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The replicator: create your own body double

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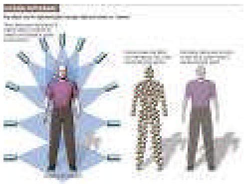
TELEPORTATION might not yet be on the cards for us humans, but Seth Goldstein and Todd Mowry may have come up with the next best thing. This pair of computer scientists are trying to build an intelligent material that can replicate a physical three-dimensional facsimile of you from nothing more than a stream of video images. If it works, all you'll need to project yourself around the globe is an internet connection and a pile of their intelligent nanodust at the other end to assemble your replica.


Enlarge image
Electronic Doppelgänger

The project is still in its infancy, but the researchers hope the new material - made of self-organising nano-computers that can stick to each other and communicate with built-in wireless - will eventually be able to shape-shift in an instant, forming a replica of anything from a banana to a human. They call it "claytronics", and the individual particles are known as claytronic atoms, or "catoms".

The possibilities are mind-boggling. For example, a lump of catoms in your house could shape-shift into a 3D facsimile of your doctor to take your pulse - while the real doctor sits in his office in front of a camera, holding your claytronic doppelgänger's wrist. The claytronic cellphone in your pocket could morph into whatever tool you need. Videoconferencing would gain a physical dimension, with all the participants appearing in claytronic form, and surgeons could even work on claytronic enlargements of internal organs to perform robotic tele-surgery with extreme precision.

Sure, we're not quite there yet, but the researchers have already begun working on the details of the software and hardware to make claytronics a reality. And they've attracted the interest of none other than the world's biggest computer chip maker, Intel, as a co-sponsor. The company hopes the project will lead to new ways for millions of processors to communicate with each other efficiently. "You could have a little lump of this stuff that you carry around and it could be a million different things," says Mowry, director of Intel's research labs in Pittsburgh, Pennsylvania, and Goldstein's partner in the project. "It's like the world's ultimate Swiss army knife."

Claytronics has wasted little time getting started. The idea was hatched just three years ago, after Mowry and Goldstein attended a computing conference in Virginia. Goldstein, of Carnegie Mellon University in Pittsburgh, was interested in new forms of nano-computing in which individual molecules would become data processing units. Mowry, meanwhile, was exploring new approaches to "telepresence" - computer-enhanced versions of videoconferencing.

First steps

Previous attempts to improve telepresence have involved using goggles to create illusory 3D surroundings in which people and objects can appear. But after hearing Goldstein's talk at the computing conference, Mowry realised it might be possible to program his nanoscale computing elements to form 3D replicas of distant objects and so remove the need for goggles. Goldstein liked the idea, and the project was born. Since then the pair have attracted more than a dozen researchers to work on their project. "It's absolutely going to work," says Goldstein. And their missionary zeal is slowly winning colleagues over.

"My first reaction was, 'Gosh, this is just science fiction,'" says Jason Campbell, a robotics expert at Intel who now works on the project. "But the more you look at it, the more likely it seems that we will be able to manufacture these things. I think there's a good chance we'll get to see it. Now whether that's five or 20 years, I don't know."

It's probably safe to say that it will be closer to 20. I visited Goldstein's lab earlier this year to see for myself what they had actually built. The group has managed to get four catoms to operate, but during my visit only two of them were working. These first-generation catoms are cylinders 4.4 centimetres in diameter and about 3.6 centimetres high, ringed with 24 electromagnets that push and pull them around each other. They also contain rudimentary computer processors and touch connectors that draw electricity from the board the catoms stand on.

The demonstration I saw consisted of the two catoms shuffling and jerking as they attached and detached from each other in a seemingly chaotic dance. But the motion is not random, Goldstein explained. It demonstrates their ability to attach and move around each other. Not particularly impressive, but Goldstein insists this is a mere proof of concept. He is already working on designs for catoms the size of marbles, and really impressive behaviour should begin to emerge when hundreds of these devices are allowed to interact at once.

He's also planning ahead for when the catoms are scaled to below a millimetre across. Then, he says, they will move about by switching electrostatic forces on and off, rather than using electromagnetism. And at that scale, they can fasten onto each other with a kind of microscopic Velcro, or they might borrow the adhesive tricks insects and geckos use to walk on ceilings.

"The hard part is not going to be the hardware," Goldstein says. "If you just look at the way processing power and manufacturing in general have been scaling, it's a no-brainer. The hardware is inevitable, so we can concentrate on what I think are the hardest problems, and that's the software issues. We don't know how to build robust, reliable distributed systems," he admits.

But he's making headway with one of the most important problems to be solved - powering the catoms. Their tiny target size means each catom will not be able to carry its own power source, so they will have to rely on an external supply. This will come from a "power platform" with positive and negative contacts on which the catoms will sit. Those catoms not touching the platform will rely on intermediate catoms to feed them with power and close the circuit, says Babu Pillai, a computer scientist at Intel.

How do you get catoms to distribute power throughout a claytronic object, given that the object's shape and the individual catoms' locations with respect to each other are supposed to be ever-changing? The answer is to have a dynamic power-routeing mechanism that can automatically find the best way of making connections between catoms, says Pillai, who is working on algorithms to solve the problem. "You have to have collaboration between these little robots to do any powering at all," he says.

Pillai and his colleagues have run computer simulations of various circuits and control algorithms, and have shown that catoms in a claytronic mass can self-organise to form claytronic "wiring", creating a power network that permits current to flow through catoms in series. However, this series network cannot power a functioning claytronic entity. So the powered processors would now begin to expand the power network, switching power to their neighbours to create more complex networks and feed power to still more catoms.

Spreading the power

Properly programmed, the catoms could then self-organise into an electrical grid, providing the entire claytronic mass with power through parallel circuits. "You can grow the region that's nicely powered until you cover the whole mass," says Pillai.

Computer simulations show that from a single initial current source, a large claytronic mass can bootstrap itself up to give itself a good power supply, as the catoms create their own circuits on the fly. Eventually, says Goldstein, advanced claytronic objects will be able to wrap themselves around a battery and so become independent of the power platform, carrying the battery around inside like an internal organ.

When the catoms are small enough to create a uniform-looking mass, those on the surface of the claytronic object could change their colour or brightness to mimic the appearance of any material, and could also sense physical pressure, temperature, light intensity and so on, and feed the data to a computer. Meanwhile, catoms on the inside of the object would form struts for structural support and act as conduits for power.

But for now there are several more basic problems Goldstein has yet to solve. How do you write distributed programs to coordinate the behaviour of millions of individual units with no central control unit? "It's almost scary to imagine having hundreds of thousands or even millions of independent computing devices that you need to program," says Peter Lee, a programming expert at Carnegie Mellon working with Goldstein. "You need to somehow communicate with a small number of catoms and hope that the whole mass can organise itself to do something."

To date, no one has succeeded in creating a program to successfully control hundreds of robots, let alone millions. However, Michael DeRosa at Carnegie Mellon thinks he has found a way of simplifying the problem. He wants to morph his claytronic objects not by moving the catoms en masse, but by inverting the problem and focusing on manipulating cavities or gaps within the claytronic mass to change its shape. That way, you only need to coordinate the catom layers surrounding the cavities rather than whole blocks of catoms. Catom layers around these voids might be instructed to move step-by-step to change the space's location and shape, displacing successive layers in the process. You could enlarge one side of a hollow, for example, to create a protrusion at the surface, or shrink it to form a depression.

Producing the desired behaviour will be difficult, says John Holland, an expert in complexity and emergent behaviour in computer systems at the University of Michigan. It will take a long time to develop software clever enough to enable applications like telepresence, he says. "That seems a long way away to me."

Goldstein concedes this is going to be a major hurdle. "I think the fundamental challenge to computer science is the complexity issue," he says. But he is optimistic DeRosa's work might show the way forward.

There are other doubts about the team's design. David Wolpert, an expert in distributed computer systems at NASA's Ames research lab in California, has his doubts about the use of electrostatic forces to move the catoms around. It's "a real big monkey wrench" in the system, he says, because such forces propagate away from individual catoms, making it difficult to control local movement of an individual catom. Wolpert also says coordinating millions of catoms will be very difficult - but not necessarily impossible. "I certainly think in principle it could be done."

Goldstein acknowledges there could also be security issues if claytronics does eventually become a reality. You have to be sure the right person is telling a catom what to do, and that it is doing what it's told, he says.

Despite these difficulties, he's ploughing ahead with the next stage. Within a year, he plans to build coin-sized 2D catoms light enough to form simple 3D objects. "That'll be a huge step forward," he says.

Even if claytronics doesn't ultimately succeed, Goldstein won't be disappointed. "My motivating philosophy is that this is a way to bring a lot of interdisciplinary researchers together to look at some of the really hard problems in computer science," he says. But he's optimistic. Making claytronics happen, he says, would be "incredibly cool".

Flexible robots

Claytronics is not the only project attempting to build a reconfigurable robot. Wei-Min Shen and colleagues at the University of Southern California's Polymorphic Robotics Laboratory, Marina del Rey, have demonstrated flexible robotic contraptions that can flex like caterpillars. Units can join together to form something resembling a snake, or a multi-legged insect such as a centipede, or even curl up into a ring.

Each module is a little smaller than a brick, and is effectively an autonomous computer with its own battery, motor, connectors and sensors. The units use the sensors to probe the local terrain and decide on the most suitable configuration for moving, and then communicate with infrared signals to tell each other how to decouple and recouple. If the configuration they choose doesn't work, they simply detach and try a new one.

"The concept is that you build a robot that can automatically change its shape and size according to environmental feedback," says Shen. "If it sees a hole in the wall or a pipe, it can become a snake and go through the pipe. If it needs to climb stairs, it can grow legs. Or if the terrain is downhill, it can become a ball and roll down."

So far Shen's system has linked up to 20 units, and there are plans to coordinate 100 within the next few years. "Eventually we will have thousands," he predicts. His team had to abandon its original goal of making the units small enough to go through a keyhole because of power demands - to be autonomous, they need their own batteries, and that makes them bulky.

Shen's reconfigurable robots could eventually explore jungles on military missions or search buildings for criminals or terrorists. The work has attracted interest from NASA too. Late last year, the space agency announced a $28 million grant to Shen's group to develop reconfigurable robotic systems for space missions. Eventually such devices could explore inaccessible locations on other planets, form tools or self-repairing instruments, and even act as forward construction gangs to build bases for astronauts.

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