Programmable Matter

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In the past 50 years, computers have shrunk from room-size mainframes to lightweight handhelds. This fantastic miniaturization is primarily the result of high-volume nanoscale manufacturing.

While this technology has predominantly been applied to logic and memory, it's now being used to create advanced microelectromechanical systems using both top-down and bottom-up processes.

One possible outcome of continued progress in high-volume nanoscale assembly is the ability to inexpensively produce millimeter-scale units that integrate computing, sensing, actuation, and locomotion mechanisms. A collection of such units can be viewed as a form of *programmable matter*.

CLAYTRONICS

The Claytronics project (www.cs.cmu.edu/~claytronics) is a joint effort of researchers at Carnegie Mellon University and Intel Research Pittsburgh to explore how programmable matter might change the computing experience. Similar to how audio and video technologies capture and reproduce sound and moving images, respectively, we are investigating ways to reproduce moving physical 3D objects.

The idea behind claytronics is neither to transport an object's original instance nor to recreate its chemical composition, but rather to create a physical artifact using programmable matter that will eventually be able to mimic the original object's shape, movement, visual appearance, sound, and tactile qualities.

Researchers are using nanoscale technology to create microrobot ensembles for modeling 3D scenes.

Synthetic reality

One application of an *ensemble*, comprised of millions of cooperating robot modules, is programming it to self-assemble into arbitrary 3D shapes. Our long-term goal is to use such ensembles to achieve *synthetic reality*, an environment that, unlike virtual reality and augmented reality, allows for the physical realization of all computer-generated objects. Hence, users will be able to experience synthetic reality without any sensory augmentation, such as head-mounted displays. They can also physically interact with any object in the system in a natural way.

Catoms

Programmable matter consists of a collection of individual components, which we call claytronic atoms or *catoms*. Catoms can

- move in three dimensions in relation to other catoms,
- adhere to other catoms to maintain a 3D shape,
- communicate with other catoms in an ensemble, and
- compute state information with possible assistance from other catoms in the ensemble.

In the preliminary design, each catom is a unit with a CPU, a network device, a single-pixel display, one or more sensors, a means of locomotion, and a mechanism for adhering to other catoms. Although this sounds like a microrobot, we believe that implementing a completely autonomous microrobot is unnecessarily complex. Instead, we take a cue from cellular reconfigurable robotics research to simplify the individual robot modules so that they are easier to manufacture using high-volume methods.

Ensemble principle

Realizing this vision requires new ways of thinking about massive numbers of cooperating millimeter-scale units. Most importantly, it demands simplifying and redesigning the software and hardware used in each catom to reduce complexity and manufacturing cost and increase robustness and reliability. For example, each catom must work cooperatively with others in the ensemble to move, communicate, and obtain power.

Consequently, our designs strictly adhere to the *ensemble principle*: A robot module should include only enough functionality to contribute to the ensemble's desired functionality.

Three early results of our research each highlight a key aspect of the ensemble principle: easy manufactura-

Figure 1. Claytronic atom prototypes. Each 44-mm-diameter catom is equipped with 24 electromagnets arranged in a pair of stacked rings.

bility, powering million-robot ensembles, and surface contour control without global motion planning.

HIGH-VOLUME MANUFACTURABILITY

Some catom designs will be easier to produce in mass quantity than others. Our present exploration into the design space investigates modules without moving parts, which we see as an intermediate stage to designing catoms suitable for high-volume manufacturing.

In our present macroscale (44-mm diameter), cylindrical prototypes, shown in Figure 1, each catom is equipped with 24 electromagnets arranged in a pair of stacked rings. To move, a pair of catoms must first be in contact with another pair. Then, they must appropriately energize the next set of magnets along each of their circumferences.

These prototypes demonstrate high-speed reconfiguration—approximately 100 ms for a step-reconfiguration involving uncoupling of two units, movement from one pair of contact points to another, and recoupling at the next pair of contact points. At present, they don't yet incorporate any significant sensing or autonomy.

The current prototypes can only overcome the frictional forces opposing their own horizontal movement, but downscaling will improve the force budget substantially. The resulting force from two similarly energized magnet coils varies roughly with the inverse cube of distance, whereas the flux due to a given coil varies with the square of the scale factor. Hence, the potential force generated between two catoms varies linearly with scale. Meanwhile, mass varies with the cube of scale.

These relationships suggest that a 10-fold reduction in size should translate to a 100-fold increase in force relative to mass. Energy consumption and supply will still be an issue, but given sufficient energy, smaller catoms will have an easier time lifting their own weight and that of their peers, as well as resisting other forces involved in holding the ensemble together.

Our finite-element electromagnetic-physical simulations on catoms of different sizes appear to confirm this approximation and closely match our empirical measurements of magnetic force in the 44-mm prototypes. We're also studying programmable nanofiber adhesive techniques that are necessary to eliminate the static power drain when robots are motionless, while still maintaining a strong bond.

POWERING MICROROBOT ENSEMBLES

Some energy requirements, such as effort to move versus gravity, scale with size. Others, such as communication and computation, don't. As microrobots (catoms) are scaled down, the onboard battery's weight and volume exceed those of the robots themselves.

To provide sufficient energy to each catom without incurring such a weight and volume penalty, we're developing methods for routing energy from an external source to all catoms in an ensemble. For example, an ensemble could tap an environmental power source, such as a special table with positive and negative electrodes, and route that power internally using catom-to-catom connections.

To simplify manufacturing and accelerate movement, we believe it's necessary to avoid using intercatom connectors that can carry both supply and ground via separate conductors within the connector assembly. Such complex connectors can significantly increase reconfiguration time.

For example, in previously constructed modular robotic systems such as the Palo Alto Research Center's PolyBot (www2.parc.com/spl/projects/modrobots/chain/polybot/index.html) and the Dartmouth Robotics Lab's Molecule (www.cs.dartmouth.edu/~robotlab/robotlab/robots/molecule/index.html) it can take tens of seconds or even minutes for a robot module to uncouple from its neighbor, move to another module, and couple with that newly proximal module.

In contrast, our present unary-connector-based prototypes can "dock" in less than 100 ms because no special connector alignment procedure is required. This speed advantage isn't free, however: A genderless unary connector imposes additional operational complexity in that each catom must obtain a connection to supply from one neighbor and to ground from a different neighbor.

Several members of the Claytronic team have recently developed power distribution algorithms that satisfy these criteria. These algorithms require no knowledge of the ensemble configuration—lattice spacing, ensemble size, or shape—or power-supply location. Further, they require no on-catom power storage.

SHAPE CONTROL WITHOUT GLOBAL MOTION PLANNING

Classical approaches to creating an arbitrary shape from a group of modular robots involve motion planning through high-dimensional search or gradient descent methods. However, in the case of a million-robot ensemble, global search is unlikely to be tractable. Even if a method could globally plan for the entire ensemble, the communications overhead required to transmit individualized directions to each module would be very high. In addition, a global plan would break down in the face of individual unit failure.

To address these concerns, we're developing algorithms that can control shape without requiring extensive planning or communication. While this work is just beginning, Claytronics researchers have had early success using an approach inspired by semiconductor device physics.

This approach focuses on the motion of *holes* rather than that of robots per se. Given a uniform hexagonal-packed plane of catoms, a hole is a circular void due to the absence of seven catoms. Such a seven-catom hole can migrate through the ensemble by appropriate local motion of the adjacent catoms.

Holes migrate through the ensemble as if moving on a frictionless plane, and bounce back at the ensemble's edges. Just as bouncing gas molecules exert pressure at the edges of a balloon, bouncing holes interact frequently with each edge of the ensemble without the need for global control. As Figure 2 illustrates, edges can contract by consuming a hole or expand by creating a hole, purely under local control.

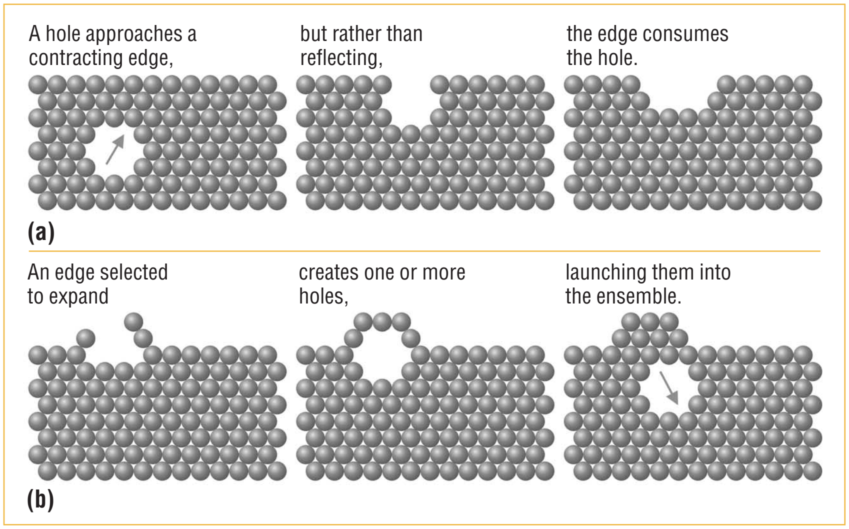

Figure 2. Hole motion. Edges can (a) contract by consuming a hole or (b) expand by creating a hole, purely under local control.

We initiate shape formation by "filling" the ensemble with holes. Each hole receives an independent, random velocity and begins to move around. A shape goal specifies the amount each edge region must either contract or expand to match a desired target shape.

A hole that hits a contracting edge is consumed. In effect, the empty space that constitutes the hole moves to the outside of the ensemble, pulling in the surface at that location. Similarly, expanding edges create holes and inject them into the ensemble, pushing its contour out in the corresponding local region.

Importantly, all edge contouring and hole motion can be accomplished using local rules, and the overall shape of an ensemble can be programmed purely by communicating with the catoms at the edges. Hence, we use probabilistic methods to achieve a deterministic result. Our initial analyses of the corresponding 3D case suggest surface contour control will be possible via a similar algorithm.

Our initial research results suggest it may be possible to construct, power, and control large microrobot ensembles to model 3D scenes. While many difficult problems remain, successful implementation of a dynamic physical rendering system could open the door to a new era of human-computer interface design and new applications.

Economic feasibility also poses a high bar to the manufacture and deployment of multimillion-robot ensembles. However, the innovative application of high-volume manufacturing techniques bridged a similarly large gulf in cost and physical scaling in computer hardware.

Achieving the Claytronics vision won't be straightforward or quick, but by taking on some of the problems associated with operating and building these ensembles, we hope to advance the state of the art in modular reconfigurable microrobotics and encourage others to undertake related research. ■

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