

Solid Free-Form Fabrication For Self-Sustained Robot Ecologies: Challenges And Opportunities

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Summary: *We report on ongoing investigations of the potential for Solid Free-form Fabrication (SFF) processes to autonomously manufacture entire fully functional complex electromechanical systems, and of the application of such technology to a self-sustained robot ecology. Two complementary approaches are considered: (a) A universal fabrication system capable of autonomously manufacturing arbitrary machines, and (b) a parsimonious fabrication process that can achieve arbitrary functionality by redesign.*

Extended Abstract

Solid Free-form Fabrication (SFF) is the term currently used to describe the class of manufacturing technologies, formerly known as Rapid Prototyping technologies, that includes fused-deposition modeling (FDM), stereo-lithography (SL), selective laser sintering (SLS), shape deposition modeling (SDM), laser engineered net shaping (LENS), selective area laser deposition (SALD) and others. These processes are distinguished from traditional fabrication processes such as molding, casting, or machining, by involving the addition of material to the work piece during fabrication, usually in thin strata. This allows such processes to construct parts of almost arbitrary geometry. The vast majority of uses of current SFF technology is in the communication of design information, design visualization, and injection-mold tooling production. With a realistic model of a part in hand, however, it is natural to want to use it, thus giving birth to the idea of "functional rapid-prototyping". There is significant development effort and notable success already in improving the durability and functionality of the parts produced by these processes. Some of the most recent innovations allow the fabrication of fully dense metal parts that are, apart from surface finish, comparable or superior to cast or machined parts, but in geometries that are impossible to cast or machine in a single piece (Griffith *et al*, 1996). Other processes have been developed which can fabricate and weld ceramic and cemented carbide parts (Marcus *et al*, 1998). Piezo-ceramic actuators that include conductors and other materials have been fabricated via an FDM-plus-thermal-densification process (Safari *et al*, 2000). Processes are being investigated which can write electronic components directly to the surface other structures (Williams *et al*, 2000), even high-temperature intolerant materials, such as plastics (Barrow, 1997). SFF optics based on sintered glasses are also being investigated (Barrow, 1997). Clearly the range of materials and potentially functional products being produced by SFF processes is exploding.

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Beyond the fabrication of functional parts, lies the fabrication of fully functional systems. Early work along these lines has been performed by one of the authors (Lipson and Pollack, 2000). The Golem robots demonstrate the capability of an SFF process (FDM in this case) to fabricate complex, articulated mechanical assemblies in a single process, and having been designed via a simulated evolutionary process, arguably represent the first ever physical incarnation of artificial life. Nevertheless, Golem robots require significant human input and exogenous components (power, control, actuators) to be actively functional. The ability to build components that are exogenous to the SFF process, such as sensors or electronics, into a part has been demonstrated (Li *et al*, 2000; Weiss and Prinz, 1998), but the actual autonomous fabrication of sensors, actuators, power sources and circuitry along with structure in an SFF process is only beginning to be investigated (Sun *et al*, 1998). There is much work to be done before the “workpiece” can literally walk out of the fabrication system under its own power.

Two paths towards universal fabrication

The cited research and development efforts are intended to increase the universality of SFF processes in terms of material options, product types and functionality. They can ultimately combine and lead to two types of universal fabrication systems.

The first type of universal fabrication system is a synthesis of fabrication processes to approach a “basis set” of compact autonomous, multi-process, multi-material systems. This universal fabrication system might consist of a rather complex array of various complementary fabrication processes (SFF and possibly others) that together ensure that any given design can be fabricated autonomously. Such a “top down” system attains universality by guaranteeing the ability to produce arbitrary formations. In addition to SFF, this approach involves complex process planning. In implementing this approach we are faced with challenges such as: Given a mission profile that must support, say, rovers, what kind of fabrication processes and components do we need to have available so that all rover-related aspects are covered? This will result in fairly complex fabrication systems.

The second type of universal fabrication system is a parsimonious fabrication process using only minimal set of complementary materials. This universal fabrication system cannot fabricate any given design; instead, any desired end-product-system functionality can be reparsed in terms of the available fabrication capabilities. Such a “bottom up” system attains universality by guaranteeing that any design can be transformed into its own design space while preserving original functionality. In addition to SFF, this approach involves complex design automation challenges. In implementing this approach we are faced with challenges such as: Given that the fabrication process can produce only three types of materials – structure, conduction and actuation – how can we redesign, say, a rover, so that it is composed of only these three materials? This might result in novel and possibly nontraditional designs.

It is likely that these two approaches will converge at some intermediate form comprising both a compacted collection of fabrication processes and some design automation that transforms a given design to be manufacturable using these processes.

Required capabilities

A possible decomposition of the basic component functions comprising a generic functional electromechanical system might be structure, actuation, sensing, control, control signal distribution, energy generation/storage, and power distribution. While SFF of arbitrary structure has been demonstrated many times, all of the other categories have been demonstrated only in limited ways, and there has been no demonstration of SFF of meaningful energy generation storage. Examples of products demonstrating combinations of functions are even more difficult to find, suggesting again that synthesis and integration of processes is largely unexplored.

Applications to space systems and robot ecologies

There are very strong incentives to the application of SFF to space activity and planetary exploration. SFF systems offer the promise of building exactly the spare parts, components, and systems needed at a space station, or during a long manned voyage, reducing launch masses and costs. They might reprocess much of the mass of a planetary robotic lander into rovers, which might be altered or improved *in situ* as understanding of the explored environment improves. These applications will, in general, involve severe restrictions on the size and power consumption of systems, as well as limitation on the variety and form of feedstock materials. In any scenario in which resupply from Earth is unlikely, but mission longevity and capability are essential, *in situ* resource utilization (ISRU) systems, disassembly of systems, and recycling of rare or heavily processed materials will be essential.

Beyond space activity, a universal fabrication system forms a critical constituent of any sustained robot ecology. Initially, SFF systems can be used for fabrication and repair of traditional robots; as capabilities improve, such systems can also be used to repair and even extend their own capabilities. Ultimately, one can imagine that an architecture consisting of the appropriate basis set of the descendants of SFF systems, along with ISRU systems, and material transportation systems might collectively form a self-replicating system (Hall, 1999). At that point in technological development, mission durations become indefinite, and the fabrication of all of the machines and structures necessary for large scientific investigations, human habitations, or to perform major resource extraction becomes feasible.

Current results

Our current research addresses both challenges described above, namely (a) seeking novel SFF fabrication processes and materials capable of actuation, sensing, and control, as well as production of complete working systems, and (b) design automation processes capable of achieving a specified functionality given a constrained set of primitive materials.

We have been developing processes that can automatically design and fabricate complex machines in physical reality. We have combined ideas of evolution and self-organization together with rapid prototyping technology to make the first physical machines that were designed and fabricated with almost no human intervention. Figure 1 shows one of these machines, which were evolved to locomote over a flat terrain. In that work, the entire structural body – bars and joints – were manufactured automatically in a single step to

create a functional preassembled morphology, using commercial rapid prototyping equipment. The focus there was on automation of the design process too, and we had to manually insert the motors, rout the wiring and download the control into a microcontroller, and so the process is far from fully automatic.

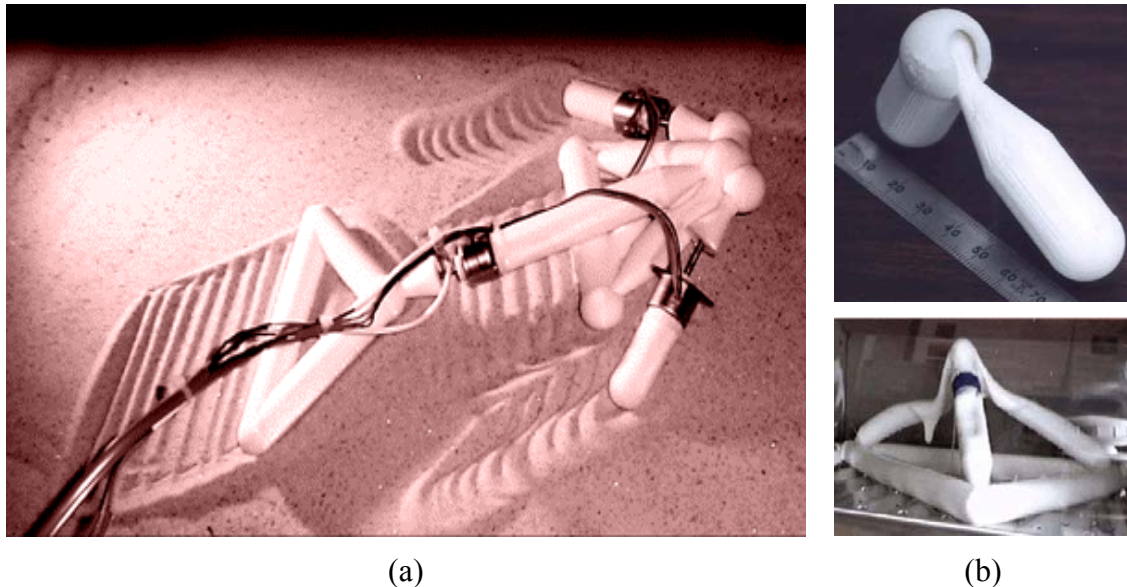


Fig 1. Locomoting machines synthesized by evolution and fabricated with minimum intervention². (a) A crawler, entire body fabricated as single preassembled unit but motors and wires manually inserted, and (b) close-up of printed joint, and another machine being melted for recycling.

A flexible fabrication system based on a 6 DOF industrial robot arm is being assembled to evaluate concepts, processes, and product forms. In one configuration, these arms might perform scanning motion while depositing material, thereby regressing into traditional rapid prototyping functionality. However, with one arm holding a piece and another depositing material, as illustrated in Figure 2, more elaborate patterns and routings can be achieved than by traditional rapid-prototyping scanning. Arbitrary deposition patterns are important for both strength considerations and for cases where fiber alignment might play a critical role in determining functional performance such as for electric conductivity and geometric tolerance. In other circumstances the robot arms might act as an assembly cell. In yet another configuration two arms might create and replace a component in a third arm. Thus with three or more independent arms, self-repair and self-extension are also possible.

By equipping the system with a variety of end-effector tooling, compatibility of multiple materials and processes can be studied. In the very near term, extrusion and FDM processes will be applied to the problem of cofabrication of structure, conductors, actuators and rudimentary control (contact switch), with the goal of producing a simple

² H. Lipson and J. B. Pollack (2000), "Automatic design and Manufacture of Robotic Lifeforms", *Nature* 406, pp. 974-978

robot requiring only the addition of a power source to begin active functioning. Figure 3 shows a manually fabricated sample of structure and conductive wiring all fabricated by deposition. Structure is ABS thermoplastic (using RP machine), wires are silver doped epoxy. The actuator materials best suited to our current process capability are electroactive polymers (EAP) (Bar-Cohen, 2001), with silicone elastomer planar films or thin annular structures seeming most promising. Additionally, some power storage technologies may be amenable to these extrusion-type SFF processes. For instance, a crude zinc-air cell might be relatively simple to make by extrusion as a sandwich of conducting layers, zinc slurry, permeable and impermeable polymer layers, and electrolyte paste.

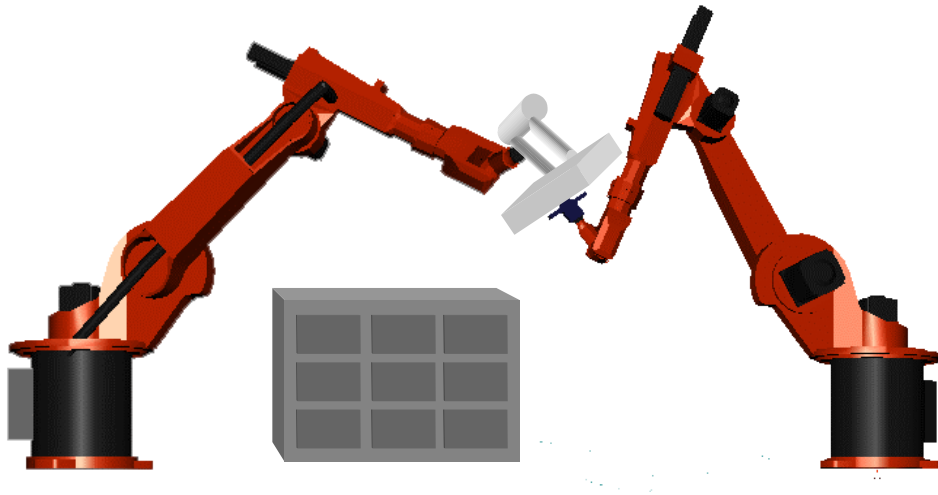


Fig 2. Two robot arms interacting to create a robot component. One holding the piece, the other depositing material. The same arms can be used to assemble pieces together or to repair and extend one another, use stock components (shown in background), and recycle unused robot parts (not shown).

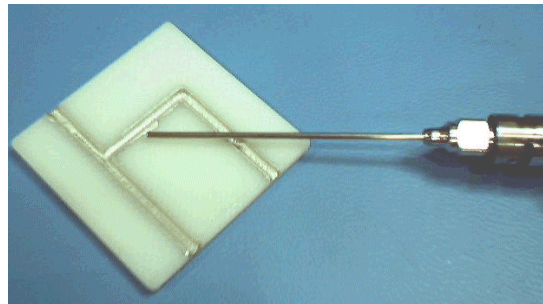


Fig 3. A manually fabricated sample of structure and conductive wiring all fabricated by deposition. Structure is ABS thermoplastic (using RP machine), wires are silver doped epoxy.

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