The soft touch

BY HELEN SHEN

Rigid robots step aside — a new generation of squishy, stretchy machines is wiggling our way.

In 2007, Cecilia Laschi asked her father to catch a live octopus for her seaside lab in Livorno, Italy. He thought she was crazy: as a recreational fisherman, he considered the octopus so easy to catch that it must be a very stupid animal. And what did a robotics researcher who worked with metal and microprocessors want with a squishy cephalopod anyway?

Nevertheless, the elder Laschi caught an octopus off the Tuscan coast and gave it to his daughter, who works for the Sant'Anna School of Advanced Studies in Pisa, Italy. She and her students placed the creature in a saltwater tank where they could study how it grasped titbits of anchovy and crab. The team then set about building robots that could mimic those motions.

Prototype by prototype, they created an artificial tentacle with internal springs and wires that mirrored an octopus's muscles, until the device could undulate, elongate, shrink, stiffen and curl in a lifelike manner[1]. "It's a completely different way of building robots," says Laschi.

This approach has become a major research front for robotics in the past ten years. Scientists and engineers in the field have long worked on hard-bodied robots, often inspired by humans and other animals with hard skeletons. These machines have the virtue of moving in mathematically predictable ways, with rigid limbs that can bend and straighten only around fixed joints. But they also require meticulous programming and extensive feedback to avoid smacking into things; even then, their motions often become erratic or even dangerous when dealing with humans, new objects, bumpy terrain or other unpredictable situations.

Robots inspired by flexible creatures such as octopuses, caterpillars or fish offer a solution. Instead of requiring intensive (and often imperfect) computations, soft robots built of mostly pliable or elastic materials can just mould themselves to their surroundings. Although

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A robot octopus can move like the real thing.

some of these machines use wires or springs to mimic muscles and tendons, as a group, soft robots have ditched the skeletons that defined previous robot generations. With nothing resembling bones or joints, these machines can stretch, twist, scrunch and squish in completely new ways. They can transform in shape or size, wrap around objects and even touch people more safely than ever before.

Building these machines involves developing new technologies to animate floppy materials with purposeful movement, and methods for monitoring and predicting their actions. But if this succeeds, such robots might be used as rescue workers that can squeeze into tight spaces or slink across shifting debris; as home health aides that can interact closely with humans; and as industrial machines that can grasp new objects without previous programming.

Researchers have already produced a wide variety of such machines, including crawling robotic caterpillars[2], swimming fish-bots[3] and undulating artificial jellyfish[4]. On 29–30 April, ten teams will compete in Livorno in an international soft-robotics challenge — the first of its kind. Laschi, who serves as scientific coordinator for the European Commission-backed sponsoring research consortium, RoboSoft, hopes that the event will drive innovation in the field.

"If you look in biology, and you ask what Darwinian evolution has coughed up, there are all kinds of incredible solutions to movement, sensing, gripping, feeding, hunting, swimming, walking and gliding that have not been open to hard robots," says chemist George Whitesides, a soft-robotics researcher at Harvard University in Cambridge, Massachusetts. "The idea of building fundamentally new classes of machines is just very interesting."

SMOOTH MOVES

The millions of industrial robots around the world today are all derived from the same basic blueprint. The metal-bound machines use their hefty, rigid limbs to shoulder the grunt work in car-assembly lines and industrial plants with speed, force and mindless repetition that humans simply can't match. But standard robots require specialized programming, tightly controlled conditions and continuous feedback of their own movements to know precisely when and how to move each of their many joints. They can fail spectacularly at tasks that fall outside their programming parameters, and they can malfunction entirely in unpredictable environments. Most must stay behind fences that protect their human co-workers from inadvertent harm.

"Think about how hard it is to tie shoelaces," says Daniela Rus, director of the Computer Science and Artificial Intelligence Laboratory at the Massachusetts Institute of Technology in Cambridge. "That's the kind of capability we'd like to have in robotics."

Over the past decade, that desire has triggered an increased interest in lighter, cheaper machines that can handle fiddly or unpredictable situations and collaborate directly with humans. Some roboticists, including Laschi, think that soft materials and bioinspired designs can provide an answer.

That idea was a tough sell at first, Laschi says. "In the beginning, very traditional robotics conferences didn't want to accept my papers," she says. "But now there are entire sessions devoted to this topic." Helping to fuel the surge in interest are recent advances in polymer science, especially the development of techniques for casting, moulding or 3D printing polymers into custom shapes. This has enabled roboticists to experiment more freely and quickly with making soft forms.

As a result, more than 30 institutions have now joined the RoboSoft collaboration, which kicked off in 2013. The following year saw the launch of a dedicated journal, *Soft Robotics*, and of an open-access resource called the Soft Robotics Toolkit: a website developed by researchers at Trinity College Dublin and at Harvard that allows researchers and amateurs to share tips and find downloadable designs and other information (see go.nature.com/8gsq4h).

Still, says Rebecca Kramer, a mechanical engineer at Purdue University in West Lafayette, Indiana, "I don't think the community has coalesced on what a soft robot should look like, and we're still picking out the core technology."

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For a video of soft robots in action, see go.nature.com/zx5bux

Perhaps the most fundamental challenge is getting the robots' soft structures to curl, scrunch and stretch. Laschi's robotic tentacle houses a network of thin metal cables and springs made of shape-memory alloys — easily bendable metals that return to their original shapes when heated. Laid lengthwise along the 'arm', some of these components simulate an octopus's longitudinal muscles, which shorten or bend the tentacle when they contract. Others radiate out from the tentacle's core, simulating transverse muscles that shrink the arm's diameter. Researchers can make the tentacle wave — or even curl around a human hand — by pulling certain combinations of cables with external motors, or by heating springs with electrical currents.

"It's a completely different way of building robots."

A similar system helps to drive the soft-robotic caterpillars that neurobiologist Barry Trimmer has modelled on his favourite experimental organism, the tobacco hornworm (*Manduca sexta*). At his lab at Tufts University in Medford, Massachusetts, 20 hornworms are born each day, and Trimmer 3D prints a handful of robotic ones as well. The mechanical creatures wriggle along the lab bench much like the real ones, and they can even copy the caterpillar's signature escape move: with a pull here and a tug there on the robot's internal 'muscles', the machine snaps into a circle that wheels away[5]. Trimmer, who is editor-in-chief of *Soft Robotics*, hopes that this wide range of movements could one day turn the robot into an aide for emergency responders that can rapidly cross fields of debris and burrow through rubble to locate survivors of disasters.

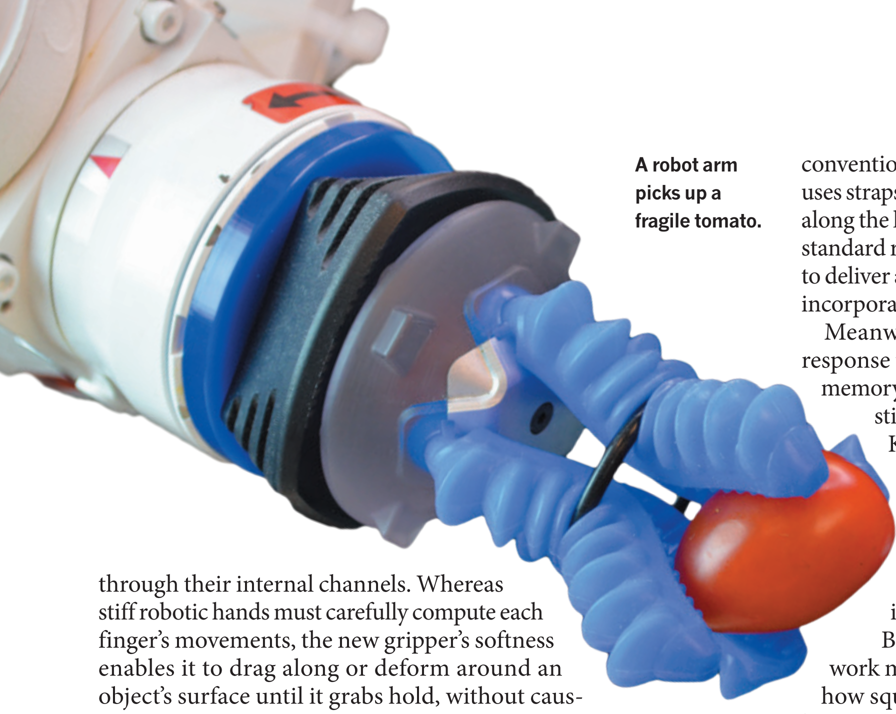
Whitesides, meanwhile, is pioneering robots that are powered by air — among them a family of polymer-based devices inspired by the starfish. Each limb consists of an internal network of pockets and channels, sandwiched between two materials of differing elasticity. As researchers pump air into different parts of the robot, the arms (or legs or fingers) inflate asymmetrically and curl. Whitesides' team has even built one device that can play 'Mary Had a Little Lamb' on the piano[6]. One of the team's four-legged creations has mastered a robot obstacle course: ambling towards an elevated partition with a clearance of about 2 centimetres, the machine drops down and shimmies underneath, demonstrating the potential of soft robots to tackle complex terrains[7].

GRABBING MARKET SHARE

Although most soft robots remain in the lab, some of Whitesides' creations are venturing out to feed industrial demand for adept robotic hands. Conventional grippers require detailed information about factors such as an object's location, shape, weight and slipperiness to move each of its joints correctly. One system may be specialized for handling shampoo bottles, whereas another picks up only children's toys, and yet another is needed for grabbing T-shirts. But as manufacturers update their product lines, and as e-commerce warehouses handle a growing variety of objects, these companies need to swap in customized grippers and updated control algorithms for each different use — often at great cost and delay.

By contrast, grippers that are made mainly of soft, stretchy materials can envelop and conform to objects of different shapes and sizes. Soft Robotics, a start-up company in Cambridge, Massachussetts, that spun out of Whitesides' research in 2013, has raised some US$4.5 million to develop a line of rubbery robotic claws. "We use no force sensors, no feedback systems and we don't do a lot of planning," says the company's chief executive, Carl Vause. "We just go and grab an object", squeezing until the grip is secure.

Made entirely of elastic polymers, the claws curl when air pumps



A robot arm picks up a fragile tomato.

SOFT ROBOTICS INC.

through their internal channels. Whereas stiff robotic hands must carefully compute each finger's movements, the new gripper's softness enables it to drag along or deform around an object's surface until it grabs hold, without causing damage. It can even pick up mushrooms and ripe strawberries, as well as plump tomatoes off a vine — tasks that have historically required the delicate touch of human workers. Soft Robotics released its first gripper for sale in June 2015, and it is running pilot programmes with six client companies involved in packaging and food-handling.

Empire Robotics in neighbouring Boston has taken a radically different approach, by marketing a robotic 'hand' that resembles a squishy stress ball. Sandlike particles inside the ball flow freely at first, allowing it to deform as it presses firmly into an object. Then, a valve sucks air out of the ball so that the grains inside are forced tightly against each other, causing the ball to harden its grip. Based on research[8] by Heinrich Jaeger at the University of Chicago in Illinois, and Hod Lipson at Cornell University in Ithaca, New York, the 'Versaball' can pick up objects in about one-tenth of a second and lift up to about 9 kilograms.

SENSE OF PLACE

As robotic octopuses, caterpillars, starfish and other malleable machines come to life, some scientists have begun to focus on better ways to control the devices' actions. "We're talking about floppy, elastic materials," says Kramer. "When something moves on one side, you're not quite sure where the rest of the machine is going to end up." That is why many applications will probably require extra sensors to monitor movement. Yet conventional position and force sensors — rigid or semi-rigid electronic components — don't always work well with soft robots that undergo extreme shape changes.

Engineers such as Yong-Lae Park are tackling this problem by developing stretchable electronic sensors. At Carnegie Mellon University in Pittsburgh, Pennsylvania, Park works on gummy patches that contain liquid-metal circuits sandwiched between sheets of silicone rubber. Poured in a variety of patterns, including spirals and stripes, these liquid circuits can be customized to sense when the device is squished or stretched, and in what direction[9].

"Stretchable sensors can be as sensitive as skin, depending on how you design them. You can tune them to respond to a slight brush of a finger or to a 30-pound weight," says mechanical engineer Robert Shepherd at Cornell, who has developed methods for 3D printing stretch-sensitive 'skins' directly onto soft robots[10]. Alternating layers of conductive and insulating material produce an electrical signal when prodded or pulled.

Stretchy sensors could have an important role in the growing field of wearable robotics. Funded by the US military, Conor Walsh at Harvard University has spent years developing and honing a soft 'exosuit' for soldiers — a comfier analogue to earlier 'Iron Man'-type exoskeletons, meant to help fighters to carry heavy loads over long distances. Users can still feel the device aiding their movement, but walking in the suit feels "pretty natural", says Walsh — a big improvement from conventional exoskeletons. Instead of bulky, rigid casings, Walsh's suit uses straps made from nylon, polyester and spandex placed strategically along the legs. And a smattering of position and acceleration sensors — standard rigid devices for now — helps to monitor the wearer's gait and to deliver assistance at the optimal times.The next step, says Walsh, is to incorporate stretchy sensors for a softer, more comfortable experience.

Meanwhile, Kramer has created a robotic fabric that moves in response to electrical current[11]. The muslin sheet, which has shape-memory-alloy coils sewn in, can scrunch by up to 60% in length when stimulated. Smart 'threads' keep tabs on the fabric's movements; Kramer weaves in stretch-sensitive silicone filaments filled with liquid metal. The concept could be used one day for sleeves or cuffs to help injured or elderly people to move. Kramer also hopes that the material might be used to assemble robots in space. Astronauts could simply drape an active skin around a piece of foam, for example, to turn it into a working robot.

But before soft robots can fly to space, much foundational work must be done on the ground. Relatively little is known about how squishy materials deform in response to external forces, and how movements propagate through soft masses. In addition, most soft robots remain attached or tethered to hard energy sources, such as batteries or compressed-air tanks. Some researchers are already eyeing the potential of biochemical or renewable sources of energy for soft robots.

The RoboSoft challenge in April could help to spur development. There, the entries will be put through their paces: challenges include racing across a sand pit, opening a door by its handle, grabbing a number of mystery objects and avoiding fragile obstacles under water. The goal, says Laschi, is to demonstrate that soft robots can accomplish some of the same tasks that stiff robots do, as well as others that they cannot.

"Stretchable sensors can be as sensitive as skin."

"I don't think soft robotics is going to replace traditional robotics, but it will be combination of the two in the future," says Laschi. Many researchers think that rigid robots might retain their superiority in jobs requiring great strength, speed or precision. But for a growing number of applications involving close interactions with people, or other unpredictable situations, soft robots could find a niche.

At Kings College London, for example, Laschi's collaborators are developing a surgical endoscope based on her tentacle technology. And her team in Italy is developing a full-bodied robot octopus that swims by fluid propulsion, and could one day be used for underwater research and exploration. The prototype already pulses silently through a tank in her lab, as the real octopuses swim in the salty waters just outside.

"When I started with the octopus, people asked me what it was for," says Laschi. "I said, 'I don't know, but I'm sure if it succeeds there could be many, many applications'." ■

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