Being There

from rapid prototyping to dynamic physical rendering

EXECUTIVE SUMMARY

Someday relatively soon, dynamic physical rendering – also called "claytronics" – could enable an array of savings in money, time, and even lives. Engineers will be able to send their claytronic replicants into the control rooms of hurricane-battered offshore rigs while remaining safely on shore themselves. Firefighters will not need to risk their lives if they can send their claytronics doubles into burning buildings to search for trapped people and pets.

Business people will be able to cross oceans and time zones for "in person" meetings without ever leaving home. Houses and skyscrapers will be designed in three dimensions instead of flat drawings, as will cars and airplanes. The potential uses of dynamic physical rendering are only beginning to become apparent – other applications surely will occur to the smart people who are working hard to make the technology useful, commonplace, and accepted in business and other applications.

Although dynamic physical rendering is still 20 years in the future, it has two precursor technologies. The first is rapid prototyping – available now. The second is called 3D faxing, which will arrive on the business scene in perhaps a decade – about ten years sooner than copies of human beings. Rapid prototyping and a related technology called 3D printing are used to build everything from machine parts to orthotics and other medical applications. 3D faxing will deploy many millions of sub-millimeter catoms (claytronic atoms) to produce the desired object. Eventually, dynamic physical rendering will take the next logical step to produce self-actuated synthetic reality – copies of people.

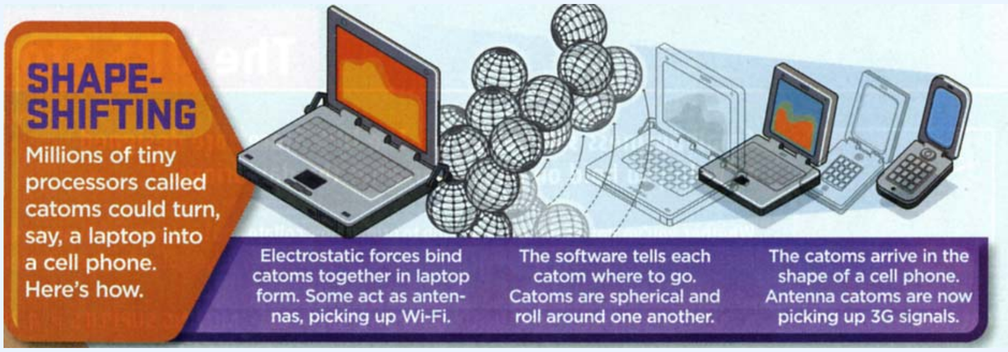
Read on to discover why you care about these three technologies – especially the synthetic reality that will be created through dynamic physical rendering. If researchers at Carnegie Mellon and Intel are correct, this technology surely will cause a paradigm shift in business, science, and politics.

INTRODUCTION

Somewhere in a Carnegie Mellon laboratory, tiny machines dance gingerly around each other, occasionally tapping together and springing apart again. Although it sounds like grad student fun and games, the implications of this research are profound. Partnering with scientists from Intel, researchers at Carnegie Mellon work toward the fast approaching day sometime in the next two decades when "the 3-D fax machine brings back the house call" with visits from synthetic doctors (Goldstein, 2005).

FIGURE 1

Even if claytronics doesn't immediately yield 3-D motion, it might be useful for producing 3-D shapes in the computer-aided design process...claytronics antennas could change shape to improve reception of different radio frequencies. A Claytronics cell phone might grow a full-size keyboard, or expand its video display as needed. It could be the ultimate Swiss Army knife.



Their technology is known variously as programmable matter, claytronics, dynamic physical rendering, or synthetic reality. Its genesis was a marriage between the idea of "smart dust" from the field of nanotechnology and some fundamentally new ideas about "catoms" – short for claytronic atoms. According to Seth Goldstein (Carnegie Mellon Claytronics Project researcher) and Todd Mowry (also a Carnegie Mellon claytronics researcher, and Director of Research at Intel), this research represents a disruptive technology that will solve "some of the most challenging problems we face today: how to build complex, massively distributed dynamic systems" (Goldstein & Mowry, 2004).

Carnegie Mellon researchers have coined the term "pario" to describe this radically new medium. Conceptually, just as audio reproduces sound and video reproduces live action, pario will take the next logical step to "render physical artifacts with such high fidelity that our senses will easily accept the reproduction for the original" (Goldstein and Mowry, 2004). In other words, these researchers plan for the state-of-the-art in 20 years to be someone you can see, hear, touch, and interact with as if s/he were standing next to you – even though the real person might be thousands of miles away.

Of course, we are not there yet. Rapid prototyping technology is the state of 3D replicant art today. Yet, rapid prototyping is not merely a conceptual ancestor to synthetic reality; it supports design precision and saves substantial time and money over traditional manufacturing techniques. Moreover, its contributions to the medical field are revolutionary.

RAPID PROTOTYPING

The basic technology for rapid prototyping consists of computer aided design (CAD) drawings that instruct a prototyping machine to build a 3-D model of an engineering design (example in Figure 2). Rapid prototyping first was developed in the 1980s. In its early iterations, the prototypes were exactly that – models of machine parts or other devices that a distant customer could examine and manipulate. Today, rapid prototyping has progressed to an array of applications that include manufacture of parts intended for production, artistic renderings, and most recently, bio-medical constructs. Figure 3 lists most of the rapid prototyping systems and materials available today.

FIGURE 2

FIGURE 3

Proto-Technologies	Base Materials
Selective laser sintering (SLS)	Thermoplastics, metals powders
Fused Deposition Modeling (FDM)	Thermoplastics, Eutectic metals.
Stereolithography (SLA)	Photopolymer
Multi Jet Modeling (MJM)	Photopolymer
Laminated Object Manufacturing	Paper
Electron Beam Melting (EBM)	Titanium alloys
3D Printing (3DP)	Various materials
Objet PolyJet Modeling	Photopolymer

Unfortunately, the “rapid” in rapid prototyping is somewhat of a misnomer. The process requires either CAD or animation modeling software to create virtual layers of a design and then transpose the layers to physical materials inside a very large and expensive prototyping machine (see Figure 4). Depending on the technology selected, machines cost anywhere from $5000 to over $1 million, with predictable sacrifices (low end) or enhancements (high end) to the finished product. The process may take from hours to days for complete rendering of each unit. For example, depending upon the methodology and materials, additive fabrication (known in the industry as AF) may require relatively longer periods for layers of production powder to dry and adhere to the material deposited with each subsequent pass of the machine.

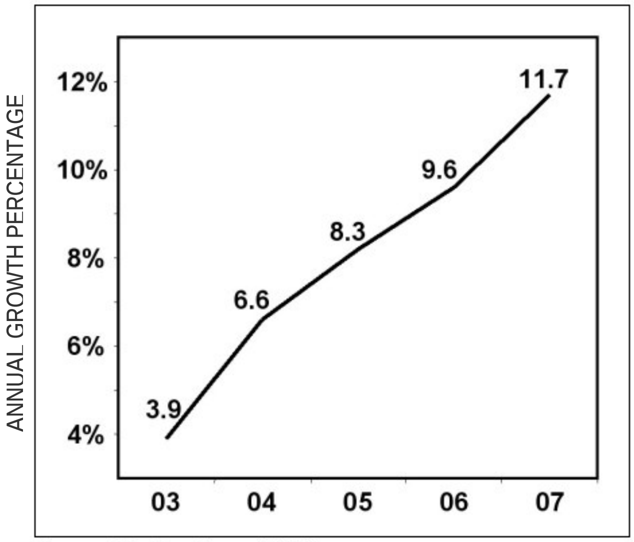
FIGURE 4

A rapid prototyping machine using selective laser sintering.

Nonetheless, rapid prototyping is growing in both use and interest. “The real key to rapid manufacturing is the elimination of molds, dies, and other forms of tooling, and the consequent eradication of manufacturing restrictions that tooling presents. Other than the time and cost savings that occur, a host of benefits are created that are only now being explored and understood” (Wohlers Associates, 2007). Although the clearest benefit of rapid prototyping likely will remain in the manufacturing arena, the technology has additional implications for supply chain management and related manufacturing processes. Moreover, “RP” appears likely to gain momentum in certain restorative medical technologies, such as joint replacements and orthotics that can be more precisely manufactured to fit a patient, yet cost less than current methods. Figure 5 graphically illustrates rapid prototyping growth in industry over the past four years alone.

FIGURE 5

Growth of Rapid Manufacturing



Source: Wohlers Report 2007

One of the least expensive methods of RP is also garnering the most attention – 3D printing. Unlike most of the other rapid prototyping technologies, 3D printing offers the advantages of lower cost, faster “prints,” and comparatively simple setup. These advantages make 3D printing attractive for many types of designers since they can view their designs in three dimensions through successive stages of the design process. Like other rapid prototyping technologies, 3D printing is creating a buzz in the medical research community as well, especially for its capabilities related to the new fields of tissue engineering and (literally) organ printing. These developing technologies will use 3D printing to combine a base matrix with human cells and thereby create replacement organs in lieu of organs from donors. Although such uses “aren’t ready for prime time” just yet, this research stream alone makes rapid prototyping an exciting field to contemplate.

FIGURE 6

Models of skulls and heads of conjoined twins produced by 3D printing to guide surgeons during separation of the twins. *Montefiore Medical Center/Medical Modeling LLC*

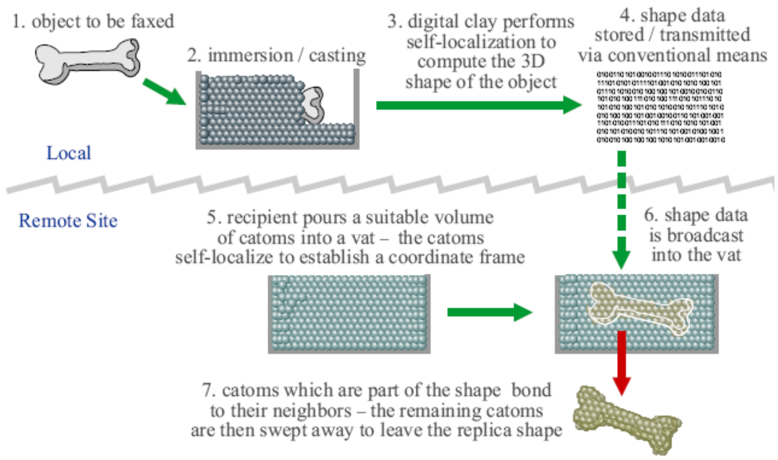
3D FAX MACHINE

The 3D fax machine currently under development at Carnegie Mellon University represents a significant *technological* advance over 3D printing or any other rapid prototyping technology. The *cognitive* leap from 3D printing to 3D faxing is nothing short of startling.

To begin with, there is no huge machine involved with 3D faxing. The “machines” are sub-millimeter sized microrobots with no moving parts. These robots, or “catoms” (claytronic atoms) will work not because of individual “brains,” but because taken together in an array of millions and directed by appropriate software (also under development), the catoms form an “ensemble” to create the three-dimensional facsimile (Pillai et al, 2006). Figure 7 illustrates the process. Another major advance of 3D faxing with catom ensembles is that the “copy” replicates the “original” in parallel time.

Although 3D faxing with catom ensembles is not yet available, developers at Carnegie Mellon project “go live” sometime within the next ten years. The technology will precede the dynamic physical rendering described in the next section by at least another decade. This is because unlike dynamic physical rendering, 3D faxing as envisioned does not require actuation and motion, which “are challenging aspects of modular robotic systems, not only because of the size and required strength of the actuators but also because of the complexity of planning and controlling their use” (Pillai, et al, 2006). In a word, it is less challenging to design and build a static array than one with the abilities to “self-reconfigure or move” (ibid).

FIGURE 7



An overview of the 3D fax scenario

Nonetheless, the technological roadblocks to 3D faxing make for a very bumpy road ahead. To date, Carnegie Mellon simply does not have a sufficient number of larger-scale, functioning microrobot models even to test the technology at this stage. Building these models will take several more years. However, the researchers have been able to test the algorithms behind their theories using simulations. To date, every test has been successful. The research team readily admits that simulations cannot foresee every challenge – this can occur only through repeated testing of the physical ensembles. The simulations *can* validate much of the theory and algorithms, and also lay the path for more research. In fact, these are the researchers’ intermediate goals.

As is the case with faxing documents, 3D faxing will occur in three steps: acquisition, transmission, and reproduction (Pillai et al, 2006). Any similarities to document faxing end there. Even comparisons to other, current technologies for 3D renderings become irrelevant at this point. “Raster” scanning techniques only work in very slow sequence; the input occurs via sampling passes on the sender side followed by layering passes on the receiver side. Resolution depends on slower scan rates with additional sampling.

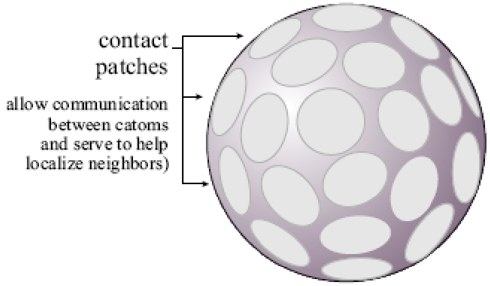
FIGURE 8

AUTOMOBILE DESIGN USING CLAYTRONICS

3D faxing reduces or eliminates these issues. Since 3D faxing with catom ensembles can occur in parallel, results will take only as long as the sender “scan.” This “scan” can come from any number of sources, the fastest of which will be by means of catom ensembles on both ends of the transmission.

Essentially, the object on the sender side gets immersed in a “bucket” of catoms. “If an object is completely embedded in a claytronic ensemble, then [any] regions without particles will correspond directly to the volume occupied by the object” (Pillai et al, 2006). The catom ensemble “knows” how to form and keep the required shape by means of software-directed electrostatic contact points (Figure 9). As noted, the sending information does not have to originate with an actual three-dimensional object; “faxed” inputs can include any one of several formats, including CAD drawings. Whether the sender provides information via a

FIGURE 9



Contact points on the surface of a module / catom "bucket" of catoms or electronic drawings, the catom ensembles on the receiving end will handle it and reproduce its output in real time instead of hours or days.

The future implications of 3D faxing go well beyond reproducing widgets or even creating biomedical devices. As mentioned, the researchers at Carnegie Mellon, believe that by sometime around the year 2029, "the 3D fax machine [will bring] back the house call" (Goldstein, 2005).

DYNAMIC PHYSICAL RENDERING

The bridge between 3D faxes and dynamic physical rendering (the technology that puts the "doctor" in the sickroom while the real doctor remains in his office) is programmable matter – the aforementioned catom ensemble. Once fully realized, researchers expect the technology to "create a physical artifact that will mimic the shape, movement, visual appearance, sound, and tactile qualities of the original subject" (Goldstein and Mowry, 2004).

The two variables that are not required for 3D faxing – actuation and motion – must become very much "present and accounted for" to accomplish dynamic physical rendering. Each catom in the pario ensemble will be "a self-contained unit with a CPU, an energy store, a network device, a video output device, one or more sensors, a means of locomotion, and a mechanism for adhering to other catoms" – all this with no moving parts (Goldstein and Mowry, 2004). Figure 10 provides a brief primer to explain the researchers' conception for dynamically rendering human beings.

FIGURE 10

For example, suppose we wish to synthesize a physical "copy" of a person. The catoms would first localize themselves with respect to the ensemble. Once localized, they would form an hierarchical network in a distributed fashion. The hierarchical structure is necessary to deal with the scale of the ensemble; it helps to improve locality and to facilitate the planning and coordination tasks. The goal (in this case, mimicking a human form) would then be specified abstractly, perhaps as a series of "snapshots" or as a collection of virtual deforming "forces", and then broadcast to the catoms. Compilation of the specification into local actions would then provide each catom with a local plan for achieving the desired global shape. At this point, the catoms would start to move around each other using forces generated on-board, either magnetically or electrostatically, and adhere to each other using, for example, a nanofiber-adhesive mechanism. Finally, the catoms on the surface would display an image; rendering the color and texture characteristics of the source object. If the source object begins to move, a concise description of the movements would be broadcast allowing the catoms to update their positions by moving around each other. The end result is the global effect of a single coordinated system.

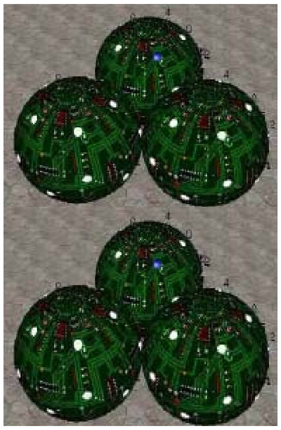
The synthetic reality thus produced will not need a Star Trek® "Holodeck" or even the special head and hand gear presently required for virtual reality interfaces (think Tom Cruise in the science fiction movie *Minority Report*®). Instead, "claytronics envisions multi-million-module robot ensembles able to form into three dimensional scenes, eventually with sufficient fidelity so as to convince a human observer the scenes are real" (Kirby et al, 2005).

Here is some of the early science behind the future reality. The claytronics researchers at Carnegie Mellon devised four major design principles: (1) each catom in an ensemble must be completely self-contained in terms of its "computation, communication, sensing, actuation, locomotion, and adhesion" to contiguous catoms; (2) once catoms adhere, continued adhesion must not require static power of any kind (this is necessary to "support efficient routing of power and avoid excessive heat dissipation"); (3) catoms must perform by means of local control (no external computing); and (4) catoms have no moving parts (Kirby et al, 2005).

Since 2005, advances have accelerated. They include (but are not limited to) the development of Meld, a programming language specific to large-scale robot arrays. With Meld, the researchers believe that they can solve many of the issues inherent to programming huge ensembles of robots (including the aforementioned problem of building and operating "complex, massively distributed dynamic systems" (Goldstein & Mowry, 2004). Next up: Carnegie Mellon researchers must produce sufficient 1-millimeter catoms to test the research in physical reality. A few billion should do, to start.

FIGURE 11

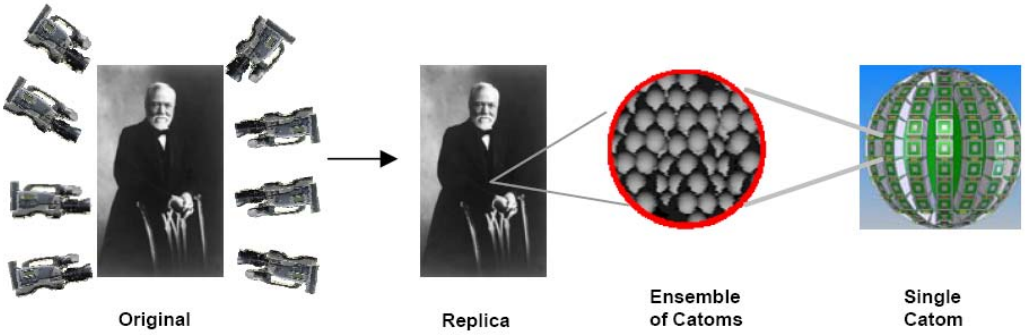
The making of the first batch of 1-millimeter catoms promises to be the equivalent of the Big Bang for the claytronics universe. For the first time ever, electronic information would form objects and interact with users of the information without the need for a "box"—such as a video display—to contain the message.



APPLICATIONS AND ISSUES

Clearly, dynamic physical rendering constitutes disruptive technology even in this early period of development. The continuum of HCI (human computer interface) from the earliest “world wide wait” days to palpable, believable representations of human beings twenty years from now represents a steep climb, to be sure. However, new technologies tend to gain momentum as they develop. Telephony required 20 years to progress from hefty “suitcase” mobile telephones to the iPhone™ – but most of the bells and whistles we accept as normal in our cell phones today hit the market at a rapidly accelerating pace during only the last 5-7 years.

FIGURE 12



Creating a claytronics replica from a 3D image

If we accept that dynamic physical rendering is coming relatively soon to an office near you, what are the implications? At first glance, being able to “reach out and touch someone” like never before is an alluring concept. After all, “old fashioned” videoconferencing is a bit like “visiting someone in prison…you talk through a glass wall, but you can’t deal with each other in a meaningful way” (Yen, 2007). The savings in corporate travel will be a boon to many companies, but clearly a bane to the airlines that depend on full fare business travel for a significant proportion of their revenue streams.

In the medical field, “surgeons could enter a room-size reproduction of a patient’s beating heart and perform repairs, which would be transmitted to tiny instruments embedded inside the patient’s body, where the actual work would be performed” (Intel, 2005). Even the least paranoid among us easily makes the mental leap from life-saving micro-surgery to destructive or even deadly applications. For example, it turns out that DARPA (Defense Advanced Research Projects Agency) is an “interested party” in the research.

In fact, the most mundane application of dynamic physical rendering – entertainment – still carries with it a downside. How much fun would it be to watch your favorite college team play its homecoming game on your living room coffee table? Yet, if too many fans stay home, college endowments could go down as ticket income and televised game proceeds diminish.

CONCLUSION

In his book *Forbidden Knowledge*, Roger Shattuck rationally notes that “Science is neither a sin nor a grail” (1996, p. 224). It may at best be overly cautious and at worst backward to contemplate restraints on research beyond those the researchers impose on themselves. On the other hand, as Shattuck goes on to say, “the free market may not [always] be the best guide for the development of knowledge” (ibid, p. 225). Dynamic physical rendering constitutes important research toward a barely imaginable future. The technology is both exciting and full of possibilities. As such, it is incumbent on us all to watch its development – carefully.

Claytronics Project Research Team at Carnegie Mellon University

FIGURES

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Figure 10: *A primer to explain the researchers’ conception in the case of dynamically rendering human beings.* From Goldstein, S. and Mowry, T. In Claytronics: A Scalable Basis for Future Robots.

Figure 11: *The making of the first batch of 1-millimeter catoms promises to be the equivalent of the Big Bang for the claytronics universe.* From Plummer, J. Sci-Fi reality: Carnegie Mellon University and Intel are at work to create 3-D representations of people and objects through the magic of claytronics.

Figure 12: *Creating a claytronics replica from a 3D image.* From Intel Corporation. Intel research Pittsburgh: Delivering results, shaping the future.

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