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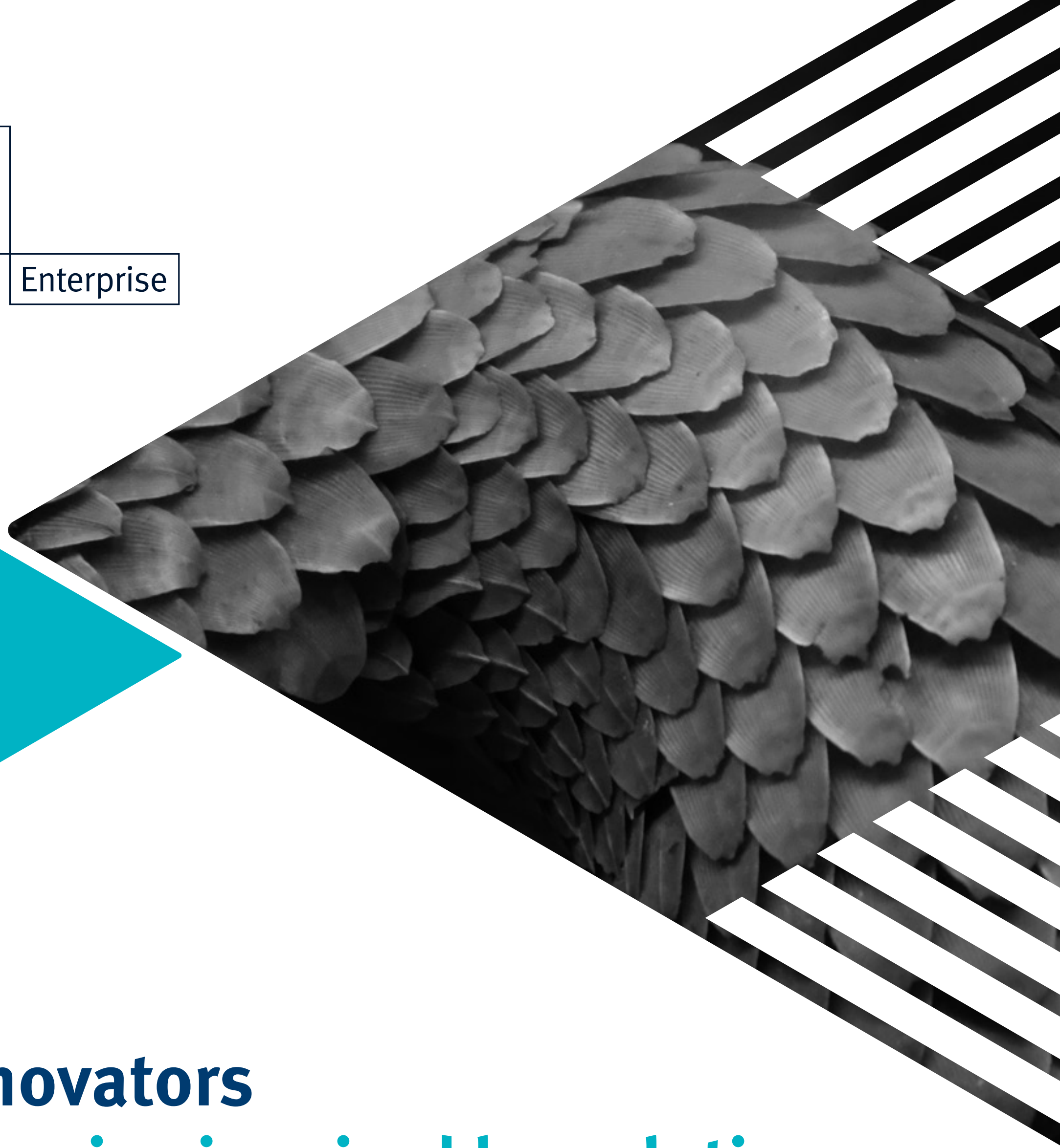

Nature's innovators
The technologies inspired by solutions from the natural world

Ian Mundell January 2024

Nature is endlessly inventive, with evolution providing sophisticated solutions to the challenges plants and animals face in their complex environments. Studying these natural innovations can help inventors make advances in their own fields of research and development, sometimes replicating natural systems, sometimes adapting them to new situations.

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The inspirational power of nature should not comes as a surprise, according to Dr Huai-Ti Lin of the Department of Bioengineering. "The whole field of aviation started as bio-inspired engineering," he observes. "The careful study of bird wings gave rise to early gliders and then to powered flight. After that, aviation went its own way."

It's not just aviation. Studying nature can help researchers devise more efficient approaches to solar energy production, robots that can operate in hostile environments, and materials that protect the human body and help it heal. Natural inspiration also promises to give us sensors with enhanced autonomy, and drones with unimagined speed and agility.

While they start with ideas that are familiar from the natural world, the solutions that emerge are often unfamiliar, and quite unlike technologies that are presently in use. While some of these technologies are already undergoing commercialisation, others are waiting for visionary companies to embrace the change, and take these new technologies to the market.

Fly like a dragonfly

When it comes to flight, the tools and systems that began with birds have worked well for large aircraft, but are not so well suited to increasingly miniature aerial systems or other tasks for which we need wings. "That's why we need to go back to nature and ask: is there something else that's closer to what we need?" Dr Lin says.

Dr Lin's own inspiration is the dragonfly, which has evolved remarkable flying abilities in order to hunt and catch prey in the air, defend territory and chase mates. "They hover, they glide, and they can perch anywhere. This is something quite unique in the insect world. The dragonfly is the most versatile micro-aerial system that you can find."

Working out how a dragonfly achieves this remarkable performance involves multidisciplinary study.

"You have to look at structural mechanics, the aerodynamics and flight mechanics involved in how flapping flight works," Dr Lin says. "Then for

Photo: Thomas Angus

Dr Huai-Ti Lin uses his dragonfly flight arena to study how dragonflies control their flight and apply their strategies for bio-inspired robotics.

the guidance aspects, you look at the kind of sensory input required to implement this flight control."

Over the past ten years, six of them with his present research group, he has studied the basic science of dragonfly flight. Now they are starting to apply the results in a series of proof-of-concept projects.

"We have real-time information about how the air flow is reacting to the wing at different locations. We're trying to implement a proof of concept on synthetic wings, so that we can monitor the exact state of lift distribution," Dr Lin says. "This could be a game-changer for controlling flexible wings."

Another inspiration came from the surface of the dragonfly wing, which is not flat, but corrugated. At speed, eddies of air are created inside these corrugations. "It's essentially an air bubble inflated aerofoil, and we are designing a new class of morphing wing that is based on this concept for microflyers."

The idea is to bring these synthetic wing concepts together with other findings on sensing to create a dragonfly-inspired microglider. "In principle, it will fly like a dragonfly, but it will not necessarily look exactly like a dragonfly," Dr Lin says.

These advances could have a wide range of applications in drone and wing design. "People from industry are definitely interested," Dr Lin says. "They are waiting for the proof of concept that we are currently working on."

Professor Julie McCann has used inspiration from fireflies to create new strategies for co-ordinating networks of sensors.

Communicate like a firefly

Insects provided a different kind of inspiration to **Professor Julie McCann** from the **Department of Computing**. Looking at the way social insects communicate by laying chemical trails had already informed strategies for moving information across networks of sensors, for example monitoring the environment or conditions inside buildings. This ensures that they can continue to operate even if individual links go down.

A different kind of problem arises when sensors in a network are put to sleep in order to extend their battery life. When they are reactivated, they need to be in sync in order to operate correctly, but this does not happen automatically. "While the sensors are asleep, their clocks drift a little bit," Professor McCann explains. "And if the clocks don't register the same time, the sensors don't wake up at the same time, and they can't communicate with each other. When one sensor is awake, others are asleep, and vice versa."

Her solution was inspired by fireflies, which communicate with pulses of light. Each species of firefly has evolved a distinct pattern of flashes, with variations for males and females. This means that flies can find appropriate mates while flying at night. This has nothing to do with telling the time, but the system can be adapted so that a waking sensor can listen to its neighbours' pulses – radio rather than light – to synchronise in time.

"We wanted a system that, even if the device had turned off by mistake or got blocked, allowed it to resynchronise again to the pulse, which represents the notion of time."

Researchers studying fireflies had already written algorithms to describe the pulse-coupled oscillations the insects use to communicate, and these were borrowed to build a synchronisation system for the sensors. After that, it became a computing problem.

Professor McCann's research provides an interesting case study on the need to combine the solutions found in nature with others that are distinctly synthetic. "If mapping between the natural world and its digital version is not quite working, we don't go back to nature to see how nature has solved the problem," Professor McCann says. "Usually, the problem is to do with the hardware or software environment, which is very different from the natural setting. For example; nature can feed itself, but we run our technologies on batteries which run out."

For example, the researchers' first thought was to get the waking sensor to synchronise its clock with the first pulse it detects. "What we found was that the sensors often missed the beat and overshot, and that desynchronised the whole network." So, a waking sensor is made to pause and listen for several beats before deciding how far forward to set its clock in order to sync with the rest of the network.

"I don't think a natural system would do that," Professor McCann says. "It's almost counterintuitive to pause and not act straight away. You'd think that would delay the whole system's ability to converge, but in truth it makes it converge faster."

These techniques, drawing on a combination of natural inspiration and human ingenuity, have been used in networks of sensors deployed to localise leaks in water mains, and to monitor growing conditions in vineyards. "In the second case, the sensors provided information that fed into life cycle models, and that allowed us to identify the water and energy going into the production of the wine," Professor McCann says.

This project was carried out by a consortium with Exeter and Glasgow universities, and the results were presented to English Wine.

The new perspective they offered led the organisation to focus on how English wine could be more competitive by emphasising sustainable production.

“Most of our projects are with industry, although not all of the results are exploited,” Professor McCann says, adding that she looks forward to a time when companies will be more confident applying these new technologies. “Often they prefer more traditional sensing mechanisms, where sensors are plugged in, but then you lose all the agility of being able to locate sensors in inaccessible places without having to wire everything up.”

Climb like a spider

Spiders were the inspiration for Professor Mirko Kovac, director of the **Aerial Robotics Laboratory** in the **Department of Aeronautics**. He wanted to design a robot able to land on a vertical structure, such as a wind turbine, in order to form robotic repair teams that could be deployed on offshore sites without humans having to place them there.

Working with other academic and industrial collaborators as part of the Offshore Robotics for Certification of Assets (ORCA) hub, Professor Kovac and his team created an autonomous drone that can attach itself to offshore wind turbines using a magnetic anchor and a spool of thread. Once attached, the robot can then carry out inspections or repairs without a human controller needing to be stationed nearby.

More recently, Professor Kovac has taken inspiration from animals such as penguins, arctic foxes and spittlebugs in order to design drones able to withstand extreme temperatures. These animals have appropriate layers of fat, fur, or other thermoregulating material that allow them to thrive in extreme conditions.

Working together with colleagues at the Swiss Federal Laboratories for Material Science and Technology (Empa), the goal was to create a drone that could be sent into burning buildings or woodlands to assess hazards and provide crucial first-hand data from danger zones.

To do this, they created a protective structural shell made of lightweight, thermally super-insulating materials like polyimide aerogel, and glass fibres. They coated this with super-reflecting aluminium to reflect heat. The super-insulation prevents the materials from shrinking and pore structures from degrading after exposure to high temperatures.

Within the protective exoskeleton, they placed the temperature-sensitive components, such as regular and infrared cameras, CO_2 sensors, video transmitters, flight controllers, batteries, and radio receivers. They also used the release and evaporation of gas from the CO_2 sensors to build a cooling system to keep temperatures down.

Photo: Thomas Angus

Professor Mirko Kovac's drone testing facility, the Brahmal Vasudevan Aerial Robotics Lab, allows the development and testing of next-generation flying robots.

The FireDrone has been tested in the laboratory, in temperature-controlled chambers, and flown close to flames at a firefighter training centre. Now the researchers are undertaking work to miniaturise the system and add more sensors to the drone so that it can be deployed in real-life firefighting missions.

FireDrone can also be used in extreme cold environments, in polar regions and in glaciers. The team has also tested the robot in a glacier tunnel in Switzerland to study how the system behaves in very cold temperatures.

"Deploying robots in extreme environments provides great benefits to reducing risks to human lives, and who better to look to than animals that have evolved their own ways of adapting to these extremes using inspirating from how animals keep cool in heat," says Professor Kovac.

Cool like a leaf

There is also inspiration to be found in the plant kingdom, with plant leaves informing the design of a solar energy collector developed in Imperial's Department of Chemical Engineering.

A typical leaf is made of different structures that enable it to move water, without active pumping, from the plant's roots to its leaves through a process called transpiration. When the water finally evaporates, it also cools the leaves. The photovoltaic (PV) leaf mimics this natural transpiration process. It incorporates natural fibres to mimic leaf vein bundles and hydrogels to simulate sponge cells, so that the flow and evaporation of water effectively and affordably removes heat from the PV cells.

In a recently published paper, the team demonstrated that a PV leaf can generate over 10% more electricity compared to conventional solar panels, which lose up to 70% of the incoming solar energy to the environment. In the process, the PV leaf also cleans the water being drawn passively fed into the solar collector.

"This innovative solar collector design holds tremendous potential for generating clean energy and water with significantly enhanced performance, while also ensuring cost-effectiveness and practicality," says **Dr Gan Huang**, who is working on the technology with **Professor Christos Markides**, head of the **Clean Energy Processes Laboratory**. "Innovative leaf-like solar collector designs can help expedite the global energy transition, while addressing two pressing global challenges: the need for increased energy and freshwater," says Professor Markides.

Reading across from nature to engineering solutions such as these is not always straightforward. "While it was not difficult for us to find inspiration from trees, the detail of designing a bio-inspired structure for the solar PV-leaf was quite a challenge," says Professor Markides. Dr Huang agrees: "This is especially true when you also need to consider the cost, the stability, and the efficiency of the system."

The PV leaf, along with a range of other solar technologies developed by the group, is being commercialised through the startup company **Solar Flow**.

Professor Christos Markides gave his inaugural lecture on 'making the most of the sun' in 2022. With **Dr Gan Huang**, he invented the nature-inspired photovoltaic leaf.

Photo: Fergus Burnett

Photo: Scaled

Scaled was founded by **Natalie Kerres** as a student on Imperial and the Royal College of Art's Global Innovation Design programme.

Protect like a pangolin

Natalie Keres looked to nature in order to design better protection against injuries, such as the falls that prove life-changing for many elderly people.

"In nature, animals have three basic kinds of protection from physical threats," she explains. "Those fast enough to flee from predators have skin. The slow ones hide in shells. Then there are scales, which provide the best combination of protection and mobility. And I was really fascinated by combination."

While scales have inspired some protective solutions, such as the armour worn by medieval Japanese warriors, most modern protection seems closer to shells. "A lot of joint protectors currently on the market are very rigid and bulky," Ms Kerres says. "They are often a solid piece of plastic that you have to wear, which is uncomfortable and does not look cool."

They also take little account of differences in age or gender, nor of the specific medical condition. "You end up with the same wrist brace for arthritis, repetitive strain injury, extension, or carpal tunnel syndrome," she says.

Ms Kerres researched the way animal scales achieve their remarkable performance during a Master's degree in **Global Innovation Design**, run jointly by Imperial and the Royal College of Art. "I was able to connect the geometry of scales with places on the body where an animal needs mobility, where it needs more impact absorption, where it needs to prevent hyperextension." She also demonstrated that changing the geometry of single scales can affect the performance of the whole structure.

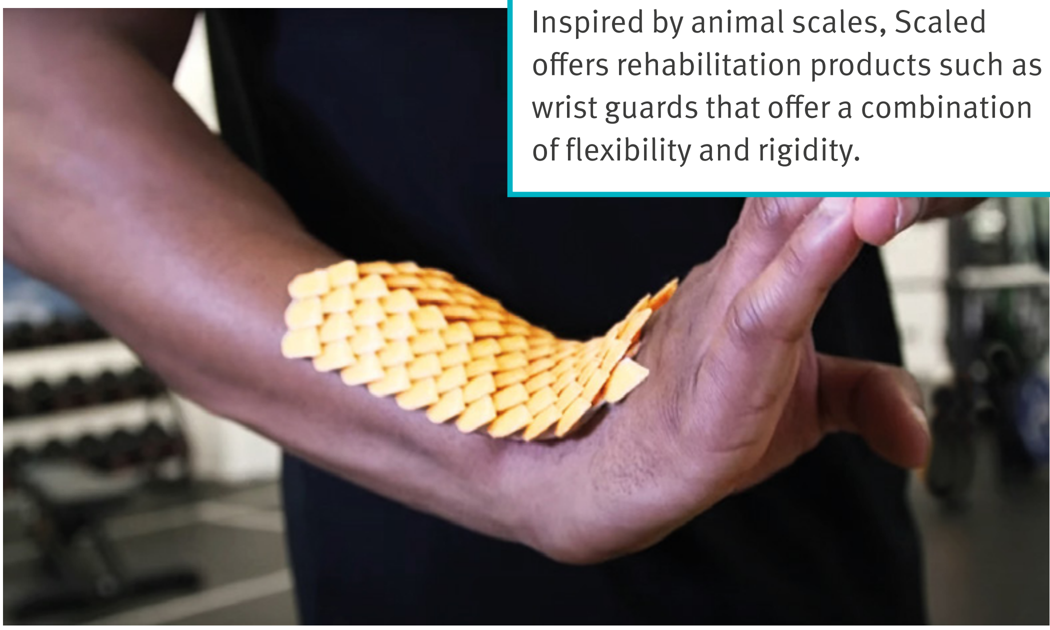
After graduation in 2020 she joined the **MedTech SuperConnector**, an Imperial accelerator for medical technologies, to explore how this idea could be developed further and eventually commercialised.

To do this she turned to 3D printing. "In the structures I wanted to create, each individual scale looks different," she says. "Making these by hand is quite impossible, and 3D printing is the only manufacturing method currently available that would allow that complexity structure."

The initial focus for her startup company, **Scaled**, was healthcare and rehabilitation products for the elderly, but testing proved impractical during the COVID-19 pandemic. Then sports physiotherapists started to show an interest. "Controlling the range of motion in joints is a really interesting unsolved problem for athletes in many disciplines, so we shifted our initial target market to elite sports."

This exploits an apparent limitation of flexible scaled materials: after a certain point the scales will lock together and the material become rigid. This makes it possible to design a wrist guard, for example, that is flexible in the range where the wrist needs to move, but then becomes rigid when further movement needs to be prevented.

One design challenge she had to overcome was how to connect together the 3D printed scales. In nature, fish or pangolin scales are connected through the skin, but that is not an option in people. "It took about two years to figure out the right materials to use, the right printer settings, and the right geometries to control the effect," Ms Kerres said.



Inspired by animal scales, Scaled offers rehabilitation products such as wrist guards that offer a combination of flexibility and rigidity.

Photo: Scaled

Scaled is currently putting its materials to the test, both in the lab and in collaboration with elite athletes in various disciplines. "It's not limited to risky sports, but also for people who have previously injured their wrists and want come back stronger, who want to be safe but don't want to be limited."

Meanwhile, research is beginning on protection for other joints, such as gloves that combine impact protection with flexibility, torso protection, and protection and support for ankle and knee injuries.

"We have a patent in the UK, which we've extended internationally, and we're looking for global partners to licence the material and how we make it," Ms Kerres says. "Hopefully, sooner rather than later, we'll have a lot of products out there to help as many people as possible."

Nature has more to say

This is just the beginning of what nature can teach us. "There's always more in nature, if you care to look," says Dr Huai-Ti Lin. "I think that going back to nature will kickstart a new direction for aviation and aeronautics."

Dr Gan Huang also believes that nature has more solutions to offer in the area of solar energy. "The distribution and shape of tree leaves and branches could also inspire the design of high-efficiency PV cells/arrays," he says. "And the micro-structures found on self-cleaning leaves (such as lotus leaves) could inspire the design of self-cleaning PV panels."

Plants could also point the way to new uses for solar energy. "It would be interesting to try to mimic photosynthesis in order to convert solar energy into organics," he adds.

Similarly, Natalie Kerres thinks there is more inspiration to be found from the way scales work in nature, and not just for protection. "In any animal with different scale structures and geometries, nature designed a process or a purpose for them, more than just a shielding effect," she says "Shark scales, for instance, are shaped so that the animal is quicker in the water. They also capture plankton, attracting fish to clean the shark's skin."

And there may also be new areas of bioinspiration in sensing and computing. "There's a movement now to make our kinds of computing much more sustainable, which means that we'll start seeing these systems being built out of biodegradable materials," says Professor Julie McCann. "So, that materials side of communication and computing could well become more bio-inspired."

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ibp@imperial.ac.uk | imperial.ac.uk/ibp

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