Functional Freeform Fabrication for Physical Artificial Life

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Abstract

Solid freeform fabrication (SFF) allows 3D-printing of arbitrarily shaped structures, directly from computer-aided design (CAD) data. SFF has traditionally focused on printing passive mechanical parts. Advances in this technology and developments in materials science make it feasible to begin the development of a single, compact, robotic SFF system – including a small set of materials - which can produce complete, active, functional electromechanical devices - mobile robots, for instance. We are advancing steadily toward this goal, and successes thus far have included the freeform fabrication of zinc-air batteries, conductive wiring, flexure joints, and combinations of these with thermoplastic structures. Several essential functionalities – actuation, sensing, and control electronics - still remain to be realized before complete electromechanical systems can be produced via SFF. Conducting polymers (CP) are a class of materials which can be used to produce all of these remaining functionalities. Successful adaptation of CP materials to SFF and their integration with our existing multi-material-SFF system is the next step in this research. When coupled in a closed-loop with an evolutionary design system, this technology becomes a bridge between the physical and the simulated, giving artificial evolution a complete physical substrate of enormous richness to explore with little or no human involvement.

Introduction

Solid freeform fabrication (SFF) is the name given to a class of manufacturing methods which allow the fabrication of three-dimensional structures directly from computer-aided design (CAD) data. SFF processes are generally additive, in that material is selectively deposited to construct the part, rather than removed from a block or billet. Most SFF processes are also layered, meaning that a geometrical description of the part to be produced is cut by a set of parallel surfaces (planar or curved) and the intersections of the part and each surface – referred to as slices or layers – are fabricated sequentially. Together, these two properties mean that SFF processes are subject to very different constraints than traditional material removal-based manufacturing. Nearly arbitrary part geometries are achievable, no tooling is required, mating parts and fully assembled mechanisms can be fabricated in a single step, and multiple materials can be combined, allowing functionally graded material properties. New features, parts, and even assembled components can be "grown" directly on already completed objects, suggesting the possibility of using SFF for the *repair and physical adaptation of hardware!* On the other hand, a deposition process must be developed and tuned for each material, geometry is limited by the ability of the deposited material to support itself and by the (often poor) resolution and accuracy of the process, and multiple material and process interactions must be understood. SFF has traditionally focused on printing passive mechanical parts in a single material, and the emphasis of research has been on improving the quality, resolution, and surface finish of parts, and on broadening the range of useable materials. Especially the latter effort has met with remarkable success: the range of materials amenable to freeform fabrication has been greatly expanded, from original soft plastics to engineering polymers, metals (Mazumder et al. 1997, Rabinovitch 2003), ceramics (IBID, Wang and Krstic 1998), electronics (Church et al. 2000), and even biological tissues (Sun and Lal 2002).

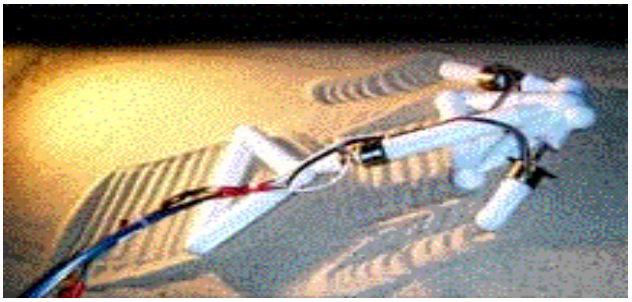


Figure 1. Evolved GOLEM robot with freeform fabricated structure

It has not escaped the notice of some that the diversity of materials and SFF processes is nearing the point at which almost any conventionally manufactured part could be made entirely via SFF processes, and that a synthesis of compatible processes may permit the fabrication of entire functional assemblies (Weiss and Prinz 1998; Safari et al. 2000) and even complete functional systems. We have pioneered the application of SFF to research in artificial life with the GOLEM robots (Figure 1) (Lipson et al. 2000), which are evolved in simulation, then constructed through a combination of freeform fabrication (of structure and articulation) and manual assembly (of actuators, control and power sources). We are now actively pursuing the development of a "basis set" or library of functionalities which are essentially geometry-

independent, accurately modeled, and mutually compatible. Such a set can in principle be used to build arbitrary electromechanical systems. One possible set would be structure, articulation, actuation, sensing, power source, logic/control, and signal/power interconnection. In pursuit of this goal, we have designed and built a multi-material-SFF research platform, and successfully demonstrated the freeform fabrication of zinc-air batteries, conductive wiring, elastomer flexure joints, and combinations of these with thermoplastic structures (Malone et al. 2003) – four of the seven functionalities on the list. It is the aim of the next phase of research to adapt a new class of materials - conducting polymers (CP) - to solid freeform fabrication, to model and demonstrate novel freeform actuators based on CP, to lay the groundwork for the freeform fabrication of sensors and logic, and to integrate all of these with the functionalities already demonstrated.

Fabrication Platform

In order to provide maximum freedom for experimentation with a wide variety of materials and processes, a custom robotic platform, control software, and two material deposition tools have been designed and constructed.

Positioning System

The initial requirement employed in the design of these tools can be stated briefly as follows: the motion control platform should provide maximal parametric freedom to the deposition processes, and permit the sequential use of many deposition processes in the course of fabricating a given object. The most significant assumption informing the design is that materials will be deposited as streams or droplets in a layered manufacturing process.



Figure 2. SFF Positioning System

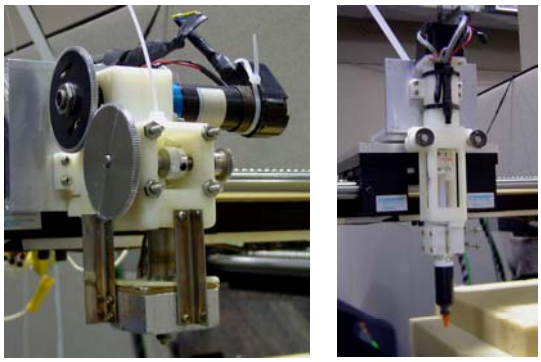
Positioning is therefore limited to three Cartesian axes, and an emphasis was placed on velocity regulation, path-following and positioning accuracy, and high acceleration to achieve fine features while printing at a constant material feed rate. A Cartesian gantry-configuration robot configuration (Figure 2) with brushless-motor driven ballscrew stages has been selected for this application for its relatively simple control, large payload capacity and rigidity, and positioning/path-following performance.

Software

A software application has been created to manage path planning and control. Multi-material objects are defined in computer-aided design (CAD) software as assemblies, then exported as multiple STL (stereolithography) files, each file describing a single part of the assembly. Within our SFF software, each component is graphically assigned a material. Each material is associated with a deposition tool and material properties governing layer thickness, deposition width and deposition rates. Geometry slicing and path generation algorithms construct unique perimeter contour- and fill raster-paths based on the tools' and materials' parameters, and combine the layers into a fabrication sequence with increasing height. Special care is needed to prioritize layers of similar heights according to interaction among materials.

Deposition Tools

For the experiments conducted thus far, two separate material deposition tools have been designed and built– one for plastics and metals, and another for liquid chemicals and pastes.



(a) (b)

Figure 3. (a) Wire-fed tool, (b) syringe extruder

The former (Figure 3a) is an extruder that feeds material in wire-form (0.050" – 0.070" diameter) through an actively air-cooled metal guide-tube and into a heated liquefier block containing a nozzle (Swanson et al. 1999). The tool has been successfully tested with solid core Pb-Sn solder wire, as well as ABS (acrylonitrile-butadiene-styrene) thermoplastic wire. A separate tool is used to deposit liquids and chemical pastes (Figure 3b). This tool accepts standard commercial 10cc Luer-lock syringe barrels and plungers. The plunger position is actuated by a linear stepper-motor capable of exerting 50 lbf. Materials are

changed by substituting a different syringe barrel and plunger in the plunger-driver component of the tool.

Currently, tool and material changes are semi-automated and time-consuming. A fully-automated tool-changing system is in the prototyping stage. When incorporated into the fabrication platform, this system will reduce the time required for tool and material changes from roughly 5 minutes to less than 30 seconds, and will provide a uniform interface for additional tools that may be required, e.g. an ink-jet for the deposition of conducting polymers.

Freeform Fabrication Experiments

Zn-Air Battery

The fabrication of a functional battery was selected as a comprehensive test of the multiple material capabilities of the previously described platform. There is little literature on the production of freeform, three-dimensional energy storage devices, though a planar thin-film cell has recently been demonstrated by Power Paper Ltd. (2003) for low-power applications. For the purpose of these experiments, a cell is defined as a device that converts the chemical potential energy between its anode and cathode materials into electrical energy by means of redox reactions: reduction (electron gain) at the cathode, oxidation (electron loss) at the anode. A battery is comprised of one or more connected cells. The essential components of a Zn-air cell are shown in Figure 4.

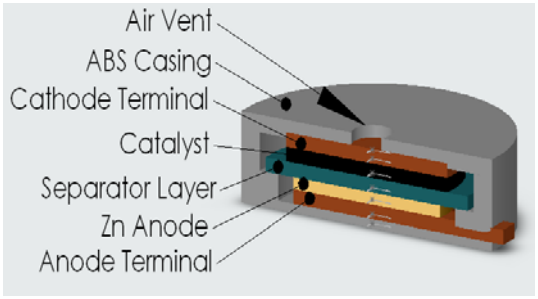
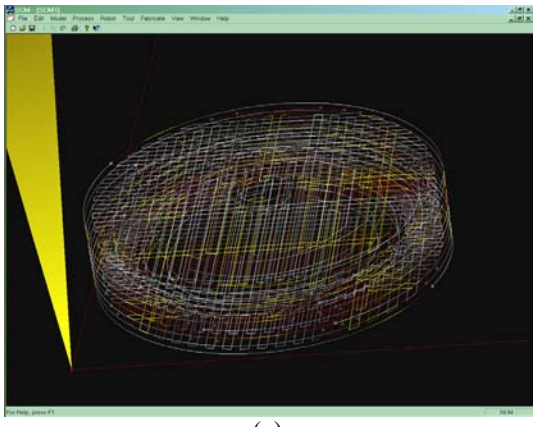


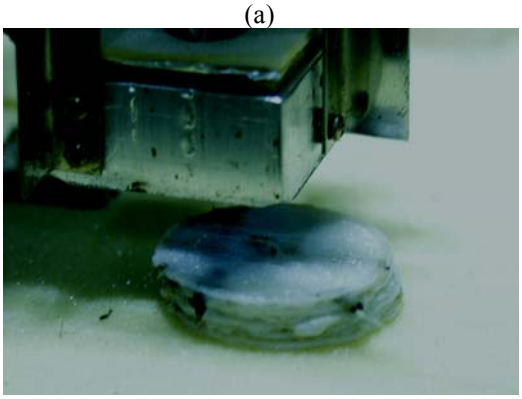
Figure 4. Cut-away model of freeform Zn-air cell

Zinc-air cell chemistry was the first considered because of its simplicity and high energy density. Several series of experiments were performed to establish the effects on cell performance of electrolyte concentration, current collector composition and geometry, cell structure and construction, and cathode catalyst composition. These experiments involved the construction of test cells by hand, without regard for the plausibility of freeform fabrication. After the initial tests were conducted, and the fundamental chemical and geometrical characteristics understood, the research shifted to adapting materials and a battery design to solid-freeform fabrication processes (see Malone et al. 2003 for details and the complete development process).

The first successfully freeform fabricated cells were unenclosed stacks of the active materials. Later experiments focused on achieving encased cells. Figure 4 shows a cross-sectional view of a successfully fabricated, encased cell design. The internal structure is very similar to the unenclosed cells. The main functional difference in the designs is that the case limits air diffusion into the cell, reducing the peak power output (~2.5mW for several hours), but prolonging the life. Figure 5 highlights some key steps in the successful freeform fabrication of this encased cell design. Producing these cells involves deposition of 5 separate materials. Polymeric materials, e.g. polyvinyl alcohol, are being investigated as a means of producing a thinner separator with lower ionic resistance, and also as a means of stabilizing the electrolyte to control evaporation and flow. These improved materials will allow exploration of less conventional cell geometries, and should improve performance as well.



(a)



(b)

Figure 5. (a) Slicing of battery model to generate tool paths, (b) final ABS layer printed

Elastomer Flexure Joints

As a demonstration of a multi-material functional mechanical assembly, a flexure joint was fabricated using ABS as the rigid end members and a 1-part, room-temperature vulcanizing (RTV) silicone as the flexible connection (Figure 6). The silicone is filled with carbon black to make it freestanding upon extrusion. The combination of electrical and mechanical functionality

within the same freeform fabricated part is highly desirable and a number of approaches have been investigated (Ting et al. 2001, Safari et al. 2000). Methylcellulose (MC) gels loaded with powdered metals are used as current collectors in our batteries. Qualitative experiments with applications of these materials outside of batteries have revealed that dehydration of the MC gel can lead to shrinkage and cracking, and that adhesion to substrates also suffers.

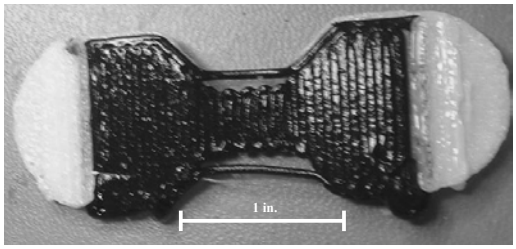


Figure 6. ABS and silicone flexure joint

A rudimentary electromechanical assembly was freeform fabricated as lines of silver / MC paste embedded in an ABS and silicone flexure joint. This device successfully carried sufficient current to light an LED (~10mA), but was too delicate to survive much mechanical use due to cracking and detachment of the conductive paste.

Conductive Wiring

Solder alloys are being investigated as a means of depositing wiring into components, and fabricating metal parts (Priest et al. 1997), and at least one commercial process exists which is capable of depositing solder alloy wiring onto a wide variety of substrates (Hayes et al. 1998). We have experimented with using a solid-core, Pb-Sn solder wire was used as the feedstock for the wire-fed extrusion tool.

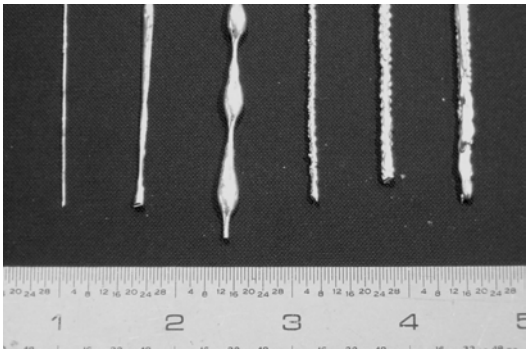


Figure 7. PbSn alloy deposited wiring

Figure 7 depicts the results of these tests. It was found that there are small, separate regions of the deposition control parameter space in which it is possible to form lines of overlapping frozen droplets of approximately 2-4mm in diameter (Figure 7,right), or a very thin but continuous wire of approximately 250μm-1mm in diameter (Figure 7,left). As a test of compatibility between materials, several ABS and solder test coupons were freeform fabricated. These tests indicate that while the two materials are thermally compatible, the solder does not wet the ABS well. As a result, the cooling rate of the solder alloy is too low, and it is prone to flowing and balling up. Active cooling may compensate for this, and ink-jet deposition of molten solder will be investigated as well.

Next Step: Conducting Polymers

Conducting polymers are long chain organic molecules in which successive atoms along the axis of the chain are bound alternately by one shared electron pair (single, or σ-bond) and by two shared electron pairs (double, or π-bond). Like most organic polymers, CP's are normally electrical insulators. By adding or removing electrons from the CP chains, and embedding positive or negative ions, respectively, into the chains to maintain electrical neutrality, it is possible to make the locations of the π-bonds less well defined (MacDiarmid 2002). Classically speaking, this allows some of the electrons more freedom to move from atom to atom, increasing electrical conductivity. Through this process known as redox doping[1], the conductivity of CP's can be varied continuously from insulating to semi-conducting[2] to metallic. This allows the fabrication in CP of many of the electronic devices currently made with doped silicon, including photovoltaic cells (Arango et al. 2000), chemical sensing (Bhat et al. 2003), optical sensing (Pede et al. 1998), force sensing (Spinks et al. 2003), transistors / redox conductivity switching (Gelink et al. 2000), organic LEDs and displays(Smela et al. 1998), and passive electronics including capacitors, resistors and inductors (Murphy et al. 1999).

Beyond these essentially electronic applications, CP's have been discovered to function as mechanical actuators, with actuation performance comparable to that of human skeletal muscle (Madden et al. 2001). If the CP is placed in contact with an electrolyte and an electrical potential is applied between the polymer and another electrode immersed in the electrolyte, free ions (and attached solvent molecules) from the electrolyte diffuse into or out from between the tangled polymer chains to compensate for the changed charge of the polymer, thereby causing the overall volume of the polymer to change (Bar Cohen 2001). Actuator applications of conducting polymers to date have been restricted primarily to planar (Madden et al. 1999, Madden et al. 2001, Sansinena et al. 1997, Spinks et al. 2003, etc.) and tubular (Ding et al. 2003, Hutchison et al. 2000) thin-film devices made from polypyrrole (PPy) and polyaniline (PA), which seem to demonstrate the best combinations of mechanical strength, actuation stress, and actuation strain. The majority of CP

[1] Other means of doping exist – see [11] for details.

[2] Both p-type, and n-type semiconductors are possible by oxidative, and reductive doping respectively.

research has involved liquid electrolytes, because liquids allow high ion mobility, hence faster actuation, but a few air-operable CP actuator designs have been investigated (Hutchison et al. 2000, Madden et al. 1999, Sansinena et al. 1997), and provide a good starting point for the selection or development of non-liquid electrolytes or encapsulation methods.

One method of producing CP films dominates actuator-related CP research –electrochemical synthesis, which is a laboratory chemistry process and not readily adaptable to solid freeform fabrication. As a control experiment and to develop experience with CP materials, we have electrochemically produced PPy film doped with PF_6^- ions, using the method of Yamaura (Yamaura et al. 1988), and qualitatively verified its actuation (Figure 8) in liquid electrolyte.

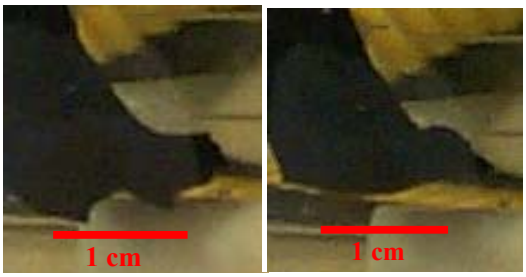


Figure 8. Rudimentary actuation of polypyrrole

Our investigations thus far have identified some promising approaches to freeform deposition of CP. Deposition of solubilized forms of doped CP, via ink-jet or syringe for instance, followed by evaporation of solvent, is one possible approach, although overcoming the poor mechanical properties of soluble forms will involve more materials science research. Another promising concept is *in situ* polymerization - deposition of a CP precursor followed by exposure to a polymerization trigger. This technique has been used for the production of CP electronics by polymerization of pyrrole monomer with, for instance, ferrocenium hexafluorophosphate as the photoinitiator (Murphy et al. 1999). Ultraviolet or electron beam irradiation of the photoinitiator/monomer blend ionizes the photoinitiator, leaving the hexafluorophosphate anion to act as a dopant, while allowing the iron cation to act as an ionic polymerization initiator. We will shortly investigate this technique for the freeform fabrication of CP actuators, but for now the achievable molecular weight of polymer, and hence mechanical properties, remains unknown. With a successful method of producing freeform actuators in hand, we will extend and validate existing electrochemical and electromechanical models (Madden et al. 2001) to more complex and non-planar actuator designs. Beyond actuators, the adaptation of conducting polymers to solid freeform fabrication opens up the possibility of tapping the rapidly expanding field of polymer electronics for high-performance circuit, sensor and optoelectronic device designs. This should permit rapid completion of the library of freeform functionalities that we are seeking. It will be possible to integrate these with actuation, structure and power sources to create entirely new classes of devices of great commercial, as well as academic interest.

Summary

A traditional approach to evolutionary robotics requires robots to be manually assembled from commercial components or custom-made components which are available in a limited range of geometries and performance levels. The ability to produce complete electromechanical systems via freeform fabrication renders the space of achievable physical robots essentially continuous. As a physical substrate in which to explore artificial evolution, freeform electromechanical systems may offer a far less rugged fitness landscape at far lower cost and effort than manually assembled or even reconfigurable robots. Building upon the successful work with the GOLEM robots, we intend to couple this technology to an evolutionary design system in a closed loop. Simulated evolution will incorporate physically accurate models of freeform functionalities. Fitness evaluations will periodically take place with physically realized individuals to refine simulation accuracy. This will permit a radical acceleration in the evolution of physical artificial systems, and will simultaneously allow a drastic reduction in the human biases contained in these physical realizations.

Acknowledgments

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