Computational Materials
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Toward Wirelessly Cooperated Shape-Changing Computing Particles

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***Abstract*—Widespread research is being conducted on computational materials. The challenge for the realization of computational materials is how to weave computers into everyday objects consisting of various shapes and form factors. One idea to achieve this vision is to build physical computational particles that can cooperatively communicate among others and thereby change the whole shape like clay. Wireless communication and power transfer are keys to making such computing particles happen. Thus, we introduce an approach to embody these particles using multiple tiny IC chips, which wirelessly cooperate with each other. This article shows the current state-of-the-art wireless communication and power transfer technologies integrated into IC chips to achieve fine-grained shape deformation of computers. Moreover, this article also presents recent trends and future directions in shape-changing human-computer interfaces research.**

CONTINUOUS PROGRESS in nanoscale manufacturing technology has led to the miniaturization of computers. Computers are embedded into each of the various edge/mobile devices around us and are wirelessly connected to each other to permeate our living space. This situation today gives us hope for the realization of a world of computing materials where unrecognizably small computers are woven into everyday objects [1]. We are particularly interested in the properties of these objects as shape-changing human-computer interfaces. As each everyday object becomes a direct interface between humans and the information world, we expect a new type of interaction that is not possible with existing static edge/mobile devices. By utilizing the human ability to grasp and manipulate, and by making the shape change of the object as an input from the user, the digital representations of the object can be manipulated and recognized physically and thus more intuitively. In addition, beyond physical input devices, the physical shape output of the objects in response to changes in the information is envisioned to achieve two-way and more seamless interaction between physical and digital worlds [2].

The challenge in realizing such a vision is how to implement computation in objects with various shapes and form factors. As a related example, a system in which multiple small components are wired together with mechanical connectors has been reported [3]. These systems consist of a collection of individual components and each component acts as a physical voxel to represent multiple types of shapes. However, these methods using uniform voxels and mechanical connectors have the disadvantage of limiting the feasible shapes of the system. Especially, they typically suffer from the temporal and smooth transition of the shape such as fluid, sand, clay, and plush toys that continuously change their shape. On the other hand, wireless sensor node technology is considered as a better choice to give computing voxels freedom to smoothly change its shape, because the shape of the joint is not restricted by the connector, and the issue of connector wear and tear is eliminated. By embedding small sensor nodes into objects and wirelessly composing a system, they realize various types of node distribution. The existing wireless sensor node systems, however, do not assume direct interaction with the user. Instead, it assumes the existence of a remotely located host computer as the interface with the user, and the vision of direct interaction through physical manipulation of objects cannot be achieved by mere miniaturization and performance improvement of such systems.

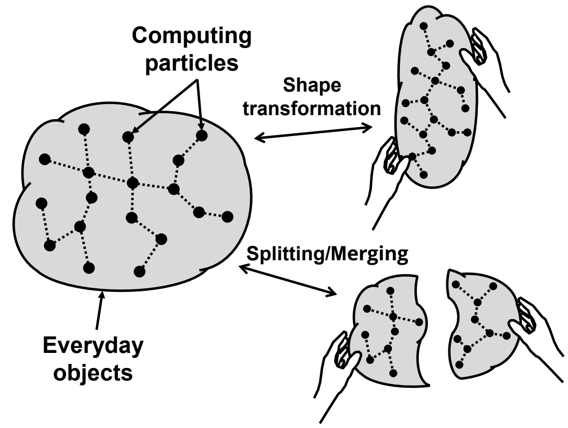

Figure 1. Everyday objects that act as user interfaces utilizing wirelessly cooperated shape-changing computing particles.

Therefore, we propose wirelessly cooperated shape-changing computing particles as a new concept that leads to the vision of computing materials (Figure 1). Herein, a huge number of small computers are embedded in everyday objects, and they can recognize each other through short-range wireless communication and freely change the overall shape of the system. The physical shape of the system is linked to the logical architecture of the system, and direct interaction between humans or the environment and the computing system is achieved through changes in the physical shape of the objects.

The differences between computing particles and existing wireless sensor nodes are the following: (i) particles interact directly with users and the environment without a host computer, (ii) particles actively communicate with each other and work as a massively parallel computer, and (iii) physical shape of particles is linked to the logical system architecture. The user manipulates the computer system by manipulating the shapes of objects as if they were clay. Particles embedded in the same object form a network and send and

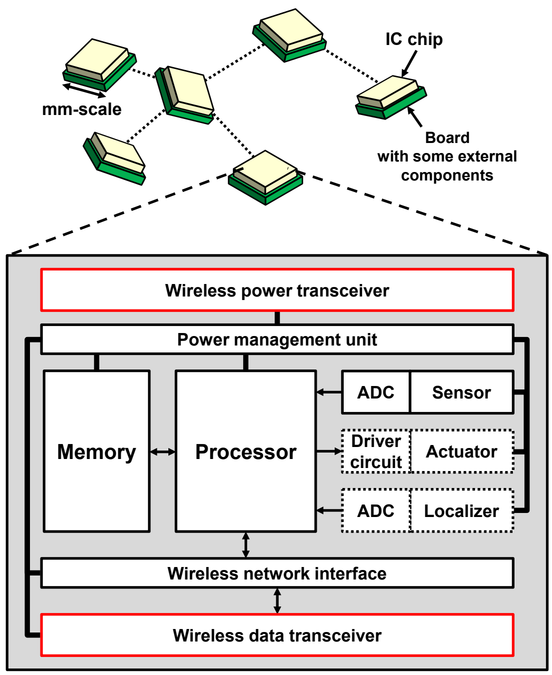

Figure 2. Architecture of computing particles.

receive data from each other to work as a single parallel computer system. When the shape of the object changes, the relative positions of the embedded particles also change, and the topology of the inter-particles network changes accordingly. The inter-particles network is also divided and combined according to splitting and merging of objects. For example, when a single object is divided into two parts, the single parallel computer system is transformed into two independent parallel computer systems. These characteristics enable efficient data routing between particles and intuitive interaction between the user and the computer.

Figure 2 shows the architecture of the computing particles. In addition to the standard components of an embedded computer, it has wireless communication circuits and wireless power transmission circuits. These are discussed in detail in later sections. Depending on the application, the system may be equipped with actuators to interact with humans and the environment through autonomous shape changes. Although this system can localize the relative positions of the particles to some extent by measuring the received signal strength (RSS) of wireless communication, some applications require more detailed relative position detection. In such cases, a localizer can be additionally installed.

In order to realize the cooperative behavior of a huge number of small computing particles and interaction between humans and computers using them, the following three points are challenging: (i) Communication, (ii) Powering, and (iii) Interaction. It is difficult to install antennas for wireless communication on small particles, and the performance as a parallel computer is limited by the performance of communication between particles. It is also difficult to supply power to multiple tiny particles. Performance and operation time are limited by the power supplied to each particle. In addition, the interaction methods between particles and humans are very different from those with conventional mobile and desktop computers. In the following sections, we discuss state-of-the-art research results on wireless communication technology, wireless power transmission technology, and shape-changing user interfaces to meet these challenges. Also, open research issues and future technology development guidelines are presented.

COMMUNICATION AMONG COMPUTING PARTICLES

By connecting multiple small particles and constructing a system collectively, multiple system shapes can be realized. However, the resulting shapes are limited when we use physical connectors. Moreover, the change in shape is accompanied by issues such as wear and tear of the connectors. Wireless connection between particles, on the other hand, does not limit the shape of the connection between the particles and allows them to freely change their relative positions.

The needed features for inter-particle wireless communications are as follows: (i) numerous particle-scale devices placed in close proximity can be connected, and (ii) sufficiently energy-efficient communications can be achieved. The size of an antenna is required to be small enough to be mounted on a tiny particle. An energy-efficient communication method is desirable to satisfy the performance and power constraints. We examine three promising wireless communication methods: 2.4 GHz band microwave, mm-

Table 1. Comparison of methods for wireless communication among computing particles.

Method	Strength	Weakness	Use cases
Microwave (2.4 GHz band)	• Low power consumption (several mW) • Long range (above several tens of meters)	• Large off-chip antenna (cm-scale) • Low data rate (up to several tens of Mbit/s) • Dielectric loss	• Low-power sparse particles working in free space or low dielectric materials
mm-wave	• Small on-chip antenna (below mm) • High data rate (several tens of Gbit/s) • Long range (above several tens of cm)	• High power consumption (~hundred mW) • Dielectric loss	• High-performance sparse particles working in free space or low dielectric materials
Magnetic coupling	• Small on-chip antenna (below mm) • High data rate (several Gbit/s) • Penetrates dielectrics	• Short range (~antenna size)	• Dense particles working in various mediums (*e.g.*, free-space, dielectrics)

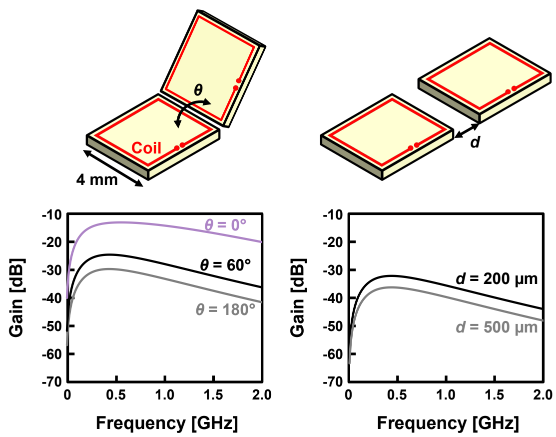

Figure 3. Magnetic coupling characteristics of on-chip antennas.

wave, and magnetic coupling. Table 1 summarizes the strength, weakness, and applicable use cases for these methods.

The 2.4 GHz ISM band wireless communication is used to connect multiple computers with low power consumption. This method has been adopted by the standards such as Bluetooth and ZigBee. The disadvantage of this approach is that it requires an antenna of the order of centimeter that resonates with the carrier wave. Although it is possible to reduce the physical dimensions of the antenna to some extent by shortening the electric length and devising the three-dimensional structure, this method hinders miniaturization [4]. Another disadvantage common to the methods utilizing radiated electromagnetic waves is losses caused by dielectric materials.

Mm-wave wireless communication methods provide a high data-rate connection. Also, the antenna size is reduced due to the use of shorter wavelength carrier waves, and the wireless communication circuit and antenna can be integrated in a single IC chip [5]. The weakness of this method is the high peak power consumption associated with the high-speed operation of the transmitter and receiver circuits. In addition, as in the previous example, dielectric loss occurs due to the use of radiated electromagnetic waves.

Magnetic coupling methods use near-field coupling for transmitting broadband signals. Unlike the methods based on carrier waves described above, it utilizes electromagnetic coupling between antennas placed in a short distance. Because there is no need for antenna resonance, the antenna can be miniaturized and integrated in an IC chip. An example of high data-rate wireless communication has been shown in [6]. However, due to the use of magnetic coupling in the near-field domain, the communication distance is limited to approximately the same size as the antenna. Therefore, it is difficult to apply it to the systems where the distance between particles is relatively far.

We examined the feasibility of the magnetic coupling method as a case study. Electromagnetic field simulations were conducted using Keysight Momentum and EMPro. The antenna is a 2 turn, 4 mm square, spiral coil, assuming installation to a 4 mm square IC chip. Figure 3 shows the simulation results. We evaluated the change in coupling characteristics according to the relative angle and relative distance between the particles. These graphs show that the magnetic coupling is weak when the coils are located side-by-side. Even in such a case, a gain of more than −40 dB is achieved over a wide frequency range, making wireless communication feasible. SPICE simulations of the transceiver circuit were performed assuming the use of 0.18-μm CMOS IC technology and the horizontal communication distance of 200 μm. The maximum transfer rate was 1.2 Gbit/s, and the power consumption was 7.4 mW for the transmitter circuit and 2.7 mW for the receiver circuit. It has been reported that the transfer rate improves with the miniaturization of the antenna and CMOS transistors [6]. Therefore the communication performance improvements are expected as the size of the particle continues to decrease.

In general, the methods using carrier waves are suitable for connecting relatively sparse particles, while the method using near-field coupling is suitable for connecting densely packed particles. In the future, it will be desirable to design and develop network protocols and parallel system architectures for computing particles based on each wireless communication method.

POWERING COMPUTING PARTICLES

Typical computers use power cords or batteries for supplying power used for computation. However, stably interfacing a great swarm of particles via cables or bulky batteries is not practical. Thus, we regard wireless power transfer as a promising approach because it can power numerous devices without physical connections.

The needed features for empowering computational materials are the following: (i) numerous computing particles composing everyday objects can be powered, and (ii) sufficient power can be transmitted without harming ambient people. The actuators are often the dominating components that determine the power requirements and the necessary peripheral driver circuits. For instance, we could integrate micro-scale electrostatic attach-detach actuators [8] into the particles by appending high-voltage generators based on small charge pump circuits. These actuators operate with 50 V input and only consume a small amount of energy (*i.e.*, current) when the attach-detach state between adjacent particles changes.

In terms of system design, two approaches exist for empowering such swarms of particles. One is to directly charge all particles, including non-line-of-sight particles (Fig. 4(a)), and the other is to power the visible particles and internally pass down power to the rest (Fig. 4(b)) [3]. While the former approach needs the power supply to penetrate the substrates and other particles, it only requires the particles to equip power receivers. Meanwhile, the latter architecture needs additional hardware (*i.e.*, power emitters, batteries) for supplying power to peripheral particles. These architectures must be selected, considering the power supply's physical properties.

Energy can wirelessly transfer via various physics, such as electromagnetic radia-

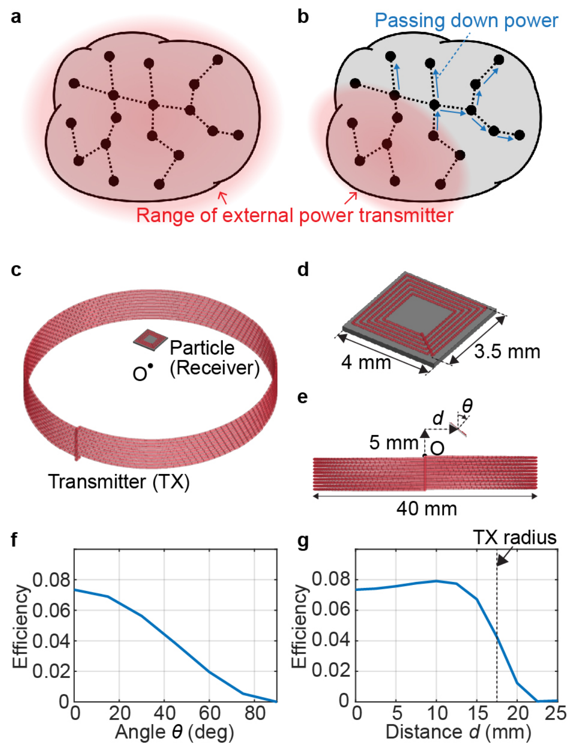

Figure 4. (a, b) Power supply architectures for powering a cluster of computing particles. (a) Directly powering all particles and (b) powering the reachable particles and internally passing down power to the rest. (c-g) Evaluations for transferring power to computing particles. (c) Overview, (d) zoom view of the particle, and (e) side view. (f, g) Simulated power transfer efficiency with varying (f) angle and (g) distance, using the parameters in (e). For attaining realistic values, we assumed that the load impedance value could be converted to value from 10 Ω to 1 kΩ, following the discussions in [7].

Table 2. Comparison of methods for wirelessly powering computing particles. Note that the power levels strongly depend on the specific situation. (LOS: line of sight)

Method	Strength	Weakness	Use cases
Optical	• Long range (up to meters) • Small receiver size (mm-scale) • Penetrates transparent mediums	• Requires LOS (blocked by opaques) • Heat issues due to conversion loss	• Low power particles working in free space or within transparent objects
Microwave	• Long range (up to meters)	• Requires LOS (blocked by dielectrics) • Receiver size must be in the same order as the wavelength • Low power due to safety concerns and low efficiency (~mW)	• Ultra-low-power particles working in free space
Mid-field	• Small receiver size (mm-scale) • Transfers through dielectrics	• Short range (several cm) • Only works within specified dielectrics • Low power due to safety concerns and low efficiency (~mW)	• Ultra-low-power particles working in dielectrics (*e.g.*, underwater)
Magnetic resonance coupling	• Small receiver size (mm-scale) • Does not require LOS (penetrates dielectrics) • High power due to small interference with tissue (~hundred mW)	• Short range (several cm)	• Particles working in various mediums (*e.g.*, free space, dielectrics) • Uniformly powering nearby particles, including those within the cluster

tion (*i.e.*, microwaves), light emission, electromagnetic induction, etc. These basing physics are similar to wireless communication. However, power transfer was developed via different routes because the significantly different power-levels cause unique challenges (*i.e.*, heating issues, safety, rated current/voltage). Table 2 summarizes the strength, weakness, and applicable use cases for the promising approaches in powering computing particles.

Microwave-based approaches use electromagnetic waves radiated from antennas [9], and optical methods use the light emitted from laser diodes. Because wave physics governs these approaches, they support long powering ranges. However, the high-frequency operation needed for propagation occurs interference with biological tissue and daily objects. Mid-field approaches use electromagnetics field between the far-field and near-field domain; this approach actively leverages the interaction with the surrounding dielectrics for focusing energy to the implanted devices much smaller than the wavelength [7]. However, this approach can not deliver high power levels due to the interaction with biological tissue. Besides, these systems need to be "ingenuity" designed for each situation because most approximate formulas assuming near-field and far-field behavior are not applicable. Wireless power transfer via magnetic resonance coupling, a near-field approach, incorporated resonant conditions into inductive power transfer for extending powering range [10]. Magnetic field hardly interacts with dielectrics; thus, this method can deliver high power levels without harming people and supports power transfer in non-line-of-sight situations. However, because this approach bases on near-field, the powering range is still narrow because the captured magnetic flux ratio to the emitted flux needs to be large for efficient powering. Thus, methods for extending range are actively explored; examples of this direction includes (a) using a 2-D array of multiplexed transmitters and (b) efficiently generating 3-D magnetic fields using cavity-based transmitters [11].

As a case study, we examined the feasibility of the magnetic resonance coupling approach. We conducted simulations using Altair FEKO, an electromagnetic field simulator based on the method of moments (MoM). Fig. 4(c-e) shows the simulation setups; the transmitter is a 10 turn, 40 mm diameter helical coil, and the receiver is a 5 turn, 3.5 mm square, spiral coil, assuming installation to a 4 mm square particle. We modeled the transmitter and receiver coils using ϕ 0.5 mm and ϕ 0.1 mm copper wires; we appended lumped capacitors for tuning the resonant frequency to 13.56 MHz (ISM band). The random positioning of computing particles (Fig. 2) introduces angular and lateral misalignment; thus we evaluated transfer efficiency with varying angle θ (Fig. 4(f)) and lateral distance d (Fig. 4(g)). These graphs show that the efficiency exceeds 5% in most setups, meaning that assuming a 1 W input, it will supply over 50 mW, which is sufficient for many computation tasks (note that the low power Qi standard, which rides on similar physics, inputs over several Watts). Although we can observe efficiency drops in misaligned conditions, equipping multiple orthogonal arranged coils would compensate for the angular misalignment. Furthermore, transmitter arrays can prevent efficiency drops associated with lateral misalignment because Fig. 4(g) shows that the transmitter coil can empower the area on top of itself.

Generally, the power transfer performance degrades as the receiver scales down, making the powering of computing particles challenging. Thus, a perfect method does not exist yet, and further investigation is needed to overcome this scaling problem. This advancement involves improving the physics, lowering the power demand of the computing systems, and system-level development to assist seamless power delivery. Our Luciola project [12] is one example of such interdisciplinary advancements, which demonstrates a millimeter-scale light-emitting particle moving in mid-air. This project's key was to incorporate wireless power and custom-designed IC chips to overcome various power/form-factor related challenges.

HUMAN-COMPUTER INTERACTION WITH PARTICLES

Up to now, researchers have been exploring shape-changing human-computer interfaces mediated by physical collective elements [13]. Here in this section, we classify them into three categories as shown in Figure 5: voxels tethered to a surface, swarms, and computing particles "dispersed" into other everyday objects, and introduce and compare each category by referring to related projects.

	Voxels	Swarms	Particles
Unit length	~ 10 cm	~ 1 cm	~ 1 mm
Computing	Uncomputable	Individual	Parallel
Communication	Master-slave		Distributed
Power	Tethered		Wireless

Figure 5. Comparison of three types of collective shape-changing user interfaces: voxels, swarms, and particles. Note that we listed the properties of particles based on what we expect them to have.

One of the most popular strategies used for shape-changing interfaces is a voxel-based pin display [14] that controls the height of each pin from a flat surface by linear mechanical actuators to render a "2.5-D" shape (*i.e.,* 3-D surface extruded from a 2-D plain) of objects. The benefit of this strategy is that the system can rely on rich hardware and software behind the surface, for both input and output shape change with relatively faster and stronger actuation. However, it also means that they always need to be tethered to a surface to communicate with a central computer and to receive driving power, and the voxels themselves are uncomputable. Also, each voxel cannot move beyond the unit's boundary of the matrix structure.

After the intensive studies on voxels connected to a surface, some researchers focused on an alternative approach of swarm user interfaces composed of centimeter-scaled self-locomotive robots, inspired by the recent results in the field of swarm robotics, such as Kilobots [15] that can locomote by vibration and collectively form a certain 2-D shape in a decentralized way. For example, Zooids [16] is a user interface with several swarms running on a 2-D desk. The central system tracks the position of swarms with a projector and sends next motion signals. Under the control, swarms show different interaction modalities such as drawing curves and areas, working as input devices like a mouse, and moving other objects. Similarly, another group developed the swarm interface system using several hand-held drones to achieve 3-D motion [17]. These swarms have a merit of higher degree of freedom for their collective shape and shape change along with the ability to compute. However, there are in general two technical issues that the swarm user interfaces have to overcome for practical use: (i) recharging batteries inside each swarm need more and more efforts as the number of swarms is increased; (ii) the communication system relying on line-of-sight visibility (*e.g.*, projection) would suffer from occlusion issues when the swarms are jammed like clay. These two issues prohibit swarm user interfaces from forming 3-D shapes and getting smaller to the scale of "particles" as depicted in the "Things vs. Stuff" figure of [16].

Thus, distributed wireless communication and wireless power transfer as we discussed in the previous sections will become crucial when computing elements become a large cluster of particles small enough to be embedded into our everyday objects, as summarized in Figure 5. On the other hand, what becomes possible if we have computing particles that can compute, wirelessly communicate and receive power, and sense (and optionally drive) shape change? We envision that such shape-changing computing particles can be literally dispersed into other materials to build a "computable composite." For example, if we hope to have a clay user interface (as shown in Figure 1) that can occasionally compute and sense its shape including splitting and merging manipulation, we can disperse the shape-changing computing particles into self-healing materials [18] such as hydrogels that repeatedly heal their mechanical failure. Nowadays, we have also access to diverse functional materials that can control, *e.g.,* their color, stiffness, material phases, etc. We foresee that shape-changing computing particles blended into such functional materials make our everyday objects computable and self-aware. Especially, computing particles dispersed into deformable materials (e.g., elastomers and liquid) will enlarge the design space of input methods for non-rigid interfaces [19], which is under-estimated so far compared to the shape output.

Another interesting application of such computing particles is for rapid yet reusable fabrication of diverse shapes. Currently, researchers are making efforts to connect a digital design and a physical object by means of rapid prototyping. For example, Shape-Aware Material [20] allows users to cut a physical sheet of paper to design a 2-D shape on the computer screen; the shape of the disposable paper after cut is recognized by the computers by measuring capacitance values of the printed conductive traces on the paper. In case of clay with dispersed computing particles inside, it will work as a physical version of a free-form modelling tool that is connected to digital information. Also, if we can implement a tiny actuator on each particle, clay by itself is able to modify its shape digitally (or "perfectly") as envisioned in [2]. Additionally, because each particle does not deform during shape change of the whole structure, it will be reusable by removing clay or any other "solvents" that disperse the particles. Thus, such shape-changing computing particles will also open up the rapid design process of diverse shapes in more reusable and sustainable way. At this point, we can say that the shape fabrication and the shape display are almost identical.

CONCLUSION

We introduced wirelessly cooperated shape-changing computing particles, a new concept of embedded computer systems which leads to the vision of computational materials. The key factors of realizing the concept were discussed, and current issues and future directions for wireless communication technology, wireless power supply technology, and human-computer interfaces were examined. We hope to advance research on each area and someday touch the surface of the digital world through everyday objects.

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