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How to get a robot collective to act like a smart material

Researchers at UC Santa Barbara and TU Dresden are blurring the lines between robotics and materials, with a proof-of-concept material-like collective of robots with behaviors inspired by biology.

“We’ve figured out a way for robots to behave more like a material,” said Matthew Devlin, a former doctoral researcher in the lab of UCSB mechanical engineering professor Elliot Hawkes, and the lead author of a paper published in the journal Science. Composed of individual, disk-shaped autonomous robots that look like small hockey pucks, the members of the collective are programmed to assemble themselves together into various forms with different material properties.

Of particular interest to the research team was the challenge of creating a robotic material that could both be stiff and strong, yet be able to flow when a new form is needed. Rather than responding to exterior forces to attain a form, robotic materials ideally would respond to internal signals, Hawkes explained, able to take a shape and hold it, “but also able to selectively flow themselves into a new shape.”

For inspiration, the researchers tapped previous work by Otger Campàs, a former UCSB professor and currently the director of the Physics of Life Excellence Cluster at TU Dresden, on how embryos are physically shaped. “Living embryonic tissues are the ultimate smart materials,” he said. “They have the ability to self-shape, self-heal and even control their material strength in space and time.” While at UCSB, his laboratory discovered that embryos can melt like glass to shape themselves. “To sculpt themselves, cells in embryos can make the tissues switch between fluid and solid states; a phenomenon known as rigidity transitions in physics,” he added.

During the development of an embryo, cells have the remarkable ability to arrange themselves around each other, turning the organism from a blob of undifferentiated cells into a collection of discrete forms — like hands and feet — and of various consistencies, like bones and brain. The researchers concentrated on enabling three biological processes behind these rigidity transitions: the active forces developing cells apply to one another that allow them to move around each other; the biochemical signaling that allow these cells to coordinate their movements in space and time; and their ability to adhere to each other, which ultimately lends the stiffness of the organism’s final form.

In the world of robots, the intracellular forces translate to inter-unit tangential force, enabled by eight motorized gears along each robot’s circular exterior, which allow them to move around each other, pushing off each other, even in tightly packed spaces.

The biochemical signaling, meanwhile, is akin to a global coordinate system. “Each cell ‘knows’ its head and tail, so then it knows which way to squeeze and apply forces,” Hawkes explained. In this way, the collective of cells manages to change the shape of the tissue, such as when they line up next to each other and elongate the body.

In the robots, this feat is accomplished by light sensors on the top of each robot, with polarized filters. When light is shone on these sensors, the polarization of the light tells them which direction to spin its gears and thus how to change shape. “You can just tell them all at once under a constant light field which direction you want them to go, and they can all line up and do whatever they need to do,” Devlin added.

For the cell-cell adhesion the researchers used magnets incorporated into the perimeter of the robotic units, magnets that could be turned to attract any other robot.

In putting the robots through their paces, the researchers found that signal fluctuations — variations in the signals sent to the robots — played a critical role in their ability to take the necessary shapes and formations. “We had previously shown that in living embryos, the fluctuations in the forces that cells generate are key to turning a solid-like tissue into a fluid one. So, we encoded force fluctuations in the robots,” said Campàs.

In the robot collective, the interaction between signal fluctuations and inter-unit forces is the difference between a tightly packed, unmoving collective and a more fluid one. “Basically, as you increase both of those, especially fluctuations, you get a more flowing material,” Devlin said. “This allows the collective to change shape. Once in formation, switching off the force fluctuations rigidifies the collective again.”

Importantly, these signal fluctuations make it possible for the robot collective to achieve their shape and strength changes with less average power than if the signal were constantly on and the robots were all pushing on each other continuously. “It’s an interesting result that we did not set out looking for, but discovered once we started gathering data on the robot behaviors,” Hawkes said. This is important, he added, for designing robots that may have to run on limited power budgets.

With all this in mind, the researchers were able to tune and control the group of robots to act like a smart material: sections of the group would turn on dynamic forces between robots and fluidize the collective, while in other sections the robots would simply hold to each other to create a rigid material. Modulating these behaviors across the group of robots and over time allowed the researchers to create robotic materials that support heavy loads but can also reshape, manipulate objects, and even self-heal.

Currently, the proof-of-concept robot collective comprises a small number (20) of relatively large units, but simulations conducted by former Campàs laboratory postdoctoral fellow Sangwoo Kim, who is now an assistant professor at EPFL, indicate the system can be scaled to larger numbers of miniaturized units, for a more materials-like aspect.

Beyond robotics, according to the paper, this and robot collectives like it could “enable the study of phase transitions in active matter, the properties of active mechanics in particulate systems and potentially help define hypotheses for biological research.” Combined with current controls and machine learning strategies, working with these robot collectives could yield emergent capabilities in robotic materials that have yet to be discovered and understood.

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