MATTER

An interdisciplinary study of matter and materials in their various forms, covering areas from synthesis to processing and fabrication, from properties evaluation to modification, and from design to applications.

Breakthrough in High-strength but Ductile Ordered Intermetallic Alloys

The strength-ductility trade-off has always been a dilemma in materials science. The higher the strength of a material, the less the ductility and toughness, meaning that strong materials tend to be less deformable or stretchable without fracture. **Professor Liu Chain-tsuan**, University Distinguished Professor in the College of Engineering and Senior Fellow of the Hong Kong Institute for Advanced Study (HKIAS) at CityU, together with his team member **Dr Yang Tao**, Assistant Professor in the Department of Materials Science and Engineering, has developed a novel alloy design strategy to overcome this challenge, paving the way for fabricating materials for operating in extreme temperatures and aerospace systems.

"Most conventional alloys comprise one or two major elements, such as nickel and iron," Professor Liu explained. "However, by adding aluminium and titanium to form massive precipitates in an iron-cobalt-nickel (FeCoNi)-based alloy, we found a significant increase in both strength and ductility."

In the prestigious scientific journal *Science*, they reported that their high-entropy alloy had a superior strength of 1.5 gigapascals, which is five times stronger than FeCoNi based-alloys, and had ductility as high as 50% in tension at ambient temperature.

They also found that adding multicomponent intermetallic nanoparticles can greatly enhance plastic deformation stability, avoiding the common problem of early necking fracture.

Professor Liu believed this innovative strategy would allow the development of alloys that can perform well in temperatures ranging from -200°C to 1000°C, thus providing a good base for developing new cryogenic devices, as well as aircraft and high temperature systems, such as aeronautical engineering applications.

In their other research also reported in *Science* recently, they revealed a new way to resolve the strength-ductility trade-off effectively by forming disordered nanoscale layers at grain boundaries in ordered intermetallic alloys.

By adding 1.5 to 2.5 atomic percent of boron to an intermetallic alloy, they found that distinctive nanoscale layers were formed between the orderly packed grains in the alloy. "This serves as a buffer zone between

The new high-entropy alloy is extremely strong but ductile.

adjacent grains, which enables plastic-deformation extensively at the grain boundaries, resulting in the large tensile ductility at an ultra-high yield strength level," said Dr Yang, who is the first author of the research.

With nanolayers formed at the grain boundaries, the alloy showed an ultra-high yield strength of 1.6 gigapascals, with tensile ductility of 25% at ambient temperature. It also maintained the alloy's strength with excellent thermal stability at high temperature.

"The discovery of this disordered nanolayer in the alloy will have an impact on the development of high-strength materials in the future, such as structural materials for applications in high-temperature settings, like aerospace, aeronautics, nuclear power and chemical engineering," said Professor Liu.

Professor Liu, Dr Yang and the team will continue to work on ultra-high strength steels, multicomponent high-entropy alloys, lightweight materials, and nanostructured materials for various applications.

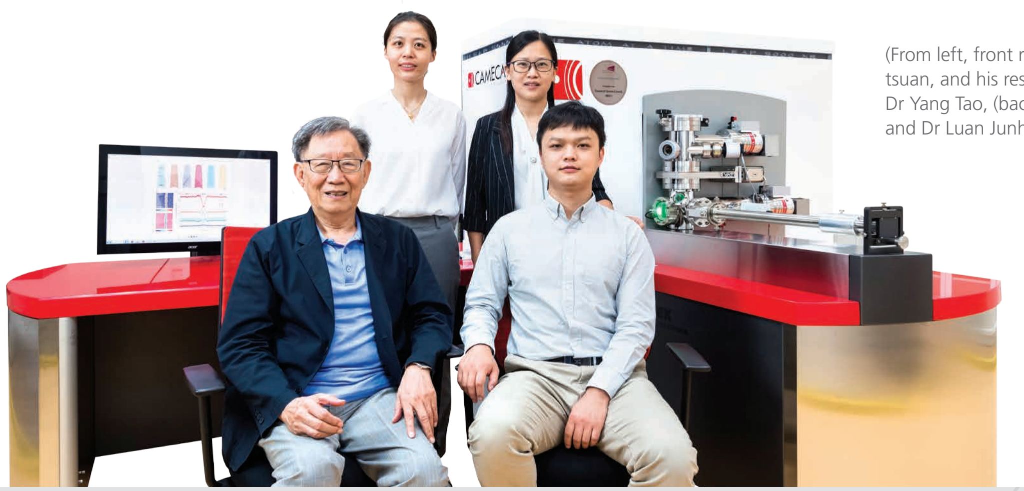
Major Award

Professor Liu Chain-tsuan

- The President's Award 2020, CityU

Key Projects

- General Research Fund:
  - Alloy Design of Novel L12-Type High-Entropy Intermetallic Alloys (HEIAs) for Advanced Structural Applications
  - Plastic Deformation Stability and Hardening Behavior of Complex High-entropy Alloys (HEAs) with Innovative Multi-component Nanoparticles



(From left, front row) Professor Liu Chain-tsuan, and his research team members Dr Yang Tao, (back row, from left) Dr Zhao Yilu and Dr Luan Junhua.

Selected Publications & Patents

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- Jiao, Z.B. & **Liu, C.T.**, "銅リッチナノクラスター強化超高強度フェライト鋼およびその製造方法", Japan patent 6584961, granted 2019.
- Jiao, Z.B. & **Liu, C.T.**, "ナノ金属間化合物強化超高強度フェライト鋼およびその作製方法", Japan patent 2019-11536, filed 2019.

Professor Lu Jian (left), Dr Liu Guo and the research team have developed the world's first-ever 4D printing for ceramics.

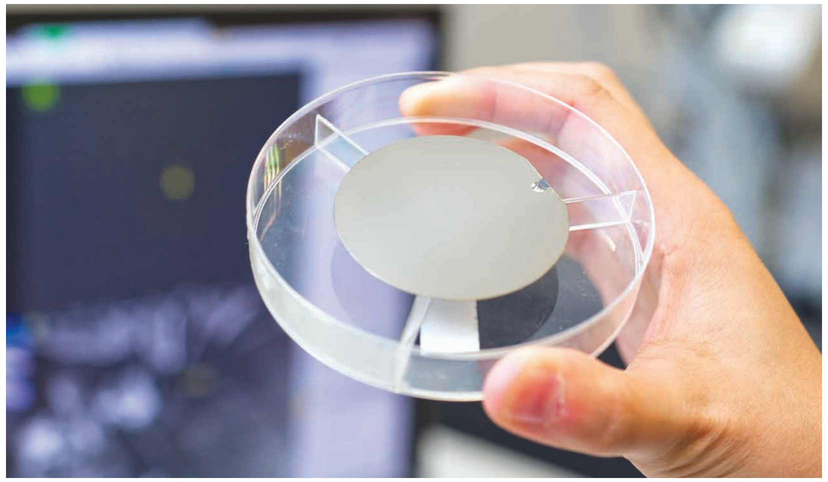
Scientific Advances in 2D/3D/4D Additive Manufacturing

Fabricating materials with complex shapes and desirable properties for various applications has long been a focus of materials scientists and engineers. A leading expert at CityU, who developed the world's first supra-nano-dual-phase alloy and four-dimensional (4D) ceramic printing, is working on integrating these two cutting-edge technologies to fabricate lightweight, high-strength metallic materials for biomedical and aerospace applications.

3D printing technology, also known as additive manufacturing, has been widely used to fabricate components with complex shapes at low cost in the manufacturing, construction, biomedical and aerospace industries. However, some applications still face limitations. For example, the 3D-printed metallic materials commonly used as moving parts in medical implants have insufficient fatigue and wear resistance, which may eventually lead to the need for a second surgery to replace the implants.

Integrating two cutting-edge technologies

Professor Lu Jian, Chair Professor of Mechanical Engineering at CityU, and Director of the Hong Kong Branch of National Precious Metals Material Engineering Research Center and the Centre for Advanced Structural Materials, is an expert in the mechanical properties of metallic and ceramic materials. He is leading a team to develop a pioneering 2D/3D/4D additive manufacturing system to fabricate metallic-based materials with desired mechanical properties for different applications.



Supra-nano-dual-phase magnesium alloy

"It is worthwhile integrating our two technologies – dual-phase nanostructuring and 4D printing – to explore any extraordinary mechanical properties or metamaterial properties that may emerge," said Professor Lu, who is also the Director of the Joint Laboratory of Nanomaterials and Nanomechanics, established by the Institute of Metal Research (IMR) of the Chinese Academy of Sciences and CityU.

Earlier, he led the team that successfully developed the first-ever supra-nano-dual-phase magnesium alloy. By using dual-phase nanostructuring technology, the team overcame the limitation of existing structural materials: high strength and high ductility cannot coexist. The new cutting-edge material developed by the team is 10 times stronger than conventional crystalline magnesium alloy and has super-deformation capacity two times higher than that of magnesium-based metallic glass. The findings were reported in the prestigious scientific journal *Nature*.

They also invented the world-first 4D printing of ceramics. The 3D-printed ceramic precursors can re-shape by themselves over time with the elastic energy stored in the stretched precursors. And the fabricated ceramics are mechanically robust with high specific strength.

Fabricating ideal implant materials

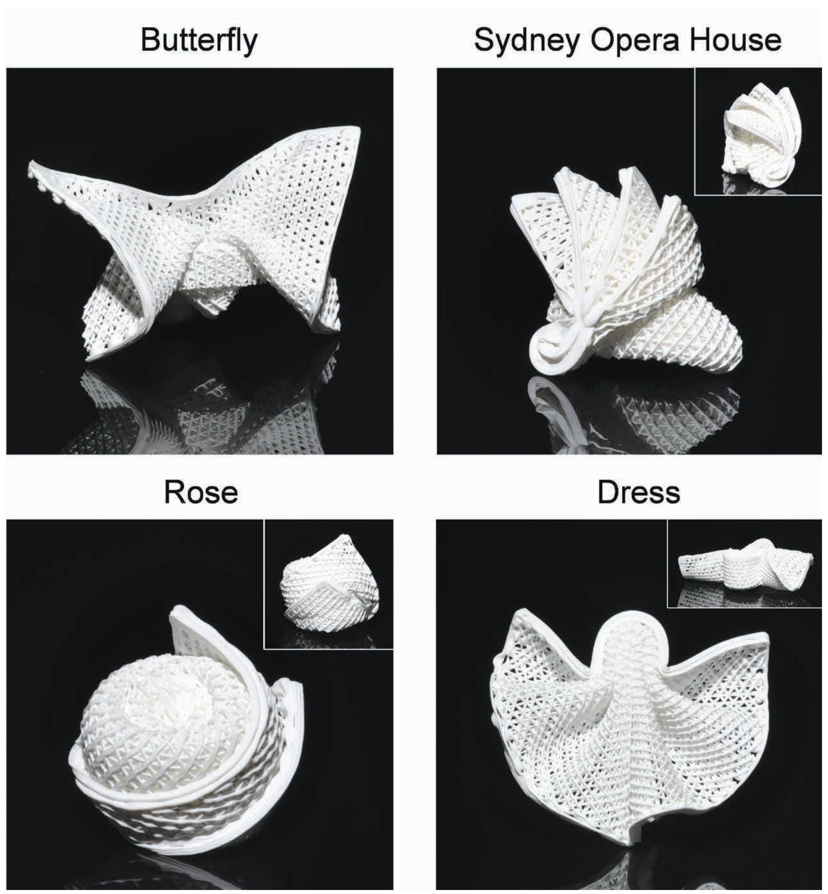
In this project, they will first develop a 2D/3D/4D manufacturing system to fabricate metallic-based materials with complex shapes, particularly those used in biomedical and lightweight structure applications. Since titanium-based alloys are considered the ideal implant material for clinical use, the team will first focus on fabricating supra-nano 3D-printed titanium-based alloy and examine its mechanical properties.

"By applying our knowledge and know-how gained in inventing the 4D printing technique, fabricating supra-nano materials, and producing surface nanostructured materials, we will further treat the 3D-printed titanium-based alloy and other metallic materials to enhance their mechanical properties. We hope to develop lightweight metallic materials with high strength and wear resistance for the medical implant and aerospace industries," said Professor Lu.

In particular, they will study the effect of post-treatment, such as Surface Mechanical Attrition Treatment (SMAT) to enhance fatigue resistance, and Physical Vapour Deposition to enhance wear resistance, on the mechanical properties of the printed materials. SMAT is a surface nano-crystallisation technology, which was first introduced by Professor Lu and **Professor Lu Ke**, Director of IMR. It involves the use of hundreds of small hard balls, which are vibrated using high-power ultrasound, so that they hit the surface of a material at high speed to enhance damage-tolerance in metallic alloys.

Biosensors for health

They aim to build up a database of 3D-printed metallic materials, with details about their mechanical properties, microstructure, treatment process and potential applications. "The database will be of great assistance to materials researchers and engineers for their research in developing more new materials and for exploring new applications," said Professor Lu. "We hope it can help facilitate the application of metallic materials in different fields, thus benefiting all of society."



The 3D-printed ceramic precursors are soft and stretchable, enabling ceramics with complex shapes, such as origami folding mimicking the Sydney Opera House.

Besides 3D printing technology, Professor Lu and his team have worked on functional metallic materials, particularly their newly developed biosensing technology based on ultrasensitive surface enhanced Raman spectroscopy (SERS). This technology can be applied in various areas, such as antibiotics detection, and food and cosmetics product safety. They are working on the feasibility of applying it in the fast detection of Covid-19, cancer and cardiovascular diseases, as well as the non-invasive detection of diabetes.

The SERS biosensing technology can be used to test contaminants in food and cosmetics.

Major Awards

- Silver Medal, 47th International Exhibition of Inventions Geneva, 2019
- The 12th Guanghua Engineering Science and Technology Award, 2018
- French Knight of the National Order of Légion d'Honneur (Chevalier de la Légion d'Honneur), 2017

Key Projects

- General Research Fund:
  - Study the Plastic Deformation Mechanism and Thermal Stability of Ultra-strong/Ductile Nano-dual-phase Alloys
  - Study the Wear and Corrosion Resistances of Ultra-Strong/Plastic Mg-Based Supra-Nano-Dual-Phase Materials
  - Development of High Strength and High Ductility Micro-alloyed Gold by Inducing Gradient Nanostructures
- Collaborative Research Fund: Joint R&D of Magnesium-based Orthopaedic Implants
- Theme-based Research Scheme: Functional Bone Regeneration in Challenging Bone Disorders and Defects
- Joint Laboratory Funding Scheme: System for 2/3/4D Additive Manufacturing of Supra-nano Metallic Materials for Biomedical and Lightweight Structure Applications
- Areas of Excellence Scheme: Aging, Skeletal Degeneration and Regeneration

Selected Publications & Patents

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- Chen, A.Y., Zhu, L.L., Sun, L.G., Liu, J.B., Wang, H.T., Wang, X.Y., Yang, J.H. & **Lu, J.** 2019, "Scale law of complex deformation transitions of nanotwins in stainless steel", *Nature Communications*, vol. 10, no. 1.
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- **Lu, J.** & Liu, G., "System and method for four-dimensional printing of ceramic origami structures", US patent US10,377,076, granted 2019.
- **Lu, J.** & Wu, G., "Metal material and a method for use in fabricating thereof", US patent US10,428,418, granted 2019.

Understanding Complex Materials through Neutron Scattering

Breakthroughs in materials development, which are essential for advances in technology, are based on scientists' understanding of material structure and dynamics. Neutron scattering is one of the most powerful techniques for exploring the nature of materials. At CityU, an expert in neutron-scattering measurements has applied this state-of-the-art experimental technique to find out the deformation and transformation behaviours in complex materials, in particular at ultra-low temperatures, opening up a new area of materials research.

"Neutron scattering is like a giant microscope," explained **Professor Wang Xunli**, Chair Professor and Head of the Department of Physics, and also a Fellow of the Neutron Scattering Society of America. "It can reveal the structure and dynamics of a material, such as how the atoms are packed and how they move, thus enhancing our understanding of a material's properties. It can be applied to physics, chemistry, biology, biomedical science, materials science and engineering."

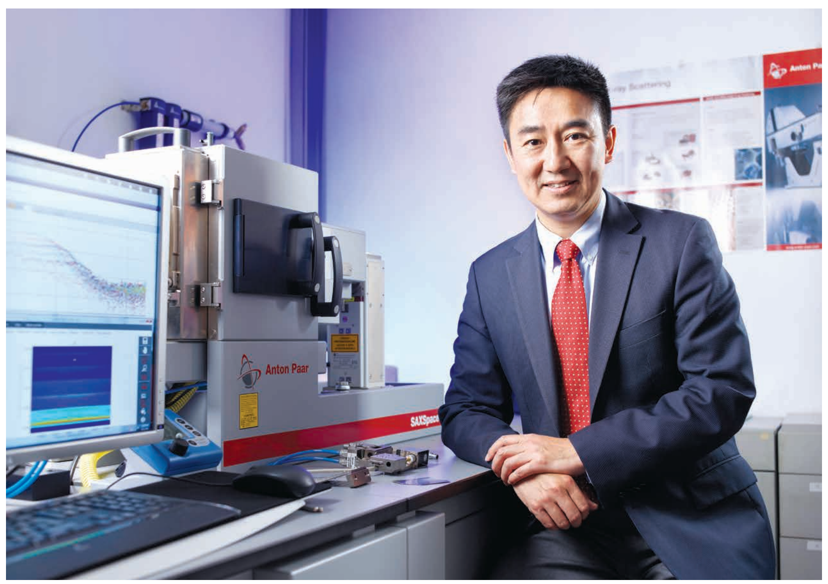
A giant microscope for materials

Neutrons are uncharged particles, so they can easily pass through material. The ways in which they bounce off a material and scatter provide scientists with important information about the material's structure and properties.

For example, experimental studies on the physical properties of amorphous materials have been very difficult owing to their disordered atomic arrangement. But using the neutron-scattering technique, Professor Wang led an international research team to overcome this challenge, and measured the atomic dynamics in zirconium-copper-aluminium metallic glass. They demonstrated the existence of high-frequency transverse phonons in metallic glass for the first time. Their findings have provided new insight into understanding the atomic structure-dynamics relationship in disordered materials.

Unveiling HEA deformation at ultra-low temperature

With the neutron-scattering instrumentation, Professor Wang and his team also discovered that high-entropy alloys (HEAs), a new class of structural materials consisting of multiple principal elements, exhibit exceptional mechanical properties at ultra-low temperatures owing to the coexistence of multiple deformation mechanisms. They revealed the sequence of deformation mechanisms in HEAs at ultra-low temperatures for the first time, opening up new terrain that very few have examined.



Professor Wang Xunli

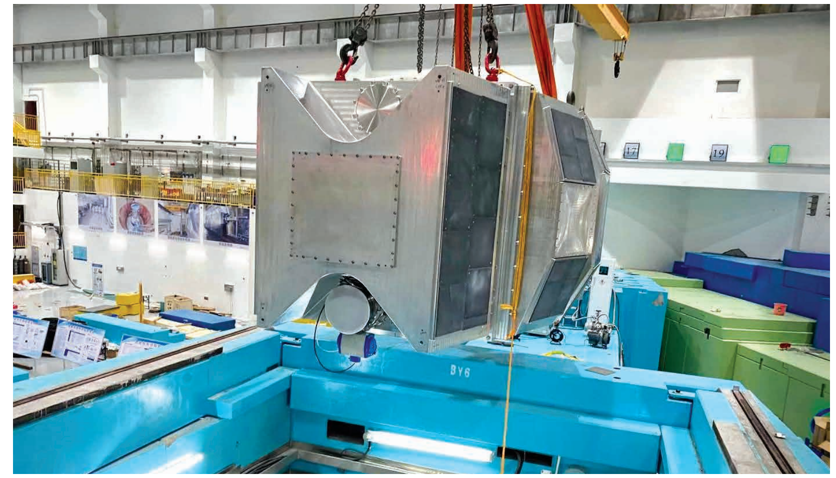
Professor Wang was awarded the Croucher Senior Research Fellowship 2021 and will use the grant to conduct an *in situ* neutron diffraction study to pursue his research on phase transformation and deformation behaviours in HEAs at ultra-low temperatures.

Advantage of close proximity to a neutron source facility

Riding on Hong Kong's proximity to the China Spallation Neutron Source (CSNS), Professor Wang has dedicated his efforts to establishing Hong Kong as a hub for neutron-scattering science in the region.

"The CSNS is one of the largest national scientific facilities in China and is situated in Dongguan, which is about a two-hour drive from Hong Kong. It offers tremendous opportunities for researchers in Hong Kong and the region," he explained. "Since there are only four neutron sources in the world, there is huge demand to use the facility for experiments and research."

Therefore, he and his collaborators have supported the construction of a multiphysics instrument (a total scattering diffractometer) at the CSNS, with the support of the Collaborative Research Fund (CRF), in exchange for dedicated access to a suite of instruments there. "This will greatly enhance education and research activity in Hong Kong and encourage the rapid growth of a strong user community," he said.



The multiphysics instrument supported by Professor Wang's CRF project being installed in the CSNS.

Promoting neutron-scattering research

Professor Wang and **Professor Chen Hesheng**, of the Institute of High Energy Physics of the Chinese Academy of Sciences (CAS), co-founded the Joint Laboratory on Neutron Scattering at CityU, with sponsorship from the CAS and the Croucher Foundation, to carry out a variety of cutting-edge research projects. Supported by Joint Laboratory Funding from the University Grants Committee, Professor Wang and his collaborators are developing an isotope labelling platform for functional materials, which will enable precise structure identification at the CSNS. The project aims to enhance the research infrastructure of Hong Kong laboratories, utilising the neutron source at CSNS to study structural and energy materials.

Previously, with the support of the Croucher Foundation, Professor Wang started the biennial Croucher Summer Course on Neutron Scattering. "I enjoy the interaction with young researchers from different backgrounds," he said. "By boosting collaboration between the Hong Kong scientific community and the CSNS and nurturing more scientists to work in neutron scattering, we hope Hong Kong can benefit from the enhancement of this science and technology research."

Major Awards

- Croucher Senior Research Fellowship 2021
- Elected Fellow, Neutron Scattering Society of America, 2020
- Lee Hsun Lectureship, Chinese Academy of Sciences, 2018
- Elected Fellow, American Association for the Advancement of Science, 2017

Key Projects

- Croucher Senior Research Fellowship: *In Situ* Neutron Diffraction Study of Competing Deformation Mechanisms in High Entropy Alloys
- Collaborative Research Fund: Hong Kong's Participation at the China Spallation Neutron Source
- Joint Laboratory Funding Scheme: Isotope Substitution to Enable Precise Structure Determination at China Spallation Neutron Source

Selected Publications

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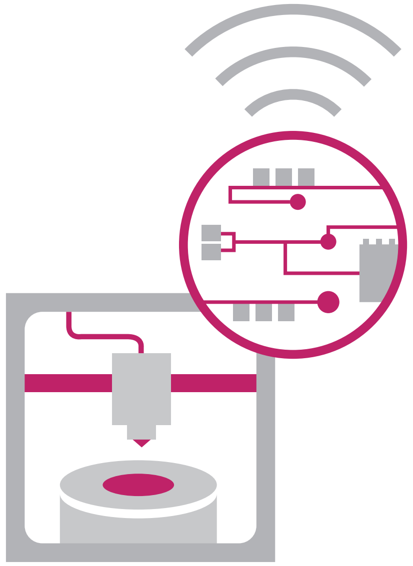
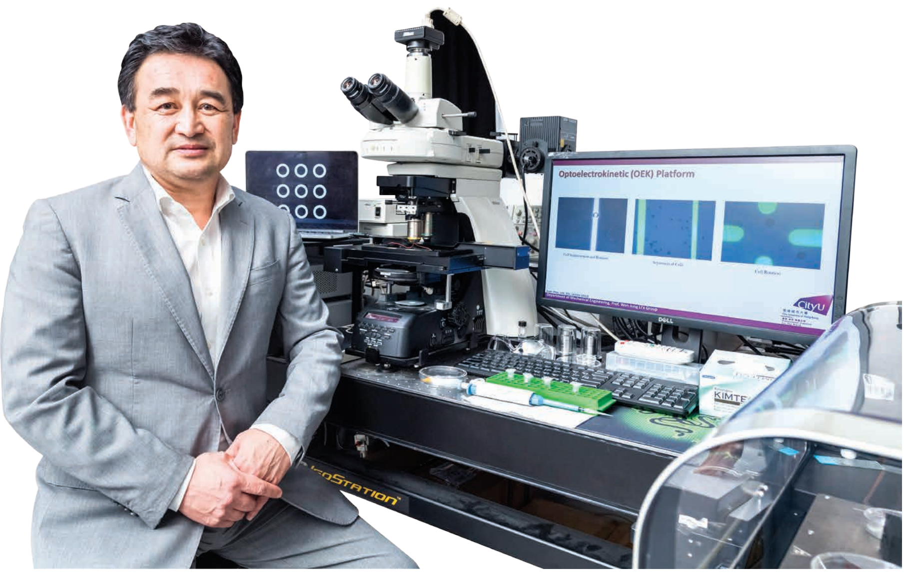
Advancing Sensing and Robotic Actuation Technology





Professor Li Wen Jung uses MEMS technology to fabricate microfluidics chips that can identify stomach cancer cells.

To take sensing and robotic actuation technologies to new heights and application domains, a collaborative research team at CityU is working on developing next-generation three-dimensional (3D) sensing systems and 4D robotics actuators for applications in digital healthcare, medical robotics and extended reality.

Professor Li Wen Jung, Chair Professor of Biomedical Engineering and Director of the Joint Laboratory for Robotic Research (JLRR), which was established by the Shenyang Institute of Automation, Chinese Academy of Sciences (SIACAS) and CityU, specialises in developing micro-electromechanical systems (MEMS) and various micro-, nano- and bio-sensing and robotics technologies.

MEMS is a process technology used to create tiny integrated devices that combine mechanical and electrical components. Ranging in size from a few micrometres to millimetres, these devices or systems can sense, control and actuate on a micro scale with high sensitivity and extreme accuracy, and generate effects on the macro scale. Based on integrated circuit technology, the batch fabrication capacity of MEMS devices enables low per-device production costs.

Fabricating sensors for health applications

Currently MEMS is widely used in applications such as actuators in inkjet printer nozzles, crash air-bag accelerometers in automobiles, projection display chips, optical switches, and blood pressure sensors. "In particular, micro-, nano- and bio-sensors are very important for digital and tele-medicines," said Professor Li. "Doctors can use many different physiological sensors to conveniently monitor their patients. And all these sensors are based on MEMS fabrication technology in one way or another."

His team has employed this widely used technology to fabricate a number of sensors for healthcare applications. One of their ongoing projects involves using flexible smart-skin sensors to decipher the correlation of a patient's arterial pulse with kidney disease progression. They also deployed MEMS to fabricate microfluidics chips that separate and identify cancer cells and stem cells, contributing to the early diagnosis of diseases and biomedical science research.

One of their current research focuses involves leveraging the latest additive 3D nano-printing technology to develop next-generation 3D sensing and 4D robotic actuation systems.

"Additive 3D nano-printing technology can integrate complex geometric features, compact electronic circuits and many new functional materials into flexible or rigid polymers, enabling the design of novel single or multi-material micro/nano sensors and actuators to have features at multiple length-scales," explained Professor Li.

Leveraging multi-material 3D nano-printing

Using an advanced 3D nano-printing system that can produce multi-layered nano-material-based structures and 3D circuitry in the JLRR at CityU, Professor Li and his team are developing flexible skin-sensors for integrating with assistive robots for the elderly, and for producing tactile sensors to enhance extended reality-based education in Hong Kong.

They will also modify the printing platform so that advanced sensing and conducting nanomaterials, such as graphene oxide, carbon nanotubes and other nanomaterials, can be embedded into 3D fabricated mechanical structures. This is expected to speed up the process of sensing device prototyping dramatically at lower cost.

Moreover, with multi-material 3D nano-printing, researchers can directly fabricate the functional body of robots, employing various soft material components with different degrees of stiffness, thus avoiding complex moulding techniques and assembly. By introducing new classes of customised materials and functionalities into 3D printing, they can fabricate new breeds of robotic actuators – 4D actuators – that are stimuli-responsive, self-morphing, and embedded with programmable architectures. The team plans to demonstrate the fabrication of several advanced actuation devices, including cell-electric-stimulation array for bio-syncretic robots, bio-syncretic cell-based actuators, and 4D micro-robots with fluorescent characteristics for biomedical applications.

"As a technologist, my research goal is very clear: develop technologies to advance human wellbeing, including extending human life, making everyday life more enjoyable, and discovering new phenomena," said Professor Li.

Major Awards

- IEEE Fellow
- ASME Fellow
- Elected President of the IEEE Nanotechnology Council (2016/2017)
- 100 Talents Awardee (Distinguished Overseas Scholar), Chinese Academy of Sciences

Key Projects

- General Research Fund:
  - Microfluidic Pervaporation Device for Fabrication of Nanoparticle-based Metalens for Dry Environment Super-Resolution Imaging
  - Development of Flexible MEMS Pressure Sensors Using Hierarchical Surface Structures for Texture Roughness Identification
  - Atomization of Viscous Fluids for Digital Scent Technology Using an Integrated Micro-droplet Generation Platform
- Innovation and Technology Fund:
  - A MEMS-based Light Detection and Ranging (LIDAR) System with Super-resolution Microlens for Enhanced Structured-light 3D Imaging and Mapping
  - An Implantable Micro-Sensing System for Tracking Animal Motion Behaviors
- Joint Laboratory Funding Scheme: Development of 3D Integrated Robotics and Sensing Structures Using Multi-layered Nano-ink Circuit Deposition
- Shenzhen Science, Technology and Innovation Commission: 大視場納米尺度超分辨測量與成像系統

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