instead of the inverse method. Finding the solutions to the problem of thin plates with CCSS, CCCS, and CCCC (where S = simply supported, and C = clamped) boundaries were previously considered impossible. Using the same approach, Xing and Liu have also made significant progress and obtained some new solutions for the in-plane free vibrations of a plate, the free vibrations of Midlin plates, and Donnell-Mushtari shells.

Computational Solid Mechanics
The group led by Professor Zhipin Qiu focuses on modeling and analysis of uncertain dynamic systems, computational solid mechanics, structural reliability, fatigue strength of vibrating systems, mechanics of composites, structural damage identification, and structural dynamic loads identification. Dr Qiu and his assistant Professor Xiaojun Wang are two of the earliest scholars to apply the nonprobabilistic set theoretical method, including interval analysis and convex models, to the analysis of uncertain structures. Their research activities were supported by the National Youth Science Foundation, the National Natural Science Foundation of China, the Institute of Engineering Physics, the National Postdoctoral Science Foundation, the Aeronautical Supporting Technology Foundation, and the Astronautic Supporting Technology Foundation.

Thermal Strength Laboratory
The research activities of the Thermal Strength Laboratory at Beihang University’s School of Aerospace Science and Engineering focus on the research and development of transient aerodynamic heating environment simulation techniques and thermomechanical testing techniques in extreme environments. These techniques are vital to the development and optimization of various heat-shielding materials and structures indispensable to hypersonic flight vehicles.

We have established an international advanced-level certified aerodynamic thermal environment simulation system. The radiation-based aerodynamic heating simulation system, developed locally, is capable of replicating the extreme severe nonlinear transient aerodynamic heating environment experienced by a hypersonic flight vehicle, with a maximum heat flux of 2 MW/m², a maximum heating rate of 210°C/s, and a maximum temperature of 1,550°C.

In recent years we have, for the first time, developed advanced noncontact, full-field, high-accuracy optical techniques for measuring shape and deformation in extreme, high-temperature environments. Using the advanced aerodynamic heating simulation system we developed and the corresponding thermal-mechanical testing techniques, we have completed more than 100 research and engineering projects for various aerospace institutes, including several innovative and challenging projects. The experimental systems and techniques have been praised by domestic research institutes and have made important contributions to the modernization of national defense.

Microstructure of Composite Material
A major emphasis of Professor Chipin Jiang’s group is understanding how the internal microstructure of a heterogeneous or composite material influences its response under real world conditions. One area of particular interest is the development of constitutive models of different fiber or particle reinforced composites, from their micromechanical principles to describing their thermal, elastic, piezoelectric, and magnetoelectric behavior. These models include a three-phase model (employing the generalized self-consistent method), the periodic microstructure model (employing an equivalent inclusion concept), the eigenfunction expansion-variational method, and the unit-cell finite element method.

Thermal Shock of Engineered Ceramic
Another major area of interest of Professor Jiang’s group is the mechanism of failure of engineered ceramics subjected to thermal shock. The group focuses on three key scientific issues: developing the evaluation theory of thermal shock resistance for ceramic materials; developing a “half-inverse method” to measure physical parameters related to thermal shock at high temperature; and developing a method for predicting the pattern of cracks created by thermal shock by studying the relation between energy (including the strain energy and the fracture energy) and the spacing, depth, length, and deflection of cracks. This project will provide new ideas and methods for this field and promote the development of thermomechanical theory in solid mechanics.

REFERENCES
Developments in the Department of Aerodynamics and the Department of Human-Machine and Environment Engineering

The Department of Aerodynamics (DA), founded in 1952, is one of the oldest disciplines at Beihang University. Professor Shijia Lu, a doctoral student of the prestigious aerodynamist, Professor Ludwig Prandtl, was the founder and first director of the institution. As one of the key disciplines in aerospace engineering, the department attracted some of the most prominent figures in aerodynamics in China at that time. Over the past 60 years, the discipline has evolved from pure aerodynamic research for aircraft applications into a wide spectrum of interests, and has made outstanding advances in computational fluid dynamics, bionic aerodynamics, the aerodynamics of high angles of attack, flow control, as well as fundamental research in boundary layer transition and turbulence.

Computational Fluid Dynamics (CFD)
Active research has been carried out both in the methodology and applications of flight vehicle aerodynamic design and the aerodynamics of high-speed trains and wind turbines. Several CFD software platforms have been developed and applied to integrated flight-vehicle propulsion system aerothermodynamics design and flight vehicle aero-thermodynamics analysis, while multiphysical studies (involving multiple physical processes) related to the aerothermodynamics of aerospace vehicles are also emphasized. Studies on flow control based on plasma/magnetohydrodynamics (MHD) momentum, energy conversion, and energy deposition mechanisms are in progress, as well as research into solitons (self-reinforcing solitary waves) and symbolic computing (a method of extended hyperbolic function based on symbolic computing was established).

Bionic Aerodynamics
Two significant achievements have been made recently in the field of insect flight aerodynamics and dynamics. In the area of aerodynamics, two new mechanisms of large aerodynamic force generation have been identified (in addition to the existing delayed stall mechanism), namely the rapid acceleration and the rapid pitching-up rotation mechanisms. In the area of flight dynamics (stability and control), it has been shown that hovering insects have three longitudinal natural modes of motion: one unstable oscillatory mode, one stable fast subsidence mode, and one stable slow subsidence mode, and thus hover flight is inherently unstable; however, control analysis shows that although the flight is unstable, it is controllable.

Boundary Layer Transition and Turbulence
The instability and spanwise reproduction process of low-speed streaks evolving in a laminar flat-plate boundary layer has been experimentally investigated in order to understand streak characteristics and the dynamic mechanisms of free-stream turbulence-induced bypass transition. It is to be noted that the streak breakdown process provides a dynamic precondition for the streak reproduction process.

A new transition route from the Klebanoff mode in a free-stream turbulence-induced transition has been found for the boundary layer bypass transition induced by the wake vortex of a 2-D circular cylinder. This transition scenario is mainly characterized as: (i) generation of secondary transverse vortical structures near the flat plate surface in response to the von Kármán vortex street of the cylinder; (ii) formation of hairpin vortices due to the secondary instability of secondary vortical structures; (iii) growth of hairpins which is accelerated by wake-vortex induction; (iv) formation of hairpin packets and the associated streaky structures.

Using the Finite-Time Lyapunov Exponents (FTLE) method, Lagrangian coherent structures (LCSs) have been successfully identified in a fully developed turbulent boundary layer and the latter transition stage, and it has been found that the hairpin-like structures were the typical LCSs in these stages.

Aerodynamics of High Angles of Attack
Complex vortex flows will be produced around major components of flight vehicles when they are flying at high angles of attack, which can be coupled with body motion and result in a series of uncontrollable flight phenomena. In particular, slender bodies can generate asymmetric vortex flows, even with no sideslip. Systematic experimental studies have revealed the evolution of the flow fields over slender bodies with Reynolds numbers, and several new flow regimes and the associated separated vortex structures have been found, including a critical onset regime characterized by asymmetric transitions of boundary layers on both sides of slender bodies, as well as critical and supercritical regimes characterized by the emergence and collapse of separated bubbles. In addition, a novel experimental technique based on artificial tip perturbations has been developed, ensuring the reproducibility of experimental results over slender bodies from model to model. The asymmetric vortex flow can also induce a wing body, with a slender body producing self-excited oscillations around the roll axis. The oscillatory motions are influenced significantly by imperfections on the nose tips and by Reynolds numbers. Based on the sensitivity of the oscillations to the nose tips, a technique for controlling the self-excited oscillations using a rotating nose tip has been developed.

Flow Control
The mechanisms of lift enhancement by the Gurney flap and its applications have been investigated. Optimum design of the Gurney flap is as follows: The flap height should be of the same order as the local boundary layer thickness so that it can enhance the lift coefficient and the lift-to-drag ratio. The key parameter influencing lift enhancement is the height of the Gurney flap, while its shape is less important.

Figure 1. Schematic of a loop heat pipe.
Through careful investigation of the synthetic jet flow control technique and its applications, a novel signal wave pattern was proposed to generate a more efficient synthetic jet. The synthetic jet has been used to control flow around a circular cylinder, during which the symmetric vortex shedding mode is observed.

Research into plasma actuator flow control techniques has generated the development of novel flow control techniques, such as plasma Gurney flap and plasma circulation control. It has been shown that these techniques can increase the lift coefficient of an airfoil.

**Department of Human-Machine and Environment Engineering**

The Department of Human-Machine and Environment Engineering (DHMEE), originally named the “High-Altitude Facility,” was founded in 1959. In 1988, the facility was renamed the Department of Aircraft Environment and Safety Supporting Engineering, and in 1998 it was given its present name.

DHMEE is dedicated to carrying out focused basic research on thermal science and applying it to meet the needs of the aeronautics and astronautics industry. One focus is aircraft icing, which is a thermodynamic phenomenon that leads to the formation of ice on aircraft during flight and can often be extremely dangerous. Another focus is the development of the loop heat pipe (LHP), which is an advanced two-phase heat transfer device that plays an important role in the thermal control on the high-power spacecraft.

Fundamental research related to aircraft icing includes: (i) icing mechanisms, theory, and experimental analysis of supercooled water impingement on airfoils; (ii) complex flow and heat transfer characteristics on the anti-icing surface; (iii) flow and heat transfer characteristics inside the anti-icing chamber; and (iv) aircraft icing modeling and simulation. Extensive experimental and theoretical studies have been conducted on various LHP (Figure 1) designs, including the ambient loop heat pipe (ALHP), the dual compensation chamber loop heat pipe (DCCLHP), and Cryogenic Loop Heat Pipe (CLHP).

Radiative heat transfer in a semitransparent medium with a graded refractive index occurs in many processes, such as the heating of glass and thermal protective coatings, the manufacture of waveguide materials, ray propagation through the atmosphere, as well as the optical measurement in flames and other semitransparent media. The rays propagating inside a graded index medium are curved lines, which are governed by the Fermat principle. Solving the problem of radiative transfer in a graded index medium is more difficult than in a uniform index medium. Our research has focused on the radiative transfer equation in a graded index medium or nonlinear scattering medium.

On a microscopic scale, many well-understood physical properties deviate from the predictions of their classic cases. In the context of radiative heat transfer, Planck’s radiation law is challenged when the separation distance between the hot reservoir and heat sink is less than the characteristic thermal wavelength (at room temperature, about 10 micrometers). We are focused on the detailed investigation and control of energy transport through electromagnetic radiation at very small distances (Figure 2). For practical purposes, our research has implications for a wide range of applications, including next generation thermophotovoltaics, solar thermoelectric energy conversion, nanoelectronics and photonics, and thermal near-field imaging technologies.

![Figure 2](image_url). Reduced thermal radiation transfer between two magnetoelectric materials (normalized to the heat transfer between two black bodies) at different separation distances, \(d / \lambda_0\) is the characteristic thermal wavelength (frequency) and \(\omega_{LM}\) are the heat transfer peaks corresponding to the resonant frequencies of the surface electromagnetic modes.
The School of Chemistry and Environment

The Beihang University School of Chemistry and Environment offers fascinating interdisciplinary research and education in bio-inspired science, nanoscience, environmental science, and technology.

T he School of Chemistry and Environment (SCE) is an emerging school, having been established only in June 2008. The school’s dean is Professor Jiang Lei. Since its opening, SCE has evolved and grown at a rapid pace. Today it stands as an important contributor to the growth of Beihang University and in the development of chemical and environmental studies all across China.

SCE comprises the Department of Chemistry, the Department of Environmental Science and Engineering, and a Ministry of Education (MOE) Key Laboratory for Bio-Inspired Smart Interfacial Science and Technology. SCE offers programs to about 200 undergraduate and 200 graduate students. Students are required to take part in at least 6 months of multidisciplinary scientific research during their undergraduate studies. SCE is equipped with modern equipment, including that for 3-D micro X-ray computed tomography, transmission electron microscopy, scanning electron microscopy, environmental SEM, atomic force microscopy, nanomechanics, Raman spectroscopy, and X-ray diffraction investigations.

Faculty

SCE has strong teaching and research teams that include 11 professors, 31 associate professors, 17 assistant professors, and 10 postdoctoral fellows. One professor has been elected as an member of the Chinese Academy of Sciences, three have been awarded Chang-Jiang Professorships from the MOE, two have been named Distinguished Young Scholars by the National Natural Science Foundation of China, and six have been placed in the Program for New Century Excellent Talents in University by the MOE. Many faculty members have received international and national awards for their achievements in research and education. A number of faculty members also serve as editors of leading international journals, including Soft Matter, Small, Advanced Functional Materials, Nano Research, and Solid State Science. Moreover, many prominent overseas chemists (such as Professor Akira Fujishima and Professor Kazuhide Hashimoto) have been welcomed into SCE as visiting professors.

Strategic Plan for Scientific Research

Since its foundation, SCE has had a long-term strategic goal to grow and improve in the fields of aeronautics and astronautics. Within the first six months, SCE developed its 2009–2038 Strategic Plan for Scientific Research. It is highly interdisciplinary and encompasses material sciences, physics, chemistry, biology, engineering, and technology. The core of the plan is bio-inspired science and nanoscience. The Strategic Plan outlines the school’s long-term goals and describes how it will accomplish these goals over the next 30 years. SCE has four research directions that provide a framework to guide short-, medium-, and long-term research.

Bio-inspired smart interface materials. The interfaces of materials play a significant role in determining their characteristics. Nature provides a perfect school for scientists and engineers to learn about this topic in the real world. Research into smart interface materials involves many areas, including the investigation of the interface effect, multiscalar structure effects, and synergistic effects; clarification of the element-structure-function relationship of biomaterials; extraction of useful engineering principles; and adaptation of models to practical applications. The strategic goal emphasizes the fabrication of bio-inspired special wetting, bio-inspired water collecting, and intelligent responsive materials as well as smart catalysts; novel technologies and innovation in the construction of multiscalar structures; the assembly and intelligence of interface materials; and the stability of smart materials.

Bio-inspired low-weight and high-strength materials. Throughout evolution, nature has evolved what is optimal using ordinary compositions. In nature, nacre, bones, spider silk, and other biomaterials possess outstanding mechanical properties. Research goals are to reveal the relationship between the multiscalar micro-structure and superior macro-mechanical properties, to extract the theoretical basis for bio-inspired low-weight and high-strength materials, to design and fabricate functional target molecules and nanostructure units, and to assemble control functional units. The overarching goal is to address possible applications of bio-inspired low-weight and high-strength materials in aerospace research, civil engineering, and other fields.

Bio-inspired energy materials and devices. In nature, some biomaterials are optimal energy conversion systems. They inspire the construction of advanced materials and intelligent devices to meet the needs of the community. This research direction focuses on the conversion mechanisms and new principles of biological systems, the multiscalar synergy effect of bio-inspired nanochannels, and the design and integration of bio-inspired energy conversion materials and devices. The main research goal is technological innovation using nanostructured materials in energy conversion.

Bio-inspired integration technology in a space station environment. Environmental control and life-supporting systems are complex and have important roles in a space station. Inspired by intelligent biomaterials, this research direction aims to investigate the mechanisms of nanocomposites for a capsule environment, and to construct multifunctional integrated nanocomposites for environmental control and life-supporting systems. The long-term strategic goal is to fabricate anti-radiation coatings against high-energy electrons, to efficiently remove carbon dioxide from the cabin air, provide oxygen and potable water, and to monitor and control temperature, humidity, and pressure in a space station.

Since its opening, SCE has evolved and grown at a rapid pace.
Achievements
Using the Strategic Plan for Scientific Research (2009–2038) as a guide, SCE has become a well-recognized center for scientific research and student training in bio-inspired science and nanoscience in China. In the past four years, SCE members have published more than 300 scientific papers in Nature, Chemical Society Reviews, Accounts of Chemical Research, Angewandte Chemie International Edition, Journal of the American Chemical Society, Nano Today, Nano Letters, Advanced Materials, and other international journals. In particular, the SCE’s work on directional water collection on wetted spider silk was featured on the front cover of Nature (2010). The SCE has undertaken more than 80 sponsored research projects, including four from the National Basic Research Program of China, six from the National High Technology Research and Development Program of China, and 41 from the Natural Science Foundation of China. SCE has also organized many important international and national academic activities, such as Xiangshan Science Conferences on Bio-inspired Materials and Devices (2011), the 1st Chemical Society Reviews International Symposium (2010), the China-Japan Bilateral Symposium (2010), and the 45th ShuangQing Forum (2010).

Looking to the Future
Learning from nature has long been a source of inspiration for scientists and engineers, and has resulted in innovation in science and technology. Further basic and applied research in bio-inspired science and nanoscience at SCE will be conducted to meet the national strategies in the areas of aeronautics and astronautics. Based on the Strategic Plan for Scientific Research, SCE invites applications and nominations of outstanding scholars of all nationalities for faculty positions. The school is committed to maintaining the unique quality of its student education and to the continued achievement of significant research results. Through the fusion of science and technology, and with the collaboration of faculty members, SCE is well on the way to being a world-class school of chemistry and the environment, with a focus on aeronautics and astronautics.
Nanomaterials with Delicate Morphologies: Controlled Synthesis and Corresponding Applications

Yong Zhao, Lidong Li, Wei Zhou, Dongyu Zhao, Dongfeng Zhang, Penggang Yin, Lin Guo*

Many scientists have recently focused their research on constructing specifically structured nanomaterials in order to tailor their unique properties and improve their intrinsic attributes. Various methodologies have been developed to achieve complicated architectures including thermal vapor deposition, electrochemical deposition, and microwave assistance. Compared with many other fabrication methods, wet chemical routes have advantages such as low cost, ease of handling, and mild reaction conditions. This review discusses the wet chemical method for the controlled synthesis of specific nanomaterial morphologies, and highlights some important applications of as-synthesized novel nanostructures. Electrospinning, a useful technique for fabricating microscopic materials with various predetermined interior structures, is also included in this review, which discusses examples of multifluidic electrospinning methods.

Much effort has been devoted to the controlled synthesis of nanomaterials in the presence of various surfactants and additives employing the wet chemical method. In our work, for instance, we determined that polyvinylpyrrolidone (PVP) with a lactam group is preferentially adsorbed on specific crystal planes, and is able to direct the synthesis of nanostructures with desired planes. Recently, the surface area ratio of two different planes was delicately tuned by simply adjusting the amount of PVP added, which resulted in a systematic evolution of the shape of copper oxide (CuO) nanostructures from cubes through truncated cubes, cubo-octahedrons, truncated octahedrons, and finally to octahedrons (Figure 1A) (1).

Increasing attention is being given to the synthesis of nanocrystals with high-index facets. This is because high-index planes usually have enhanced catalytic activities because of the high density of atomic steps, ledges, kinks, and dangling bonds. Surfactants generally have an important role in shaping the final product. In our research, using a binary surfactant system, well-shaped tetrahexahedral Au nanocrystals enclosed by 24 high-index facets were synthesized, showing enhanced electrocatalytic activity in the oxidation of formic acid (2).

Recently, we worked on the fabrication of hierarchical nanomaterials with complex geometries by patterning nano-building blocks that include metals, oxides, sulfides, hydroxides, and other materials. In the self-assembly process, the coupling force of small molecules, or the template action, is important. For instance, a sophisticated concaved polyhedron of beta-nickel hydroxide [β-Ni(OH)$_3$] was fabricated through the self-assembly of nanoplates of nickel hydroxide (3). During this synthesis, with the aid of hydrazine molecules, nickel hydroxide nanoplates pile up together and grow along a fixed direction. The novel architecture can be attributed to the inherent spatial asymmetry of the Ni(OH)$_3$ crystal structure and the directionality of hydrogen bonds. With the amount of hydrazine hydrate increasing, the shape of the Ni(OH)$_3$

![Figure 1. Delicate morphology-controlled synthesis of nanostructures can be achieved using the wet chemical method. (A) Shape evolution of the CuO polyhedrons with increasing molar ratio of PVP to CuCl$_2$·2H$_2$O, from a cube-shaped particle to a highly symmetric octahedron particle (Scale bar = 300 nm). (B) Shape evolution of hourglass-like Ni(OH)$_3$ nanocrystals with increasing amount of hydrazine hydrate, from a hexagonal nanoplate to a well-developed hourglass nanocrystal (Scale bar = 100 nm). Through multifluidic electrospinning, the complex inner structures of microspheres and nanofibers can be well controlled: (C) multichannel microspheres and wire-in-tube hollow fibers (Scale bar = 500 nm) and (D) multichannel hollow fibers and porous nanofibers (Scale bar = 200 nm).](image-url)

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of materials, providing good control over the resulting structures (Figures 1C and 1D).

The intrinsic properties of a nanomaterial are known to be highly dependent on the nanomaterial size and morphology. These relationships have been used in unique applications in a variety of areas. For instance, by doping a trace amount of bowl-like Ni in nematic liquid crystals (LCs), a perfect planar alignment of LCs can be obtained (7, 9). This application is exclusive because other doped nanoparticles (NPs) induce vertical alignment rather than planar alignment in LCs (Figure 2A).

We have also studied the photocatalytic properties of silver bromide (AgBr) nanoparticles toward methyl orange with different morphologies (10). Morphologies evolved from cubes, through truncated cubes, and finally to a highly symmetrical octahedron, with an increasing percentage of exposed specific facets. These studies clearly revealed that the octahedral AgBr nanoparticles have greatly enhanced photocatalytic activity because of the higher surface energy of the specific plane. The stoichiometric slab model of this plane is shown in Figure 2B.

When our research is considered as a whole, it suggests that both wet chemical and electrospinning methods are effective approaches for delicately controlling the morphologies of nanomaterials. As-prepared products with novel nanostructures have great potential for a variety of applications.

REFERENCES

10. H. Wang et al., Small, online at http://dx.doi.org/10.1002/smll.201200055.

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Advanced Nanomaterials for Use in the Environmental-Control and Life-Support Systems of a Manned Space Mission

Tianle Zhu1, Zhiyong Tang2, Hong Gao3, Shuhong Yu4, Yan Xing5, Qiuming Gao1*

Outer space will provide new resources, expand our living environment, and create new lifestyles. Already, we live in an era that has made space technologies a part of our daily lives, from television, radio, and global positioning system devices—such as those installed in taxis and fishing boats—to weather forecasts, the Internet, and even space-bred rice and vegetable crops. However, human exploration of outer space is still in its preliminary stage. The building of space stations is the first step in establishing a foothold in outer space. To date, the largest space station constructed is the International Space Station, which is an internationally developed research facility.

Since its start in 1992, China’s program of manned space flights and other advanced space projects has had a number of significant accomplishments. Between 1999 and 2002, four Chinese spacecrafts—Shenzhou-1 to Shenzhou-4 (or “Divine Craft”)—were launched. These missions carried out zero-gravity experiments, which tested technologies for a manned space mission. In 2003, China became the third country—after the United States and the Soviet Union/Russia—to independently send humans into space, and followed that success with two more manned missions in 2005 and 2008. In 2011, China launched the Shenzhou-8 capsule on a historic mission to carry out the nation’s first-ever docking maneuver in space, with the orbiting prototype space station module dubbed Tiangong-1 (or “Heavenly Palace”)-1. On June 16, 2012, China launched its second spacecraft (and first manned Chinese spacecraft) to dock in space, this time with the Tiangong-1 space laboratory module. The mission’s crew included the first Chinese female astronaut. These missions are part of China’s ambition to construct a multimodule space station by 2020.

Behind these achievements are unprecedented challenges and risks. Environmental-control and life-support systems (ECLSS) in space are complicated yet essential to China’s long-term goals of assembling a space station and possibly visiting the moon. The requirements for ECLSS in space are determined by the conditions in the spacecraft or space station (Figure 1): (A) the most common types of radiation in space are electrons from the Earth’s radiation belt, protons produced by solar flares, and galactic cosmic ray protons (modulated by the solar wind magnetic field) plus their secondary particles; (B) the enclosed space of the spacecraft cabin, which limits resources for firefighting and options for crew escape, and the near-zero-gravity (microgravity) environment that profoundly affects the characteristics of fire initiation, spread, and suppression; (C) the enclosed environment of the station, which can affect crew health and endanger the station itself through consumption of materials by microbes; (D) the low Earth orbit (LEO) environment in which atomic oxygen (AO, about 1 x 10^19 atoms/cm^2) and ultraviolet (UV) radiation can substantially erode materials during long-term exposure; (E) the air supply within the station, for life-supporting systems need to prove oxygen and remove carbon dioxide for the safety of the crew, as well as prevent gases such as ammonia and acetone from building to dangerous levels; and (F) the water supply, since astronauts require clean water and comfortable humidity to survive.

ECLSS are vital to China’s manned space missions. The rapid advance of modern nanotechnology provides opportunities for establishing a new generation of ECLSS in space. It is known that compared with conventional materials, nanomaterials have the advantages of small size, low mass, high performance, abundance, adjustable structure/morphology, and effective composites with multiple sizes/dimensions. Moreover, almost all technical domains covered by space research and development could greatly benefit from these emerging technologies. Because of their unique characteristics and properties, nanomaterials have potential applications in ECLSS. For example, nanosized lead, barium, cadmium, tin, rare earth elements, and their alloys/composites could be used to protect astronauts from the radiation of high-energy electrons. Carbon nanotubes, ferromagnetic nanoparticles, and other nanoparticles could

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**Figure 1.** ECLSS in space are related to the conditions in a spacecraft or space station: (A) the high-radiation environment found in space; (B) the small volume of the spacecraft cabin; (C) the favorable environment for microorganisms; (D) the low-Earth orbit environment; (E) the air supply; and (F) the water supply. AO, atomic oxygen. UV, ultraviolet. ECLSS, Environmental-control and life-support systems.
be used to protect against the radiation of high-energy protons modulated by the solar-winds and magnetic fields, and their secondary nuclei. Nanosized boron and related compounds and composites could be used to shield against the radiation of high-energy heavy ions consisting mostly of protons (with small amounts of helium and heavier nuclei).

It is hypothesized that the use of nanomaterials will greatly reduce spacecraft mass. Additionally, composites of inorganic nanoparticles and organic polymers can have important roles in managing heat and mass transfer during a fire, and ultimately serve as fire protection. Nanofibers can filter smoke and prevent the spread of bacteria and viruses that may endanger the health of astronauts. Nanoporous materials with large surface areas and high catalytic activity could adsorb and reduce poisonous and/or harmful gases, and limit the spread of microorganisms. Nanocatalysts can be used to break down carbon dioxide and produce oxygen, a requirement for clean, breathable air. The large surface area and many active centers of nanoparticles make them suitable for AO capture, and other nanoparticles such as nanosized titanium oxide (TiO$_2$) with strong UV absorption capacity can be applied as UV protection, thus avoiding substantial erosion of materials by AO and UV during long-term LEO flight. Manmade spider-silk-like fibers with adjustable surfaces/interfaces on the micro-/nanoscale could collect water with high efficiency (1), providing a possible technique for water collection and humidity control in a microgravity environment.

To realize applications in closed systems, especially ECLSS in space, nanomaterials must satisfy the requirements detailed above. Although some preliminary data on the use of nanomaterials as environmental security materials in closed systems have been reported, there has been little study on the relationship between micro- or nanostructure and material properties. Moreover, the properties of these nanomaterials have not met the requirements for practical applications, especially in terms of light weight, high performance, and multifunctionality. Therefore, it is highly desirable to explore new ideas and develop novel methods for creating materials; this is the focus of our research, which will be carried out based on the scheme show in Figure 2.

First, the design and synthesis of targeted molecules and nanostructured building blocks are of primary importance for the preparation of nanomaterials with well-defined structure and specific properties (2). Nanomaterials with different structures, such as 1-D nanowires and nanoarrays, 2-D films, and 3-D crystals, will be constructed by taking advantage of the controllable multilevel assembly and the interface collaboration/synergies on multiple scales (3–10). Subsequently, the properties of the fabricated nanomaterials including antibacterial, fire-prevention, atmosphere-purification, AO- and UV-resistance, and radiation-resistance properties will be evaluated on a variety of test platforms. Finally, the practical application of these nanomaterials with desirable properties will be explored for ECLSS in space and eventually extended to other types of closed systems such as aircrafts, submarines, high-speed trains, and closed rooms with a central air conditioner. It is believed that through the continued efforts of nanotechnology researchers, new nanomaterials will provide the theoretical and technical foundations for the transformation of traditional industries in many fields.

REFERENCES

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Biomimetic Smart Nanochannels in Energy Conversion Systems

Yan Xiang¹, Jin Zhai¹*, Lei Jiang¹,²

Nature has inspired the creation of many intelligent devices to meet the needs of an advanced society. Biomimetic nanodevices, nanochannels, and nanopores have attracted particular interest because of their potential applications in nanofluidic devices, biosensing, filtration, and energy conversion (1, 2). Here we review recent research, focusing mainly on the design and construction of smart nanochannels and their application to energy conversion systems.

Biomimetic Smart Nanochannels

Nanochannels, a vital part of living organisms, can be defined as channels with at least one cross section dimension in the nanometer range (3). Recent advances in science and engineering have enabled the production of a series of nanochannels that recapitulate the unique functions of living systems in response to external stimuli, including pH, ions, temperature, ligands, and electrical current.

We recently created light-responsive artificial ion channels using a self-organized titanium oxide (TiO₂) nanotubular array whose ion transport properties can be regulated by external ultraviolet light (Figure 1A) (4). In addition to a system directly controllable using light, we prepared a photo-induced, chemically driven, smart-gating nanochannel (Figure 1B), taking us a step closer to a real application (5). Thermo-responsive polymer brushes (6) can also be used in room-temperature ionic liquids to form a stimuli-responsive nanofluidic system that can withstand temperatures exceeding 200°C (Figure 1C). Employing a similar strategy to that for the fabrication of single-response nanochannels, dual/multiple-response nanochannels have been produced by modifying multiple-response molecules on the inner surfaces of nanochannels. We reported an artificial nanofluidic diode that displays both light-gated and pH-tunable transport properties, and has a current-rectification property (Figure 1D) (7). An integrated ionic gate and rectifier within an asymmetric single nanochannel has been obtained by modifying the pH and temperature dual-response copolymer brushes poly(N-isopropyl acrylamide-co-acrylic acid) (Figure 1E) (2). Simultaneously, another asymmetric dual-response nanochannel (3) that controls pH and temperature was created through asymmetric chemical modification (Figure 1F). The strategy of chemical modification can also be applied to incorporate other stimuli-responsive materials in designing smart multifunctional nanofluidic systems resembling living creatures in nature.

Figure 1. Various smart nanochannels developed by our team: (A) Light-regulated nanochannels based on TiO₂ nanotubular arrays. When a positive voltage is applied, cations flow from the base to the tip side, and the electrostatic traps formed by the ratchet potential inhibit ion transport through the nanotubular arrays. At negative voltage, the electrostatic traps do not form. The high concentration of cations on the tip side enhances the ionic current. UV, ultraviolet. (B) A light-induced and chemical-driven smart nanochannel. MGCB, malachite green carbinol base. MG cation, malachite green cation. (C) Temperature-responsive nanochannels modified with thermo-responsive macromolecules. T, temperature; LCST, lower critical solubility temperature. (D) Light and pH cooperative nanofluidic diode using a spiropyran-modified single nanochannel. (E) A dual-response nanochannel that is independently responsive to temperature and pH. (F) A biomimetic asymmetric hourglass nanochannel that is independently responsive to temperature and pH. PNiPA, poly (N-isopropyl acrylamide), PAA, poly acrylic acid.

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Nature has inspired the creation of many intelligent devices to meet the needs of an advanced society.

**Figure 2.** Bio-inspired energy conversion systems: (A) and (B) Photoelectric conversion system by the photo-induced proton pump in the retina. (C) Mechanism of the photoelectric conversion system, which is constructed using a photoelectrochemical cell containing three parts, with only part I irradiated by outside light. 8-hydroxypyrene-1,3,6-trisulfonate (HA) was utilized as light-driven proton pumps. The generated protons could be transported across the membrane between part I and part II and resulted in a charge imbalance on both sides of the membrane, thus creating an $E_{oc}$. (D) Power generation by an electric eel. (E) The mechanism for current generated from the charge separation within the electrical double-layer (p for cations and n for anions). (F) An energy conversion system developed using preferential ion diffusion across single ion-selective nanopores driven by a concentration gradient.

**Application of Biomimetic Smart Nanochannels in Energy Conversion Systems**

Like biological nanochannels in living systems, recently developed nanochannels have properties such as ion current rectification, cation selectivity, and gating, which can be used in energy conversion. We reported a photoelectric conversion system (8) based on smart-gating, proton-driven nanochannels, which was inspired by photoelectric conversion of the retina (Figures 2A and 2B). Figure 2C is a schematic diagram of the photoelectric conversion system. Moreover, inspired by electric eels, a fully abiotic single-pore nanofluidic energy-harvesting system that can efficiently convert Gibbs free energy in the form of a salinity gradient into electricity has been generated (Figures 2D and 2E) (9). The harvested power can be delivered to an external circuit and can drive an electrical load resistor (Figure 2F).

In summary, some of the most pressing issues the world faces relate to energy and the environment. Nature can inspire the development of novel functional materials that will help address such issues (10). Inspired by the energy conversion of the retina and electric eel, scientists have developed biomimetic smart nanochannels and applied them to energy conversion systems.

**REFERENCES**


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Smart Bio-Inspired Interfacial Materials for Unique Wettability

Ying Zhu¹, Yongmei Zheng², Lei Jiang¹

An exciting confluence of research areas has arisen in recent years where physics meets chemistry meets biology meets material science. Biological surfaces provide endless inspiration for the design and fabrication of functional interface materials with unique wettability, generating promising applications such as microfluidic devices, functional textiles, corrosion resistance, liquid transportation, antifogging, and water-collecting devices.

Biological surfaces that collect water in nature have evolved unique mechanisms, such as the capture silk of the cribellate spider *Uloborus walckenaerius*, which collects water through a combination of multiple gradients in a periodic spindle-knot structure after the wet-rebuilding process (1). This structure drives tiny water droplets (under 100 μm in diameter) directionally toward the spindle-knots for highly efficient water collection. Inspired by the roles of micro- and nanostructures (MNs) in the water collecting ability of spider silk, a series of functional fibers with unique wettability has been designed by integrating fabrication methods and technologies such as dip-coating, Rayleigh instability break-up droplets, phase separation, strategies of combining electrospinning and electrospraying, and fluid-coating. Through such fabrications, “spindle-knot/joint” structures can be tailored to demonstrate the mechanism of multiple gradients in driving minute water drops. The rough and smooth fiber surfaces, together with the gradient of chemistry components, can control the movement of water droplets in a desired direction.

In the case of larger water droplets, it has been demonstrated that geometrically engineered thin fibers have a much higher water capturing ability than previously thought. This is attributed to increased stability of a three-phase contact line due to the combination of “slope” and “curvature” effects on spindle-knots that provide sufficient capillary adhesion to retain the hanging drops (2). To extend this functionality, bead-on-string heterostructured fibers (BSHFs) have been fabricated in a one-step electrohydrodynamic method combining electrospinning and electrospraying strategies; thus, BSHFs are capable of intelligently responding to environmental changes in humidity (3).

The above research provides insights into designing functional fibers with unique wettability, either by creating special structures on the fiber surface or by modifying the surface with responsive molecules. We hope that the ongoing designs of these bioinspired structures find applications in many fields, such as for water collection, smart catalysis, filtration, and sensing, as shown in Figure 1 (4). By designing asymmetric structures (Figure 1A) or a wettability gradient on the spindle-knot (Figure 1C), unidirectional motion of water droplets may be achieved. We can modify the fiber surface with molecules that respond to light, pH, or thermal stimuli, making it possible to control the direction of motion of water droplets (Figure 1B). Water collection efficiency can be increased through the directional collection of small water droplets (Figure 1D). Smart catalysis may be realized by quickly transporting reactant droplets toward the spindle-knot created through catalysis, and taking the product droplets away from the spindle-knot (Figure 1E).

A small amount of airborne materials (such as particles) can be first captured by tiny liquid droplets, and further concentrated or filtered on a functional fiber by directionally collecting the liquid droplets toward the spindle-knot (Figure 1F).

Other biological surfaces such as plant leaves and butterfly wings display water repellency and wettability as a function of gradient features. The dynamic suspension of microdroplets on a fresh lotus leaf is related to a gradient of wettable MNs along the exterior surface of papillae, including nanohairs that play a role in water condensation and propel the directional movement of microdroplets out of the valleys and to the top of papillae (5). Biological surfaces can have anisotropy in wettability for directional water repellency. For instance, a novel taper-ratchet array on a ryegrass leaf integrates a gradient of retention at solid-liquid interfaces in contrasting directions to reversibly generate the releasing or the pinning of solid-liquid contact lines. The wings of iridescent blue *Morpho aega* butterflies have directional water repellency achieved through a directional adhesion mechanism with a flexibly oriented MN. As the butterfly wing is tipped upwards, the direction of the scales prevents the droplet from moving towards the butterfly’s body. To gain a better

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Figure 1. Schematic of the design of smart bioinspired fibers with unique wettability for promising applications. (A) Curvature in conjunction with asymmetric structures and (C) the wettability gradient on the spindle-knot for the unidirectional motion of water drops. (B) Response to light, pH, or thermal stimuli in controlling the direction of drop motion in water collection, smart catalysis, filtration, and sensing. (D) Water collection with high efficiency via the directional gathering of tiny water drops. (E) Smart catalysis via the quick transporting of reactant drops toward the catalysis spindle-knot, and moving the product droplets away from the spindle-knot. (F) Collection of materials from the air and their concentration at a spindle-knot.
understanding of these biological multistructure effects, smart bioinspired surfaces can be fabricated by combining machining, electrospinning, soft lithography, and other techniques to achieve selective control via processes such as magnetic actuation (5), weight-induced shedding and vibration-induced self-transport of droplets (6), and conductivity-induced reversible wettability (7-8). The strong MN effect may enhance water repellency. For instance, it has been shown that the multilevel MNs of iridescent blue *Morpho nestira* butterflies have low-temperature superhydrophobic properties. This finding offers insight into the characteristics of MNs on butterfly wings (9). Moreover, a MN-surface inspired by the MN feature on butterfly wings has been designed by integrating machine processing and crystal growth methods (10). Thus, the MN-surface composed of microratchets combined with nanohairs on a metal substrate has a robust icephobic/anti-icing property and outperforms nanostructured surfaces (N-surfaces), and is far better than microstructured surfaces (M-surfaces) and smooth surfaces without any structure (S-surfaces) (10). These water repellent surface properties, in conjunction with a wetting-controlling mechanism, would be of great use in applications such as icephobic/anti-icing surfaces (Figure 2A), light- and electricity-modulated liquid transport (Figure 2B), anisotropic wettability for selective particle transport (Figure 2C), antifogging/self-cleaning at low temperatures (Figure 2D), reversible rolling of a drop by two superhydrophobic Wenzel and Cassie states (Figure 2E), and high-temperature-induced or vibration-induced movement of a drop on oriented taper-ratchet arrays.

In summary, biological surfaces with unique wettability inspire the design of smart multifunctional materials for promising applications. Future research will enhance the design of smart interface materials with water-collecting, anti-icing, antifrosting, or antifogging properties for practical applications, and the design of a novel fluid-controlling surface that can be extended to aerospace, industry, microfluidics, and water control applications.

**REFERENCES**


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CHAPTER 6

A New Concept for a High-Speed Ground Transport System: The Aero-Levitation Wheel-Rail Train

Qiulin Qu¹, Kesong Liu², Huawei Chen¹, Dianshen Li², Hao Guo¹, Rong Zhang³, Deyuan Zhang³, Peiqing Liu¹*, Lei Jiang²,⁴*

High-speed ground transport systems can greatly shorten travel times and reduce the distance between regions so as to promote interregional resource sharing and stimulate rapid economic development. High-speed wheel-rail trains have been developed and operated in many countries (1), such as the Japanese Shinkansen, the German Inter City Express (ICE), the French Train de Grande Vitesse (TGV), and the China Railways High-Speed (CRH), which all play an important role in improving rail traffic. The maximum operating speed of a high-speed wheel-rail train can reach up to 380 km/h, but it requires expensive maintenance costs because of wheel-rail contact wear. In order to avoid this type of wear, magnetic levitation trains have been developed, such as those in Japan and Germany. A magnetic levitation train flies only a few inches above a guideway surface, using magnets to create both lift and thrust. Such trains can be operated at up to 500 km/h and there is no wheel-rail contact wear. However, construction costs and power requirements are huge, and magnetic fields may have negative effects on human biology.

During the 1980s, Japan proposed and studied an “Aero-Train” (2), which floats on a u-shape guideway utilizing the “wing-in-ground” effect. The Aero-Train abandons the concept of traditional high-speed wheel-rail train systems, using lift (provided by the “wings”) to support the full weight and guide the direction. Therefore, the Aero-Train requires a larger wing area necessitating a redesign of the overall layout. In addition, a new u-shape guideway needs be designed and constructed, the costs of which are unknown.

Recently, a new concept for high-speed transportation, the Aero-Levitation Wheel-Rail (ALWR) train, was proposed and studied at Beihang University (3–5). The ALWR train introduces several advanced aviation technologies and bio-inspired strategies into a traditional high-speed wheel-rail train transport system. The “wings” are mounted at the top and sides of the train to generate lift to support part of the ALWR train’s weight (see Figure 1). The train carriages are made from carbon fiber-reinforced composite structures to reduce weight. These technologies can...

Figure 1. The first configuration of the ALWR train: (A) The ALWR train can run at up to 500 km/h on the railway. (B) The roof wings that are near the top of the carriages can generate lift utilizing the ground effect. (C) The side wings mounted close to the ground can generate lift, also due to the ground effect. (D) The ducted biological propeller provides additional thrust.

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and reducing speed, resulting in lift created by the train body. The lift from the train body and the side wings together support a portion of the train’s weight.

Biologically Inspired Aviation Propeller

A ducted “biological” propeller is mounted at the ALWR train’s tail, which provides part of the propulsive force. The propeller is made from carbon fiber-reinforced composite materials.

The blade resembles the flipper of a humpback whale (7). Some tubercles (round modules) are located on the blade’s leading edge, which give this surface a scalloped appearance. Compared with traditional blades, the biological blade delays the stall angle by approximately 40%, while increasing lift and decreasing drag.

Aerodynamic Braking

In order to stop the high-speed ALWR train safely and effectively, the aerodynamic brake is designed as an auxiliary braking system (8), consisting of a series of panels located on the upper wing surface.

When the aerodynamic braking panel is deployed upwards, the air in front of the panel is blocked and a sizable negative pressure is generated because of the flow separation created behind the panel. This leads to a pressure difference between the front and back of the panel, creating additional pressure drag and thereby the auxiliary braking force.

Composite Carriage-Body Structures

It is important to reduce the mass of the ALWR train carriage-body, which contributes the most weight of the train. Such reduction could produce savings in the traction, suspension, brake, and other subsystems. The introduction of carbon-fiber-reinforced composites shows promise, as such materials offer high strength- and stiffness-to-weight ratios, more cost effective fabrication methods, high damping capacity, durability, and are readily molded into an aerodynamic shape (9).

The natural structures of biological organisms can provide beneficial information for the fabrication of artificial composites. For example, the cocoon shells of silkworms are lightweight and possess excellent mechanical properties. Birds such as goshawks have optimized skeletal structures that can provide the strength required for flight. Inspired by

mitigate the contact pressure between wheels and railways, thus reducing wear. The propeller is included as an auxiliary power source to make up for the wheel-rail driving force loss caused by the wings’ aerodynamic lift and lighter carriages. Through optimization of existing train body shapes and application of drag reduction technology on the train surface inspired by shark skin, the ALWR train could be operated safely at up to 500 km/h. In addition, the ALWR train enhances the ability of safe and smooth operation by utilizing aerodynamic braking technology.

The ALWR train is based on a traditional high-speed wheel-rail train and can be operated on existing high-speed railways. Therefore, its development costs would be significantly reduced.

Key Technologies in the Development of the ALWR Train

Wing-in-Ground Effect

There are two possible aerodynamic configurations which can provide enough lift to support part (but not all) of the ALWR train’s weight. One is installing wings on the train’s roof and sides (see Figure 1), the other is redesigning an n-shaped bottom for the train and mounting wings on the sides (see Figure 2).

In the first configuration, the roof wings are near the top of the carriages, and the side wings are mounted close to the ground. The wings create a so-called ground effect, which would generate significant lift. When a wing is flying near the ground at a positive angle, the airflow in the channel between the wing’s lower surface and the ground is hampered, increasing pressure and reducing speed, resulting in a pressure increase at the wing’s lower surface and thus creating lift. Simultaneously, the wing-tip vortices move outward along the span-wise direction due to the ground mirror effect, resulting in a decrease of the airflow downwash angle and induced drag. As a result, the wing’s lift and nose-down pitch moment increase, induced drag decreases, and the aerodynamic center moves backward, an outcome known as the ground effect. Certain vehicles are designed to use the ground effect to improve their aerodynamic efficiency (6).

In the second configuration, the airflow in the passage between the train’s n-shape bottom and the ground is blocked, increasing pressure and reducing speed, resulting in lift created by the train body. The lift from the train body and the side wings together support a portion of the train’s weight.

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Figure 2. The second configuration of the ALWR train. The airflow in the channel between the train’s n-shaped bottom and the ground is hampered, resulting in lift created by the train body. This lift plus that created by the side wings can together support a large portion of the train’s weight. (A) Front view and (B) sideview.
these design concepts, the carriage-body of ALWR trains has been developed using a composite sandwich structure with double layer cocoon-like skins and a bird-skeleton-inspired core (see Figure 3). The skin and core are made of carbon/epoxy composites and bonded into a single structure.

The skin, fabricated by filament winding, has a multidirectional fiber distribution, which produces high bending stiffness and avoids wrinkling failure. The core, fabricated by braiding technology, carries more transverse forces and avoids shear failure and stress cracking. In addition, the hollow structure enables the body to contain components for power generation, leak detection, cooling and noise control.

Drag Reduction Using Shark Skin

As the speed of the ALWR train increases, the ratio of aerodynamic resistance to the total drag gradually grows, reaching up to 90% as the speed tops 500 km/h. Aerodynamic drag encompasses both pressure drag and friction. Pressure drag can be reduced by optimizing the shape of the ALWR train’s front and rear carriages, while frictional resistance can be reduced by engineering a shark-skin-like surface covering.

The surface of shark skin has unique microstructures with superior surface characteristics such as drag reduction and hydrophobicity. The fast and agile shark with its superior drag reduction hydrodynamics (the so-called “shark-skin effect”) has attracted attention, particularly for what we can learn about energy-saving streamlining. Shark skin is covered with placoid scales containing tiny ridge-like structures arranged parallel to the swimming direction. “Riblets” formed by naturally arranged placoid scales decrease drag, allowing the shark to reach amazing speed with minimal effort. Biomimetic riblets were investigated and experimentally confirmed the hypothesized drag reduction effect. Airbus and Boeing have constructed shark-skin-inspired riblets (i.e., simple u- or v-shaped microgrooves) on the surface of some aircraft and achieved 5–8% skin friction drag reduction in flight experiments (10). Over the last several years, a bio-replication process—in which shark skin was used as a direct template—was proposed to fabricate a biomimetic drag-reduction microstructure and has since been shown to reduce drag by up to 13%.

As compared to simplified u/v-shaped microgrooves, natural shark skin has superior drag reduction capabilities due to its heterogeneous riblet structure over the body of the shark. To reduce energy consumption, attempts are being made to improve the skin of the ALWR train using improved drag-reduction riblets (see Figure 3).

The ALWR train’s development will make the life of travelers quicker and more convenient, while also lowering manufacturing and operating costs. At the same time, its development will drive the improvement and development of a large number of high-tech and related industries.

REFERENCES AND NOTES
The School of Computer Science and Engineering

The School of Computer Science and Engineering is dedicated to delivering groundbreaking innovation in the field of computer science and technology and to providing inspiring educational programs for its students.

The school became a national key institution in the field of computer software and theory in 2001, and in the field of computer science and technology in 2007.

Wei Li  Qinping Zhao  Jinpeng Huai

The School of Computer Science and Engineering (SCSE) has carried out pioneering research in the field of computer science for over 50 years. The school began as a numerical computing center established in 1958 by Beihang University. In 1975, it expanded to offer the first computer software major at the university. In 1978, the Department of Computer Science and Engineering was founded, and in September 2002, it became the School of Computer Science and Engineering. In 2007, the school was ranked by the Ministry of Science and Education as one of the top three computer science schools in China.

SCSE is proud of its excellent faculty, which includes two members of the Chinese Academy of Sciences, 35 professors, 47 associate professors, and more than 30 assistant professors. It has three internationally renowned scholars as distinguished professors and academic leaders: Professors Wei Li, Qinping Zhao, and Jinpeng Huai.

Professor Li has made several distinguished contributions to theoretical computer science, including open logic for scientific discovery, practical parallel operation semantics, formalized semantics, and revision calculus. Professor Zhao has proposed many innovative methods in the fields of modeling and realistic rendering and led the effort to build the first distributed virtual-reality system in China. Professor Huai has made groundbreaking achievements in the areas of Internet software technology and systems, including algebraic theories for cryptographic protocol analyses and a zero-programming method for process-based software development.

The school has three departments (Computer Science and Technology, Computer Application Engineering, and Information Security), five key research laboratories, five research centers, and one computer teaching experiment center. The key research laboratories are the State Key Laboratory for Software Development Environment (NLSDE), the State Key Laboratory of Virtual Reality Technology and Systems (VR), the Key Laboratory of Beijing Municipality for Advanced Computer Technology (ACT), the Engineering Center of the Ministry of Education for Advanced Computer Application Technology, and the Key Laboratory of Beijing Municipality for Network Technology. It is worth noting that SCSE is the only computer science school in China that has two State Key Laboratories in the domain of information science.

Research Center of Excellence

Since its establishment, the school has played a pivotal role in the progress of computer science in China. Over the last two decades alone, it has made significant contributions to the frontiers of computer science research. Scientists at the school have presented many innovative theoretical results and made technological breakthroughs in the following fields:

- Computer science theory
- Big-data science and engineering
- Virtual reality
- Distributed and high-performance computing
- Intelligent systems and pattern recognition
- Software engineering
- Large-scale information systems.

In addition to its remarkable fundamental research work, the school has high-profile teams that have taken the lead in the development of national information technology infrastructure, including the national computational grid and cloud infrastructure, national scientific data infrastructure, and information systems for the national South-to-North Water Diversion project as well as China’s giant program to expand its airline capabilities.

The school became a national key institution in the field of computer software and theory in 2001, and in the field of computer science and technology in 2007. Since 2000, the school has completed nearly 400 projects funded by the National Natural Science Foundation, Key Fundamental Research Program, High-Tech Program, and National Key Engineering projects supported by the Ministry of Science and Technology, and international cooperative projects, with total research funding of over 800 million yuan (US$125 million). Currently, the school has 130 active research projects funded by government agencies and by industry. For the past three years, the annual funding of the school has exceeded 100 million yuan (US$16 million).

Over the past decade, the school has published nearly 1,500 papers in peer-reviewed journals and has been awarded 219 patents. According to statistics provided by the Chinese Science and Technology Information Institute, the school is ranked in the top two globally for the award of patents on virtual reality. The achievements and accomplishments of the faculty have been widely acknowledged through high-profile awards and recognitions, including a 2nd Prize National Natural Science Award, a 1st Prize National Science and Technology Progress Award, 10 2nd Prize National Science and Technology Progress Awards, two 2nd Prize National Science and Technology Innovation Awards, two Ho Leung Ho Lee Awards, and a number of awards presented by provincial and ministerial agencies. With regard to teaching, the school has received one 1st Prize and two 2nd Prize National Teaching Achievement Awards, and three 1st Prize and two 2nd Prize Provincial and Ministerial Teaching Achievement Awards.

For the past three years, the school has purchased over 100 million yuan (US$16 million) of research equipment and has active research projects supported by the Ministry of Science and Technology, national fundamental research program, high-tech program, and national key engineering projects. The faculty have been widely acknowledged through high-profile awards and recognitions, including a 2nd Prize National Natural Science Award, a 1st Prize National Science and Technology Progress Award, 10 2nd Prize National Science and Technology Progress Awards, two 2nd Prize National Science and Technology Innovation Awards, two Ho Leung Ho Lee Awards, and a number of awards presented by provincial and ministerial agencies. With regard to teaching, the school has received one 1st Prize and two 2nd Prize National Teaching Achievement Awards, and three 1st Prize and two 2nd Prize Provincial and Ministerial Teaching Achievement Awards.
Educational Program

The school has made every effort to teach students computer science theory and facts as well as practical skills and professional ethics. Decades of dedication have resulted in an open, collaborative, and innovative atmosphere where students are encouraged to embrace challenging tasks, explore unknown areas, and innovate. Many excellent students have demonstrated their talents at the school. In 2001, the school team was the winner in the .Net Software Development Contest for Asian Students sponsored by Microsoft. In 2002, another student team won the silver award at the e-gate Open launched by SchlumbergerSema. In 2004, a student team took first place at the international GSM and Java Smart Card Application Development Contest. In 2008, a student team won the gold award at the Fifth “Grid Plugtests” Global Grid Algorithm and Program Design Contest. Computer science students have also performed well in campus academic competitions. Of the 20 Fengru Cup Extracurricular Scientific Contests held at Beihang University, nine team championships have gone to the school. Graduates of SCSE have enjoyed an exceptional reputation for their excellent academic research skills, strong self-motivation, and teamwork.

Worldwide Collaboration and Outreach

International collaborations have been a focus in the development of SCSE. The school has established long-term cooperative relationships with well-known universities in the United States, Germany, Britain, Japan, and Hong Kong, with the multinational corporations Intel, IBM, Microsoft, Quantum, AMD, and Nokia, and with domestic corporations such as Lenovo, Huawei, Digital China, and Langchang. The school also collaborates with various other international organizations. The W3C China office established at BUAA in 2006 has greatly encouraged web standardization in China. Since 2012, strongly supported by the domestic and overseas web communities, Beihang University has been the fourth of the “Host Institutions” of W3C, with the other institutions being the Massachusetts Institute of Technology, the European Research Consortium for Informatics and Mathematics, and Keio University. Furthermore, in 2007, the school worked with other Object Web and Orientware partners and launched an OW2 consortium to foster the open-source middleware community. The school regularly holds high-profile international conferences, such as WWW 2008 and the first U.S.–China Computer Science Leadership Summit in 2006.

Facing intense competition in an era of ever-changing information technology, SCSE will continue to push the frontiers of computer science and engineering to meet the demands of the national development strategy and contribute to national scientific and technological innovation in the 21st century. By targeting cutting-edge computer science, promoting interdisciplinary scientific research and exploring emerging research areas, the school will continue to provide top intellectual and innovation resources for China and the rest of the world. All faculty and students at the school are motivated to continue the school’s rich half a century heritage and do their best to build a first-class and world-famous school of computer science and engineering.

For more information:
School of Computer Science and Engineering
scse.buaa.edu.cn
State Key Lab of Software Development Environment
www.nlsde.buaa.edu.cn
State Key Lab of Virtual Reality Technology and Systems
www.vrlab.buaa.edu.cn
Challenges and Opportunities in Big-Data Science and Engineering

The State Key Laboratory of Software Development Environment (NLSDE) is an open scientific center that focuses on fundamental research, applied fundamental research, and cutting-edge high-tech approaches in software theory, technology, and the development of computers and advanced networks.

Vision and Mission
Advances in modern computing and communication technologies have ushered in the new era of ultra-large-scale systems (ULSs), in which people, sensors, computers, and networks are intertwined to create large and sophisticated systems beyond the complexity of any preceding ones. In a ULS, there are millions of functional actors running tens of millions of service instances simultaneously, and processing on an extreme scale all types of dynamic sensor data including structured and unstructured data. Typical ULS examples are online service systems and metropolitan-scale cyber physical systems such as the Smarter Planet, Internet of Things, intelligent transportation management systems, autonomous power grid systems, and disaster response systems. Such emerging systems have challenged computer scientists and engineers to efficiently design, develop, and maintain complex software infrastructures that are sustainable, manageable, robust, and enduring, and which deliver rich, on-demand services with high usability. Additionally, the proliferation of sensors, mobile phones, and many new data sources has resulted in a growing data deluge, where the growing volume of data often overwhelms the current processing capacity provided by conventional data management and processing pipelines.

Addressing the above challenges requires an interdisciplinary approach involving researchers from relevant fields such as software engineering, data mining, visualization, and distributed computing. The latest advances in these fields are needed to advance fundamental research and core technologies in the area of big-data science and engineering. With regard to big-science theory, researchers at NLSDE have worked on a new calculus model for big data. They have also developed cutting-edge big-data technologies such as semantic models for massive unstructured data management and a Service Orientated Architecture (SOA)/cloud-based data processing environment as well as a crowdsourcing-based data analysis methodology. Using these theoretical results and technological achievements, a variety of data-intensive applications such as the national eScience repository and an urban intelligent transportation system have been implemented and now are widely deployed in production services. The figure below illustrates NLSDE’s vision for big-data science and engineering.

Research Highlights
R-Calculus and Data Science. To study the evolution of data and knowledge extracted from data, researchers at NLSDE proposed a formal inference system for revision called R-calculus. R-calculus has been shown to be sound, complete, and reachable. This means that R-calculus can present all possible ways to resolve the inconsistency between data and knowledge extracted from data. To study data in a massive information system that is a type of ULS, researchers at NLSDE proposed a random massive algebraic system based on basic algebra operations to simulate the behavior of the massive information system, and analyzed its phase transition property and complexity. For unstructured data management, the researchers proposed a data pyramid model. This model provides a unified, integrated, and associated description for heterogeneous and unstructured data, and supports intelligent data services such as associated retrieval and data mining. Using this model, an unstructured data management system has been developed.

Big-Data Clouds. To resolve the problem of reliable net resource management, the NLSDE laboratory proposed a series of new methods for the reliable aggregation and scheduling of net resources and developed iVic, an internet based virtual computation environment. For the reliable composition of web services in network software, the laboratory built a model for web service composition based on trust computing, proposed an assurance method for the reliability of service composition based on logic and probability, and established a development and execution environment for reliable-service-oriented software. The development and execution environment for service-oriented software has been widely applied to a variety of big-data areas including e-government, satellite navigation, spatial information, geological exploration, and telemedicine. An environment that supports collaboration was established to encourage the development and execution of an SOA-based satellite observation and control system, remote sensing information public service platform, and telemedicine collaborative image analysis system. The research results have already been incorporated into the standardization of e-government in China and SOA both in China and around the world.

Information Transportation System. Urban traffic is an issue in all major cities in China. To alleviate traffic congestion and provide real-time information to drivers, the NLSDE laboratory was funded in 2005 by the Beijing municipal government to start research into an intelligent transportation system (ITS). Considering the current situation in China and the direction of research into ITSs, NLSDE chose to build a floating-car–based dynamic traffic information collecting and processing system.
For instance, the system in Beijing uses global positioning system (GPS) location data obtained from more than 15,000 taxis and buses to compute a live traffic information map that refreshes once every four minutes. The average traffic information coverage exceeds 90% and the average accuracy also exceeds 90%. This system is already deployed in 29 cities in China and provides services to many enterprise partners such as Google, Garmin, Nissan, and Toyota.

**Big Data in eScience.** Since 2007, NLSDE has undertaken the development of a national scientific data infrastructure (www.escience.gov.cn) in China to support long-term scientific data sharing. This aims to enable co-innovation among scientists, educators, and students in many scientific domains, ranging from biology to earth sciences. In 2009, this national data portal was officially released online for public access, providing data services including data harvesting, data preservation, data querying, and data mining. Currently, with nearly 100,000 registered users, the
The portal of national scientific data infrastructure (www.escience.gov.cn) in China.

The AS level topology of the global IPv6 backbone network.

Research on Virtual Reality

The State Key Laboratory of Virtual Reality Technology and Systems (VR Lab), sponsored by Beihang University, is the first national science and research base in China to conduct basic and applied research in the field of virtual reality. The members of the laboratory include teachers and postgraduates from the School of Computer Science and Engineering, School of Control Science and Engineering, School of Mechanical Engineering and Automation, and the School of Biological Science and Medical Engineering. The VR Lab is devoted to technological innovation and system development in virtual reality (VR) through interdisciplinary collaboration.

The laboratory’s major research directions are modeling theory and methods in VR, augmented reality, and the human-computer interaction mechanism; distributed VR method and technology; and platforms and systems in VR. The VR Lab has established an open fund to finance exploratory research in these directions.

After years of effort, the VR Lab has established its superiority and specialty in the discipline of intersection and integration, and made much headway in both theoretical research and system development. Specifically, it has developed software systems such as the real-time 3-D graphics platform, BH-Graph; distributed interactive simulation platform, BH_RTI; created experimental environments to support related VR research, such as a force-feedback environment; and designed and fabricated a variety of devices. Examples of these devices include the haptic device, devices for natural phenomenon data acquisition and modeling, devices for mobile real-time video acquisition and modeling, devices for the experimental simulation of human blood circulation, and a series of application systems that have positive social and economic benefits. These application systems include an ingenious simulation system for the opening ceremony of the Beijing Olympic Games, a rehearsal scheme and decision system for the National Day parade, a video-based virtual scene generating system, a topological design for Cockpit, human-computer environment ergonomics evaluation, augmented-reality collaborative working environment for the maintenance of key aircraft components, and full-mission flight simulator with six degrees of freedom.

In the next few years, the VR Lab will focus on three research areas: (i) digital modeling of human organs and virtual surgery, (ii) data acquisition and simulation of natural phenomenon, and (iii) augmented reality technology and methods.

Digital Modeling of Human Organs and Virtual Surgery

Various human tissues and organs have complicated microstructures, usually coupled with biological activity involving multimodality, nonlinearity, and viscoelasticity, which pose a great challenge for the high-fidelity digital modeling of human organs. Virtual surgery operations, such as incision, suture, and intervention, will prominently change the geometrical topology of the digital model, as well as its accompanying biomechanical characteristics and physiological properties, which makes real-time virtual surgery simulation more difficult. Driven by the great demand of national medical health care, the VR Lab is engaging...
in interdisciplinary fundamental research on three scientific issues: (i) multiscale geometrical modeling theory for human organs, (ii) physical and physiological modeling theory for human organs, and (iii) simulation and evaluation theory for virtual surgery. The research outcomes are expected to provide a breakthrough in related technical bottlenecks in surgery training, surgery project argumentation, and surgery planning and rehearsal, and thus promote precise, minimally invasive, and personalized surgery.

**Multiscale Geometrical Modeling of Human Organs.** According to the morphology characteristics of human organs, the VR Lab studies the morphological change rule among different individual organs employing advanced digitized methods, and explores key problems in high-precision digitalization, multiscale geometrical modeling of the human body, morphological feature extraction of volumetric tissues, and vectorization of digital human models. These efforts will help establish high-precision and high-fidelity 3-D interactive digitized human organs for virtual surgery.

**Physical and Physiological Modeling of Human Organs.** The VR Lab studies new theories on accurate acquisition and correct representation of physical (mechanical) characteristics both of the healthy and the diseased human body. Meanwhile, the laboratory researches new methods of quantitatively formulating the interaction between human organs and medical instruments, new technologies for quantitatively depicting changes in local tissue structure and function, and the overall conditions and vital signs brought about by surgery. It will thus attempt to establish a comprehensive technical system for the physical and physiological modeling of human organs.

**Simulation and Evaluation of Virtual Surgery.** The VR Lab performs a series of studies on biomechanics-based haptic feedback mechanisms, making efforts to (i) fabricate a human-computer interactive device with multiple degrees of freedom that combines the virtual surgery haptic environment with kinesthesia, (ii) establish models to consistently represent the geometrical, physical, and physiological features of soft tissues, (iii) explore high-performance technologies for collision detection and responses, and (iv) establish quantitative analysis models and evaluation methods, all for the final purpose of implementing surgery simulation and evaluation.

**Supporting Platform and Prototype System for Virtual Surgery and Training.** By integrating various advanced technologies, the VR Lab expects to establish a more credible generic virtual surgery supporting platform that is capable of personalized modeling, force-feedback interaction, and high-fidelity rendering. Additionally, the VR Lab plans to develop a prototype system for the simulation of typical surgeries, and apply it to surgery training, planning, and rehearsal.

**Data Acquisition and Simulation of Natural Phenomenon**
In VR, acquiring real data of various natural phenomena (e.g., light, smoke, fire, and fluid)—and efficiently processing, analyzing, and reusing the data—will greatly improve virtual environments. A study is in progress at the VR Lab to fabricate natural-phenomenon acquisition devices, and establish data models for data-driven simulation and validation. The models will be used in fields such as special effects in film production, military simulations, and disaster training.

**Data Acquisition and Simulation of Fire and Smoke.** Fire and smoke are typical heterogeneous media with sparse density distributions of particles. High-fidelity analysis and reconstruction of smoke and fire are therefore difficult. The VR Lab has developed data acquisition devices, such as BH_DOME, for fire and smoke. Using the data acquired with these devices, a participating media model that can describe the density field of the media and the properties of light propagation has been proposed. The laboratory is also working on devices for the acquisition and computation of a fire temperature field, and exploring techniques for modeling the special effects of fire.

**Data Acquisition and Simulation of Fluid.** The complexity of a fluid’s time-varying movement affects the accuracy and integrity of acquired data, and brings about spatial-temporal inconsistency. The VR Lab is developing high-speed acquisition devices to acquire and observe the microscopic changes of fluid motion, devices for observing and simulating interactions between solids and fluids, and devices for comparing and testing relevant dynamics parameters. An example is a device based on the whirlpool phenomenon that simulates bubbles and vortexes produced by solid-fluid interactions using a particle-based Lagrangian approach.

**Structure of a Parallel Physical Simulation and Rendering Platform.** Realistic simulation and rendering of complicated natural phenomena have great spatial-temporal complexity. This calls for a dedicated parallel physical simulation and rendering engine to improve
efficiency. At present, the laboratory is designing and developing a platform that runs on a multigraphics processing unit (GPU) cluster with 16–32 nodes each having four GPUs. This platform, with high-efficiency, low-level unified communication facility and an easy-to-use parallel programming environment, supports flexible resource allocation, multiuser remote accessing, extensions of physical simulation and rendering engines, and the testing and analysis of parallel simulation and rendering performances.

Augmented-Reality Methods and Techniques
Application of VR technology requires the continuous development of new techniques and methods for the seamless integration of virtual and real environments. Recently, the VR Lab has conducted in-depth research on a theoretical approach and technology related to augmented-reality content comprehension, augmented-reality localization registration, VR interaction, mobile device-based interaction, augmented-reality scene integration, and augmented-reality light and shadow composition.

Mutual Understanding Between VR and Reality. Mutual understanding between VR and reality is a necessary condition for their integration. The VR Lab makes use of effective information-acquisition techniques and devices to acquire information of the virtual and real worlds, and to mine effective content containing essential characteristics and objective laws as well as investigating knowledge representation and information description methods and theory systems for virtual, real, and augmented-reality environments. Multidimensional feature space and mapping rules between virtual and real environments will be set up by studying their information representation and modeling techniques, for the purpose of continuously promoting mutual comprehension between the virtual world and real world.

Information Interaction Between the Virtual World and Real World. By researching comprehension between virtual information and real information, the laboratory is further developing information channels between them, revealing their objective laws, and discovering their inherent relations. From the perspective of multidimensional space (temporal, spatial, and optical domains and their associated domains), the laboratory is studying theory, approaches, and techniques related to the mechanism of information interaction, the highly efficient composition of multidimensional content, mobile device-based portable interaction, and augmented-reality content composition.

Augmented-Reality Representation and Reaction. Seamless augmented reality has long been one of the laboratory’s goals. This includes the development of a seamless, efficiency measuring and evaluation system in augmented reality, representation of indexes and information, systems for describing professional knowledge of VR, and knowledge bases in accordance with VR application standards. Furthermore, seamless augmented reality involves cognitive-based realistic augmented reality representation, accurate knowledge-based augmented reality effects, and cognition-based augmented reality reactions. The study of all of these aspects will help perfect expanding measures and evaluations, and help develop related indexes.

Data acquisition device BH_DOME (BH, Beihang University).
The School of Mechanical Engineering and Automation

The Beihang University School of Mechanical Engineering and Automation provides interdisciplinary research and educational opportunities in the sciences of mechanical engineering, flight vehicle engineering and manufacturing, and material processing and control engineering.

The School of Mechanical Engineering and Automation (SMEA) has a long and distinguished history that goes back to the establishment of the Beijing Institute of Aeronautics [the former name of the Beijing University of Aeronautics and Astronautics (BUAA), also known as Beihang University] in 1952.

SMEA was established in April 1998 through the merging of the Manufacturing Engineering Department and the Mechatronics Engineering Department. The school covers three national level key disciplines: Mechanical Engineering, Aeronautical and Astronautical Science and Technology, and Materials Science and Engineering. SMEA is growing rapidly into an internationally renowned, research-oriented school of mechanical engineering.

People and Departments

Over the past 60 years, more than 15,000 students have completed graduate degrees in mechanical engineering at Beihang University. Because of the solid scientific and engineering background they have gained in various training programs at the university, there has been high demand among employers for these graduates. Currently, SMEA comprises eight academic departments with an outstanding team of teaching and research faculty. At the end of May 2012, there were more than 160 faculty and staff, including 46 professors and 57 associate professors. Several faculty members have earned titles from the Chinese Ministry of Education, including one who holds the Chang-Jiang Professorship, two professors who are supported by the Outstanding Youth Fund, and nine teachers who have been awarded the honor “New Century Excellent Talents.”

Each year, SMEA enrolls approximately 210 undergraduate and 280 graduate students, of whom more than 40 are doctoral students. At present, total enrolment at SMEA is 1,900.

Departments at SMEA

- Department of Mechanical Manufacturing and Automation
- Department of Mechatronics Engineering and Automation
- Department of Mechanical Design and Automation
- Department of Industrial and Manufacturing Systems Engineering
- Department of Material Processing and Control Engineering
- Department of Aircraft Manufacturing Engineering
- Department of Industrial Design
- Institute of Robotics

SMEA has always explored ways to provide a rich education and research environment.

Research

After 60 years of development and growth, SMEA has made considerable progress in both education and research. In particular, in the past decade, the school has been officially listed in China’s Action Plan for the Revitalization of Education in the 21st Century. SMEA has demonstrated excellence in the advanced design and manufacturing of aerospace technology, improved its innovative engineering and technical talent training system, and developed unique educational and research programs. The academic reputation of SMEA is steadily growing through the continuing expansion of cooperation between research and education.

A brain surgical robot system.
SMEA has always explored ways to provide a rich education and research environment. The school has established a group of technology-based and specialized laboratories, including two national key specialized laboratories (the Robotics Institutional Laboratory and the Mechanical Design and Automation Laboratory) and two provincial or ministerial-level key laboratories (the Flexible Manufacturing Systems Laboratory and the Digital Design and Manufacturing Laboratory).

In the area of advanced aerospace design and manufacturing technology, SMEA has established six education and research centers: the Complex Digital Product Design and Manufacturing Engineering Research Center, the Advanced Processing Technology Research Center, the Advanced Sheet Metal Forming Technology Research Center, the Advanced Robotics Technology Research Center, the CAD Education and Experiment Center, and the Mechanical Design Education and Experiment Center. These centers, by providing high-level environments, have improved the overall research capacity and provided experimental equipment for SMEA's educational programs.

In recent years, SMEA researchers have participated in more than 700 research projects, improving SMEA's rank among the top Beihang University schools in terms of funding granted for scientific research [122 million yuan (US$19.3 million) in 2011]. The school has won five national science and technology awards and 35 provincial and ministerial level scientific and technological awards.

**Research Fields**

**Modern mechanisms and robotics.** The school focuses on the design of large-displacement flexure, including the methodology of large-displacement flexural pivots and the theory of compliant stages for micro-/nanomanipulation and manufacturing.

**Digital manufacturing technology and systems for aviation products.** Emphasis is placed on theory, methods, technologies, and their applications in establishing advanced integrated manufacturing systems, and developing rapid-response capabilities and platforms for aviation product development.

**Advanced processing technology and equipment for aerospace engineering.** Another focus of SMEA is on aerospace engineering materials and their structural complexities. There are strict requirements of precision and finished-surface quality for aircraft parts. The school has developed a series of advanced processing technologies, such as high-speed milling, high-speed cutting, vibration-assisted machining, and age-forming technology to meet these demands. In addition, the school employs nondestructive testing technology to evaluate and ensure the quality of finished materials/products, using equipment developed in investigations of testing principles.

**Flexible assembly technology for aircraft manufacturing.** Aircraft manufacturing involves assembling a variety of complex systems in an optimal, automated, and efficient manner. The application of advanced technologies such as numerical controls, robotics, and flexible manufacturing systems greatly improves aircraft assembly. Currently, SMEA's strategic research directions are digital assembly, robotic automation, and flexible tooling technology.

**Design and manufacturing technology for bionic smart structures.** Besides the work of biologically inspired engineering, the school is developing new bio-aided processing technologies that directly use biology to facilitate micro-, nano-, and multiscale structures. There are three main modes: bio-forming technology that directly uses abundant natural bio-prototypes to fabricate bio-shape-based structures, bio-assembly technology that uses fine structures as units to fabricate multiscale complex structures by way of self-assembly or extraforce aided assembly, and bio-machining technology that uses biomaterials and bio-growing processes to fabricate recyclable and bio-transformable materials.

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Advanced Manufacturing Technologies for Aerospace Engineering

Deyuan Zhang, Jun Cai*, Min Wan, Huawei Chen, Yonggang Jiang, Xinggang Jiang, Xun Li, Weidong Li, Xiangdong Wu

Aerospace engineering is a rapidly developing field. Airplanes have traditionally been constructed of metals—usually alloys of aluminum. However, more advanced materials such as titanium alloys, carbon fiber composites, and bio-inspired hybrids with higher mechanical strength, lower density, and even intelligent functions, are increasingly being developed and implemented in airplane manufacturing. The fabrication, machining, and forming technologies for the materials used in aerospace engineering differ from the technologies of traditional metals (1). Scientists and engineers at the School of Mechanical Engineering and Automation (SMEA) have developed a series of advanced machining and forming technologies over the past two decades. The methodology and theory of vibration-assisted machining (VAM) have been studied to improve the machining quality and efficiency of parts made with difficult-to-machine materials. Age-forming technology has been developed for the task of integral panel fabrication, and new bio-aided manufacturing technology has been proposed to efficiently fabricate multiscale parts.

VAM Technology for Difficult-to-Machine Materials

VAM adds small-amplitude, low- or high-frequency tool displacement to the cutting motion of a tool. The tool tip is driven in a small reciprocating (1-D VAM) or elliptical motion (2-D VAM) whose centroid moves in the direction of the cutting velocity (2). For appropriate combinations of cutting velocity, tool amplitude, and frequency, the tool periodically loses contact with the cutting chip (or leaves the workpiece entirely, in the case of 2-D VAM), and the traditional continuous-contact machining process converts to a contact machining process that is noncontinuous, instant, and reciprocating (Figure 1A). Consequently, machining forces can be reduced and thinner chips generated. This in turn leads to improved surface finishes, better form accuracies, and near-zero burring compared with conventional machining. Tool life, especially the life of diamond tools for cutting ferrous materials, is dramatically extended by VAM. When cutting brittle materials, VAM has been found to increase the depth achieved in ductile-regime cutting, allowing fine surfaces to be manufactured without grinding and polishing.

Age-Forming Technology for High-Stiffener Integral Panels of Aluminum Alloy

The forming of large aluminum alloy panels to attain airfoil sections and complex curvatures for use in modern metal aircraft and aerospace structures has many problems that are not easily resolved by conventional mechanical forming methods. To accurately manufacture large aircraft integral panels, we developed a unified aging-creep multiscale constitutive model for the analysis and simulation of the correlations between the mechanical properties, strain, and age-creep parameters of aluminum alloys (4). The input parameters of the equation are the initial stress level and heat treatment parameters. The outputs of the model include property parameters, namely creep strain, yield strength, precipitate relative volume fraction, and mean radii of precipitates. The model can be used to describe the development of microstructures and yield strengths with creep time. The results of the study (4) were in agreement with experimental results at different stress levels. From the prediction of spring back using the finite element method and the displacement adjustment method, a forming-error calculation algorithm and a spring back compensation algorithm were also developed (Figure 2). An interactive die-surface-modification system for age-forming was also established using the commercial finite element method preprocessing software ABAQUS/CAE to implement an optimized design for a die surface (5).

Bio-Aided Manufacturing of Multiscale Structures

Bio-aided fabrication technology uses the metabolic function, growing process, special composites, and the complex structures of living creatures to fabricate functional materials, structures, and apparatus with submicron to macrosopic dimensions (6). There are three main types of technology: bio-forming technology that directly uses abundant natural bio-prototypes to fabricate bio-shape–based structures, bio-assembly technology that uses fine structures as units to fabricate multiscale complex structures by way of self-assembly or extra-force–aided assembly, and bio-machining technology that uses bio-materials and bio-growing processes to fabricate recyclable and bio-transformable materials.

Microorganisms provide good templates since there are many species in nature that have specific shapes and dimensions on the micro-/nanometer scale. They can be made rigid and conductive or magnetic through the deposition of functional coatings (Figure 3A–D). These electromagnetic particles have greater advantages when they are used as electromagnetic-wave–absorbing material fillers since they have preferable shapes, dimensions, and structures, and their fabrication is cost-effective and highly efficient (6, 7). Diatoms have strong silica frustules with transparent and delicate multiscale structures, 2-D pore arrays, and large surface areas. Additionally, the pore size of a diatom can be further adjusted with hydrofluoric acid treatment. Therefore, diatoms can be assembled in an array or layer and then bonded with the substrate to form microchips for biosensors, solar cells, batteries, and microfluidic applications (Figures 3E and 3F) (8). In addition to microorganisms, macroscale biological organisms can be used for forming prototypes.
Figure 3. Functional particles, apparatus, and surfaces made with bio-prototype-aided manufacturing technology. (A) Rod-like particles obtained through electroless deposition of CoNiP film onto Bacillus cereus. (B) Flaky particles obtained by electroplating Ag film onto Coscinodiscus diatomites. (C) Hollow spiral particles obtained by electroless deposition of copper film onto Spirulina platensis. (D) Broken-section view of copper-coated S. platensis. (E) Cymbella perpusilla frustules with delicate multiscale structure assembled and bonded onto glass-based substrates through hydrofluoric acid-assisted bonding to build chips for biosensing use. (F) Detailed view with arrays of large pores (foramen) and myriad sieve pores of about 40 nm on diatom frustules. (G) Bionic drag-reduction surface with vivid scales replicated from shark skin.

For example, shark skin has been replicated to fabricate a drag-reducing surface (Figure 3G); the drag reduction range of this vivid biomimetic surface is much higher than that of a bionic surface with just simplified grooves (9). In summary, the fabrication of multiscale structures with bio-modes is a new and multidisciplinary research field that has great potential and deserves close attention.

REFERENCES

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Nature’s Design Paradigm for Modern Mechanisms and Bionic Robots

Guanghua Zong, Tianmiao Wang, Yidu Zhang, Shusheng Bi, Xilun Ding, Diansheng Chen, Wei Wang, Jianhong Liang, Hongzhe Zhao, Yueri Cai, Xu Pei, Jingjun Yu

Man-made mechanisms are the source of innovation in the mechanical domain. In the 18th and 19th centuries, mechanisms played an important role in the manufacture of spinning machines, steam engines, and internal-combustion engines. They also contributed to the emergence and development of the machines of modern industry. With the rapid development of modern science and technology such as computer science, biomimetics, and control technology, there are new challenges and development opportunities in the field of modern mechanisms.

Inspiration for the creation of mechanical devices often comes from observing the natural structures and movements of living organisms, such as birds and fish. Understanding the wide use of modularity, compliance, and metamorphism in nature may lead to the design of new mechanisms and robots, such as flexure or compliant mechanisms (1), metamorphic mechanisms (2), and bionic robots. Flexures are jointless elastic structures that derive motion from material compliance. Compliant mechanisms transfer motion, force, or energy through the deflection of flexible members, resulting in high-precision, simple, and lower-cost designs. The mobility of a metamorphic mechanism changes as it moves from one configuration to another, leading to variable topology of the mechanism. Although this design philosophy incorporating nature has been applied to high-precision flexure systems in manufacturing, deployable mechanisms in aerospace research, and compliant bionic robots, there remain theoretical and technological challenges related to design methodology, control technology, and performance testing. In the past 10 years, researchers at the Robotics Institute of Beihang University have focused on these important problems and carried out systematic research on flexure systems, metamorphic mechanisms, and bionic robots.

The educational kit toolbox contains various types of flexure modules, and two rigid plates, and the components can be assembled into a variety of specified motion types. The kit is useful in verifying Maxwell’s scientific rule about the relationship between constraints and degrees of freedom as well as encouraging children to be creative and design objects on their own.

Design Methodology of Flexure Systems

Our nature-inspired paradigm for creating flexure systems is based on the effective use of distributed-compliance flexure modules with a rigid mathematical foundation called screw theory (3). The research focuses on: (i) a closed-form geometric framework for type synthesis of flexure systems based on mappings of geometrical, physical, and mechanical building blocks; (ii) quantification of key performance attributes such as compliance, mobility, and accuracy; and (iii) an analytical compliance-based design methodology for developing high-performance flexure systems (Figure 1).

Flexure systems also make excellent educational kits or toys, such as Lego products. A design concept for a flexure-based reconfigurable educational kit has been proposed, and a prototype is shown in Figure 2.
Figure 3. Development of bionic fish propelled by oscillating pectoral foils. (A) Picture of a live cow-nose ray swimming in an aquarium. (B) Robotic Fish I was developed in 2006, and can float and dive quickly with a velocity of 0.8 body lengths per second (BL/s). (C) Robotic Fish II (2008) can swim with a velocity of 0.9 BL/s. (D) Robotic Fish III (2009) has a bionic body shape and can swim at 1.1 BL/s. (E) Robotic Fish IV (2010) is driven by pneumatic artificial muscle and has an entirely flexible body. (F) Robotic Fish V-1 (2010) is driven by multiple fin rays. (G and H) Robotic Fish V-2 (2011) has an internal skeleton and shows good form and function compared with its live counterparts. (I) Experimental platform with towing belts to carry out experiments using the series of robotic fish.

Figure 2. A Lego-like educational kit. (A) Flexure modules. (B) Prototype.
mechanism and biological properties to the research, a new type of metamorphic mechanism, called the compliant metamorphic mechanism, has been proposed and its methodology of analysis and design has been described. The achievements integrate the structural composition principle of the metamorphic mechanism in terms of biological characteristics, enable the building up of mechanism models based on metamorphic genes and cells, and establish mathematical models of the relationship among a work-stage matrix, an origin metamorphic matrix, and a metamorphic matrix. Using these models, configuration synthesis of the metamorphic mechanism can be achieved (4).

High-Performance Bionic Robots

Fish that propel themselves with oscillating pectoral fins, such as manta rays and cow-nose rays, have good propulsive efficiency and maneuverability. Five generations of bionic fish prototypes propelled by oscillating pectoral foils have been developed at the Robotics Institute in the past seven years, as shown in Figure 3. Some exceed a speed of one body length per second and others have achieved high-mobility movements such as backward swimming and turning with zero radius (5).

Bionic research on the kinematics of caterpillars suggests an efficient climbing robot configuration that is a good compromise between weight and flexibility. A compliant bionic climbing caterpillar robot with modularity has thus been developed (6), as shown in Figure 4. Two different modules, namely the joint module and the attachment module, have been designed. By combining these modules in series, different prototypes that mimic the kinematics of the inchworm or tobacco hornworm have been built. The most reliable climbing gait is realized if the robot is composed of seven joint modules. A prototype has been successfully tested on a number of flat vertical surfaces, such as glass windows and clean interior walls.

REFERENCES

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The School of Economics and Management

The Beihang University School of Economics and Management is recognized as one of China's leading business schools—offering business and professional education and conducting cutting-edge economic and management research. The school's management science and engineering discipline is a top-tier national key discipline in China.

The Beihang University School of Economics and Management (SEM), originally established in 1956 as the Department of Aeronautic Engineering Economics, is one of the earliest management schools founded at a science- and engineering-oriented university in China. Over the past 55 years, the school has made many significant contributions to scientific research and education. More than 6,000 undergraduate and graduate students have graduated from the school. The total enrollment at SEM is approximately 3,100: 800 undergraduate students and 2,300 graduate students. Among the graduate students, there are about 370 Ph.D. students, 290 Master’s students, 150 Executive MBA students, 480 MBA students, and 1,000 Master’s of Engineering students. Each year, SEM also accepts more than 80 international students.

SEM comprises seven academic departments: Business Administration, Information Management and Information Systems, Management Science and Engineering, International Economics and Trade, Insurance and Risk Management, Finance, and Accounting. The school has a Complex System Analysis and Managerial Decision Support Laboratory (a Ministry of Education Key Laboratory in Management Science and Engineering) and a City Operation and Emergency Support Simulation Technology Laboratory (a Beijing Key Laboratory). Additionally, the school has established important research centers and laboratories, including the Research Center of Complex Data Analysis, the Research Center of Finance, the Advanced Management and Technology Lab, and the Human Factors and Behavioral Economics Lab.

Faculty

The school has 105 full-time faculty and staff. The faculty includes 42 full professors, 33 associate professors, and 23 assistant professors. Among them, there is one Foreign Member of the Royal Swedish Academy of Engineering Sciences, one Yangtze River Scholar, two winners of the National Outstanding Young Scientist Fund, 10 winners of the National New Century Talents Award, and two winners of the National Excellent Doctoral Dissertation Award.

The honorary dean of SEM, Professor Siwei Cheng, was the vice-chairman of the 10th Standing Committee of the National People’s Congress of the People’s Republic of China and the President of the Association of Chinese Soft Science Research. His research areas include complex science, the virtual economy, and venture capital investments. He is widely known as “the father of China venture capital” and his thoughts and views have a profound influence on both academic and professional communities.

The dean of SEM is Professor Huwen Wang, whose research areas are in applied statistics and complex data analysis. In 2001, she was awarded the Distinguished Youth Science Foundation award. She has published more than 100 peer-reviewed papers and four academic monographs.

SEM also has several world-class economists and scientists, including Professors Haijun Huang, Ruoen Ren, and Wanhua Qiu.

Yangtze River Scholar Professor Haijun Huang is another Distinguished Youth Science Foundation winner. His research areas are in transportation planning and management as well as transportation behavior modeling. The research group he leads has published more than 100 articles in the field of transportation and logistics management that are included in Science Citation Index (SCI). In 2011, he became the first chief scientist of the National Basic Research Programs in Management Science and Engineering. His study, “Behavior-Based Spatial-Temporal Features of Urban Traffic Flow Distribution and Numerical Study,” was awarded the 2nd Prize National Natural Science Award bestowed by the State Council of China.

Professor Ruoen Ren is a well-known economist in China. He has worked at several respected institutes including the Department of Economics at the Massachusetts Institute of Technology, the International Monetary Fund, the Organization for Economic Cooperation and Development, and the World Bank. He is also a member of the Science and Technology Committee of the Ministry of Education of China.

Professor Wanhua Qiu is a famous scientist in the field of operational research, project management, and entropy theory. She is recognized as a pioneer and the most influential scholar to apply entropy theory to management science. She serves as a member of the Management Science and Engineering Discipline Evaluation Group of the Academic Degrees Committee of the State Council of China.

Strategic Plan

As a premier institute for management and economics research and education, SEM will establish three comprehensive systems: a system for scientific discipline development based on management science and engineering discipline; a system for research development supported by nationally funded projects including the National Natural Science Foun-
Achievements
SEM has long been committed to outstanding research and education. Since 1985, faculty members have completed more than 180 NSFC projects, including six key projects and one major international collaborative project, as well as two NBRP projects, six NHRDP projects, and many leading research projects supported by government and/or industry. Annual research funding exceeds 15 million yuan (US$2.4 million). Since 2000, the faculty has published more than 4,000 academic papers in peer-reviewed journals, with 273 papers included in the SCI/Social SCI, 809 papers included in the Engineering Index (EI), and 416 papers included in the Index to Scientific & Technical Proceedings (ISTP). Additionally, members have published 300 academic books. In China, SEM is ranked highest in terms of the number of articles published in world-class journals and has a highly regarded academic reputation in China. The educational achievements of SEM are also remarkable. Since 2001, three dissertations have been awarded the title of National Excellent Doctoral Dissertation. At the same time, the school’s teaching program, based on practice and case studies, is at the highest level nationally. In 2011, five management cases won the second national 100 Excellent Management Cases award and were accepted into the Business Case Library of the Richard Ivey School of Business in Canada.

International Collaborations
To promote leading research and encourage students to contribute to the international academic community, SEM has actively developed international collaborations and academic exchange programs. This includes cooperative research projects, international academic conferences, joint degree programs, faculty exchanges, inviting renowned scholars or professors to give lectures, and encouraging professors, scholars, and students to go abroad. By 2012, SEM had established academic exchange agreements with many business institutes around the world including the École Supérieure de Commerce de Paris Europe School of Business, the Politecnico di Milano School of Management, and the Solvay Brussels School of Economics and Management at the Université Libre de Bruxelles. The school has also established several cooperative programs, including a Master of Marketing degree program with the Melbourne Business School at Melbourne University in Australia, an Aviation MBA Degree program with the John Molson Business School at the University of Concordia in Canada, and a Master of International Business program with the Grenoble Advanced Business School in France. A number of international academic conferences are jointly hosted with well-known international research institutes, colleges, and universities. These international conferences include 10 sessions of the International Conference on Industrial Management, the 38th International Conference on Computers and Industrial Engineering, and the 6th International Conference on Partial Least Squares and Related Methods.

Looking to the Future
With a long history of excellence in economics and management research and in education, SEM will strive to conduct cutting-edge research and to build a platform for innovation in business management of large and complex projects. It will also prepare students as future business leaders with a global vision, independence, and creativity. SEM is developing into a high-level, research-oriented school of economics and management, and is recognized as such both in China and on the world stage.
Recent Advances in K-Means Clustering: Data Mining Thinking

Junjie Wu*

K-means clustering (or simply K-means) is perhaps the oldest yet most popular clustering algorithm. Given its advantages—including high efficiency, excellent explainability, and wide data adaptability—K-means has been used for a broad range of data-intensive applications (1, 2) and has been thoroughly studied. K-means has been ranked second among the top 10 data mining algorithms (3), and become the de facto benchmark for new clustering methods. Nevertheless, there remain important problems regarding K-means. First, little research has been done to determine the effect of data imbalance (i.e., the skewed distribution of true cluster sizes) on K-means. This is fundamentally dangerous since data imbalance is universal, but its negative impact on K-means may not be noticed. This problem motivated our studies on the uniform effect and validation measures of K-means. Second, although distance functions for K-means have been proposed, little common ground between studies has been found. It is thus crucial to establish a general framework for distance functions that work for K-means. This motivated our study on the generalization and variants of K-means. Finally, it is interesting to use the potential of K-means as a tool to improve other learning systems, which motivated our study on K-means-enabled rare class analysis. The following highlights our recent series of work addressing these issues and summarizes our important findings (4).

Uniform Effect Versus Cluster Validity. Recently, researchers have identified data factors that may strongly affect K-means clustering. However, data imbalance has not been studied despite its ubiquitous presence in real-life data. To address this, we presented an organized study of the uniform effect of K-means (5). We first formally proved that K-means has the uniform effect of generating clusters of equal size. We then sought out empirical evidence by applying K-means to 18 real-world data sets with known true-cluster labels. Our results showed a significant uniform effect of K-means, which implies that performing K-means on highly imbalanced data may generate very poor results, but without the researcher being aware. One could argue that this effect can be detected through cluster validation. However, our experimental results indicated that the widely adopted entropy measure (E) cannot uncover the uniform effect. This exposed the need for a more comprehensive study on validation measures.

We therefore conducted an organized study on 16 external validation measures collected from various research fields (6). Four steps were employed to identify the suitable measures for K-means. Step I filtered out four redundant measures. Step II identified two defective measures, E and P (purity), which could not capture the uniform effect. Step III normalized the remaining measures using various optimization strategies. Empirical studies showed that normalization is essential for measures to have a consistent ranking over a series of results, and to detect the uniform effect of K-means. Step IV examined various properties of the measures. We finally recommended three measures—\( I^n \) (normalized variation of information), \( VD_a \) (normalized van Dongen criterion), and \( R_n \) (normalized Rand statistic)—for K-means validation. This study provided a standard for the cluster validation of K-means and also established a general procedure for selecting the right measures for clustering algorithms.

K-Means Distances and Variants. A key design issue of K-means is concerned with distance functions, yet existing related studies are fragmented. We therefore established a general framework for all distance functions suitable for K-means clustering (7, 8). The general objective of K-means (\( obj \)) is: \( \min \sum_{i=1}^{k} \sum_{x \in C_i} f(x, m_i) \), where \( f \) denotes the generalized distance, \( x \) is the \( i \)th data instance, and \( m_i \) is the centroid of cluster \( C_i \). We recognized that a distance function fits K-means if the two-phase iterative process of K-means can converge. We call such a distance the point-to-centroid distance (P2C-D), which can be used for K-means without modifying the iterative process and the centroids of arithmetic means. This is crucial for retaining the high efficiency of K-means. We then proved that a distance \( f \) is a P2C-D if there exists a continuously differentiable convex function \( \phi \) such that \( f(x, y) = \phi(x) - \phi(y) - (x - y)^T \nabla \phi(y) \). This means P2C-D is the only distance suitable for K-means with centroids of arithmetic means. P2C-D was further divided into two categories: Type-I P2C-D with strictly convex \( \phi \) such as the squared Euclidean distance (SED) and KL-divergence (KLD), and Type-II P2C-D with convex but not strictly convex \( \phi \), such as the cosine distance (COS) and the \( L_p \) distance (8). To the best of our knowledge this work was the first to define Type-II P2C-D for K-means. Extensive experiments demonstrated that using suitable distances for different data could improve the clustering quality substantially. In particular, Type-II P2C-D performed extremely well for many data sets, whereas the widely-used SED was a poor choice in most cases. This is important information for K-means users.

The P2C-D-based framework also provides insights into how to enhance K-means clustering. Previous studies have shown that Info-K-means (K-means with KLD) is often inferior to spherical K-means (K-means with COS) in text mining. However, we argued that this should be largely attributed to the “zero-value dilemma” of Info-K-means (9). To handle this, P2C-D was used in \( obj \) to elicit an equivalent objective for K-means (\( obj' \)): \( \max \sum \hat{n}_k \phi(m_k) \), where \( \hat{n}_k \) is the size of cluster \( C_k \). Letting \( \phi = -H \), the negative Shannon entropy, we have the objective of Info-K-means (\( obj' \)): \( \min \sum \hat{n}_k H(m_k) \), which only computes centroid entropies and hence will not fall into the zero-value dilemma. We then designed an algorithm called SAIL (summation-based incremental learning) with two variants V-SAIL and PV-SAIL to solve this new objective. Experiments demonstrated the advantages of these algorithms over spherical K-means (9). In particular, the algorithms performed well in a real-world landmark recognition task, as shown in Figure 1.

Rare Class Analysis Using K-Means. Given its merits, K-means may be used to enhance other learning systems. We take rare class analysis as an example, where researchers are interested in predicting rare instances hidden in a massive number of normal instances. We argued that the class imbalance problem is closely related to complex data concepts, and therefore it is inadequate to simply manipulate the class sizes (10). The traditional resampling and cost-sensitive methods contribute little to the modeling of complex concepts, and therefore may seriously degrade the prediction accuracy of normal classes.

We proposed a novel algorithm called COG (classification using local clustering) for rare class analysis (10). As an essential part of COG, K-means is employed to perform local clustering within each normal class, and produce sub-classes in relatively balanced sizes. In this way, we not only rebalanced the classes, but also decomposed the complex concepts into various simple concepts, as illustrated in Figure 2.
data sets with highly imbalanced classes, we further integrated the oversampling technique into COG, and proposed the COG-OS (COG with oversampling) algorithm. Extensive experimentation demonstrated that COG and COG-OS performed much better than state-of-the-art methods, without seriously compromising the prediction accuracy of normal classes. Particularly, COG and COG-OS were very competitive in network intrusion detection and credit card fraud detection (Figure 2).

In many instances “simple is best,” which is why we focused on K-means and are interested in its potential for handling large data sets. The presented series of work not only enriches clustering and optimization theories, but also provides valuable practical guidance for important applications. There are still many topics that require further study, such as improved detection of nonglobular clusters and eliminating the uniform effect, introducing kernels and uncertainties to basic models, and adapting K-means for large graph data.

Figure 1. Results of landmark recognition. The data are “Oxford_5K” containing 5,060 images of 11 different Oxford, UK landmarks, but with severe noise added. After noise removal, V-SAIL was employed with the number of clusters $K = 11$, and finally nine landmarks were successfully recognized. For instance, “All Souls” and “Radcliffe Cam” clusters are almost perfect (“m/n” means m out of n images in that cluster contain the correct landmark), but “Magdalen” and “Ashmolean” clusters contain some false positives (annotated by red rectangles).

Figure 2. Illustration of COG. (A) A synthetic data set containing three classes with 133, 60, and 165 instances. (B) Directly employing linear support vector machines (SVMs) obtained only one hyperplane (denoted MMH) that ignored Class 2 completely. (C) COG was instead employed, by first performing local clustering with $K = 2$ within Class 1 and Class 3, separately. (D) COG then employed linear SVMs to model four subclasses and Class 2. Ten hyperplanes were learned in a pair-wise manner. (E) Hyperplanes for the subclasses with the same parent classes were removed to refine the model. Class 2 was successfully recognized. (F) Training time comparison between COG and linear SVMs on a private credit card data set with 67,763 normal instances and 13,374 fraudulent instances. COG employed local clustering on the normal class with $K = 5$. The runtime of COG is further decomposed to compare the time taken for learning each hyperplane between a subclass and the fraudulent class, as shown in the pie chart.

REFERENCES


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Daily Commuting Behavior of Transit Passengers

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Urban transit plays a vital role in reducing road traffic congestion by offering alternative means of travel. Indeed, it directly affects the quality of urban life. Investigations into the behavior of urban commuters in a transit system have long been of interest to scientists (1). One essential feature of commuting in large cities is that passengers are likely to have to stand in vehicles during the morning peak period and suffer discomfort because of crowding. Crowding in a transit system critically affects commuting behavior. Lam et al. (2) used stated-preference surveys to investigate the effects of crowding for the Hong Kong Light Rail Transit. They found that passengers are more sensitive to in-carriage crowding while on a journey with a longer travel time. A survey of commuters in the Beijing metro system (3) found that many passengers leave home early to avoid serious in-carriage congestion during their daily commute.

To characterize this phenomenon, the in-carriage congestion cost (4, 5) is generally formulated as a function; that is, \( C(n, \tau) = g(n) \), where \( \tau \) is the travel time of a train, \( n \) is the number of passengers in the train, and \( g(n) \), increasing with \( n \), is the average crowding cost per unit time. In this study, we investigated passengers’ daily commuting behavior in a transit system with multiple origins and a single destination. This situation may emerge when a metro or bus line serves a monocentric city, where all commuters are assumed to work in a highly compact city center and live in the surrounding suburban area.

As shown in Figure 1, we consider a transit line connecting the original stop \( H_1 \) to the workplace \( W \) while passing through \( H_2, \ldots, H_{n-1} \) and \( H_n \) stops. On each weekday, there are \( N_1, N_2, \ldots, \) and \( N_n \) commuters who use the transit line from stops \( H_1, H_2, \ldots, \) and \( H_n \) all the way to the workplace \( W \), respectively. All commuters are homogeneous in the sense that they have the same desired arrival time, value time the same, and evaluate in-carriage crowding the same way.

The generalized commuting cost (6) of a commuter who rides on transit run \( j \) at \( H_i \) is \( TC_{ij} = \alpha T + \lambda_i + \beta j \), where \( \alpha T \) is the in-carriage time cost, with \( \alpha \) being the unit time cost and \( T \) the travel time from \( H_i \) to \( W \). The term \( \lambda_i \) is the total crowding cost of a commuter taking transit run \( j \) at stop \( H_i \), which is a function of the number of passengers and the in-carriage travel time; that is, \( \lambda_i = \sum_{n=0}^{N} (g(\Sigma_{n=0}^{N} n^{m}) \tau) \), where \( n^m \) is the number of passengers who take transit run \( j \) at \( H_i \), and \( \tau \) is the in-carriage travel time from \( H_i \) to \( H_j \). The term \( \beta j \) is the early/late arrival penalty when taking transit run \( j \) (7). In equilibrium, the generalized commuting cost is identical for all transit runs actually chosen during rush hour. Mathematically, this requirement can be expressed as \( TC_j = TC \) if \( n' > 0 \) and \( TC_j \geq TC \) if \( n' = 0, j \in Z, i = 1,2,\ldots,K \), where \( TC \) is the equilibrium total generalized commuting cost from \( H_i \) to \( W \) and \( Z \) is the run number set. It states that, for a given transit station \( H_i \), the travel cost for run \( j \) is equal to the equilibrium cost if run \( j \) is used by some commuters from that station, and the travel cost for run \( j \) is not less than the equilibrium cost if it is not used by any commuters from that station.

To reflect the effects of limited capacity, we can set \( g(n) \rightarrow \infty \) when \( n \rightarrow N_{\infty} \), where \( N_{\infty} \) is the maximum physical capacity (8). We consider two types of capacity constraints, namely the physical capacity (the maximum number of passengers that a train can safely load) and the seat capacity (the number of seats in the train). Commuters who want to board a full transit run should arrive earlier and wait longer to get boarding priority and thus experience peak-period queuing at the stop. By introducing the seat capacity, we can study the asymmetric property of using a transit service; for example, the different degree of discomfort experienced by sitting and standing commuters. Passengers who board a transit run at upstream stops will have seats and will not be affected by the crowding condition at downstream stops. This asymmetrical property is a challenging but important subject in transit modeling. With a given transit timetable, an equilibrium departure pattern of commuters from all stops, \( \{n'_j, x'_j | i = 1,2,\ldots,K, j \in Z\} \), can be obtained by solving \( K \) interrelated minimization problems; that is, \( \min \Sigma_{n=0}^{N} (Z_{min} + \Sigma_{n=0}^{N} g(\Sigma_{n=0}^{N} n^{m}) \tau) + \Sigma_{n=0}^{N} (\Sigma_{n=0}^{N} (n'_j + x'_j)) \delta(j), i = 1,2,\ldots,K \), subject to \( \Sigma_{n=0}^{N} (n'_j + x'_j) = N_i, n'_j \geq 0, x'_j \geq 0, \Sigma_{n=0}^{N} n'_j \leq N_i, \Sigma_{n=0}^{N} x'_j \leq N_i, j \in Z \), where \( G(x) = f^2(x^2 + 0) \), \( Z \) is the set of run numbers chosen by commuters, \( N_i \) is the standing capacity of a carriage, and \( N_i \) is the number of seats provided in a transit run.

From the first-order optimality condition of the minimization problems, we analytically obtain the following results. (i) The commuters living closer to the destination/workplace take trains that are simultaneously chosen by those who live further from the workplace, with the on-time arrival train used by commuters from all stations. In particular, there exists a ‘saturated’ time period for each station, during which the departure rate of commuters is identical and maximal. These characteristics of the commuters’ behaviors can be observed in Figure 2A. (ii) At equilibrium, if there are some transit runs leaving stop \( H \) in a saturated state, the commuters who can ride on these runs at this stop experience lower schedule delay cost. (iii) If there are some transit runs arriving at destination \( W \) in a saturated state, these saturated runs would be concentrated in a period around the start time to reduce the schedule delay cost. The period during which arrival transit runs are fully occupied is called the saturated period. (iv) If there is a stop where no commuter boards the saturated runs, then all commuters downstream of that stop would avoid commuting in the saturated period. (v) The upstream commuters would first board the transit runs that leave the original stop during the saturated period. (vi) For stops where not all commuters can board the saturated runs, the departure time duration of commuters increases monotonically with the distance of the boarding stops from the workplace. (vii) For stops where not all commuters can board the saturated runs, the commuters of that stop will first manage to board the saturated run if it is available. As a result, these commuters, boarding a saturated run, should arrive earlier and wait in a queue for their desired run at equilibrium. (viii) In instances with a seat capacity constraint, the equilibrium departure time distribution still exists and there is a watershed for stations along the corridor. Commuters boarding trains at stations upstream of the watershed can take seats during their journey, while those boarding trains at stations downstream of the watershed have to stand. All these analytical results are numerically validated and demonstrated by examples, as shown in Figure 2.

Recently, we conducted a survey for eight business days when inclement weather was not an issue around the No. 13 Light Rail Transit in Beijing. This rail line is located in an area containing more than 20 universities and many high-tech companies; most commuters are white-collar workers for whom penalties for late arrival are not excessive. Xizhimen Station is in the central business district representing the workplace of all commuters. In Beijing, the period 8:00 a.m. to 9:00 a.m. is the desired arrival period, while the desired arrival time at Xizhimen is 7:50 a.m. to 8:40 a.m. (9).

We found that the number of passengers increases rapidly when the runs arrive early closer to the desired time and decreases when the runs
arrive late progressively further from the desired time. Additionally, the number of passengers on each run considerably exceeds the seat number \( N = 176 \) and fluctuates about a plateau during the desired arrival time period. We used the survey data to calibrate the relationship between in-carriage population \( n \) and run number \( z \). Both linear and nonlinear relationships are examined using a regression method, but we found that the linear relationship is true. The slope of the function \( n(z) = a \) if \( z \leq 10 \) and \( -68.53 \) if \( z \geq 17 \). The in-carriage congestion function is \( \frac{dn}{dz} = -\frac{b}{a}[\frac{dn}{dt}] \), where \( b \) is a positive parameter to be validated from the survey. Hence, given the linear schedule delay penalty ratio, the in-carriage congestion cost function is a linear function of the number of passengers.

REFERENCES AND NOTES
6. Since the focus is on passengers’ behavior, economic factors such as transit fare are not considered.
7. The schedule delay penalty was first considered by W. S. Vickrey, American Economic Review 34, 414 (1969).
9. For schools, hospitals, and other public corporations, the work start time is 8:00 a.m. or 8:30 a.m., while for finance and other businesses, the work start time is 9:00 a.m. Because of walking or transferring distance from Xizhimen Station to their final destination, passengers generally take another 10–20 minutes to arrive at work. Thus, the peak period observed in Xizhimen is about 7:50 a.m. to 8:40 a.m. (Runs 10–17).

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The School of Biological Science and Medical Engineering

The mission of the School of Biological Science and Medical Engineering is to improve human health, on the Earth and in space, through cross-disciplinary research and educational activities.

The School of Biological Science and Medical Engineering (SBSME) at Beihang University was established on October 23, 2008, originating from the Department of Biomedical Engineering that was initiated in January 2002. Since its opening, SBSME has grown and evolved at a rapid pace and now plays an important role in the development of biomedical studies and education throughout China. The school’s current dean is Professor Yubo Fan. Professor Fan is one of the leading scientists of biomedical engineering in China, and his major research areas of interest are biomechanics, biomaterials and tissue engineering, and rehabilitation engineering. He is president of the Chinese Society of Biomedical Engineering (CSBME), which strongly promotes the development of biomedical engineering in China, especially with respect to training and educational programs.

The school consists of three departments (the Department of Biomedical Engineering, the Department of Biological Science and Technology, and the Department of Rehabilitation Engineering), two research centers (the Research Center for Space Life Science and the Research Center for Medical Devices), the National Ministry of Education’s Key Laboratory of Biomechanics and Mechatronics, and the National Ministry of Civil Affairs’ Key Laboratory of Rehabilitation Technical Aids. Twelve laboratories—which cover 4,000 square meters and include more than 200 pieces of testing instruments and equipment—are available for scientists conducting biomedical research on the molecular, cellular, tissue, organ, and system levels.

Faculty
Currently, the school has 52 faculty members, including 10 professors, 14 associate professors, 21 assistant professors, and 10 postdoctoral fellows. Many of the faculty members are very accomplished, holding distinguished titles and awards. Professor Fan serves as the president of CSBME and the vice president of the China Strategic Alliance of Medical Device Innovation. Professor Fengyuan Zhuang and Professor Hong Liu are a member and a corresponding member of the International Academy of Astronautics (IAA), respectively. Professor Liu is also a foreign member of the Russian Academy of Natural Sciences. One of the professors has been named a Distinguished Young Scholar from the National Natural Science Foundation of China, and four have been selected for the Program for New Century Excellent Talents in University of the Ministry of Education (MOE). A number of faculty members serve as editors for leading international journals focused on biomedical engineering fields. Moreover, SBSME welcomes six world-renowned scientists as honored professors and 11 as guest professors, including professors Shu Chien, Van C. Mow, Savio L.-Y. Woo, Erwin Neher, and David F. Williams.

Education
SBSME provides two undergraduate programs (in biomedical engineering and biotechnology), three Master’s degree programs (in biomedical engineering, basic medicine, and special medicine), and one doctoral-level program (in biomedical engineering). Each year, about 50 undergraduates, 50 Master’s-level students, and 15 doctoral students enroll into the school’s programs. Currently, student enrollment has reached 368, with 198 undergraduates, 96 Master’s-level students, 74 doctoral students, and four international students.

Research
The school has four main areas of research: (i) Biomedical Engineering in the Cardiovascular System (cardiovascular fluid mechanics, cardiovascular tissue engineering, cardiovascular artificial organs, cardiovascular system bioinstrumentation, alteration and countermeasures of the cardiovascular system in space flight, and antiload of the cardiovascular system in flight); (ii) Biomedical Engineering in the Musculoskeletal System (bone loss in space flight, orthopedic biomechanics, dental biomechanics, biomechanics of implants and prosthetics, computer-aided orthopedic surgery, biosensing and bioinstrumentation in the musculoskeletal system, and aviation musculoskeletal biomechanics); (iii) Human Performance and Rehabilitation Engineering (ergonomics and rehabilitation engineering); (iv) Space Life Sciences (bioregenerative life-support systems, space physiology, and cellular/tissue engineering in space).

In the past five years, more than 100 research projects from SBSME have been funded, including projects from the National Basic Research Program of China (“973” program), the National Natural Science Foundation, the National High-Tech R&D Program (“863” program), the National Key Technology R&D Program, and local government and industry. In addition, more than 150 peer-reviewed papers have been published in international and national academic journals within the last three years alone.

Collaboration
SBSME collaborates with more than 50 foreign universities and institutions, including Columbia University in the United States, Queen Mary University in the United Kingdom, and the State Scientific Center of the Russian Federation’s Institute for Biomedical Problems, as well as many domestic universities, hospitals, and industrial companies. More than 50 foreign scholars from countries all over the world visit the school each year. The school also organizes several international and national academic events, such as the World Congress on Medical Physics and Biomedical Engineering (WC2012) and the 16th International Academy of Astronautics (IAA) Humans in Space Symposium (2007).
Future
SBSME is pursuing a leading position in biomedical engineering in China through fusing information from the biological sciences, medical sciences, and engineering disciplines and conducting cross-disciplinary scientific research and educational activities.

The World of Biomedical Engineering at Beihang University
How Do Woodpeckers Avoid Head Injuries?

Lizhen Wang¹, Ming Zhang², Yubo Fan*¹

It is a miracle of nature that head injuries do not result from a woodpecker continually drumming a tree at speeds of about 6–7 meters/second (m/s) and a deceleration of >1,000 gravity units (g). The behavior is carried out for many reasons including feeding, nest construction, ritual drumming to claim territory and attract mates, and even to relieve tension (1). However, the drumming results in deceleration forces of about 1,200 g, which is hundreds of times more than astronauts endure during takeoff and reentry. If a person was simply banging their head against a wall, headaches would ensue, if not concussions, diffuse axonal injury, or even retinal detachment. Impact-related human head injuries are often the leading cause of morbidity and death in both industrialized and developing countries. Given the damaging effects that head banging causes in humans, we wondered why the countryside was not “littered with dazed and dying woodpeckers.”

Presumably, woodpeckers have the ability to functionally adapt to impact forces, allowing them to peck rapidly without injury. These adaptations have attracted the attention of not only ornithologists and biologists, but also researchers in the mechanical and electronic sciences. New mechanical devices have been developed based on the momentum transfer mechanism of a woodpecker’s drumming, including a low-inertia lightweight hammer (2) and a vibration isolation system (3–5). The shock absorption mechanism of the woodpecker’s head has become a meaningful research topic.

An early, classic ornithological study indicated that woodpeckers have powerful protractor quadrii and protractor pterygoidei muscles that form a muscular shock absorber or distributor by holding the beak in resilient rigidity (6). A more detailed study was later conducted by May et al. (7, 8) that dissected the heads of two woodpeckers of the species Phileoceastes guatemalensis. It was shown that this woodpecker has special anatomy such as a long tongue, strong neck muscles, little cerebrospinal fluid, and a very narrow subdural space. High-speed photographs of a living woodpecker striking a surface were also analyzed. It was found that the trajectory of the strikes was determined to be essentially straight with a maximum preimpact velocity of 749 cm/s and deceleration of 1,200 g. A quarter of a century later, Ivan Schwab, an ophthalmologist at the University of California, shared the 2006 Ig Noble Prize in ornithology with May to bring wider attention to the often overlooked work (9). Recently, the unique

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Figure 1. (A) The pecking trajectory of the Great Spotted Woodpecker and the Eurasian Hoopoe on the transverse section during pecking. (B) Micro-CT image of the Great Spotted Woodpecker’s head. The outer layer covered on the upper beak is 1.6 mm longer than that of the lower beak. In contrast, the inner bone structure of the upper beak is about 1.2 mm shorter than the lower beak. (C) Micro-CT image of the Eurasian Hoopoe’s head. The outer layer and the inner bone structure of the upper beak are 0.95 mm and 0.8 mm shorter than the lower beak, respectively.
topology of the woodpecker’s skull, small amount of cerebral fluid, and specialized tongue and hyoid bone, have been implicated in decreasing
the stress of an impact (10). Further, a study by Gibson claimed that a
woodpecker’s brain is oriented differently within its skull compared to
humans and suggested that the increased contact area between the brain
and the skull might be the most important reason that brain injuries are
prevented during high-speed impact (11). However, most birds in nature
have the same brain orientation within the skull as the woodpecker yet
have been observed to sway, faint, and fall to the ground when they
accidentally hit the window pane, which makes the lack of head injuries
in the woodpecker all the more mysterious.

Mechanical force can stimulate changes in bone microstructure and
strength, enabling some adaptability in response to environmental
changes (12). However, little is known about such mechanical properties
and microarchitecture for the woodpecker’s head in combination
with cranial kinesis in a quantitative sense, or how these characteristics
compare to other birds. Therefore, we have explored the difference in ki-
nematics between living woodpeckers and other kinds of birds, quantita-
tively analyzed the microarchitectures and mechanical properties of the
birds’ heads, and evaluated the length of upper/lower beak based on nu-
merical simulation methods (1). Although it would be valuable to study
a large number of individuals for each species, we have examined one
sample for each species to minimize the use of living birds. Using this
smaller sample size, we were able to determine that the Great Spotted
Woodpecker’s head moves as a rigid body in a smooth curve compared
to other birds (Figure 1A). Further, we observed that the woodpecker
can consciously adjust its pecking behaviors when striking different
objects, which helps prevent impact-induced head injuries. The evolu-
tion of the woodpecker’s beak structure has produced an optimized and
functional adaptation for the bird’s specific lifestyle (Figure 1B and 1C).
The outer layer covered on the upper beak is 1.6 mm longer than that
of the lower beak; in contrast, the inner, high-strength bone structure of
the upper beak is about 1.2 mm shorter than the lower beak. The lower
beak appears to absorb most of the stress caused by impact (Figure 2).
These characteristics significantly decrease the risk of brain injury in
the woodpecker.

The protective properties of the woodpecker’s head and beak have the
potential to inspire new designs for devices in areas such as aeronautics
and sports. One area of great importance, for example, is developing
better protective devices for the human head, and insights from biologi-
cal studies such as these combined with engineering factors may lead to
better crash-helmet designs.

REFERENCES
    **221**, 1141 (2007).
    (1979).
    (2002).

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Applications of Image-Based Human Musculoskeletal Modeling

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Human musculoskeletal injuries commonly occur from scenarios such as car accidents, wars, sports activities, or even landing after ejecting from an aircraft. Over the years, a number of studies have improved our biomechanical understanding of musculoskeletal injuries and have pointed to bone deformation or bone strain as a principal cause of these types of musculoskeletal injuries in humans (1). Unfortunately, performing a strain analysis of bone is almost impossible in vivo, particularly during an impact. However, advances in image-based musculoskeletal modeling may help expand the accuracy and utility of models for studying the injury biomechanisms underlying musculoskeletal disorders, outcomes of surgical treatments, and musculoskeletal and neuromuscular impairments to help improve biomedical engineering.

The finite element (FE) method as a means of numerical simulation to simulate bone strain is one promising modeling approach. Here we describe how we have used this method to create musculoskeletal models of the whole human body and its applications, including determining the pressure distribution in a parachute landing, the outcome of different surgical interventions, and simulating the bone remodeling process after dental implantation. First, we developed a FE model of the entire human body using data derived from magnetic resonance imaging (MRI)/computed tomography (CT) images of both living subjects and cadavers (2–5). The geometry for each individual component of the human musculoskeletal system—including head, spine, arms, legs, and feet as well as the insertion sites of the ligaments—were determined from the MRI images and analyzed by the image processing software MIMICS (Materialise, Inc., Belgium) (Figure 1). Using the grayscale contrast of the different tissues, the segmentations of cartilage, cancellous bone, and cortical bone were then performed under the guidance of a radiologist. Using this geometric data, a 3-D FE model was reconstructed for each of the scenarios below using the FE software ABAQUS (Simulia, Inc., USA). For each scenario, input variables such as acceleration and load boundaries were used as alternate parameters to characterize the injury mechanism. In addition, every part of developed FE model was validated by comparing the joint shape or degree of the FE model with that from the MR images or literature. The kinematics for each scenario were then simulated with the FE model.

1. Exploring the mechanism of ankle injuries after parachute landings.

Parachuting is a high-risk activity that can lead to serious injuries and degenerative disease of the joints. Eighty percent of parachuting-related injuries involve the lower extremities, and most of these are related to the ankle joint. Understanding the biomechanics of a parachute landing would be valuable for improving parachutist training and developing protective devices. Therefore, we used the FE model to evaluate the standing stability with plantar pressure distribution (PPD) and to assess the effects of limb laterality, ankle inversion, and stabilizer on PPD during unipedal standing based on human musculoskeletal modeling. It was

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Over the years, a number of studies have improved our biomechanical understanding of musculoskeletal injuries and have pointed to bone deformation or bone strain as a principal cause of these types of musculoskeletal injuries in humans.

shown that ankle inversion harmed the stability during landing with the nondominant foot due to the decreased anteroposterior force ratio and local plantar contact area. Ankle brace improved the standing stability with increased total contact area (2).

2. Evaluating long-term outcomes of surgeries.
It is important to choose the optimal surgical procedure before performing the operation in the clinic. Musculoskeletal modeling was used to evaluate and compare the biomechanical performance of a knee following different surgical procedures, namely hybrid surgery (HS, C45Fusion with C56ProDisc-C arthroplasty) and two-level fusion (TLF) (3). We also modeled the mechanical performance of a proximal femoral nail antirotation device (PFNA) during healing (4) and analyzed the effect of tunnel creation on articular stress deterioration after single-bundle or double-bundle anterior cruciate ligament (ACL) reconstruction (5). The range of motion (ROM) and adjacent intradiscal pressures (IDPs) were calculated under flexion, extension, lateral bending, and axial rotation. Stress and strain distribution, total strain energy density (SED) along the femur and PFNA were analyzed while subjects were walking or stair climbing. The stress distributions were calculated in the knee following ACL reconstruction under the compression, rotation, and valgus torques. It was concluded that the biomechanical performance of HS was superior to TLF, that double-bundle ACL reconstruction could significantly change the stress environment in the articular surface in the long term, and that PFNA should be removed after healing.

3. Simulating the trabecular architecture remodeling after dental implants.
To predict how the microarchitecture forms surrounding four dental implant systems behave during healing, we used a model combining both the adaptive and microdamage-based mechanosensory mechanisms of the bone remodeling process. We mainly focused on the changes in the trabecular architecture that surround dental implants (6). The model’s predictive results for the orientational and ladder-like architecture surrounding the implants matched well with known outcomes of animal experiments and clinical observations. In addition, the architectural features around four typical dental implant systems in alveolar bone were evaluated and compared. A suitable estimation of how the jawbone is remodeled to adapt itself to mechanical environments could shed insight on the optimal design of implant systems.

In summary, the biomechanics of the human musculoskeletal injury can be modeled as an external load on the bone, but this creates a complex 3-D dynamic boundary value problem. Further, a tissue’s internal biomechanical response cannot be completely measured by experimental techniques and analytical models can only address limited problems, such as those with regular geometry, simple boundary conditions, and homogeneous material properties. However, the musculoskeletal finite element model has been shown to be superior to other numerical methods because it can be developed more accurately, based on the MR images of the living human.

REFERENCES

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Swirling Flow in the Arterial System and Its Potential Clinical Applications

Xiaoyan Deng*, Yubo Fan*, Xiao Liu, Anqiang Sun, Zufeng Ding, Fan Zhan, Zengsheng Chen

Unlike a river’s curving that causes sand siltation, the human aortic arch possesses a 3-D spiral-shaped spatial geometry. This special geometry makes blood flow through the aortic arch with a corkscrew-like pattern. Since this swirling flow pattern is seen not only in the aorta but also in other parts of the arterial system, such as large arteries, scientists have wondered whether this flow pattern has physiological significance. The scientific community has widely speculated on this question (1–3) and generally believes that it likely has a positive physiological role. However, so far, no one has really studied it systematically. We believe that the aorta’s spiral-shaped geometry and resulting swirling blood flow is a typical example of ‘form follows function’ in the circulatory system and makes the human ascending aorta susceptible to atherosclerotic plaque formation.

Is There a Physiological Significance of Swirling Flow?
To address this question, we carried out a series of theoretical and experimental studies (4–7). We conducted a numerical simulation of the blood flow in aorta models—constructed from magnetic resonance images of the human aorta—and demonstrated that the 3-D spiral structure induces the swirling flow in the ascending aorta. Further, we found that the swirling flow effectively stabilizes the blood flow in the aorta, compensating for the adverse effect of aortic curving on blood flow and, as a result, reduces/suppresses flow disturbance and flow separation. This, in turn, lessened the deposition/accumulation of atherogenic macromolecules such as low density lipoproteins (LDLs) on the arterial wall and enhanced the oxygen supply to the arterial wall (Figure 1). We then performed an ex vivo experimental study comparing the LDL accumulation in test rabbit aortic segments under normal flow and swirling flow conditions. The results showed significantly reduced LDL accumulation in the arterial wall of the swirling flow condition (7), further verifying our hypothesis.

Potential Clinical Applications of a Swirling Flow
Inspired by the aforementioned findings, we hypothesized that the mechanism of swirling flow might be clinically applicable to solving (i) the occlusion of small caliber (<5–6 mm) arterial prostheses due to acute thrombus formation; (ii) the restenosis of arterial bypasses due to intimal hyperplasia; (iii) the restenosis of endovascular stents; and (iv) the blockage of vena cava filters (VCFs) by captured blood clots. To investigate these hypotheses, we carried out a series of preliminary studies to test each of the scenarios (8–13).

First, we conducted a numerical study of blood flow patterns in small caliber arterial prostheses. Because the blood flow rate within small caliber arterial prostheses is rather low, the resulting wall shear stress is not high enough to suppress acute thrombus formation. We compared the wall shear rate distribution in a small diameter arterial prosthesis with a swirling flow pattern to one with normal flow condition (8). The results clearly showed that, at the same flow rate, the swirling flow created an approximately 50% increase in the wall shear rate (hence wall shear stress), which we speculated could reduce the probability of acute thrombus formation in the small diameter arterial prosthesis. To verify this, we designed an experiment comparing platelet adhesion in a small-diameter glass tube under swirling flow and normal flow conditions. The results demonstrated that the swirling flow could indeed suppress platelet adhesion to the glass tube by enhancing wall shear stress (9–10).

Next, we performed an S-type arterial bypass in a canine model to create a swirling flow in the bypassed host artery and compared this to a conventional bypass (11). The results demonstrated that the S-type bypass induced a swirling flow in the host artery and could indeed suppress the formation of intimal hyperplasia along the floor of the host artery.

We then explored the possibility of applying the swirling flow mechanism to a coronary bifurcation stenting strategy (12). Coronary bifurcation stenting still has some significant challenges to overcome as a coronary interventional treatment since the geometry of the bifurcation compromises the hemodynamic performance of a stent, making the restenosis rate for this type of stenting much higher than that of a straight artery stenting. However, our numerical study showed promising results and demonstrated that creating a swirling flow could significantly improve the hemodynamic performance of the bifurcation stenting.

To investigate whether the mechanism of swirling flow could also be beneficial for the design of vena cava filters (VCFs), we carried out an experimental study and compared the work efficiency of a vena cava filter under swirling flow and normal flow conditions (13). The results revealed that designing vena cava filters with a structure that induces a swirling flow has the potential to solve the blockage problem of VCFs.

In conclusion, our studies indicate the swirling flow of blood within the arterial system appears to play important physiological roles. It might have a function to protect arterial walls from certain vascular diseases by suppressing the deposition/accumulation of LDLs on the arterial wall and enhancing the oxygen supply to the arterial wall. Moreover, incorporating a mechanism to create a swirling flow pattern into vascular interventional therapies and the design of vascular devices has the potential to improve clinical outcomes.

REFERENCES

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Cellular Responses to Mechanical Stimuli

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Mechanical factors are important in the development, growth, and maintenance of tissues as well for functions such as bone production, muscle contraction, and cardiovascular tissue remodeling. Mechanobiology is an emerging scientific field at the interface of biology and engineering. It encompasses several broad research areas including cellular and molecular responses to mechanical loading, the interrelationship between mechanics and biological processes such as growth, remodeling, adaptation, and repair, and the impacts of the mechanical environment on an organism’s health, illness, or injury. Our group’s research addresses the integrated mechanobiological responses of cells to microenvironmental stimuli, with a focus on cells that are involved in the regeneration and pathology of cardiovascular tissues. We have developed and patented several cellular mechanical loading devices, including a multimodality bioreactor that offers multiple mechanical environments and an improved flow chamber system that reproduces physiological arterial flow conditions. Using these devices, we have investigated the effects of mechanical loading on the growth, proliferation, differentiation, and apoptosis of various cell types and discuss some of our findings here.

Stem Cell Mechanobiology

Rat bone marrow-derived mesenchymal stem cells (rBMSCs) exposed to arterial-like flow expressed an increased number of cells with an endothelial phenotype compared to those exposed to a steady laminar flow. In addition, the combined treatment of shear stress stimulation and vascular endothelial growth factor (VEGF) resulted in a more profound endothelium oriented differentiation compared to each of the individual stimulation conditions alone (1). Cardiomyogenic differentiation of rBMSCs was induced by mechanical loading alone, with strain stimulation proving to be more effective than shear stimulation (Figure 1). When rBMSCs were exposed to both mechanical and biochemical factors, expression levels of cardiomyocyte-related markers significantly increased to a degree suggesting a synergistic interaction between the two stimuli (2, 3). In addition, varying the magnitude of the mechanical load induced rBMSCs to differentiate into different mechanosensitive cell types. For example, a low level of fluid shear stress (FSS) (5 dyne/cm²) produced an osteogenic-like differentiation of rBMSCs, while a medium level (10 dyne/cm²) was cardiomyogenic, and a high level (15 dyne/cm²) promoted differentiation to endothelial cells. Taken together, these results suggest that mechanical loading is an important factor that can affect the type of cell into which rBMSCs differentiate.

Figure 1. Distributions of luminal surface LDL concentration (c_w) and the normalized oxygen flux (Sh) to the aortic wall in three aortic models. Model 1 possesses all the geometrical features of the human aorta; Model 2 is the same as Model 1 but with the three supra-aortic branches removed; Model 3 does not possess any 3-D spiral structure of the aorta. (A) For Model 1, except for Regions A and B which have relatively high c_w, LDLs distribute somewhat evenly and c_w is relatively low along the ascending aorta. The distribution of c_w for Model 2 is very similar to that for Model 1. However, for Model 3, the distribution of c_w along the outer wall of the ascending aorta becomes uneven when compared with Model 2 and c_w is significantly elevated in the descending aorta. (B) The distributions of Sh for Models 1 and 2 are very similar. However, for Model 3, in Regions E, H, and F, the oxygen supply (Sh) to the aortic wall is significantly lower than those for Models 1 and 2. The results therefore indicate that the swirling flow in Models 1 and 2 can suppress the deposition of LDLs along the ascending aorta and enhance oxygen supply to the aortic wall.

Figure 2. Schematic showing the clinical applications of swirling flow. (A) Swirling flow created in a small-diameter arterial prosthesis significantly enhances wall shear rate (WSR), or wall shear stress, which might suppress acute thrombus formation. (B) The swirling flow induced in the S-type arterial bypass suppresses the formation of intimal hyperplasia along the floor of the host artery. (C) The swirling flow created in an axis-deviated bypass model alters the overall flow pattern in the bypassed host artery and eliminates the slow recirculation flow zone with low wall shear stress, which always occurs along the host artery floor of the conventional bypass model and has been known to be associated with the development of intimal thickening and hyperplasia (14). (D) The swirling flow created in a helical graft with noncircular cross section enhances the wall shear stress along the inner wall of the graft (15).

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Mechanobiology of Differentiated Cells

Using a similar methodology, we have investigated the effects of mechanical loading on several other, differentiated cell types. Rat aortic endothelial cells demonstrated the ability to distinguish steady laminar flow from pulsatile flow (unpublished observations). Mechanical loading, including both shear stress and strain, affect vascular smooth muscle cell proliferation and migration, as evidenced by the altered expression levels of two key factors that have been implicated in the cellular response to mechanical signals: BKCa and IKCa proteins (unpublished observations). Finally, human periodontal ligament cells showed the ability to regulate metalloproteinase-1 and-2 in response to shear stress, which appeared to be regulated through the extracellular signal-regulated kinase (ERK) and P38 signaling pathways (4). Taken together, these results suggest that mechanical loading is an important factor affecting cell proliferation and migration.

Cellular Responses to Biomaterials

Regenerative medicine treatments that combine the use of cells and materials may open new options for tissue/organ repair and regeneration. A recent study investigating the effects of biomaterials on cell behavior showed that carbon nanotubes and 200 μg/mL nanosized hydroxyapatite, co-cultured with mesenchymal stem cells (MSCs), could induce osteogenic differentiation in vitro and ectopic bone formation in vivo, and combining biochemical reagents with these biomaterials had a synergistic effect (5, 6). Nanosized hydroxyapatite co-cultured with cortical cells proliferation and migration.

New Insights into the Characterization, Synthesis, and Application of Biomedical Materials

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REFERENCES

5. X. Li et al., Biomaterials 33, 4818 (2012).

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Figure 1. Strain stimulation induces enhanced cardiomyogenic differentiation of rBMSCs compared to shear stimulation. NC, negative control (rBMSCs treated with regular complete medium); FSS, rBMSCs exposed to shear stress of 10 dyne/cm² for 24 hours; Strain, rBMSCs exposed to cyclic strain of 10% at a frequency of 1 Hz for 24 hours; PC, positive control (normal neonatal rat cardiomyocytes). (A) rBMSCs were incubated in Texas red isothiocyanate-conjugated phalloidin to stain all F-actin filaments (red) and with DAPI to label the nuclei (blue) after 24 hours of strain or shear stimulation. Shear stress and strain were carried out from the left to right. Scale bar, 50 μm. (B) mRNA expression levels of GATA-4, β-MHC, Nkx2.5, and MEF2c were assessed by quantitative real-time RT-PCR analysis seven days after treatment. (C) The expression of cTnT was assessed using indirect immunofluorescence staining 14 days after treatment. Scale bar, 50 μm. Results are shown as the mean±SD values (n=3). *P<0.05 compared to the NC group; #P<0.05.

With the development of medical implantations, tissue engineering, and regenerative medicine, an increasing number of clinical treatments depend upon the use of biomedical materials. Our group studies the effects of the biomechanical environment on material degradation and the effects of nanomaterials on the biological body—two areas that are often overlooked. Moreover, we are investigating potential new uses for materials and are working to expand the applications of materials used for small-diameter vascular reconstruction and bone tissue regeneration.
Mechanical Load Accelerates the Degradation Process of Biomaterials

After being implanted into the body, the degradable biomaterials are in a complex biomedical environment. We investigated the effects of mechanical loads on the degradation of natural polymers, synthetic polymers, or their composites. Varying types of mechanical loads were used to test these materials, including tensile loads, compressive loads, combinative loads, and different cyclic loads. The degradation processes of the materials were then studied by characterizing their molecular weight, mass loss, mechanical properties, and morphologies (1, 2). Each material demonstrated an acceleration of degradation rates after exposure to a mechanical load (Figure 1). These results suggest that the in vitro degradation process of scaffolds and implants under load should be carefully considered to ensure appropriate degradation rates.

Sulfated Silk Fibroin Improves Small-Diameter Vascular Grafts

In order to improve the antithrombogenicity and cytocompatibility of small-diameter blood vascular grafts, we fabricated an electrospun sulfated silk fibroin nanofibrous scaffold (S-silk scaffold) and further explored its potential application for tissue engineering of small-diameter vascular grafts. Our results showed that the anticoagulant activity of S-silk scaffolds was significantly enhanced compared to silk fibroin nanofibrous scaffolds (3). Vascular cells showed strong attachment to the S-silk scaffolds and proliferated to form a monolayer with increased expression of some phenotype-related marker genes and proteins (Figure 2). Our study indicates that the S-silk scaffold combined with vascular cells is a promising candidate for small-diameter vascular reconstruction.

Carbon Nanotubes Improve Cellular Osteogenic Differentiation and Induce Bone Formation

The results of in vitro biochemical analyses of attached stem cells and in vivo analyses after implantation into mice indicated that carbon nanotubes increase the concentration of bone-inducing proteins. Additionally, findings showed that these proteins might not only improve cell attachment and proliferation but also cause differentiation of the inducible cells derived from soft tissues to osteogenic cells, which form inductive bone (4).

Biological Effects of Nanomaterial Implantation

To simulate the biological effects of nanoparticles induced by the wearing of nanocoated knee joint implants, rats received an intraarticular injection of titanium oxide (TiO₂) nanoparticles. The TiO₂ nanoparticles accumulated in the knee joint and resulted in severe synovial injury, including synovial hyperplasia, hypertrophy, lymphocyte and plasma cell infiltration, and oxidative damage (5). Moreover, the histopathological changes [shown by hematoxylin-eosin (HE) staining] in the heart, lung, liver, and kidney indicated the dissemination of intraarticular TiO₂ nanoparticles from the joint cavity into the rest of the body.

REFERENCES

4. X. M. Li et al., Biomaterials 33, 4818 (2012).

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MRI-Based Cerebral Atrophy Patterns in Normal Aging and Neurodegenerative Diseases

Shuyu Li, Fang Pu, Haijun Niu, Yubo Fan, Deyu Li

The prevalence of dementia, especially Alzheimer’s disease (AD), is one of the most important issues affecting health-related quality of life in older adults. The amount of cognitive and locomotor decline a person experiences during aging are key determinants of their functional status. However, noninvasive imaging methods, such as MRI-based techniques, have enabled antemortem detection and characterization of brain abnormalities and may independently, or synergistically with other clinical measures, enhance our ability to predict functional outcomes. Beyond their clinical diagnostic utility, noninvasive imaging methods promise to reveal objective biomarkers that can facilitate the identification of individuals who have a high risk of cognitive decline and dementia. Moreover, these techniques may provide outcome measures for future prevention and treatment trials. Neuroimaging studies have already revealed significant differences in cerebral atrophy patterns between normal aging and patients with amnestic mild cognitive impairment (aMCI) and/or AD (1, 2). Therefore, we have built upon sophisticated computerized techniques and MRI techniques and explored the cerebral atrophy patterns in normal aging and degenerative diseases. We believe that structural brain abnormalities have the potential to be used as biomarkers for detecting the onset of neurodegenerative disorders.

Cerebral Atrophy Pattern in Normal Aging. The morphology of the cortical surface is a macroscopic probe for the underlying cytoarchitecture, which varies under the conditions of normal aging and neurodegenerative diseases. In normal aging, the 3-D anatomy of the central sulcus (CS) attracts the interest of numerous scientists because its 3-D morphology is vital for determining the correspondence between its anatomy and motor and sensory function (3). However, the relationships between the 3-D morphology of the CS and age remain controversial and under debate. Notably, these previous studies mainly focused on the middle surface of the CS and neglected the morphology of the anterior (corresponding to the posterior wall of precentral gyrus) and posterior (corresponding to the anterior wall of postcentral gyrus) walls of the CS. The precentral and postcentral areas differ in their cytoarchitecture, and these regions interact to contribute to motor and somatosensory functions, respectively. Therefore, we employed a sulcal mapping method to investigate the morphological changes of the anterior and posterior walls of the CS during normal aging (4). The anterior and posterior walls of the CS were manually outlined from high-resolution structural MRI data of 295 right-handed, healthy participants (age range: 18–94 years).

Surface reconstruction and parameterization methods were employed to create anatomical correspondence between surface locations across participants in order to compare the differences of the surface morphology in a vertex-by-vertex style. Four surface metrics, including average sulcal length (SL), surface area, fractal dimension (FD), and sulcal span, were used to represent the 3-D morphology of the CS. We found significant age-related decreases in the surface area for all of the CS walls (Figure 1A), the SL for posterior walls of the CS, and the FD for posterior wall of the right CS. Age-related increases were found in the sulcal spans between the anterior and posterior walls (Figure 1B). Specifically, age-related changes in surface morphology progressed more rapidly in the posterior walls compared with the anterior walls. Taken together, our results reveal age-related changes in the surface morphology of the CS and provide new insights into the normal aging process.

In addition, we investigated the age-related volume reduction of 90 regions in the whole brain based on the automated anatomical labeling (AAL) atlas in a large cohort of healthy participants. We found that most of regions showed significant age-related gray matter (GM) volumetric reductions, except for the temporolimbic regions, the posterior cingulated gyrus, the inferior occipital gyrus, and pallidum. These results agree with our previous studies that did not find age-related volumetric changes in the limbic and paralimbic regions (unpublished data).

Cerebral Atrophy Pattern in Neurodegenerative Diseases. aMCI is an intermediate cognitive state between normal aging and AD. Previous studies have found significant GM and white matter (WM) atrophy in aMCI compared with normal aging (5, 6). However, there are relatively fewer research studies on the sulcal morphology in aMCI subjects. Therefore, we explored changing patterns in sulcal morphology in aMCI patients and age-matched normal controls using a quantitative surface-based method (7). We computed 3-D gyrification indexes (GI)
of both cerebral hemispheres and morphological metrics (the SL and average depth) for nine prominent sulci in each hemisphere. We found that the GI did not significantly differ between groups. Interestingly, we observed that the SLs and depths of the left superior and inferior frontal sulci in aMCI subjects showed significant differences compared with the normal controls. Our results showed sulcal morphology changes in aMCI patients and provided insights into the cognitive decline process.

AD is a neurodegenerative disease characterized by progressive dementia. The hippocampus is particularly vulnerable to damage at the very earliest stage of AD. We evaluated critical AD-associated regional changes in the hippocampus using machine learning methods (8). High-resolution MR images were acquired from 19 patients with AD and 20 age- and sex-matched healthy controls. Regional changes of the bilateral hippocampi were characterized using computational anatomical mapping methods. Patients with AD showed significant deformations in the CA1 region of the bilateral hippocampi, as well as the subiculum of the left hippocampus. There were also some changes in the CA2–4 subfields of the left hippocampus among patients with AD. Moreover, the left hippocampal surface showed greater variation than the right one compared with healthy controls (Figure 2A). In order to validate the reliability of these surface features in discriminating AD and healthy controls, cross-validation experiments were employed and the accuracy was more than 80% for the bilateral hippocampi. Our results showed that subtle and spatially complex deformation patterns of the hippocampus in AD patients could be detected using machine learning methods.

Most studies that attempt to clarify structural abnormalities related to functional disconnection in patients with AD have focused on exploring pathological changes in cortical gray matter. However, white matter fibers connecting these cerebral areas may also be abnormal. Using the optimized voxel-based morphometry (VBM) method, we investigated WM volume changes of whole-brain structural MRI data acquired from 19 patients with AD and 20 healthy subjects (9). Compared with the control group, AD patients showed significantly reduced WM volumes in the posterior part of the corpus callosum (CC) and the temporal lobe in the bilateral hemispheres (Figure 2B). Our findings suggest that these abnormalities in WM regions may contribute to the functional disconnections in AD.

In summary, atrophy of cortical surface and brain tissue was found in both normal aging brains and those with degenerative diseases by combining sophisticated computerized techniques with MRI techniques. The abnormal morphometric changes in neurodegenerative brain, mainly distributed in the temporal region and WM regions, were different from those in a normal aging brain. Our studies contribute to the global endeavor that aims to discover biomarkers using structural MRI data to help differentiate brains with degenerative disease from healthily aging brains.

REFERENCES

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Bioregenerative Life Support Systems in Space: A Research Update

Hong Liu*, Yuming Fu, Dawei Hu, Enzhu Hu, Leyuan Li, Beizhen Xie

Bioregenerative life support systems (BLSS) are artificial ecosystems consisting of many complex symbiotic relationships among higher plants, animals, and microorganisms. As the most advanced life support technology, BLSS can provide a habitation environment similar to the Earth’s biosphere for space missions with extended durations, in deep space, and with multiple crews. Biotechnology and engineering control technologies are perfectly integrated to build BLSS according to the principles of ecological systems. Almost all requirements for human life support can be produced within BLSS, including fresh air, clean water, and nutritionally valuable food. Progress in achieving manned space flight in China is moving forward rapidly, which is driving the development of BLSS technology. At the School of Biological Science and Medical Engineering at Beihang University, a series of studies have been conducted by Professor Hong Liu’s team to advance BLSS, from basic theory to the critical elemental technologies. Here we discuss some of the recent results.

Based on these conceptual configurations, we carried out a series of studies on the key biological units, including plant cultivation, animal breeding, and waste treatment (Figure 1). Sixteen crop candidates were selected according to Chinese sitology criteria and dietary habits that would meet the special requirements of the BLSS (3). Porous tube-culture technologies were then successfully established for these crops, and we subsequently assessed the effects of environmental factors such as CO₂ concentration and light source on crop growth. Our results determined that the optimal CO₂ concentration for producing both pak choi and lettuce was 2,000–3,000 μmol·mol⁻¹. In addition, a red-white LED was more conducive to the accumulation of antioxidant compounds in Gynura bicolor DC compared to a red-blue LED, which suggests that the former is a more appropriate light source choice for plant cultivation.

We then developed a new prototype for a vegetable production facility to be used in a space station or Martian spacecraft (Chinese patent ZL 201010117620.5). This facility was capable of simulating the effect of microgravity and the continuous cultivation of leaf vegetables on root modules. Further, the facility provided 259.4 g of edible biomass of lettuce per week at 0.3 kW. The efficiency of this facility, based on the Q-criterion, was 7.0×10⁻⁴ g²·m⁻³·J⁻¹, which was better than similar equipment designed previously in Russia and the United States. We also proposed using two candidate insects (the silkworm and the yellow mealworm) as a source of animal protein for astronauts in the BLSS (4, 5). These insects have higher nutritional value than previously proposed animal candidates, such as fish and pork, and are easier to rear and manage in a space station. Most importantly, these insects can be fed on plant waste (e.g., straw, bran, vegetable roots, and old leaves) in the BLSS, which improves the insulation and stability of the system. Our results showed that for the BLSS containing yellow mealworm and silkworm, the coefficient of system closure reaches 99.53% (5), which is higher than the system only containing silkworm (99.40%) (2), and the system without an animal-rearing unit (98.68%) (1). In terms of waste treatment, we established a soil-like substrate (SLS) technology to process residual plant material utilizing microbes and earthworms. A
Figure 2. Plan for a ground-based, integrated, bioregenerative life support system experiment: (A) composition of the experimental system; (B) interior design of the habitation module; (C) interior design of the plant cultivation module; (D) diagram of system components and material flow.

A series of SLS preparation devices were constructed with parameters that were optimized to shorten the preparation period. With the optimized preparation period, we achieved 98.6% and 93.1% degradation of plant cellulose and lignin, respectively (6). In order to treat a crew’s urine and feces and increase the closure of the system, we established a spirulina photobioreactor for urine purification (7) and microbial fuel cell (MFC) facilities which serve to both treat feces and generate electricity (8).

In addition to the experimental tests, the above technologies were subjected to computational studies using control theory in combination with computer simulations to ensure the effective integration of each component and the stable operation of the entire system. A mathematical and simulation model describing the components in such a system were established based on experimental observations (13). For the next stage of our research, we will build China’s first large-scale, integrated BLSS experimental system and recruit between one and four human participants to intensively investigate and test the system’s design, construction, operation, and regulation (Figure 2).

These studies on the key units and system integration of BLSS not only play a vital role in space life support, but also have the potential to be used for applications on Earth. For example, the technologies for porous-tube nutrient delivery and for optimizing environmental factors could also be applied to the cultivation of plants in places not suitable for plant growth, such as deserts, islands, seas, and city buildings. The SLS technology and the process for mealworm rearing can be used in agricultural waste treatment. Crop straws can be used to cultivate mushrooms or to feed mealworms after fermentation treatments. The SLS can also be used as fertilizer, which would increase the soil’s organic matter content and improve its physical, chemical, and structural properties. And finally, the MFC technology could play an important role in wastewater recycling and for online analysis of water biotoxicity.

REFERENCES


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The School of Transportation Science and Engineering

In order to keep up with the rapid advances in the transportation field, Beihang University formed the School of Transportation Science and Engineering (STSE) on October 28, 2007. The school has integrated resources from multiple related departments in the university to improve the transportation field group. STSE has six departments and two lab centers: the departments of Transportation, Aircraft Airworthiness Engineering, Airport and Road Engineering, Automobile Engineering, Civil Engineering, and Internal Combustion Engine, and the Lab Centers of Transportation and of Civil Engineering.

STSE focuses on the characterization of air-ground coordination, vehicle-road coordination, and air-ground-information integration. Research at STSE broadly covers aeronautics, astronautics, and ground transportation, with the goal of achieving interdisciplinary integration and addressing major national needs. To enhance research on the efficiency and safety control of an integrated air-ground transportation system, STSE focuses on several major research directions, including: intelligent vehicle-ground coordination and safety control, control of integrated air-ground-information for airport ground transportation, demands management for integrated transportation systems, aircraft airworthiness technology, development and optimization of intelligent vehicles, and the structure and state safety monitoring of airport pavement.

STSE has built many key research centers above the provincial and ministerial levels, including the Airworthiness Technology Research Center (ATRC) of National Laboratory for Aeronautics and Astronautics, the General Aviation Engineering Research Center (in Beijing), and Beijing’s Key Laboratory of Vehicle-road Coordination and Safety Control.

ATRC is one of the three airworthiness technology institutions recognized by the Civil Aviation Administration of China. ATRC is one of the three airworthiness technology institutions recognized by the Civil Aviation Administration of China. The General Aviation Engineering Research Center has participated in drafting the Beijing General Aviation Industry Development Plan. By establishing the Beijing General Aviation (Group) Co. Ltd. together with Beijing Automotive, ATRC has been making efforts toward advancing aviation technology developments. Based on development strategies emerging from industries such as new-energy vehicles and the Internet of Things, STSE is keen to new and innovative ways to combine production, teaching, and scientific research with the utilization in intelligence transportation systems (ITSs), the “internet of vehicles,” and new-energy vehicles. Over the past three years, a number of teaching-research-production cooperative platforms have been established, including the Beihang-Zhicheng Champion Group Electric Vehicle Advanced Technology Research Institute, the Beihang-Jiangyin New-Energy Vehicle Research Institute, the Beihang-Keli ITS Advanced Technology Research Institute, and the Beihang-Jinyi Internet of Vehicles Technology Associated Labs. In order to deepen this cooperation, STSE—as a standing council unit—initiated and established the National ITS Technological Innovation Strategic League, the China Internet of Vehicles Technological Innovation Strategic League, and the China Automotive Manufacturing Equipment Innovation League.

Of the 80 faculty members at STSE, 17 are professors, 20 are associate professors, more than 97% have Doctorates, and over 85% have overseas study or research experience. STSE’s staff includes members who participate in a Changjiang Scholars Innovation Team of the Ministry of Education, a member of the China Engineering Academy, two state-level candidates for the New Century Hundred-Thousand-Ten Thousand Talents Project, three candidates for the New Century Excellent Talent Project of the Ministry of Education, and one faculty member who received the Beijing Prominent Teacher award.

With recent funds from the “211” and “985” programs, STSE has built scientific innovation platforms for air-ground information, modern aviation management and coordinated operations, and safety control of integrated transportation systems. In addition, the school has created a top-notch experimental environment for air-ground coordination of airport ground control, intelligent vehicle-road coordination, and aircraft airworthiness technology in China.

Over the last three years, STSE has undertaken hundreds of research projects from the “863” program, the “973” program, and the National Natural Science Foundation of China as well as carried out over 50 research projects at the provincial- and ministerial-level, and received research funding totaling more than 400,000 yuan (~US$63,000) per capita per year. In the past five years, 167 papers from STSE have been recorded by the Science Citation Index (SCI) and 585 by the Engineering

Figure 1. (A) Driving Behavior Analysis Test platform. (B and C) Intelligent Vehicle Control Test platform.

Astronautics, and ground transportation, with the goal of achieving interdisciplinary integration and addressing major national needs. To enhance research on the efficiency and safety control of an integrated air-ground transportation system, STSE focuses on several major research directions, including: intelligent vehicle-ground coordination and safety control, control of integrated air-ground-information for airport ground transportation, demands management for integrated transportation systems, aircraft airworthiness technology, development and optimization of intelligent vehicles, and the structure and state safety monitoring of airport pavement.

STSE has built many key research centers above the provincial and ministerial levels, including the Airworthiness Technology Research Center (ATRC) of National Laboratory for Aeronautics and Astronautics, the General Aviation Engineering Research Center (in Beijing), and Beijing’s Key Laboratory of Vehicle-road Coordination and Safety Control.

ATRC is one of the three airworthiness technology institutions recognized by the Civil Aviation Administration of China. ATRC is one of the three airworthiness technology institutions recognized by the Civil Aviation Administration of China. The General Aviation Engineering Research Center has participated in drafting the Beijing General Aviation Industry Development Plan. By establishing the Beijing General Aviation (Group) Co. Ltd. together with Beijing Automotive, ATRC has been making efforts toward advancing aviation technology developments. Based on development strategies emerging from industries such as new-energy vehicles and the Internet of Things, STSE is keen to new and innovative ways to combine production, teaching, and scientific research with the utilization in intelligence transportation systems (ITSs), the “internet of vehicles,” and new-energy vehicles. Over the past three years, a number of teaching-research-production cooperative platforms have been established, including the Beihang-Zhicheng Champion Group Electric Vehicle Advanced Technology Research Institute, the Beihang-Jiangyin New-Energy Vehicle Research Institute, the Beihang-Keli ITS Advanced Technology Research Institute, and the Beihang-Jinyi Internet of Vehicles Technology Associated Labs. In order to deepen this cooperation, STSE—as a standing council unit—initiated and established the National ITS Technological Innovation Strategic League, the China Internet of Vehicles Technological Innovation Strategic League, and the China Automotive Manufacturing Equipment Innovation League.

Of the 80 faculty members at STSE, 17 are professors, 20 are associate professors, more than 97% have Doctorates, and over 85% have overseas study or research experience. STSE’s staff includes members who participate in a Changjiang Scholars Innovation Team of the Ministry of Education, a member of the China Engineering Academy, two state-level candidates for the New Century Hundred-Thousand-Ten Thousand Talents Project, three candidates for the New Century Excellent Talent Project of the Ministry of Education, and one faculty member who received the Beijing Prominent Teacher award.

With recent funds from the “211” and “985” programs, STSE has built scientific innovation platforms for air-ground information, modern aviation management and coordinated operations, and safety control of integrated transportation systems. In addition, the school has created a top-notch experimental environment for air-ground coordination of airport ground control, intelligent vehicle-road coordination, and aircraft airworthiness technology in China.

Over the last three years, STSE has undertaken hundreds of research projects from the “863” program, the “973” program, and the National Natural Science Foundation of China as well as carried out over 50 research projects at the provincial- and ministerial-level, and received research funding totaling more than 400,000 yuan (~US$63,000) per capita per year. In the past five years, 167 papers from STSE have been recorded by the Science Citation Index (SCI) and 585 by the Engineering
Index (EI) and the Index to Scientific & Technology Proceedings (ISTP), of which six have been published in *Transportation Research Part B, Part C*, and *Part E*, all top journals in the field of transportation.

About 600 undergraduates, 400 postgraduates, and 10 postdoctoral students are currently enrolled at STSE. The school has a Transportation Science Innovation Lab and a Practical Teaching Lab, as well as several student innovation training opportunities including the Freescale Cup intelligent car competition, Honda’s Fuel-Efficient Car competition, the Formula SAE competition, the Steel Structures Education Foundation Architectural Structure competition, the ITS Design competition, the Student Research Training Program, the Fengru Cup Science and Technology Competition, and the Challenge Cup Science and Technology Competition. STSE has also started an internationally focused experimental civil engineering class, which enables student exchanges with well-known universities throughout the world. This class hopes to cultivate high-level talent with an international perspective and ability to communicate and collaborate with their international colleagues in the civil and transportation field.

Further, STSE is developing a program that enables undergraduate students majoring in civil engineering to add an international component, which will serve to further advance avenues for undergraduates to interact with well-known civil engineering universities in the United States, such as the Georgia Institute of Technology, the University of Minnesota, and Clarkson University. The percentage of undergraduates who choose to continue their graduate studies at STSE is high, and more than 98% of STSE graduates move into transportation-related careers. They are able to find well-paid jobs immediately following graduation and have received recognition by employers in a wide range of occupations such as design, management, scientific research, and teaching in the transportation, civil construction, aviation, aerospace, and civil aviation fields.

STSE started and hosted the 1st and 2nd International Symposium on Aircraft Airworthiness, hosted the 4th Sino-Japan Geotechnical Symposium, and won the right to host the 2012 Chinese Overseas Transportation Association International Conference of Transportation Professionals. STSE takes an active part in international exchanges and cooperation, with collaborations at ITI (in Germany) and Anstalt für Verbrennungskraftmaschinen List (in Austria) and by building international laboratories that exchange and co-teach students from universities in America, Germany, France, England, and Japan.

*Figure 2. Clockwise, from top left: Students from STSE attending the BUAA-ESTACA (École Superieure Des Techniques Aeronautiq) Program; the 12th COTA International Conference of Transportation Professionals (CICTP 2012) organized by Beihang University; students from STSE who won first prize in the National Structure Design Contest for College Students; the 2nd International Symposium on Aircraft Airworthiness held in 2011 in Beijing.*
As a new research establishment, the Airworthiness Technology Research Center (ATRC) of Beihang University is dedicated to discovering new mechanics and principles of flight safety and providing improvements and solutions to existing methods. Some new achievements on safety strategies, safety boundary prediction techniques, and issues of occupant protection, icing effects, and nondestructive testing are reviewed here.

The application of airworthiness defines the condition of an aircraft and supplies the basis for judgment of the suitability for flight of that aircraft. Both experience and research provide essential information for judging the airworthiness of an aircraft.

New safety control strategies
Today, the system development process model recommended by the Society of Automotive Engineers in SAE ARP 4754 and the accompanying safety analysis techniques in SAE ARP 4761 have become standards in the aviation industry. However, incidents and accidents of the latest types of aircraft show the continuing existence of latent risks. Among the biggest challenges is the recognition and control of latent risks under such practical restrictions as cost and schedule. Inspired by the System-Theoretic Process Analysis Theory of Professor N. Leveson of MIT, Yi Lu and Gong Zhang at ATRC established a risk classification and safety control structure, incorporating both technical and human factors, and applied it to the development of a low-cost, remotely piloted blended-wing-body subscale flying vehicle with encouraging flight test records (Figure 1). Lei Gong and Gong Zhang also proposed (3) a unified approach integrating risk identification and an active control strategy, using the development of the flight control system of an unmanned aero vehicle as an example.

Prediction of safety boundaries
At the level of physical risks, the prediction of the safe operation boundaries of an aircraft and its systems is vital. With respect to aircraft structures, Junjiang Xiong and colleagues at ATRC have focused on load cycle identification to minimize experimental duration of full-scale accelerated fatigue tests (4), and applied it to the accelerated fatigue tests of a helicopter tail (Figure 2A). For aero-engines, Shuiting Ding and his team stress on the assessment of risk sensitivity and probability. In a recent study, Ding and colleague Jiaokun Cao (2) took into account the uncertainty of factors and the interactions between parameters, and improved the design of a reciprocating aircraft engine, while Zhang and Ding (5) developed a numerical approach, integrating one-way fluid structure interaction and probabilistic risk assessment for life-limited parts of aero-engines. If aircraft engine components are exposed to severe thermal and aerodynamic loads, the compression system surge can become an important risk. To predict the surge margin, ATRC’s Xiaofeng Liu and Lei Zhao (6) presented an approximate nonlinear surge margin model of aircraft engine compression systems by expansion of the equilibrium manifold for nonlinear systems.

Occupant protection
In order to test occupant protection and impact load reduction, Dayong Hu et al. (7) performed a full-scale vertical drop test of a crashworthy...
and remains a serious concern. Among the key considerations are the prediction of ice shapes due to water drop impingement on aircraft surfaces and the aerodynamic effects of icing. The prediction of ice shapes can be modeled using two-phase and multiphase flow simulations, with a hybrid Eulerian-Lagrangian model widely used. Peng Ke and colleagues (9) extended and improved the known vicinity algorithm based on the geometry test in the hybrid Eulerian-Lagrangian model and developed a binary search method to accelerate the particle in the cell test and the trajectory/face intersection test. To determine the aerodynamic effect of icing, ATRC’s Jianghao Wu and others (10) took a general airfoil (NACA 23012) and a business jet airfoil as examples, and added critical ice shapes on them (through 45 minutes in an icing environment). It is shown that at the same angle of attack, the lift of the airfoil decreases, while the drag increases, and the maximum lift:drag ratio becomes smaller because of ice accretions (Figure 2D).

Nondestructive Testing
The acoustic emission (AE) technique is used as a nondestructive testing tool to evaluate structural damage, which is critical in the aging aircraft. Tian He et al. (11) developed a near-field AE beam-forming method with reduction of modal threshold frequency to improve the accuracy of burst AE source localization from structurally damaged materials. The potential of this method for engineering application was explored through rotor-stator rubbing tests, and experimental results demonstrate that the proposed method can effectively determine the region where rubbing occurs.

As techniques and technologies to assess aircraft airworthiness improve, so will the quantification of safety boundaries, human factors, and environmental tolerance, all of which are still major concerns. Ongoing research at ATRC plans to address these issues in order to make aircraft safer for passengers and aircraft crew alike.

REFERENCES
Research on Driving Behavior and Safety of Road Traffic

Yunpeng Wang*, Tieqiao Tang, Guangquan Lu, Guizhen Yu, Daxin Tian

In China, there are more than 60,000 deaths due to the road traffic accidents annually. With economic development and vehicle number soaring, vehicles have brought increasingly severe problems to road transportation, including vehicular congestions, accidents, and pollution. Therefore, a group of scientists and engineers at Beijing Key Laboratory for Cooperative Vehicle Infrastructure Systems and Safety Control of Beihang University are focused on researching the driving behavior and safety of road traffic in an attempt to solve these problems and to enhance the safety of the current road traffic system (Figure 1).

**Figure 1.** Research on road safety is focused on three aspects: driving behavior, road traffic safety analysis, and techniques for creating a cooperative vehicle-infrastructure system.

Understanding Driver Behavior

Generally, driving behavior is largely determined by the psychological state of the person controlling the vehicle and is the factor most significantly impacting road traffic. Understanding driver behavior enables the development of techniques and technologies to improve road traffic safety. An eye-tracking device, Smart Eye, has been used to follow the eye movements of drivers at intersections (1) and it was found that drivers pay more attention to moving objects (such as other vehicles, bikes, and pedestrians) when crossing an intersection without a traffic signal. Risk perception of a driver largely determines that driver’s response. Lu and colleagues (2) hypothesized that drivers may react according to the perceived risk, which fluctuates around a target level. They propose a critical, quantitative indicator of homeostatic risk perception in a car-following scenario, which may help explain driving behavior.

Analysis of Driving Behavior

Driving behavior is also dependent on road infrastructure (e.g., ramps, traffic interruptions) and traffic information [e.g., the driver’s ability to forecast his/her future traffic situation (driver’s forecast effect, or DFE), the driver’s memory of his/her past driving behavior (memory effect), and the effect that car horn use has on driver behavior (honk effect)]. Tang et al. employed a micro simulation traffic behavior model to develop new driving behavior models accounting for road infrastructure such as ramps (3), traffic interruption probability (4), and DFE (5), all to explore complex traffic phenomena, including stop-and-go traffic and wave properties of traffic flow.

Analysis of Road Traffic Safety

The number of traffic accidents is considered as a useful indicator for evaluating road safety. However, because accident location, time, and type, are so varied, the frequency in which accidents are recorded is generally low. Therefore, collecting sufficient accident data requires long periods of observation. To overcome these shortcomings, traffic conflicts, defined as critical incidents not necessarily involving collisions, is proposed as an alternative indicator to evaluate road safety situation. Lu and colleagues (6) proposed a model to describe the relationship between road traffic accidents and conflicts. Tang et al. (7) employed the driving behavior model (4) to further study the effects of the traffic interruption probability on driving safety and found that the model could reduce the traffic risk coefficient, demonstrating that driving safety could be improved by considering this variable. Tang (8) also explored the effects of roadside memorials on the safety of the driving behavior and developed a driving safety model.

Techniques for Cooperative Vehicle Infrastructure

With the development of wireless communication, Cooperative Vehicle Infrastructure System (CVIS) is beginning to be considered as an effective tool to resolve such complicated traffic problems. The new CVIS has been tested as a way to improve the performance and safety of road traffic in China. Wang (9) proposed a merging control algorithm for vehicles on a freeway using Vehicle Infrastructure Integration (VII) techniques based on the V2V and V2I wireless networks. Zhang (10) proposed an algorithm of vehicle-vehicle conflict detection at intersection without traffic signals, based on the V2I wireless network.

**REFERENCES**

The School of Astronautics (SA) was established in 1956. One of its greatest early achievements was the launch of the Beijing No. 2 Modern Rocket in 1958 (Figure 1). Today, the school consists of five departments: Spacecraft and Launch Vehicle Technology; Aerospace Propulsion; Guidance, Navigation and Control; the Image Processing Center; and the Space Science Institute. In addition, the school runs the Education Ministry Key Laboratory of Spacecraft Design Optimization and Dynamic Simulation and the Beijing Key Laboratory of Digital Media.

At present, the school has around 110 faculty and staff members, including 24 full professors and 43 associate professors. There are close to 900 undergraduate students, approximately 360 Master’s students, and 140 Ph.D. students. The honorary dean of the school is professor Faren Qi, who is the chief designer of Chinese Spaceships Shenzhou 1 through 5. He is also a member of Chinese Academy of Engineering.

Department of Spacecraft and Launch Vehicle Technology
This department has 10 professors and 12 associate professors. More than 100 research projects are being conducted, supported by the National Natural Science Foundation of China (NSFC), the National High-Tech R&D Program (“863” program), as subprojects of aerospace engineering and administration departments, and by international research foundations from the United States and Europe. On average, more than 200 papers are published in domestic or international journals each year and over a dozen patents are authorized. Work is also presented at academic conferences, and several monographs and textbooks are published annually.

Some of the primary research areas include structural and multidisciplinary optimization of aerospace flight vehicles, orbit and attitude dynamics and control, adaptive space structures/mechanisms and their control, spacecraft dynamic simulation and microsatellite technologies, and precision guidance and control methods and experiments. The project “Optimization Theories and Algorithms for Complicated Structures” was awarded the First Grade Natural Science Prize of Chinese Universities by the education administration of China in 2002. The application software that was developed, called the Engineering System of Structural Optimization for Spacecraft (ESSOS), has been applied to the structural engineering designs of several satellite programs, including the meteorology satellites FY-3 (which is currently performing well) and FY-4 (under development).

Dynamic simulation technology was applied to the design of the MS-1 satellite attitude and orbit control system by the DongFangHong Satellite Company, Ltd. and to the onboard computer upgrade of the Beidou second-generation navigation satellites.

The program in Space Flight Mechanics and Space Control Technology was awarded the Third Grade National Defense Science and Technology Progress Prize. The adaptive structural and new space payload technologies were awarded The First and Third Grade Science and Technology Progress Prizes of Beihang University, respectively, in 2011.

Department of Aerospace Propulsion
The Department of Aerospace Propulsion came out of the former Department of Rocket Design and Rocket Engine, which was founded in 1956. Within the Department of Aerospace Propulsion, the Liquid Rocket Engine Design and Solid Rocket Motor Design groups were established in 1958, the same year that the Beijing-2, the first modern research rocket in Asia, was successfully launched. At present, there are 40 faculty members, including 9 professors and 15 associate professors. The annual enrollment is approximately 60 undergraduate students, 35 graduate students, 15 doctoral students, and several foreign students.

The department occupies an area of approximately 6,000 m² where the advanced aerospace propulsion laboratory and vacuum plumes laboratory are located, and maintains long-term academic exchanges and scientific research collaborations with departments and agencies in the United States, Russia, Europe, and numerous other countries.

Research areas include liquid rocket engines, solid rocket motors, electric propulsion, and other space propulsion. Some of the research focuses include rocket engine vacuum plumes, multidisciplinary design optimization, full-flow staged combustion cycle engines, hybrid rocket motors, attitude and orbit control rocket engines, aeropulse nozzles,
solid propellant combustion driven gas dynamic lasers, arc jet engines, colloid micro-thrust engines, scramjets, spray and combustion technologies, and ignition technologies.

Department of Guidance, Navigation and Control
The history of department of Guidance, Navigation and Control can be traced back to 1958 when Professor Lin Shi established the first aeronautics gyroscope and inertial navigation research specialty in China. In 1988, the first key discipline “inertial technology and navigation equipment” was authorized. In 2005, it was formally renamed the Department of Aerospace Guidance, Navigation and Control. The department focuses on developing and researching subsystems for a variety of spacecraft.

At present, there are 13 faculty members, including three professors, three associate professors and seven lecturers. The annual enrollment is approximately 30 undergraduate students, 25 graduate students, three doctoral students, and several foreign students.

The primary areas of research are adaptive control and intelligent control theory and application, aerospace dynamics and control, hypervelocity vehicle guidance and control techniques, hybrid system theory and application, autonomous navigation, and optimal filtering techniques.

The department carries out seven projects for the National Science Foundation of China. Approximately 300 papers have been published on domestic or international journals, including AIAA Journal of Guidance, Control and Dynamics, IEEE Transactions on Aerospace and Electronic Systems, Acta Astronautica, Acta Mechanica Sinica, Sensors & Actuators A: Physical, or presented at academic conferences. Thirteen patents have been authorized.

The Image Processing Center
The Image Processing Center (IPC, also called the Department of Space Informatics) was founded in 1984 and employs fifteen faculty members (three full professors and six associate professors). IPC provides diverse opportunities at all levels of education, including undergraduate, Master’s, and Ph.D. programs. We are proud of the open, friendly culture that has been a feature of IPC since its inception. Faculty members keep their office doors open to encourage informal meetings with students and colleagues, while graduate students organize frequent department-wide social activities. The department’s strong support for collaboration creates an ideal environment for study and research.

IPC is a multidisciplinary department, focusing mainly on image processing and pattern recognition (IPPR)-based technologies and their application. This involves three disciplines: control science and engineering, computer application, and biomedical engineering. IPC is one of the most important centers for IPPR research in China, especially in the aeronautics and astronautics, and biomedical imaging application fields. The sponsors of IPC projects include the NSFC, the ministry of Science and Technology in China, and the “863” program among others. Primary research areas include image science and vision, target detection and recognition techniques, multimodality image processing techniques, and biomedical image processing and application.

Many high level papers from IPC on both theoretical and practical research have been published in internationally renowned journals, including IEEE Transactions on Pattern Analysis and Machine Intelligence, Pattern Recognition, Optics Express, Journal of the Optical Society of America, IEEE Geoscience and Remote Sensing Letters, and Computerized Medical Imaging and Graphics.

The Space Science Institute
The Space Science Institute (SSI) was founded in 2010. The goals of the Institute are to study physical processes in space with an emphasis on their application to aeronautics and astronautics industry. The first director of SSI is Professor Jinhua Cao, a Changjiang Scholar of the Ministry of Education of China. The SSI currently has seven scientists and four engineers. Professor Tielong Zhang, the principal investigator for the fluxgate magnetometer instrument on the Venus Express mission of the European Space Agency, works at SSI as a Changjiang Lecture Scholar. The SSI research team participates in many space missions, which include four Chinese missions: Dongfanghong-2, Shijian-4, the Double Star Program (a joint China/ESA mission), and Chang’E (a Chinese lunar mission), as well as two ESA missions (Cluster and Venus Express), and a French mission, TARANIS. They have a strong heritage and broad expertise in the development of spaceborne scientific payloads as well as the analysis of data from such missions. A number of staff have been in charge of developing the first spaceborne high-energy particle detector and first spaceborne search coil magnetometer (for the Chinese ZH-1 mission) in China. SSI is constructing a Laboratory for Space Environment Exploration Technology, which will be equipped with a small super vacuum chamber and zero magnetic field chamber. In addition, the science team at SSI is also undertaking seven projects of NSFC, one of which is a Key Project.

The main research areas of SSI are magnetospheric physics, space weather, comparative planetology, and space environment exploration technology.

International Graduate Education
With regard to graduate education, SA emphasizes the generation of specialized knowledge in the aerospace field through systematic training, encouraging graduates to focus on research problems in aerospace engineering that utilize the expertise of the school. Graduates can therefore become qualified engineers shortly after completing their training. Our graduates have received very positive feedback about their aerospace engineering abilities. Many universities and research institutes abroad involved in aerospace research send their students and young engineers to our school to participate in the Master’s and Ph.D. programs, making SA one of the most popular destinations for international graduates in astronautics in China. Every year more than 10 international graduates from many different countries (including Russia, Ukraine, South Korea, Pakistan, and Egypt) enter SA. Each year, the school also accepts several graduate level visiting students from Europe and United States. All courses for international graduates are given in English. More than 150 international graduates have obtained Master’s or Ph.D. degrees from SA, and most of them are still in the aeronautics industry or academic departments in their home countries. Some outstanding students have even become chief designers or department heads in aerospace engineering.

International students can apply to study the following majors: Flight Vehicle Design; Guidance, Navigation, and Control; Aerospace Propulsion Theories and Engineering; Pattern Recognition and Intelligent Systems; and Space Physics.
Rocket Engine Research

Guobiao Cai, Yu Liu, Xu Xu, Lijun Yang, Haibin Tang

Here we present an overview of rocket engine research carried out in Beihang University. These activities include experimental, analytical, and theoretical work related to hybrid rocket motors, full-flow staged combustion cycle engines, aerospike nozzles, scramjet and hypersonic aerodynamics, gel propellant, and the vacuum plume effect of thrusters.

Hybrid Rocket Motors

Hybrid rocket motors, due to their inherent operational safety, throttle ability, start/stop/restart capability, and potentially low cost, provide promise for future aerospace propulsion applications. In, for example, research rockets, launch vehicles, boosters, space engines, and spacecrafts. Combustion chamber flow and the characteristics of fuel regression rate for GOX/HTPB, H₂O/HTPB, and N₂O/HTPB systems have been simulated using both 2-D and 3-D models for the different motors (1). The optimal design schemes for hybrid rocket motors have been obtained through multidisciplinary design optimization (2). The motor propellant combinations above have been tested on different motor diameters of Φ45mm (GOX/HTPB, H₂O/HTPB, and N₂O/HTPB, Φ105mm (N₂O/HTPB), Φ220mm (N₂O/HTPB), and Φ300mm (H₂O/HTPB). Fuel regression rate correlations of \( \dot{m} = aG \) were obtained. Dual-thrust throttling tests were carried out successfully (Figure 1). The \( c^* \) (characteristic velocity) efficiency was as high as 97.3% when using a diaphragm mixing device in the aft-chamber, and extended hot firing was carried out for up to 120 seconds.

Full-Flow Staged Combustion Cycle Engines

The full-flow staged combustion (FFSC) cycle engines are preferred for their high performance, good reliability, and low maintenance costs, which meet the needs of a reusable launch vehicle propulsion system. The gas-gas injector is a key technology found in FFSC engines. Gas-gas combustion has a simpler reaction process compared with traditional liquid-liquid or gas-liquid combustion. Together with dimensional analysis of the gas-gas combustion phenomena (here the dimensional analysis is a theoretical method to find or check relations among physical quantities by using their dimensions), nondimensionalization of the 3-D Navier-Stokes equations for a multicomponent gaseous mixing reaction flow was conducted. Scaling criteria, including four prerequisites, were obtained to ensure the similarity between different combustion conditions. The criteria imply that when these prerequisites of inner flow field are satisfied, the size and the pressure of gas-gas combustion chamber can be changed, while the heat transfer characteristic of the chamber can still be qualitatively similar. Their relationship could be quantitatively correlated as \( q \propto p_c^{0.4} d_i^{0.2} \) where \( q \) is the heat flux, \( d_i \) is the chamber diameter, and \( p_c \) is the chamber pressure. The relationship was verified with both numerical simulations and hot-firing experiments for a single-element injector model from 0.92 MPa to 6.1 MPa and a multielements injector model from 1.64 MPa to 3.68 MPa.

Aerospike Nozzle

The aerospike nozzle is considered to have better performance at “off-design” altitudes than that of the conventional bell-shaped nozzle, since its plume is open to the atmosphere on one side and free to adjust, allowing the engine to operate at its optimum expansion at all altitudes. Both experimental and theoretical studies were performed on aerospike nozzles that were either six-cell tile-shaped, one-cell linear, or three-cell with round-to-rectangle (RTR) primary nozzles (3). It was found that all three kinds of aerospike nozzles demonstrated good altitude compensation capacities and showed better performance at off-design altitudes than bell-shaped nozzles. In cold-flow tests, the six-cell tile-shaped and one-cell linear aerospike nozzles showed high thrust efficiency at design altitude. Employing GH₂/GO₃ as propellants, hot-firing tests were carried out on a three-cell aerospike nozzle engine with RTR primary nozzles. These results were obtained under two nozzle pressure ratios lower than design altitude. Near a nozzle-to-pressure ratio (NPR) of 50, efficiency was 92% to 93.5%, while it was 95% to 96% at NPR = 350. An efficiency of over 98% at the design point is expected. This experimental data validates the proposed aerospike nozzle contour design and optimization method.

Scramjet and hypersonic aerodynamics

The supersonic combustion ramjet (scramjet) is a promising candidate for enabling hypersonic flight in the future. At Beihang University, dual-mode scramjets have been studied extensively. A test rig with an air flow rate of 2 kg/s and a maximum temperature of 1,800K (1,527°C) was established, and a suite of in-house software was developed to study the supersonic combustion flow fields in the scramjet combustor. Simulations and experimental verification have been carried out in the areas of supersonic combustion and flame holding (4–5), supersonic atomization, ramjet-scramjet mode transition, scramjet internal/external integrated flow fields calculation, and scramjet/vehicle integrated optimization design. Studies on different scramjet flame holders—cavity, strut, or aero-ramp—enabled elucidation of the mechanisms of ignition and flame holding. A novel aero-ramp/gas pilot flame-
integrated flame holder was studied in depth (Figure 2), with theoretical and experimental results showing good agreement and demonstrating its advantages with respect to flame holding and arrangement flexibility. Experiments on scramjet mode transition by means of changing the fuel air equivalence ratio and inlet total temperature showed unique hysteresis phenomena, which could be explained both theoretically and using high-speed photography.

Gel Propellant Application in Rocket Engines
Gel propellant holds promise for application in future aerospace travel because it combines the advantages of both solid and liquid propellant. From the viewpoint of fluid mechanics, gels behave as time-dependent viscoelastic fluids. Previous studies, which assumed liquid sheets are in a completely relaxed state, showed that non-Newtonian liquid sheets are more unstable than Newtonian sheets. But evidence shows that some shear-thinning (non-Newtonian) viscoelastic liquids have greater stability than Newtonian liquids. In brief, these studies showed that when the axial tension (a stress generated at the nozzle because of the large deformation of the liquid) is not zero, increasing axial tension dampens disturbance waves on the viscoelastic liquid sheets, allowing a viscoelastic liquid sheet with specific physical properties to behave with greater stability than the corresponding Newtonian liquid sheet (6). This sheds light on experimental evidence demonstrating that the non-Newtonian fluid is more difficult to atomize. Moreover, when compared with the analysis of the liquid sheet in a completely relaxed state, the effects of the elasticity and viscosity of the liquid on the instability are more complicated when the axial tension is not zero. The increasing elasticity of the liquid no longer always destabilizes the sheet but, in contrast, stabilizes the sheet under certain conditions.

Analysis of the Vacuum Plume Effect of Thrusters
An experimental system to analyze vacuum plumes (7) has been constructed at Beihang University. Its main component is a cylindrical liquid helium-driven internal cryopump, which is fixed in a 12.6 m length and 5.2 m diameter chamber (Figure 3A). The base pressure in the vacuum chamber holding a firing thruster can be maintained at about 10^{-3} Pa. An experimental investigation of the plume plasma from a 40 mN ion thruster has been undertaken using this vacuum system (Figure 3B). The ion thruster used in this experiment is a 20 cm diameter, two-grid ion thruster using xenon as propellant. Using a Faraday probe, a Langmuir probe, and a retarding potential analyzer, measurements were taken in both the horizontal and vertical planes, providing data on the special distribution of plasma properties, including the floating potential (between 2 and 12 V), the plasma potential (between 11 and 23 V), the electron temperature (between 0.9 and 3.8 eV), and the density (between 2.0×10^9 and 2.4×10^{10} cm^{-3}). Plume aerodynamic experiments using a 10 N bell-shaped thruster impacting a plate were also conducted. The background pressure was 7.3×10^{-3} Pa and the simulative orbit altitude was 110 km.

REFERENCES
Structural Optimization and Nonlinear Astrodynamics in Spacecraft Design

Hai Huang¹, Shenyan Chen¹, Renwei Xia¹, Zhicheng Zhou¹, Ming Xu¹, Yinghong Jia¹, Shijie Xu¹

The final performance or service quality of a spacecraft, as well as the success of the space mission, is very much dependent on the advanced technologies used in the systems. There is increasingly active research in this field at universities and institutes, particularly as stricter requirements are being introduced in modern spacecraft design. Here we outline recent achievements in spacecraft structural design and orbital dynamics at the Beihang University School of Astronautics.

Approximation and its Applications in Spacecraft Design

In the past 10 years, the Beihang University structural optimization team has successfully applied these theories and methods in aerospace engineering. They developed system software called the Engineer ing System of Structural Optimization for Spacecraft (ESSOS), which can integrate with commercial finite element analysis (FEA) software like Patran/Nastran. ESSOS can call the FEA software to conduct the structural analysis and the optimization performed using the iterative method. The sequence of solutions of the second-level approximate problems converges on the solution to the first-level approximation problem, and the sequence of solutions to the first-level approximation problems converges on the solution of the original problem. A complete finite element analysis is executed only at the beginning of each first-level approximation stage in the iterative design procedure.

The constraints could be limitations on stresses, displacements and basic into a sequence of approximate problems with a smaller number of explicit constraints.

Obviously, the higher the fidelity of the approximate problem, the smaller the number of iterative steps or finite element analyses required to reach the optimal solution. A critical aspect of this field is determining exactly how to construct approximate functions for the original implicit constraint functions of a problem. Early work focused mainly on the first Taylor expansion and its variants, but the convergence of optimization processes was not satisfactory in many cases. The concept of constructing an approximation function using data from multiple points, rather than just a single point as done in the traditional Taylor expansion, was first tested by Haftka (2). More recently, a team working on structural optimization at Beihang University proposed a two-level, multipoint approximation concept (3) that put forward the notion of a multipoint approximation function based on the function values and derivatives taken at several points during the process of iterative optimization. In addition, the dual method (4) was combined with the abovementioned concept to guarantee the optimum seeking efficiency. This method is able to find optima in dual space with a very small number of variables, reaching a solution more easily. However, the dual method works only for problems demonstrating a special property known as variable separable form, meaning that there are no cross-product teams of functions.

By using the two-level, multipoint approximation, the original structural optimization problem is transformed into a sequence of explicit approximate problems called first-level approximate problems, in which the constraint numbers are reduced and the original constraint functions are substituted with high-quality multipoint approximate functions. To efficiently solve each of the first-level approximate problems, second-level approximate problems are introduced, which are of the variable separable form and can be solved efficiently using the dual method. The sequence of solutions of the second-level approximate problems converges on the solution to the first-level approximation problem, and the sequence of solutions to the first-level approximation problems converges on the solution of the original problem. A complete finite element analysis is executed only at the beginning of each first-level approximation stage in the iterative design procedure.

Structural Optimization Based on Two-Level Multipoint Approximation and its Applications in Spacecraft Design

Structural optimization describes the search for minimal physical weight or design cost, while maintaining requirements such as strength, stiffness, and dynamic performance. Addressing a structural optimization problem using so-called mathematical programming methods is usually impractical because of the heavy computational burden, particularly for large-scale problems. By employing approximation concepts (1), problems can be more efficiently solved using a process in which most constraints are temporarily ignored and only a few critical ones are retained. These remaining constraints are then replaced with explicit approximations, thereby transforming the original optimization problem

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Figure 1. Examples of the application of structural optimization technology to determine the design with minimum weight. (A) The finite element model of an application satellite that has a compacted state (1) at launch and a working state (2) when deployed in orbit. (B) A microsatellite designed on campus by a Beihang University student. The project provides students with a practical opportunity to use ESSOS to find the design with the minimum structural weight.
Research on Nonlinear Astrodynamics

Nonlinear astrodynamics is the application of advanced, innovative mathematical tools developed in nonlinear dynamical systems to the field of orbital mechanics, including formation flying, solar sail displaced orbits, and cislunar transfer. Some of the interesting research in this field, performed by the astrodynamics group at Beihang University, is described below.

Nonlinear Periodic and Quasi-Periodic Formation Flying

The theory of Hamiltonian dynamical systems has been applied in the field of formation flying in aerospace engineering in order to reach beyond classical theories (6). The problem of the existence of $J_1$ invariant relative orbits has been solved from a unique perspective using this theory. Furthermore, a novel numerical approach for determining $J_2$ invariant relative orbits is proposed from the dynamical system point of view (7).

Another application is to address the innovative concept of quasi-periodic cluster flight, which is quite different from periodic relative orbits and holds bounded trajectories with no restriction on initial conditions, and no requirement for measurements. Therefore, the outdated restrictions imposed by the classical theories, namely that the bounded trajectories in cluster flight must be periodic, will be replaced by the quasi-periodic cluster flight developed in this research.

Dynamics and Control for Displaced Orbits Above Planets

Certain mathematical techniques in the field of dynamical systems have been applied to analyze the nonlinear dynamics of a displaced orbit above a planet. An innovative controller was designed to stabilize the motions near the unstable equilibrium (8) for the displaced orbits. The important contributions of this work are: (i) the necessary and sufficient conditions of stability for the motion near the equilibrium are given; (ii) it has been proven from a numerical perspective that motions near the equilibrium include period orbits and their asymptotic lines; (iii) the controller not only changes the instability of the equilibrium, but also modify the topology of the equilibrium (9).

The innovative result derived from this paper can be applied to the solar sail in a way that is quite different from the classical findings so far in research on the circular restricted three-body problem (CR3BP).

Space Manifold Dynamics and Its Applications in Cislunar Transfer

This research deals with how to design the low-energy transfer trajectory in the cislunar space. The orbital elements of all possible lunar capture trajectories were provided by the dynamical system technique, from which the minimum energy to leave the lunar surface was deduced and found to be quite different from that obtained using the CR3BP and Hill Models (10). From the point of view of the libration point theory, the low-energy trajectories are considered as the ones passing through the $LL_1$ or $LL_2$ libration points in cislunar space.

Furthermore, the theory of Halo orbits which exist near the two libration points can be used to design the low-energy transfer trajectories. This research indicates that the direct low-energy trajectories from Earth to Moon pass through the Halo orbit near the $LL_1$ point, while those passing through the Halo orbits near the $LL_2$ point are indirect (from Earth to Sun and then to Moon, the so-called weak stability boundary trajectories). Moreover, the relationship between the orbital elements of the transfer trajectories and the different positions on the Halo orbit have been investigated with regard to all indirect trajectories (Figure 2).

REFERENCES


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The School of Instrument Science and Opto-Electronic Engineering

The School of Instrument Science and Optoelectronic Engineering (SISOE) at Beihang University is a newly established school, opened in December 2003. Professor Guangjun Zhang was elected as dean in 2003 and Professor Jiancheng Fang succeeded him in 2005. Since its foundation, the school has always adhered to the mantra of “harmony, innovation, and development,” and has moved from strength to strength, now playing an increasingly important role in the growth of Beihang University as well as in the development of aeronautics and astronautics in China.

The school comprises four departments: Measurement and Control, Inertial Technology and Navigation Instruments, Optical Engineering, and Remote Sensing Science and Technology; two institutes: Optoelectronic Technology, and Small Satellites and Deep Space Exploration; and a teaching center. One group within SISOE was honored as a National Natural Science Foundation Innovative Research Group in advanced inertial instrumentation and systems technology, and two groups were honored as Chang Jiang Scholars Innovative Research Teams in precision optomechatronics technology and novel inertial instruments and systems technology.

The school offers undergraduate and graduate programs in various subject areas, including Instrument Science and Technology, which is regarded as a national level key discipline. There are 695 undergraduates, 287 doctoral students, and 578 Master’s students studying in different programs in the school. Students are encouraged to take part in multidisciplinary scientific research during their studies. Six months of research training rotating through different laboratories and industrial sites is required for all undergraduates.

Faculty

The school has a team with exceptional ability in both teaching and research. It includes 167 staff members, consisting of 31 professors, 42 associate professors, 54 lecturers, and 12 postdoctoral fellows. Three professors—Peide Feng, Junen Yao, and Zhonghua Zhang—serve as members in the Chinese Academy of Engineering; Professor John Zarnecki is supported by Recruitment Program of Global Experts (Thousand Talents Program); three professors—Guangjun Zhang, Jiancheng Fang, and Wei Jin—were honored as Chang Jiang Scholars; four professors—Guangjun Zhang, Jiancheng Fang, Lei Guo, and Lijun Xu—were honored as Distinguished Young Scholars; and 16 professors have been elected to the Program for New Century Excellent Talents in University.
The school has also a “973” program chief scientist and five “863” program consultant committee members. Many faculty members have received international and national awards for their achievements in both research and education.

**Strategic Plans in Science and Technology Research Quantum Instruments**

Advances in modern physics and quantum manipulation have allowed instruments based on quantum effects to be rapidly developed in recent years. These high-precision, quantum instruments will likely be widely employed in many fields in the near future. SISOE has a long history and broad experience in developing inertial sensors and image instruments, which has led to the development of atomic gyroscopes, atomic magnetometers, and quantum image instruments. Devices for ultra-high sensitivity magnetic field and rotation measurement with atomic spin are under development. Potential areas of application include detection and measurement of biological and space magnetic fields, and underwater autonomous robotics navigation for deep sea oil and mineral exploration.

**Micro/Nano Inertial Sensors**

Micro/Nano inertial sensors, such as Micro-Optical-Electro-Mechanical System (MOEMS) and Micro-Electro-Mechanical System (MEMS) devices have potentially significant advantages in cost, size, and weight, and are expected to dominate the entire low- and medium-performance range of inertial sensor market in the near future. The Integrated Optics Gyro (or optical gyro on a chip) is a typical MOEMS inertial sensor and has been a sought-after goal for several years. SISOE has a long history and broad experience in developing MEMS/MOEMS inertial sensors, and has made significant advances in integrated optics gyroscopes, resonant MEMS gyroscopes, micro/nano grating accelerometers, and photonic crystal and photonic crystal fiber resonators.

**Deep-Space Exploration**

Three micro-nano satellites have been successfully developed to demonstrate and validate identical-orbit, in situ, multipoint, and multiscale space exploration. The scientific objectives for these formation flying satellites are probing the distribution variation in the current, plasma environment, and tracking high-energy particles in the near-earth space environment in space-time resolution.

Star sensors are important attitude determination components of spacecraft for deep-space exploration. In the past 10 or more years, through the support of many national research projects, SISOE has carried out comprehensive research on high precision miniature star sensors and achieved advances in many key technologies. A series of high precision miniature star sensors have now been produced and successfully applied in several satellite programs.

SISOE began studying the basic theory of fiber optic gyroscopes in the 1980s, and has now built a complete theoretical system for fiber optic gyroscopes. Breakthroughs in the development of some core components include the fiber couplers that maintain polarization, integrated optical modulators, and the antiradiation fiber-optic light source. Moreover, technologies derived from this work have been applied in many fields, such as navigation for deep-space exploration, current transformers, and inclinometers in oil wells. In the future, the plan is to develop MOEMS and photonic crystal fiber gyroscopes, while other new principles, new methods, and new materials in the field of fiber optic sensors will be studied and explored.

**Aviation Remote Sensing**

Due to the significant demand of aviation remote sensing in China, SISOE has successfully developed a high-precision Position and Orientation measurement System (POS), the performance of which is comparable with that of other top-level devices such as the POS/AV610. Additionally, these POSs have been successfully applied to X-band InSAR, digital cameras, and other observation devices, and the imaging resolution has been improved from 2.7 m to 0.5 m in the vertical and from 0.5 m to 0.15 m in the horizontal dimension.

A novel integrated imaging system for detecting multiparameters (hyper spectral, image, and structure information) with high accuracy is under development, and capable of accomplishing 3-D shape measurement based on fly-point and high-resolution imaging by using the transmitted light of an acousto-optic device. The system can be used to dynamically monitor the structure and the vertical distribution of physiological parameters of the vegetation.

**International Collaborations**

The school has established close collaborations with a number of overseas universities and research institutions. Professor John Zarnecki, the vice president of the Royal Astronomical Society in the United Kingdom, has been brought to SISOE, supported by the Recruitment Program of Global Experts. Professor Richard Holdaway, the director of RAL Space at the Rutherford Appleton Laboratory and fellow of the Royal Academy of Engineering in the United Kingdom, is employed as honorary professor. Professor Roger Davies, head of Astrophysics at Oxford University and the president of the Royal Astronomical Society in the United Kingdom, is a visiting professor at SISOE. Professor Brian Culshaw, director of the Society of Photographic Instrumentation Engineers, is also a visiting professor. SISOE hosts the international symposium on Instrument and Control Technology every two years and the China-U.K. Workshops on Space Science and Technology have been held seven times since 2006 (sponsored by the China National Space Administration).

**Achievements**

The school attaches great importance to the creation of high-quality research laboratories. Currently, SISOE houses the National Key Laboratory of Science and Technology on Inertial, the Key Laboratory of Precision Optomechatronics (Ministry of Education), and the Sino-UK Joint Laboratory on Space Science and Technology. Within the fields of aeronautics and astronautics, the school has made significant advances in advanced inertial devices and systems, precision optical and electrical testing, spacecraft attitude measurement and control, and advanced sensor technology. Since 2006, SISOE has won 10 National Technology Achievement Awards.

Since its beginnings nearly 60 years ago, SISOE has become a hub for the development of inertial navigation technology and airborne test technology, as well as a cradle for the training of exceptional researchers. Of the top 10 gyroscopes that have been researched and developed in China, seven of them originated from SISOE, clearly indicating its significant contribution to the fields of inertial science and technology.
Ultrahigh Sensitive Magnetic Field and Rotation Measurement with Atomic Spin

Jie Qin1,2, Shuangai Wan1,2, Yao Chen1,2, Rujie Li1,2, Tao Wang1,2, Jiancheng Fang1,2*, Chunru Wang3*, Lei Jiang1,4*

With the development of atomic spin manipulation technologies, particularly the demonstration of atomic spin in the spin exchange relaxation free (SERF) regime (1), new atomic spin devices with ultrahigh sensitivity, such as atomic magnetometers (AMs) and atomic spin gyroscopes (ASGs), have been developed in recent years (2, 3).

Atomic Magnetometers

Atomic spin has magnetic momentum, which can precess around a magnetic field, so the atomic spin can be used to measure the magnetic field. AMs based on SERF have been demonstrated in recent years and shown to achieve an ultrahigh sensitivity of 160 aT/Hz1/2 (4, 5). Compared with superconducting quantum interference device (SQUID) magnetometers, AMs feature ultrahigh sensitivity, compact size, and noncryogenic operation, promising a new era for ultrahigh sensitivity magnetic field measurement.

To develop an ultrahigh sensitive magnetometer for space applications, such as magnetic field measurement and analysis in space and on a lander, an AM was developed that utilizes cesium (Cs). Since power consumption is an important consideration for space applications, Cs—which can operate in the SERF regime at lower temperatures than potassium (K) or rubidium (Rb)—was chosen to conserve power. A sensitivity of 8 fT/Hz has been achieved with this AM, the somewhat limited sensitivity being due to magnetic field noise from the magnetic shield barrel. To further improve the sensitivity, a new magnetic shield barrel is under construction with a better shielding factor and a lower magnetic field noise. Increasing the active measurement volume using a coated alkali metal cell is an effective way to boost sensitivity. Using paraffin to coat cells is known to be effective, but they can only operate at temperatures under 80°C. Coating materials with an operational temperature above 80°C are under development. By decreasing the strength of the residual magnetic field, Cs can be used in the SERF regime below 80°C and has a higher density relative to K and Rb. Thus, the sensitivity of the AM can be improved using a larger alkali metal cell, and the power consumption of the whole system will be decreased (Figure 1A). AMs have been shown to have a higher sensitivity than SQUID magnetometers, but reach ultrahigh sensitivity only at a relatively high frequency (a few tens of Hz), while SQUID magnetometers have achieved fT/Hz1/2 with a flat noise spectrum near direct current (DC) frequencies. To improve the sensitivity of AMs near DC frequencies, a feedback controlled pump laser system is under development to precisely manipulate the atomic spin and keep the scale factors stable enough (Figure 1B). A probe laser system with squeezed states is also under development to improve the sensitivity (Figure 1C).

Atomic Spin Gyroscopes

Atomic spin is able to keep pointing in its original direction in the inertial coordinate system, so the atomic spin can be used to sense rotation as well. The gyroscope is one of the key sensors for inertial navigation applications and there is a strong need to have a more precise gyroscope to improve navigation performance. However, the available gyroscopes are either mechanical or optical, and improvements of these gyroscopes have been very slowly in the past decade. The SERF-based ASG, developed in recent years, may prove to be a good way to build high-performance gyroscopes due to its ultrahigh sensitivity and compact size (2).

An SERF-based ASG using xenon-cesium (129Xe-Cs) has been developed for navigation in underwater autonomous robots. Both the nuclear spin of 129Xe and the electron spin of Cs are used for rotational measurement. A drawback of previous ASGs was the long time (several hours) needed for the spin exchange optical pump (SEOP) process to be completed, severely limiting its application. The SEOP process for

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The outcomes of project included: a better understanding of the impact of space on the biological characteristics of bacteria and mammalian cells; greater insight into ways to estimate the microbial pathogenicity; and the space environment had induced changes in bacterial pathogenicity and certain metabolic pathways. Partial sequencing of the bacterial genome in the samples showed that the bacteria had traveled several million kilometers, making it the longest duration and farthest distance traveled for a Chinese space mission. Upon the return of the spacecraft, it was found that 61 (95.32%) of the samples survived and were able to grow in the laboratory. The microbes were identified as Escherichia coli, Salmonella typhimurium, and Staphylococcus aureus. A study on the effect of space on the production of these microorganisms was carried out. The effect of space on the production and activity of certain biological agents in bioengineered cells was also studied.

REFERENCES

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Cell Culture Experiment System for Space Research
Shangchun Fan1, WeiWei Xing1, Changting Liu2

With the rapid development of aerospace science and technology, studies examining the effects of a space environment on biological systems are becoming increasingly important (1). Apart from obtaining information on how to protect and adequately provide for astronauts, the unique nature of the space environment can also be used for biological research that may more broadly benefit human health (2, 3).

Our work includes both basic and applied research in space life and biological sciences. The research program began by looking at how living in space changed the growth parameters of mammalian and microbial cells, and whether a marker gene sensitive to a space environment could be found (4–6). Experiments aboard various space flights examined the effect of the space environment on tissues and cells, down to the protein and DNA level (7–9). The effect of space on the production and activity of certain biological agents in bioengineered cells was also studied (10).

Sixty-four biological samples were carried into space on the Shenzhou-8 spacecraft, which orbited Earth for 16 days and 13 hours, and traveled 11 million kilometers, making it the longest duration and farthest distance traveled for a Chinese space mission. Upon the return of the spacecraft, it was found that 61 (95.32%) of the samples survived and the space environment had induced changes in bacterial pathogenicity and certain metabolic pathways. Partial sequencing of the bacterial genomes was performed as well as transcription and proteome analysis. The outcomes of project included: a better understanding of the impact of space on the biological characteristics of bacteria and mammalian cells; greater insight into ways to estimate the microbial pathogenicity;...
and increased knowledge of the types and nature of genetic variation caused by a space environment and how they related to the genome, transcriptome, proteome, and epigenome. This research utilizing pathogenic bacteria will aid in the design of new strategies for disease prevention and support the launch of a space platform for the production of pharmaceuticals using engineered bacteria.

Automated cell culture requiring no human intervention, while using real-time imaging of cells is a growing trend in cell biology and especially important for space research. Figure 1 shows a prototype platform developed for evaluating the basic concepts and functions of a fully autonomous culture system for space research.

The system provides automated cell culturing, microscopy imaging, and intelligent image processing. The cell culture unit in Figure 1 combines dedicated cell culture chambers designed for a space environment with the necessary control devices (i.e., sensors and actuators). Pie-shape quartz chambers, sealed completely for working in a vacuum, are supported by stainless steel loops that cushion the apparatus during launch and landing. The measurement and control parameters include temperature, pressure, liquid flow, pH, and CO₂ concentration. The intelligent analysis and control unit drives all sensors and actuators, working autonomously or via remote control. Figure 2 shows M249 neuron cells in different culture stages, grown using this system on the Shenzhou-8 spacecraft.

REFERENCES
4. C. A. Allen, PhD Dissertation of The University of Texas Medical Branch 7, 45 (2007).
School of Physics and Nuclear Energy Engineering

History
The School of Physics and Nuclear Energy Engineering (SPNEE) was started in 1952 as a part of the general physics teaching program at Beihang University. In 1997, it became the Department of Physics in the School of Science and finally, due to its rapid growth, became its own school in the form of SPNEE in 2009. The first Master’s students were enrolled in 1981 (in optics) and the first doctoral students in 1999 (materials physics and chemistry/condensed matter physics).

Faculty and Staff
Currently, there are over 90 faculty and staff in the school, including 27 professors, 25 associate professors, and one member of the Chinese Academy of Engineering Sciences, Professor Jun’en Yao.

Departments and Centers
The school consists of three departments and one educational center—the Department of Physics, Department of Applied Physics, Department of Nuclear Science and Technology, and the Education Center for General Physics—covering diverse fields including condensed matter physics, theoretical physics, optics, radio physics, and nuclear science and technology. In addition, the school has one Key Laboratory of the Ministry of Education—the Key Laboratory of Micro-Nano Measurement-Manipulation and Physics established in 2009—and one international research center—the Research Center for Nuclear Science and Technology established in 2011.

Education
Two undergraduate programs (applied physics and nuclear physics) and five graduate programs (condensed matter physics, theoretical physics, particle and nuclear physics, optics, and radio physics) currently support 299 undergraduate students, 111 Master’s students, 78 doctoral students, and four international students studying in the school.

Scientific Research
The school maintains a high standard of work and a dynamic research team encompassing both applied and basic research activities to keep up with the rapid advancements being made in scientific knowledge and technologies. A number of faculty members participate in international collaborations across the globe. The school is responsible for a number of national research projects including the National Science and Technology Support Program, the National Magnetic Confinement Fusion Program, the National High-Tech Projects, and the National Natural Science Foundation Projects. The school publishes over 100 scientific papers each year in international, peer-reviewed journals and files over 20 patents in the following research areas:

- **Condensed Matter Physics/Materials Physics**: Low-dimensional nanostructure, spintronic materials and devices, semiconductor physics, thin solid films and devices, advanced energy materials, optical materials, carbon materials, and computational physics/materials science.
- **Theoretical Physics**: Quantum transport, topological theory, soft matter physics, and complex systems.
- **Optics**: Electron optics and ultramicroscopy, nano-optics and optical sensors, laser and information optics, silicon photonics and devices, and precise optical measurement.
- **Particle and Nuclear Physics**: Nuclear technology and nuclear fusion materials, nuclear structure and nuclear reactions, particle physics, nuclear astrophysics, and mass measurement.

Awards
Several outstanding research awards and recognitions have been granted to our faculty, such as the Achievement in Asia Award (Robert T. Poe Prize) from the Overseas Chinese Physics Association (2009, Jie Meng), the GSI Exotic Nuclei Community (GENCO) membership award (2010, Jie Meng and Bao-Hua Sun), the 1st Prize Natural Science Award from the Ministry of Education (2010, Rong-Ming Wang), and the Humboldt Research Award (2011, Isao Tanihata).
Condensed Matter Physics/Materials Physics

Tuning the range, magnitude, and sign of the thermal expansion in intermetallic Mn$_3$(Zn, M)$_x$N(M=Ag, Ge)

Neutron diffraction is used to reveal the origin and control of the thermal expansion properties of the cubic intermetallic compounds, Mn$_3$Zn$_x$N. We show that the introduction of Zinc (Zn) vacancies induces and stabilizes an antiferromagnetic phase with huge spin-lattice coupling that can be tuned to achieve zero thermal expansion (ZTE) over a wide temperature range. This establishes a quantitative relationship and mechanism to precisely control the ZTE of a single material, enabling it to be tailored for specific device applications.

Real-time observations on crystallization of gold nanorods into spiral or lamellar superlattices

Real-time observations on gold nanorods evolving into spiral or lamellar superlattices are demonstrated using a universal optical microscope. 2-D critical nuclei and screw dislocations are found to initiate the crystallization process, and kinetics of the superlattice growth are determined to be similar to that of classical crystal growth, where three basic modes are involved: spiral, layer-by-layer, and dendritic. The observations may provide a simple and robust way to reveal the various kinetic processes of nanoparticles.
Atom-Resolved Evidence of Anisotropic Growth in ZnS Nanotetrapods

ZnS nanotetrapods were investigated by atom-resolved microscopy characterization and quantitative simulation. The octahedron core enclosed with Zn and sulfur- (S-) terminated surfaces was verified. Four hexaprism-shaped arms were selectively grown from Zn-terminated surfaces of the core by alternately stacking zinc blende and wurtzite structures. An anisotropic growth mechanism was proposed and later proven by the synthesis of ZnS nanoparticles and nanobelts.

Self-assembled ordered arrays of nanoscale germanium Esaki tunnel diodes

We have self-assembled regimented arrays of vertical ~100 nm diameter germanium (Ge) Esaki tunnel diodes using nanosphere lithography. Measurements of the current-voltage characteristics of individual nanodiodes using conductive atomic force microscopy at room temperature revealed pronounced negative differential resistance under forward bias, with a peak to valley ratio of 2–4. These diode arrays could constitute a neuromorphic circuit architecture exhibiting collective computational activity.

Evidence of surface-preferential Co distribution in ZnO nanocrystal and its effects on the Ferromagnetic Property

Scanning transmission electron microscope images present solid evidence that distribution of cobalt (Co) in zinc oxide (ZnO) nanocrystals is preferentially at the surface. The higher Co concentration at the surface (resulting in smaller distances between Co ions) and oxygen vacancies (V) that make for more effective magnetic exchange between Co ions, allow second-phase Co$_3$O$_4$ and Co-H-Co bridge structures to form more easily during O$_2$ or H$_2$ annealing. The inhomogeneous distribution of transition metal is a general state in diluted magnetic semiconductors and is important to take into account in future studies.

Role of interface dipole in metal gate/high-k effective work function modulation by aluminum incorporation

The interface dipole and its role in the effective work function (EWF) modulation by aluminum (Al) incorporation was investigated. Our studies showed that the interface dipole located at the high-k/silicon dioxide (SiO$_2$) interface caused an electrostatic potential difference across the metal/high-k interface, which significantly shifted the band alignment between the metal and high-k, consequently modulating the EWF. The electrochemical potential equalization and electrostatic potential methods were used to evaluate the interface dipole and its contribution. The calculated EWF modulation agreed with experimental data and could provide insight into the control of EWF in future p-type metal-oxide-semiconductor technology.

Deposition mechanism and microstructure of pyrocarbon prepared by chemical vapor infiltration with kerosene as precursor

Large-size carbon/carbon composites (Φ450 x Φ230 x15 mm$^3$) have been produced by chemical vapor infiltration with kerosene as a precursor. The microstructure of pyrocarbon was examined by polarized light microscopy and scanning electron microscopy. The infiltration rate limitation by parameters such as temperature. The results showed that rough laminar carbon constitutes the majority of the matrix at a medium temperature (about 1,100°C), while smooth laminar and isotropic structures occur at temperatures lower than 1,000°C and higher than about 1,200°C, respectively. The apparent activation energy of kerosene decomposition in the temperature range 900°C–1,200°C is 125.6 kJ/mol.

Layer Resolved Structural Relaxation at the Surface of Magnetic FePt Icosahedral Nanoparticles

The periodic shell structure and surface reconstruction of metallic iron-platinum (FePt) nanoparticles with icosahedral structure has been quantitatively studied by high-resolution transmission electron microscopy with focal series reconstruction with sub-angstrom resolution. The icosahedral FePt nanoparticles fabricated by the gas phase condensation technique in a vacuum have been found to be surprisingly oxidation resistant and stable under electron beam irradiation. Controlled removal of the (111) surface layers in situ results in a similar outward relaxation of the new surface layer. This unusually large layerwise outward relaxation is discussed in terms of preferential Pt segregation to the surface, forming a Pt-enriched shell around an Fe-rich FePt core.
Backward rectifying and forward Schottky behavior at Au/Nb-1.0 wt%-doped SrTiO3 interface
Gold-nobium- (Au/Nb-) 1.0 wt %-doped SrTiO3 junctions were successfully fabricated by a magnetic-controlled sputtering and annealing process. Backward diode-like behaviors were observed in an as-prepared junction and one annealed at 350°C. Transition to Schottky behavior was found in a junction annealed at 750°C. The Schottky junction showed linear capacitance-voltage ($C^{-2-V}$) relationship in the reverse condition with barrier heights determined to be 1.6 eV. The results of current-voltage ($I-V$) measurements revealed that high-temperature annealing can alter interface barriers and thereby significantly ameliorate the stability of leakage current.

Enhanced photocatalytic activity of Ag microgrid connected TiO$_2$ nanocrystalline films
One reason for a high photo-generated carrier recombination ratio was determined to be the charge accumulation caused by the uneven reaction area on a photocatalyst surface. We connected titanium dioxide (TiO$_2$) nanoparticles with a conducting silver (Ag) microgrid and observed obvious photocatalytic activity improvement. The improvement was attributed to the electron-hole separation by the metal-semiconductor contact and the large specific area of the metal grid, which increased the O$_2$ absorption and transported the electrons to the reaction sites. This structure lowers the electron accumulation and improves the utilization ratio of the photoexcited carriers.

Quantitative understanding of formation and stability of Ge hut islands on Si(001)
Germanium (Ge) hut island formation on silicon(001) [Si(001)] has been comprehensively analyzed using first-principle calculations of energies, stresses, and the strain dependence of Ge/Si(105) and (001) surfaces combined with continuum modeling. A quantitative assessment is provided on strain stabilization of Ge(105) facets, including the critical size for hut nucleation or formation, and the magnitude of surface stress discontinuity at the island’s edge and its effects on island stability. The study has brought new quantitative insights to the understanding of Ge hut formation and stability.

Theoretical Physics

Effect of Intrinsic Oxygen Vacancy on the Electronic Structure of γ-Bi$_2$O$_3$
Oxygen vacancy is an intrinsic defect in metal oxides, which has a great effect on the crystal’s electronic structure and physical properties. The influence of the intrinsic oxygen vacancy on the crystal and electronic structures of gamma-bismuth oxide powder (γ-Bi$_2$O$_3$) was studied. Results show that the vacancy preferentially occupies the tetrahedral O$_{8c}$ site. This makes γ-Bi$_2$O$_3$ lose I23 symmetry and leads to a flat band structure. The quadrivalence post-transition ions M4+ (M = S, Se, or Te) doping can keep I23 symmetry by forming MO4 units, and can result in dispersive valence bands and energy levels in the band gaps. These characteristics are beneficial for the mobility of the photogenerated carriers.

Topological phase in a one-dimensional interacting fermion system
A one-dimensional (1-D) interacting topological model was studied by means of the exact diagonalization method. It was found that the topological phases are not only robust to small repulsive interactions, but also are stabilized by small attractive interactions. Additionally, finite repulsive interactions can drive a topological nontrivial phase into a trivial phase, while the attractive interactions can drive a trivial phase into a nontrivial phase. The phase diagram in the parameters’ space was obtained and the effective Hamiltonian at the large-U limit discussed. These results were obtained using cold atoms trapped in a 1-D optical lattice.

Supercurrent reversal in quantum dots induced by spin-pump effects
The spin-pump effects caused by a rotating magnetic field on a supercurrent in a superconductor–quantum-dot–superconductor system were studied theoretically. By tuning the magnetic-field strength, the sign of the supercurrent could be changed from positive to negative, which results in a π-junction transition. The π-junction transition could also be tuned by the quantum dot energy level. The tunable π-junction transition was noted in the image of the current carrying density of states, which clearly shows the enhancement, suppression, and reversion of the supercurrent.

Thermal entanglement and teleportation in a two-qubit Heisenberg chain with Dzyaloshinski-Moriya anisotropic antisymmetric interaction
We investigated thermal entanglement of a two-qubit Heisenberg chain in the presence of the Dzyaloshinski-Moriya (DM) anisotropic antisymmetric interaction and entanglement teleportation when using two independent Heisenberg chains as the quantum channel. It was found that the DM interaction could excite entanglement and teleportation fidelity. Entanglement teleportation will be better realized via an antiferromagnetic spin chain when the DM interaction is turned off and the temperature is low. However, the introduction of the DM interaction can cause the ferromagnetic spin chain to be a better quantum channel for teleportation.
Splitting of the rate matrix as a definition of time reversal in master equation systems

Motivated by recent progress in nonequilibrium fluctuation relations, we presented a generalized time reversal for stochastic master equation systems with discrete states, which is defined as a splitting of the rate matrix into irreversible and reversible parts. An immediate advantage of this definition is that a variety of fluctuation relations can be attributed to different matrix splittings. Additionally, we found that the accustomed total entropy production formula and conditions of the detailed balance must be modified appropriately to account for the reversible rate part, which was previously ignored.

Optics

Energy transfer processes in Tm\textsuperscript{3+}-doped aluminate glass

We have quantitatively studied the energy-transfer processes between trivalent thulium (Tm) ions in aluminate glass with different Tm\textsuperscript{3+} concentrations. Our emphasis was placed on the determination of the microscopic and macroscopic parameters—the critical radius of these energy transfer processes, i.e., cross relaxation \textsuperscript{4}H\textsubscript{6}→\textsuperscript{2}F\textsubscript{4}+\textsuperscript{1}F\textsubscript{4} and donor–donor energy migration \textsuperscript{4}H\textsubscript{6}→\textsuperscript{2}F\textsubscript{4}+\textsuperscript{1}F\textsubscript{4}. For the 1.8 \textmu m emission in aluminate glass, only a slightly slower increase rather than quenching, even at a high concentration (higher than 15 wt %), was observed. Quantitative evidence indicated that high-order multipolar coupling mechanisms played an important role in energy transfer processes and, based on these results, would be helpful to predict efficient host materials and impurity concentrations to prevent the depopulation of the \textsuperscript{2}F\textsubscript{4} energy level.

Space-shifting digital holography with dc term removal

A numerical space-shifting reconstruction approach in digital holography was described. This method was able to very effectively remove the dc term in the reconstruction by utilizing the periodicity and the space-shifting property of an inverse discrete Fourier transform. Since the entire process does not need any additional holograms and specific requirements for the recording optics, this approach can be a convenient, practical, and widely effective way to remove the dc term from in-line or off-axis digital holography.

Cantilevered bimorph-based scanner for high speed atomic force microscopy with large scanning range

A cantilevered bimorph-based resonance-mode scanner for high speed atomic force microscope (AFM) imaging was presented. High speed scanning was realized with the bimorph-based scanner vibrating at the resonant frequency driven by a sine wave voltage, while slow scanning was performed by the tube scanner. AFM images of various samples were obtained. By manually moving the sample of polished aluminum foil surface while scanning, the capacity for dynamic imaging was demonstrated.

Circle-coupled resonator waveguide with enhanced Sagnac phase-sensitivity for rotation sensing

We propose a configuration of an integrated waveguide structure consisting of resonators coupled to an arc-shape waveguide. We showed theoretically that enhanced sensitivity was given by positive dispersion of the system, and the coupled resonators’ contribution manifests itself as an enhancement of phase shift imparted by the Sagnac effect. A clearer physical analysis indicated that the enhancement was dependent on slow light in form, but in physical essence it had no relation with slow light property predicted in the waveguides. This optimized system was preferable compared with a conventional gyroscope. Such a configuration can be used to realize a highly compact optical gyroscope for rotation sensing.

The study for measuring rotor speed and direction with quadrant photoelectric detector
Jian-qiang Qian, Yimin Cui, and Ping Xu, Measurement 41, 626 (2008).

A non-contact method for the measurement of rotor speed and direction based on a quadrant photoelectric detector was proposed and the corresponding device was developed. The device can measure the speed of the rotor and its direction. Experimental results show that the device can effectively get rid of both electronic noise and external disturbances and can also avoid the effect of the change of optics facial intensity. The measurement range is 1–200,000 rpm and the relative error is 0.001%.

Nuclear Science & Technology

Baryons with U_{i}(3)\times U_{k}(3) Chiral Symmetry IV: Interactions with Chiral (8,1)+(1,8) Vector and Axial-vector Mesons and Anomalous Magnetic Moments

We constructed all SU_{i}(3)\times SU_{k}(3) chirally invariant anomalous magnetic—i.e., involving a Pauli tensor and one-derivative—interactions of one chiral-(8,1)+(1,8) meson field with chiral-(6,3)+(3,6), (3, 3)+(3, 3), and (8,1)+(1,8) baryon fields and their “mirror” images. We calculated the F/D ratios for the baryons’ anomalous magnetic moments predicted by these interactions in the SU(3) symmetry limit and found that only the [(6,3)+(3,6)]-[(3, 3)+(3, 3)] ratio reproduces the result F/D=1/3, close to the value obtained from the experiment.
Calculation of the strong internal conversion, demonstrates that there should be another nuclear level above that identified from isomer-decay spectroscopy, in support of mass spectrometry. The measured excitation energy was 4.56(10) MeV. The neutral-atom half-life was known to be 17 μs. This is the shortest-lived isomer known. The rotation scheme with 27 newly identified g-rays and three band structures has been established and their configurations are discussed. The backbend associated with the alignment of a pair of $\pi g_{9/2}$ neutrons has been found in the negative-parity yrast band, while the positive-parity dipole band has been assigned as a magnetic rotation band with a configuration of $\pi g_{9/2}^2 \otimes \nu h_{11/2}^2$. Particle-rotor model calculations were also performed to interpret the rotational structures in $^{112}$In.

The quasi-elastic scattering angular distribution of the proton drip line nucleus $^{17}$F on $^{12}$C at 60 MeV

The quasi-elastic scattering angular distribution of the proton drip line nucleus $^{17}$F on a $^{12}$C target was measured at 60 MeV. The experimental data have been compared with the theoretical analysis based on an optical model and continuum discretized coupled channels (CDCC). The total reaction cross-section was deduced from the angular distribution of the quasi-elastic scattering data, and then compared with the existing data for the other weakly and tightly bound nuclei on the $^{12}$C target using a universal function. It was concluded that the breakup effect is not important for weakly bound projectiles on the light target, as also demonstrated by the CDCC analysis.

Light quark mass dependence of the D and $D_s$ decay constants

The light quark mass dependence of the D and $D_s$ meson decay constants was studied using a covariant formulation of the chiral perturbation theory (ChPT) at next-to-next-to-leading order (NNLO). Using the hard perturbative quantum chromodynamics (HPQCD) lattice results for the D (D$_s$) decay constants as a benchmark, it was shown that covariant ChPT can describe the HPQCD results better than heavy meson ChPT at both NLO and NNLO. Within the same framework, the ratio of $f_D/f_{D_s}$ was estimated to be 1.22±0.05-0.04, which agrees well with the HPQCD result of 1.226(26).

Magnetic rotation in $^{111}$In

The high spin states of indium-112 ($^{111}$In) have been investigated with in-beam γ-ray spectroscopic methods using a palladium-110(Lithium-7,5n)$^{111}$In[$^{10}$Pd(Li,5n)$^{111}$In] reaction at a beam energy of 50 MeV delivered by the HI-13 tandem accelerator at the China Institute of Atomic Energy. A level scheme with 27 newly identified g-rays and three band structures has been established and their configurations are discussed. The backbend associated with the alignment of a pair of $g_{9/2}/d_{5/2}$ neutrons has been found in the negative-parity yrast band, while the positive-parity dipole band has been assigned as a magnetic rotation band with a configuration of $\pi g_{9/2}^2 \otimes \nu h_{11/2}^2$. Particle-rotor model calculations were also performed to interpret the rotational structures in $^{112}$In.

The way to suppress hydrogen blistering in tungsten-based plasma facing materials in future nuclear fusion devices
Hong-Bo Zhou and Guang-Hong Lu, Nucl. Fusion 50, 115010 (2010).

By investigating the physical origin of hydrogen-helium interaction in tungsten based on the calculated energetic and diffusion properties using a first-principles method, it was suggested that helium (as well as other noble gas such as argon and neon) can suppress the hydrogen blistering in tungsten by the formation of a helium-hydrogen layer on the surface to block the hydrogen permeation, or the formation of a helium-vacancy complex to block the hydrogen molecule formation.

Isospin-dependent pairing interaction from nuclear matter calculations

The isospin dependence of the effective pairing interaction was discussed on the basis of the Bardeen, Cooper, and Schrieffer theory of superfluid asymmetric nuclear matter. It was shown that the energy gap, calculated within the mean field approximation in the range from symmetric nuclear matter to pure neutron matter, was not linearly dependent on the symmetry parameter owing to the nonlinear structure of the gap equation. Moreover, the construction of a zero-range effective pairing interaction compatible with the neutron and proton gaps in homogeneous matter was investigated, along with some recent proposals of isospin dependence tested on the nuclear data table.

Direct measurement of the 4.6 MeV isomer in stored bare $^{111}$Sb ions

The core-excited isomer in fully-ionized antimony-133 ($^{111}$Sb) was directly studied for the first time by applying the novel technique of isochronous mass spectrometry. The measured excitation energy was 4.56(10) MeV. The neutral-atom half-life was known to be 17 μs. This is the shortest-lived isomer measured directly with mass spectrometry techniques. The extended in-flight half-life of the bare ions in the ESR, which is due to the exclusion of the strong internal conversion, demonstrates that there should be another nuclear level above that identified from isomer-decay spectroscopy, in support of shell-model calculations. This measurement opens up a new half-life domain for storage-ring measurements.

Calculation of $\alpha$ preformation for nuclei near N=162 and N=184

The $\alpha$ preformation factor and the penetration probability were carefully analyzed for heavy and superheavy even-even nuclei. The penetration probability of an $\alpha$ cluster in the parent nucleus was calculated within the Wentzel–Kramers–Brillouin approximation. The $\alpha$ preformation factors in different shell regions were compared and it was shown that shell effects play an important role in $\alpha$ preformation. The results indicate that the deformed-subshell region at N = 162 is different from that at N = 152, and Z = 114 and N = 184 may lie in the closed-shell region.

Influence of nuclear physics inputs and astrophysical conditions on the Th/U chronometer

The production of thorium and uranium are key steps in r-process nucleo-cosmochronology. With the combination of improved nuclear and stellar data, a detailed investigation of the r-process abundance pattern in the very metal-poor halo stars has been made, based on the classical r-process approach. It was found that the influence of nuclear mass uncertainties on a thorium/uranium chronometer can approach 2 gigayears (Gyr). Moreover, the ages of the metal-poor stars HE 1523-0901, CS 31082-001, and BD +17°3248 were determined as 11.8±3.7, 13.5±2.9, and 10.9±2.9 Gyr, respectively. The results can serve as an independent check for age estimates of the universe. This work has been highlighted as “Calibrating the cosmic clock” in the Synopsis of the American physical society website.
The School of Software

The School of Software has an ideology of providing a creative educational environment to help its student to develop the necessary practical skills.

The Beihang University School of Software, founded in 2002, aims to build a top-ranking institution by fostering versatile, creative, international, market-oriented, and practically trained individuals in the field of software engineering, through the implementation of a new educational system. For the past 10 years, the school has focused on developing close cooperation with top global enterprises and encouraging internationalization. The school is highly regarded and is seen as a pioneer among software colleges in China, becoming one of the country’s most competitive schools in several areas including mobile Internet, cloud computing, Internet marketing, and SAP Enterprise Resource Planning (ERP).

Cooperation with Top Global Enterprises
The School of Software has reached levels of cooperation with international commercial enterprises that is uncommon among even the best universities around the world. In the past two years, the following collaborative laboratories have been established at the school:

- Lenovo: Mobile Cloud Computing Lab
- Lenovo: Mobile Testing & Application Adaptation Lab
- Adobe (USA): Rich Internet Applications Lab
- Research in Motion, Ltd. (Canada): Mobile Cloud Computing Lab
- Ericsson (UK): Cloud Computing Lab
- HTC (Taiwan): Cloud Computing Lab
- China Mobile Lab
- VIA Technologies, Inc. (Taiwan): Integrated Circuit Design Lab
- SAP (Germany): Enterprise Resource Planning Lab
- Sina.com: Cloud Computing Lab
- Qihu360: Cloud Computing Lab
- Microsoft (Japan): Japanese Application Software Lab
- Baidu: Baidu Internet Marketing Lab
- Linux Technology Training Center
- Advanced Micro Devices Lab (USA)
- Google Camp (USA)
- Mercury Interactive Software Quality Assurance and Testing Lab (USA)
- Graduate Remuneration

The quality of education delivered by the School of Software is reflected in the salaries of its postgraduate students. Statistics provided by the Internship & Career Center show that graduates of the school’s Master’s program receive significantly higher entry-level compensation packages than graduates of any other schools of software in China (see table) and other disciplines at Beihang University. This is independent of where the student obtained their undergraduate degree and is evidence of the quality of education and of our graduates.

Rational Risk Taking
The School of Software has an ideology of providing a creative educational environment to help its student to develop the necessary practical skills. The school invites top professionals from relevant fields to advise students on their dissertations and to lecture them on technical subjects, while teaching about the most modern technologies and success cases in the industry. Additionally, students work on projects run by enterprises in the collaborative laboratories noted above. The school encourages students to carry out high-risk projects and to establish startup companies, but in a rational manner. It fully supports innovative ideas in a multitude of ways. The following are examples of students who have put their ideas into practice.

Shanbin Gong, who is still in our Master’s program, founded 500ccc.com in January 2011 and is the president and CEO of the company. The company’s website is one of the principal e-commerce websites in China. Moreover, in late 2011, Chinese Internet giant, Tencent, made an investment of 30,000,000 yuan (US$4.71 million) in Gong’s company. At present, the market value of the business-to-consumer company exceeds 200,000,000 yuan (US$31.4 million).

Deguo Mu, a postgraduate student, founded Bejing Iyuba Technology Co. Ltd. after resigning as General Manager of the Game Business Unit at Renren Japan in October 2011. Under his guidance, 20 students in the school are now working on the development of foreign-language learning applications. With 100,000 users every day using various products for language study, Iyuba has been listed as one of the top three most popular language study websites in China. This website has emerged as a leader among language learning sites and applications such as QQ, Renren, weibo.com, and Baidu search.

<table>
<thead>
<tr>
<th>Year of Graduation</th>
<th>Number of graduates in Master’s program</th>
<th>Average monthly salary of Beihang School of Software Master’s graduates (yuan)</th>
<th>Average monthly salary for all Master’s graduates in China</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>764</td>
<td>7,347</td>
<td>4,000</td>
</tr>
<tr>
<td>2010</td>
<td>785</td>
<td>7,655</td>
<td>4,500</td>
</tr>
<tr>
<td>2011</td>
<td>1,331</td>
<td>10,215</td>
<td>5,000</td>
</tr>
<tr>
<td>2012 (expected)</td>
<td>1,800</td>
<td>11,500</td>
<td>6,000</td>
</tr>
</tbody>
</table>

*1 yuan equals ~US$0.157

Unveiling Ceremony for the RIM Lab (Canada)
Yuanpin Yang, a graduate student, cofounded jiepang.com, which remains at the top of Location Based Social network services in China, while declining an offer of a full fellowship from Carnegie Mellon University in the United States.

Chao Cui started his own software business after graduating. The products made by his company have been downloaded almost 1,000,000 times. He was awarded “The Most Valuable Star for Investment” and “The Star of R&D Team” in 2011. As a result, Chao Cui recently received investment of 4,500,000 yuan (US$700,000).

The First Cloud Computing Seminar in Fall 2011: more than 600 students have attended our Mobile Cloud Computing MSE Program, which is among the world’s largest program of its kind.

Majors
Students at the School of Software can major in one of 10 disciplines, including mobile cloud computing, SAP ERP, Internet marketing, embedded software, and Japanese software engineering. The school was the first in China to initiate these highly competitive majors.

International Communication and Collaboration
The School of Software organized a series of international seminars presented by A. C. Turing award winners Dr. Adi Shamir (April 2009, Israel), Dr. John Hopcroft (June 2009, United States), and Dr. Tony Hoare (October 2009, United Kingdom).

Needs of the State
The School of Software is honored to be an educational and training base for the Chinese Ministry of Industry & Information Technology (MIIT) and the National Development and Reform Commission (NDRC).

As requested by MIIT, the Software Department of MIIT, and the National Software & Integrated Circuit Design Center, the school has helped build the MIIT Mobile Cloud Computing Education & Training Center. The school’s dean, Dr. Wei Sun, serves as the chief scientist and is charged with the responsibility of significantly boosting education and training in the field of mobile cloud computing. In fall 2011, the school enrolled more than 600 graduate students in this major; this is the largest enrollment worldwide for this discipline.

Following government guidance to extensively develop mid- and small-size enterprises, the school has facilitated cooperation between the China Software and Integrated Circuit Platform and the company Baidu, resulting in the creation of an Internet marketing program, another first in China. The school is expecting more than 400 postgraduate students in this area.

To support the Talents Training Program in Western China, the Western Department of the NDRC authorized the school to run the project “Collaboratively Preparing Enterprise Informationalization Talents in Western China.”

Social Responsibility
Since 2008, together with Tsinghua University, the China Center for Information Industry Development, and the Zhong Qingyan Information Research Institute, the School of Software has run monthly New Era Management Seminars and published magazines bimonthly. The content of the seminars and magazines, which includes information technology, enterprise management, ancient Chinese literature, economics, finance, and innovation, has attracted audiences of about 30,000, comprising mainly those in mid-level and top management. Furthermore, the school has invited well-known researchers and even leaders of the state to give presentations. The school has raised its reputation through these activities and fulfilled its duty to serve society.

New Model of Creative Education for Undergraduates
The School of Software is developing a plan for the most talented undergraduate students known as the Software Pioneer Class, a group of 20–30 students chosen annually. The school will establish a scholarship of 150,000 yuan (US$23,560) for each candidate, and make arrangements for executives of large IT companies to be their advisors, thus preparing future leaders in this area.

Mr. Li Yi (second from right), deputy standing member and chief secretary of the China Mobile Internet Industry Union, was made a professor of the School of Software in May 2012.
The School of Humanities and Social Sciences
(School of Public Administration)

The School of Humanities and Social Sciences (SHSS; also known as the School of Public Administration) at Beihang University was established in 1997, growing out of the original Department of Public Administration, Department of Social Science, and Institute of Higher Education. It is one of the first schools established in China that teaches public administration and that offers a Master of Public Administration (MPA). The school now has 74 faculty members whose research includes public administration and policy, higher education, economics, environmental governance and policy, social management, and science and technology policy. In addition to four teaching units—the Department of Public Administration, Department of Economics, Academy of MPA Education, and Center of Culture and Art Education—the school also boasts 12 research units, including the Institute of Higher Education (IHE), Workshop for

Environmental Governance and Sustainability Science (WEGSS), Institute of Safety, Security and Emergency Management (ISSEM), and Institute of Anti-Corruption (IAC).

SHSS offers three doctoral degree programs (public administration, educational economy and management, and generalized virtual economy management), eight Master’s degree programs (public administration, education economics and management, social security, education, industrial economics, national economics, philosophy of science of technology, and applied psychology), one MPA program, and three undergraduate programs (public administration, economics, and Chinese language). These programs are recognized for their variety, quality, innovation, and international focus.

In 2002, the academic direction of the school was reassessed and the decision was made to focus on the study of public administration, using a combination of methods including qualitative and quantitative analyses, as well as historical data. Research fields in which SHSS particularly excels are higher education in engineering, security and emergency management, environmental governance and policy, and anticorruption. These research programs are being carried out as follows:

(i) Research at IHE focuses on the theoretical and empirical problems in the policy and management of high-level education and training for engineers within the mass education system in China.

(ii) ISSEM is devoted to studying the theory and practice of safety, security and emergency management, especially on large public projects in modern-day China.

(iii) The mission of WEGSS is to promote the interdisciplinary study of ecological, environmental, energy problems, as well as other governmental, corporate, and social governance problems related to sustainable development and the development and practice of sustainability science as it relates to policy and institutionally relevant applications.

(iv) IAC is devoted to anticorruption research and education and to providing feasible policy recommendations to all levels of government and nongovernment public sectors.

These studies provide leadership and direction for the school, whose aim is to build a world-class public administration school in China.

For more information: www.hss.buaa.edu.cn
The School of Political Science

The School of Political Science (SPS) was founded on December 26, 2008. Its origins date back to the Politics Teaching and Researching Office established in 1953. The school now has 18 full-time faculty members, including two professors and eight associate professors, while many domestic and foreign visiting experts work as part-time professors and researchers. Twelve of the full-time teachers on staff have Ph.D. degrees.

The school consists of five teaching and research sections: the Basic Tenets of Marxism, Contemporary Marxism in China, Modern History of China, Ideological & Moral Cultivation and Basics of Law, and Political Theory Courses for Postgraduates; and four research centers: the Chinese Marxism Research Center, the Ideological and Political Education Research Center, the National Conditions Research Center, and the Cross-cultural and Innovative Development Research Center. Two Master’s degrees are conferred, in Marxist theory (primary discipline) and the philosophy of Marxism (secondary discipline). SPS also has a research base named the Communist Party of China (CPC) Construction Capital Colleges Research Base that undertakes the study of the leadership of the CPC, the creativity of the CPC’s grassroots organizations, and the prevention of and penalties for corruption in colleges and universities. The school provides the ideological and political theory courses for all of the school’s undergraduates, postgraduates, and doctoral students, and also offers courses in philosophy, religion, history, and politics to the students of College and University Teaching Community, XueYuan Road Zone. All teachers are committed to high-quality curricula and student training, and have received several national and provincial teaching awards.

In recent years, the faculty has presided over more than 50 national, provincial, and Beijing municipal level social science projects. Additionally, teachers have undertaken a wide range of teaching work, actively engaged in scientific research, and published almost 100 papers in top journals, such as those found in the Chinese Social Sciences Citation Index.

SPS attaches great importance to international academic exchange. In recent years, the school has sent a number of teachers to the United States, United Kingdom, Canada, Japan, Singapore, and New Zealand as visiting scholars. At the same time renowned international experts have also visited the school. Cooperative relations with the East Asian Institute at the National University of Singapore and at other academic institutions have also been established. We sincerely welcome experts interested in education, philosophy, history, politics, and religion.

For more information: ipth.buaa.edu.cn

The School of Law

Beihang Law School (BLS), established in 2002, is one of the best-known law schools among the more than 600 in China. BLS has 52 full-time academic and administrative staff, including 45 faculty members (10 of whom are doctoral supervisors), 13 full professors, and 17 associate professors.

Recognizing excellent education as a central goal, the school has over 500 students taking advantage of a comprehensive educational structure with Bachelor of Laws (LLB), Master of Laws (LLM), LLB dual degree, Juris Master, and Doctor of Laws (LLD) programs. BLS emphasizes not only proficiency in legal theory, but also high-tech knowledge in aeronautics and astronautics, and information technology, as well as demonstrable abilities in the practice of law. The students have won several important awards in international and domestic contests, including the Best Oralist in the 2010 First Annual IDEA China Open Moot Court and the first prize in the National Challenge Cup in 2011.

The school has built an integrated educational structure with special emphasis on key disciplines. It has seven research centers, three teaching centers, and seven research institutes specializing in high-tech related laws. In January 2012, the BLS held an inauguration ceremony for the National Research Center of Air Traffic Management Law and Standards, which is operated by the Law School and sponsored by the State Air Traffic Control Commission of China. This is the first national think tank in this field in China. In 2012, the Law School established a Legal Education and Practice Base funded by the Ministry of Education.

For more information: fxy.buaa.edu.cn
The School of Foreign Languages

The history of the School of Foreign Languages (SFL) is one of dedication and commitment by a team of remarkable people who set up and nurtured what has now developed into one of the top institutions in China for foreign language teaching and research. The school, which grew out of the Foreign Languages Department (1977–2007), began enrolling undergraduates in 1978 and graduate students in Linguistics and Applied Linguistics in 1985. It was one of the first institutions in China to offer such programs. With the approval of the Ministry of Education, in 2010 the school began offering doctoral programs in all fields related to Foreign Languages and Literature.

The faculty at FSL includes more than 100 scholars working at the forefront of linguistic, literary, and translation studies in a professionally oriented research environment. They support a vigorous academic community dedicated to the success of its students and to the advancement of research.

The school has all the advantages that a nation’s prestige university can have—a wide range of excellent undergraduate and postgraduate programs, and a variety of faculty and research disciplines to cater for the needs of any individual student.

FSL’s full degree programs (Bachelor’s, Master’s, and Ph.D.) feature the application of computer technology in language and translation teaching and research, corpus-based linguistic studies and translation studies, cognitive linguistics, and rhetoric and communication. Labs are open to both faculty and students interested in corpus-based linguistic research, computer-aided translation research, and language teaching research.

The School of Foreign Languages offers many options for language- and culture-related study and research through the following nine departments and divisions:

- Department of Applied English
- Department of English Literature
- Department of German Studies
- Department of Linguistic Science and Engineering
- Department of Rhetoric and Communication
- Department of Russian Studies
- Department of Translation and Interpretation
- Division for Teaching English as a Second Language (non-English major postgraduates)
- Division for Teaching English as a Second Language (non-English major undergraduates)

An array of programs is provided by the abovementioned departments and divisions, allowing students to customize their course schedules based on individual needs as they strive to achieve their professional goals.

The school has close ties with the international community. Its strategic partners are worldwide, including leading universities in Australia, Germany, Russia, the United Kingdom, and the United States. Every year, both faculty and students benefit from many of the school’s exchange programs, joint research projects, and summer school programs.

For more information: fld.buaa.edu.cn

Professor Xiang Mingyou, dean of the English Department signs a memorandum of understanding with Professor David Kaufer, head of the Department of English at Carnegie-Mellon University, Pittsburgh in the United States.

The faculty at FSL includes more than 100 scholars working at the forefront of linguistic, literary, and translation studies in a professionally oriented research environment.
CHAPTER 16

The Beihang Institute of Advanced Studies in Humanities and Social Sciences

The Beihang Institute of Advanced Studies in Humanities and Social Sciences (BHIASHSS) was established in November 2010 in response to a new round of higher education reform. To support competitive liberal arts programs and to further the goal of exploring innovative methods to reform and develop high-quality education in the liberal arts, the institute focuses on integrating liberal arts education into specialized education as well as cultivating the talents of the top students to help them become future leaders who are well-versed in both Chinese and Western culture. With the encouragement and assistance of the other related faculties and institutes, the BHIASHSS strives to strengthen the entire university as well as to promote its influence in various disciplines in the humanities and social sciences.

The institute is led by a board of directors, but the Dean assumes overall responsibility for its mission. The current chief director is Jinping Huai, also President of Beihang University, while Quanxi Gao, a prestigious jurist and political philosopher, is Dean. BHIASHSS consists of five research institutes—the Institute of Jurisprudence, the Institute of Finance and Economics, the Institute of Politics and International Relations Studies, the Institute of Sociology and Public Policy, and the Institute of Classics—and a Center for International Cultural Communications, as well as the Zhixing Experimental Classes in Liberal Arts. The institute provides the opportunity for outstanding academic talent to be engaged in liberal arts education and studies in the humanities and social sciences.

BHIASHSS provides a four-year undergraduate course. In the first year, general education focusing on classic Chinese and Western readings is offered. In the second year, primary interdisciplinary education is given, concentrating on three disciplines: politics, economics, and jurisprudence. In the third and fourth years, professional education in politics, economics, and jurisprudence is emphasized. Top experts and scholars from Peking University, Tsinghua University, Renmin University of China, and the Chinese Academy of Social Sciences, amongst others, are invited as lecturers to conduct the teaching. The core courses are given in small classes, with an assistant professor present in each class to help students individually. The institute makes every effort to enrich its teaching resources and plans to establish a complete educational system for Bachelor’s, Master’s, and doctoral degrees in the next three to five years.

BHIASHSS also hosts such various annual academic activities such as lectures, seminars, forums, study groups, and workshops. It is dedicated to furthering broad, multilevel academic communication and cooperation with universities overseas through academic summer camps, student exchanges, study visits, and joint education programs.

For more information: gyy.buaa.edu.cn, boguan.buaa.edu.cn
BUAA Sino-French Engineer School
(École Centrale de Pékin)

With the support of both the Chinese and the French governments, Beihang University (BUAA) and Groupe des Écoles Centrales (GEC) jointly founded the Beihang University Sino-French Engineer School (École Centrale de Pékin, ECPk). This first international engineering college in China combines the model of French engineering education with the considerable resources of Beihang University higher engineering education to cultivate high-level international general engineers.

The educational model of ECPk is recognized as a paradigm of Sino-French cooperation on education by the governments of both countries. François Fillon, the former French Prime Minister, visited ECPk and spoke highly of its achievements. Laurent Fabius and Jean-Pierre Raffarin, together with administrators and ambassadors of both countries, also visited ECPk. In 2010, the school received the honor of being included in the Excellent Engineer Training Program of the Ministry of Education of China.

ECPk started recruiting students in September 2005 and, in 2011, its pioneering group of graduating engineers was the first in China with a French/European engineering diploma (EUR-ACE). The students of ECPk have solid foundations in mathematics and physics, multidisciplinary engineering, comprehensive practical and training experience, trilingual capabilities (Chinese, English, and French), and a multicultural sensibility. ECPk has established an innovative enterprise partnership system and currently collaborates with thirteen top-level enterprises both domestically and abroad, including COMAC China, TOTAL, Schlumberger, and the European Aeronautic Defense and Space Company.

ECPk has established broad cooperation in science and technology in the years since its launch. For example, since 2007 BUAA and GEC have organized an annual scientific workshop aimed at increasing the research collaboration in the fields of mechanics, material, automation control, and information science. This collaboration was pivotal in the founding of the International Associated Laboratory in Mechanics, Material, Control and Information Science (LIA 2MCSI) in 2010 as a common laboratory for supporting joint research projects between BUAA/National Laboratory of Aeronautics and Astronautics, China (NLAA) and GEC/Centre National de la Recherche Scientifique, France (CNRS). To date, the LIA 2MCSI has supported 25 joint research projects.

During the 5th workshop on Sino-French technology cooperation held at BUAA in 2011, the establishment of the Chinese Alliance for Sino-French Science and Technology Cooperation was proposed. The new alliance—currently led by BUAA—is now a reality, with 29 sponsors including six top-level universities, 16 research institutes, and seven companies. The areas of focus include aeronautics and astronautics, information technology, life sciences, and new energy.

Since 2010, ECPk formed its own research groups and laboratories focused in three domains: information science, material science, and applied mathematics. These research group and laboratories have developed strong collaborations with French research establishments. The information science research team participated and played an important role in the Chinese national “863” program research project “Smart City,” which aims to study the future of advanced information technologies in the next generation of intelligent city. The research in the materials laboratory focuses mainly on fluorinated nanocarbon materials and their use as solid lubricant or electrode components for primary lithium-carbon monofluoride batteries. The materials laboratory conducts fundamental research, supported by the National Natural Science Foundation of China, as well as having industry contacts to develop advanced next generation batteries using fluorinated carbon materials. The applied mathematics laboratory is a multidisciplinary research and collaboration laboratory whose interests span fluid mechanics, numerical simulation of differential equations, symbolic computation, and algebraic biology.
Beihang University is a multidisciplinary, research-oriented university of engineering science and technology with an emphasis on aeronautical and astronautic engineering. Beihang University was the first university dedicated to the study of aeronautical and astronautic engineering in China and one of the first universities to be funded by the “211” and “985” programs.

Beihang University has distinct advantages in many research areas such as aviation, aerospace, jet propulsion, information science, materials science, mechanics, transportation science, instrumentation science, and management science. Its primary national leading academic disciplines rank seventh in China. Beihang University has seven National Key Laboratories and twenty-five Provincial and Ministerial Key Laboratories. The National Aeronautical Science and Technology Laboratory, built in 2006, is a prime example of the emphasis that this research-oriented university places on the study of aeronautic and astronautic engineering. Beihang University boasts a large number of renowned scientists and professors, including 17 members of the Chinese Academy of Sciences and Chinese Academy of Engineering, 14 scholars in the National Recruitment Program of Global Experts, 41 Professors in the Chang Jiang Scholars Program, and 31 recognized by the National Science Fund for Distinguished Young Scholars.

During the 11th Five-Year Plan, Beihang University undertook 16 national “973” and 336 national “863” programs. The university is ranked among the top five Chinese universities in per capita funds raised for scientific research. Beihang University has been awarded 28 national prizes. It is remarkable that four research projects have won the 1st Prize National Technology Innovation Award and another three have won the 1st Prize National Science and Technology Progress Award—the most national top prizes for science and technology received by any Chinese university in the past seven years.

Beihang University aims to become a world-class university in the aeronautics, astronautics, and information technology fields. It continuously pursues the support and generation of the highest quality research talent and is devoted to creating an environment that nurtures and promotes excellence in science and engineering innovation.

Beihang University sincerely invites qualified researchers to join it in creating a glorious future for Beihang University!

**Types of Positions Available**

- Position offered by the Recruitment Program of Global Experts (One Thousand Talents Program)
- Position offered by the Chang Jiang Scholars Program
- Position offered by the Recruitment Program of Global Young Experts (One Thousand Young Talents Program)
- Position offered by Beihang University’s Zhuoyue Program of Professors
- Position offered by Beihang University’s Zhuoyue Program of Associate Professors

**Disciplines and Specialties Sought**


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