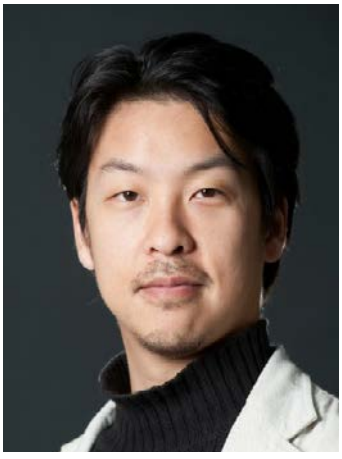
machine design

Biomechanics Brings Robotics to the Mobile Era



Sangbae Kim, professor at Massachusetts Institute of Technology, is leading the bio-robotic revolution with his work on the MIT Cheetah, a robotic running and jumping animal.

Tell me about yourself and your background.

I was born in Seoul, South Korea, where I attend Yonsei Universtiy. I graduated with a bachelor's in mechanical engineering. Afterwards I attended Stanford University to obtain my master's degree and my PhD. Stanford is where I started working with bio-robotics for the first time. In 2006, I worked with the Mark Cutkosky lab to develop the Stickybot, which won Time Magazine's Best Invention 2006 (http://news.stanford.edu/news/2010/august/gecko-082410.html). Stickybot is a gecko-inspired robot that could climb walls. I invented the directional adhesive that allowed the tiny hairs on the gecko's feet to cling to the walls. The interaction between the molecules of the toe hair and the wall is a molecular attraction called "van der Waals force." This allows the gecko to hang on and support its weight on one toe while placing the other on the surface. I studied a lot about biomechanics and biology and those principles in mobile platforms. Afterwards I completed one post-doc year in Harvard at the microrobotics lab. In 2009, I started my assistant professorship at MIT and started working on my bio platform. This past year in 2016 I was awarded tenure at MIT.

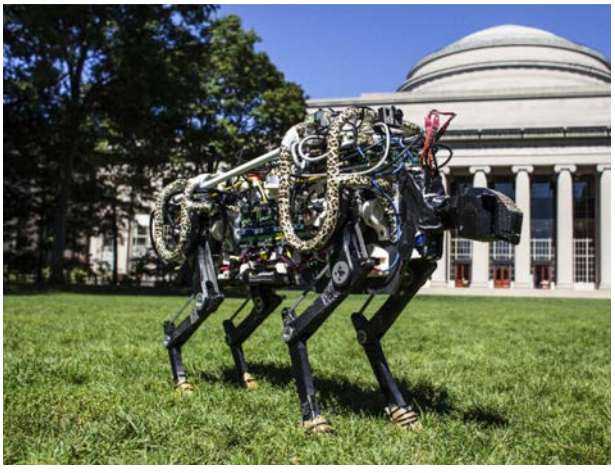
Your current work with robotics is trying to replicate animal and human motion. Why is this important for current robotics?

Engineering industry robots are not capable of moving. If you look at the animal world, everything is moving. When it comes to the mobile platform for robotics, the design paradigm must be completely different. Humans are not always aware where their foot is when they move. When humans go hiking, we do not control the placement of our feet or arms with sub-millimeter accuracy. We have a different priority in terms of control. It is more about maintaining balance and achieving force control. It is a different control priority and to be achieved, the machine needs to be designed differently. For example, manufacturing robots can be made to walk but they are not designed to control force. Those robots also do not perform negative work. Negative work implies that you can absorb the shock from the ground, hence you are able to respond to your environment. We have been redesigning the robotic system so that you can perform negative work. If you think about all machines, whether it be an engine or robot, they have been designed to do negative work only. Robotic arms, for example, never collide into anything for this reason; they do not dynamically interact with their environment. That is why you do not see many robots move like an animal or human being.

The Stickybot is a gecko-inspired robot that can climb walls and glass surfaces via small hairs and adhesives underneath its feet.

How is your current work involving the MIT Cheetah robot helping redefine the robot design paradigm?

In recent years, the scientific robotics community has focused on the potential role of robots in society, postulating functions and capabilities in areas ranging from home services to disaster response. The development of a legged ro-



The MIT Cheetah project is led by Sangbae Kim. He foresees that the next robotic evolution will be a mobile one and that robots need to learn how to respond to their environment.

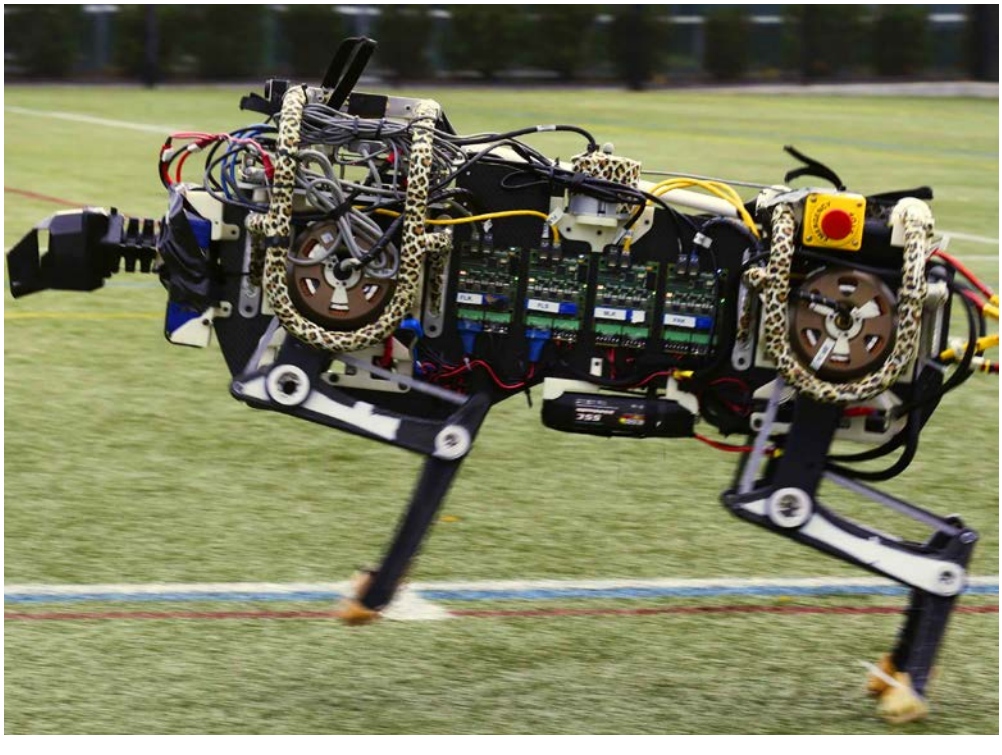
bot capable of dynamic behaviors has been a great challenge. Funded by the DARPA M3 locomotion program, our work on the MIT Cheetah has made significant contributions in the areas of robustness, dynamic capability, and efficiency, utilizing a novel design based on the extraction of biological principles in nature.

We chose the cheetah because it was the fastest of all land animals, so we learned its features the best, but there are many animals with similarities. The MIT Cheetah is capable of running up to 13.5 mph, achieving efficiency rivaling that of the real animal (cost of transport of 0.45, the lowest in the class), and turning and jumping over an 18-inch high obstacle to a robust landing. It has garnered significant interest among students and the general public alike, illustrating the attraction and popular excitement engendered by advances in robotics today.

The constituent technologies that enable the MIT Cheetah's achievements have been the major focus of my research at MIT. The work exemplifies an understanding of the requirements of animal locomotion and shows the effectiveness of bio-inspiration as a design tool. Along with proprioceptive actuation research, we developed impulse-planning algorithms that allow for stable, variable speed running, turning, and jumping. The bio-inspired leg structure of the robot plays an important role in its dynamic performance by minimizing leg inertia. The constituent technologies that enable the MIT Cheetah's achievements have been the major focus of my research at MIT.

Designing a high strength-to weight ratio leg design is critical in many aspects. Lightweight limbs will minimize the impact loss, swing cost, and improve force-control bandwidth. The strength requirement is severe in dynamic locomotion. Observing how leg designs in nature satisfy low inertia and complexity without compromising strength, I hypothesized that employing a tensegrity-like structure found in musculoskeletal systems would significantly reduce bone stress by decreasing bending moment, hence distributing the stress more uniformly. This hypothesis was applied to the leg design of the MIT Cheetah. According to finite element analysis of the MIT Cheetah design, the stress reduction was 80% at static test, and 40% throughout a running stride with 550N ground reaction force.

This design principle can change the design para-



The MIT Cheetah can not only run and jump, but also detect unplanned obstacles and react accordingly. The MIT Cheetah using LIDAR sensors can detect incoming hurdles and plan a jump to avoid them.

digm of robotic structure and human assistive devices where strength-to-weight ratio is critical. We developed a running algorithm of the MIT Cheetah, based on hypotheses formed by biomechanical studies. The constitutive hypotheses are (1) animals prescribe the net impulse of each stride by force-profile commands to balance the vertical momentum loss induced by gravity; (2) in the swing phase, the leg is tracking a trajectory with a relatively constant swing period (supported by dog-running data): and (3) the sagittal plane controller can be largely decoupled from the frontal plane controller. Utilizing high-bandwidth proprioceptive actuators, the amount of vertical impulse at each step is planned and executed to match the vertical impulse requirement. As a result, we successfully developed a highly stable galloping algorithm capable of running up to 33 mph in simulation and outdoor bounding of the MIT Cheetah in real time (https://youtu.be/XMKQbqnXXhQ). As we expanded the capability of the robot, we developed an autonomous obstacle-jumping algorithm. Once the LIDAR sensor detects the profile of the obstacle and distance from the robot, the real-time optimization runs to adjust the step size to match the stride with respect to the obstacle, and find a feasible jumping trajectory and calculate the proper amount of vertical impulse to clear the obstacle (https://youtu.be/_luhn7TLfWU).

How do you feel bio-robotics can change the world of automation and the job place?

I believe that we are entering an era of mobile robotics. By robots becoming more mobile we can use them in life-and-death situations, for delivery of goods, and environments that are hazardous for humans to enter. We currently do not have machines that can follow human speeds. We are living in an era that allows for cars, trains, planes, and even space travel only because we have created an infrastructure that allows it. If we look at Fukushima, the site of the nuclear plant disaster in Japan, there are areas that humans can still not enter. Regardless of the radiation, the major drawback is that we do not have reliability in our current machines to survey a dangerous landscape.

The MIT Cheetah is possible due to the work done at the university level. Can you describe the importance of university research for innovation?

I believe it to be pioneering. The machine we are building nobody ever built before. Five to six years ago when I started on this project, nobody said it was possible. Everyone said that designing a machine that could run and jump electrically was science fiction. Many said that it was only achievable via hydraulics. Hydraulics are powerful and used in a variety of machines, but are inefficient. Only with electronic actuation were we able to build a machine with the same efficiency as a real live animal. The university level is the only place that can take on this new direction and change how people think.