Biomimetic Robotic Mechanisms via Shape Deposition Manufacturing

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Abstract

At small scales, the fabrication of robots from off-the-shelf structural materials, sensors and actuators becomes increasingly difficult. New manufacturing methods such as Shape Deposition Manufacturing offer an alternative approach in which sensors and actuators are embedded directly into three-dimensional structures without fasteners or connectors. In addition, structures can be fabricated with spatially varying material properties such as specific stiffness and damping. These capabilities allow us to consider biomimetic designs that draw their inspiration from crustaceans and insects. Recent research on insect physiology has revealed the importance of passive compliance and damping in achieving robustness and simplifying control. We describe the design and fabrication of small robot limbs with locally varying stiffness and embedded sensors and actuators. We discuss the process planning issues associated with creating such structures and present results obtained via Shape Deposition Manufacturing.

1. Introduction

"*Behold Behemoth… His bones are tubes of bronze his limbs like bars of iron.*" [Job 40:18]

Unlike animals, today's robots are built much like this description of Behemoth, with stiff aluminum tubes and bars of steel. They also have far fewer sensors and actuators than any creature of nature would. As a result, they are fragile and generally not suited for operation outside the laboratory.

This lack of robustness, in terms of both physical construction and task execution, seen in conventionally engineered robots has lead to an increasing interest in *biomimetic* solutions that take direct inspiration from biology. Examples of this work include muscle-like actuators and controllers that mimic nervous systems. We argue that these systems must be combined with biomimetic physical structures if robots are to become robust.

We are interested in building small robots that can survive in harsh conditions. At small scales, it becomes increasingly unattractive to build robots from off-the-shelf components assembled to structures with fasteners. The robots are difficult to assemble and fragile. Fasteners and connectors work loose, limbs break, and motors and bearings fail as they become contaminated with grit.

Layered manufacturing provides a different way to create small robots. With processes such as Shape Deposition Manufacturing it is possible to create almost arbitrary three-dimensional structures that encapsulate actuators and arrays of sensors without fasteners or connectors, as shown in Figure 1.1. In addition, it is possible to create structures with spatially varying material properties such as specific stiffness and damping. In combination, these capabilities make it possible to design and fabricate biomimetic robot structures. For small mobile robots, we draw particular inspiration from the lower animals such as arthropods.

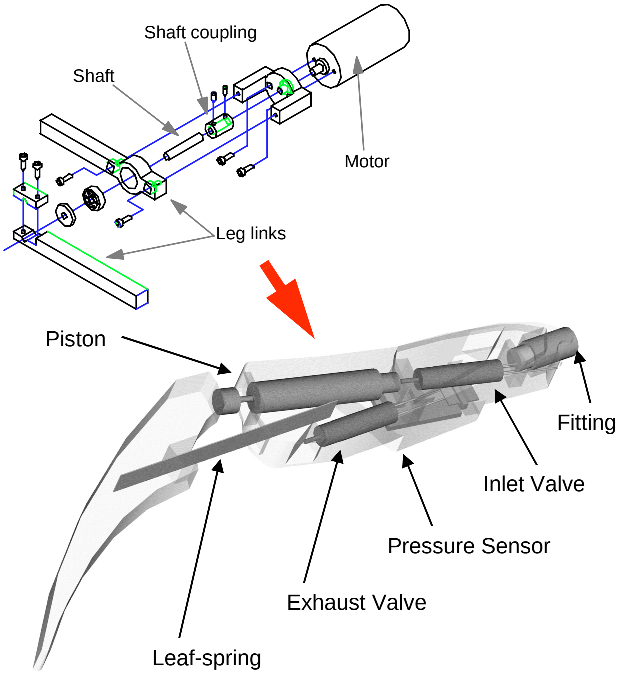


Figure 1.1 In the conventional approach, connecting a motor to a leg mechanism requires many small components and fasteners. In a leg built by Shape Deposition Manufacturing, parts are encapsulated in structural materials.

In the following sections we first review recent results from the study of insects. The results have implications for the design and control of small robot limbs. We then introduce the Shape Deposition Manufacturing process and its capabilities. We focus on the design and process planning issues associated with creating robot limbs with graded materials and embedded sensors and actuators. These issues are then illustrated with examples. Finally, we discuss ongoing work to improve design and process planning tools for creating biomimetic robot structures.

2. Behold Blaberus: lessons from insect physiology

2.1 Robust Mechanisms

Nature uses soft materials frequently and stiff materials sparingly (Vogel, 1995). Stiff materials such as teeth, mandibles and bones often have special applications where rigidity is essential to function. Even bone is not uniformly stiff it is most dense and rigid where loads are highest and becomes relatively spongy at the interior. More generally, the range of “softness” or stiffness in nature is exceptional, from the soft tissues of a sea anemone to the stiffest shells of bivalve clams. In many instances this range can be found within a single individual. Animals often have cuticles, shells or bones connected by softer or more compliant tissue.

Arthropods, despite their apparently stiff exoskeletons, follow the same pattern. Insect cuticle is surprisingly compliant and contributes to their ability to change shape and slip through the smallest of cracks. Even the calcified shells of crabs have large areas that bend, buckle and bulge during locomotion (Blickhan, Full and Ting 1993).

Human engineers have preferred stiffer materials such as metals, composites and ceramics. Part of the reason for the difference between human and natural technologies may result from a difference in apparent design philosophy. Nature’s prime rule often appears to be sufficient strength — not a resistance to deformation, but to failure. Adding extra material to reduce bending and buckling appears costly and in some cases risky because of brittleness, whereas providing sufficient strength may be cheap.

Efforts to introduce compliant materials into robots have been slow. At large scales, flexible robot links are a challenge to control. Precise endpoint control and suppression of oscillations in flexible manipulators remain active research topics. In insects, these problems do not arise, partly because of low mass and a high passive damping coefficient (insect limbs are approximately critically damped (Garcia and Full, in press)). Also, as discussed in the next section, insects, like other animals, do not employ the high-gain feedback control found in most robots.

In short, the addition of tailored compliance could make small robots more robust. But how is this to be accomplished? Small robots are already formidably complex and difficult to assemble. As the size shrinks, the difficulty of assembling compliant elements into an existing structure becomes prohibitive. Fasteners and connectors are also notorious failure points, they tend to work loose and they are frequently the sites of stress concentrations.

A different method of fabrication is needed — one that allows multiple materials, sensors and actuators to be integrated into a single monolithic structure.

2.2 Simple, Robust Control

For the most part, today’s mobile robots also move as we imagine Behemoth would, ponderously picking their way over the terrain. Complex feedback loops ensure sound foot placement, posture control and distribution of ground forces.

In contrast, simple animals can rapidly scramble over rough surfaces. For example, the cockroach (*Blaberus discoidalis*) can traverse a fractally distributed collection of obstacles up to three times its body height (Full, *et al.*, 1998). Significantly, they do this without appreciably slowing down or changing their basic locomotion pattern. There is no precise foot placement, no follow-the-leader gait, and no time to react to sensory feedback. They can get away with this because they are remarkably stable and insensitive to unexpected perturbations.

To begin with, the sprawled posture of insects provides stability with respect to unexpected loads and variations in terrain. Interestingly, insects have large horizontal forces under normal locomotion and substantial internal forces (often minimized in robotic locomotion strategies).

Recent studies of insect physiology have revealed other ways in which passive, dynamically stable behavior is achieved as a result of the interplay between feedforward control and “preflexes” (Full and Koditschek, in press; Kubow and Full, 1999; Meijer and Full, in press). Preflexes are the near zero-order response of the mechanical system due to the intrinsic, non-linear properties of the musculo-skeletal system (Brown and Loeb 1997). When control hierarchy is considered, preflex control lies

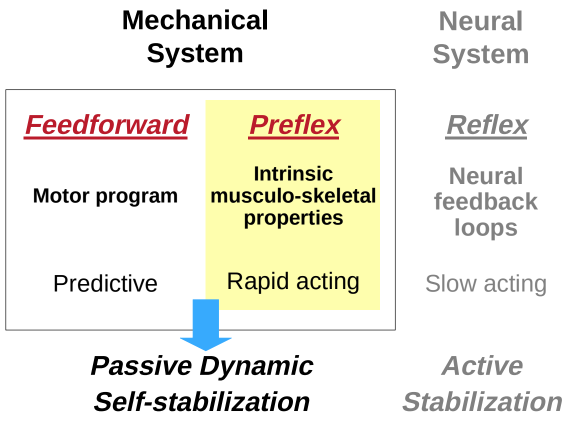


Figure 2.1 Control contributions in dynamic arthropod locomotion. Passive, dynamically stable behavior is the result of the interplay between feedforward control and intrinsic, musculoskeletal “preflexes” (figure courtesy of R. J. Full; see Full and Koditschek, in press).

between feedforward control and feedback control, as shown in Figure 2.1. Thus, disturbances are rejected, but without the time delay of feedback control (Ahn and Full, 1997; Full *et al*., 1998).

Looking in greater detail at insect limbs, we find that multiple muscles for each joint are specialized for different roles (propulsion, energy storage, damping). Fig 2.2 shows the forces produced by two different muscles located at approximately the same location and receiving approximately the same stimulus during locomotion. Muscle 177c generates its peak force earlier, when it can produce a useful thrust force; 179 produces little net work over the locomotion cycle. Both muscles also dissipate energy. In other words, some of the muscles in insects function as we would expect of actuators in robotics while others are essentially a passive + active suspension.

Figure 2.3 shows the force/displacement curve for the complete hind leg of the cockroach *Blaberus discoidalis* in an unactuated direction. The slope of a best fit line indicates passive compliance, which was expected. More surprising is the significant energy dissipation as indicated by the difference between the forward and return paths.

When the legs are considered in unison, they tend to make the cockroach body oscillate at a frequency of approximately 12Hz, its preferred running gait. Thus, like larger animals, cockroaches are dynamic running machines that behave approximately as an inverted spring/pendulum (Full and Tu, 1990; Blickhan and Full, 1993).

Moreover, substantial restoring forces can arise from these passive compliance and damping elements when they are subjected to perturbations such as would arise from a foot encountering an unexpected bump or dip. For the hind legs of the cockroach, they can be as large as four times the body gravity force (Full and Dudek, unpublished).

In summary, the picture that emerges is one of a system with actuators whose actions are superposed on passive elements that help to stabilize the body and keep it running at a preferred frequency. Active, sensor-based control (e.g., for changes in heading) is superposed on a basic motor program that does not change significantly with variations in terrain. Preflexes keep the locomotion stable in the short term and minimize the effects of unexpected variations.

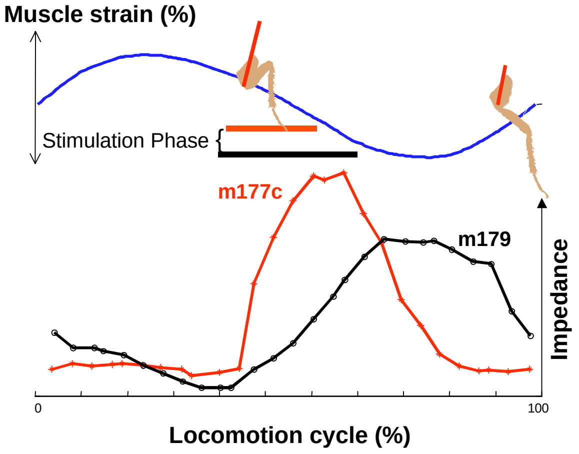


Figure 2.2. Cockroach muscles 177c and 179 are stimulated at the same point in the locomotion cycle, but 177c contributes its maximum force for propulsion; 179 functions as a spring/damper suspension (from Meijer and Full, in press, Ahn and Full, 1997).

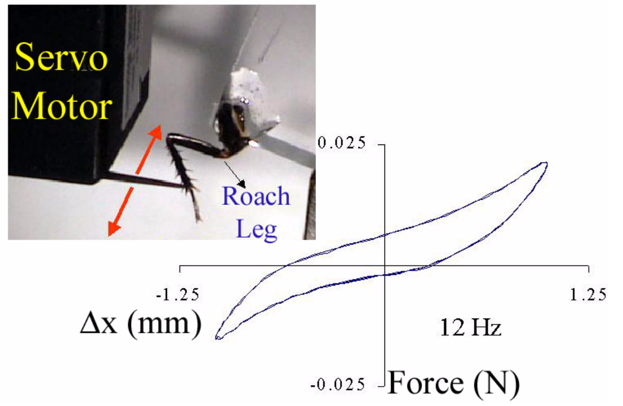
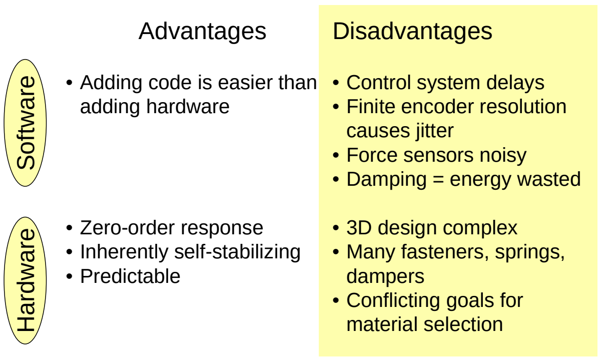


Figure 2.3. Direct impedance determination of an insect leg. An isolated leg of a cockroach (Blaberus discoidalis) was oscillated at a given frequency and displacement by a lever while force was measured. The leg operated as a spring and a damper. (unpublished data from Full and Dudek)

The advantages of passive compliance have also been recognized in robotics for tasks such as force control and assembly. However, with a few notable exceptions such as Remote Center of Compliance (RCC) devices (Whitney, 1986), series-elastic actuators (Pratt, 1995) and spring-legged hoppers (Raibert, 1986; Brown and Zeglin, 1998), passive compliance and damping have seen relatively little use as part of a control strategy.

In our own experience, springs and dashpots are usually considered at some point in designing a new robot arm or hand, but are ultimately left off because of the complexity and bulk they add. It just seems easier to “do it in software” — hence the popularity of impedance control. How-



	Advantages	Disadvantages
Software	• Adding code is easier than adding hardware	• Control system delays • Finite encoder resolution causes jitter • Force sensors noisy • Damping = energy wasted
Hardware	• Zero-order response • Inherently self-stabilizing • Predictable	• 3D design complex • Many fasteners, springs, dampers • Conflicting goals for material selection

Figure 2.4 Despite the obvious advantages of implementing tuned impedance in hardware, the difficulties encountered in their manufacture preclude this option in favor of software implementation. However, software impedance control introduces a new set of concerns.

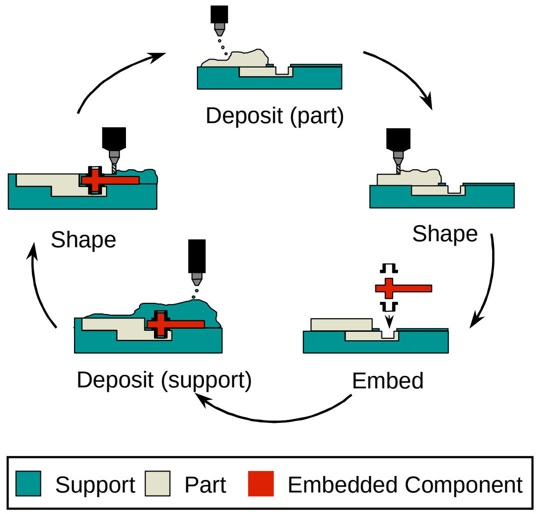


Figure 3.1 Shape Deposition Manufacturing consists of an alternating cycle of material deposition and shaping (in this case, machining). Prefabricated components can be embedded in mid-cycle.

ever, we pay a price for this easy solution. At low speeds the limited resolution of our velocity sensing makes it challenging to obtain enough damping without jitter. And if we look at the activity of the motors, a substantial fraction of their effort is devoted to providing "artificial damping."

Shape Deposition Manufacturing, presented next, can reduce the difficulty in manufacturing mechanisms with built-in compliance and damping. With this shift in what is practical to manufacture, it becomes appropriate to shift some of the control burden from software to hardware.

3. Fabrication of Biomimetic Structures

As we have seen, robust robot mechanisms with tailored, multi-material structures and integrated sensing and actuation are not practical to fabricate with traditional methods. The fundamental limitation in traditional manufacturing methods lies in the fact that mechanisms are built by first fabricating subcomponents and *then* assembling them. Thus, we are constrained to designing mechanisms which *can* be assembled, and that rely on traditional materials and fastening techniques. Again, this compromises their robustness (mechanisms which can be assembled can fundamentally be *dis*assembled).

3.1 Shape Deposition Manufacturing

Shape Deposition Manufacturing (SDM) is a developing Rapid Prototyping technology (Merz *et al.*, 1994) in which mechanisms are *simultaneously* fabricated and assembled. As shown in Figure 3.1 the basic SDM cycle consists of alternate deposition and shaping (in this case, machining) of layers of part material and sacrificial support material. In the example shown, the support material has been first machined to create a mold for the bottom surface of the part. Part material is then deposited and subsequently shaped by a machining operation, completing the basic cycle.

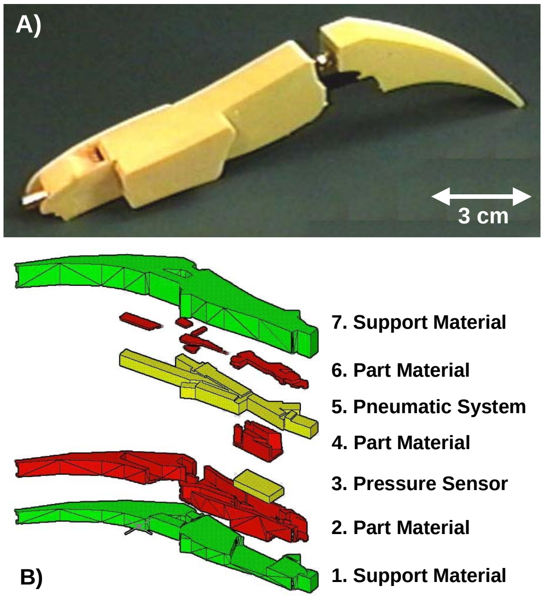


Figure 3.2 a) Prototype linkage with embedded components. A pneumatic piston, two solenoid valves and a pressure sensor are embedded inside the structure of a linkage joined by a steel leaf spring. b) Process plan in the form of a sequence of material layers and embedded components.

This cycle of material deposition and removal results in two key features:

1. Building parts in incremental layers allows us complete access to the internal geometry of the mechanism.
2. By varying the materials used in the deposition process, we can spatially vary the material properties of the mechanism itself.

As we will see in the following sections, these two features allow us to circumvent some of the limitations that traditional manufacturing imposes on design of small robots.

3.2 Mechanisms with Embedded Components

Access to the internal geometry of parts during the SDM process allows us to embed prefabricated components inside the structure of the part. These embedded components can be structural members that add strength or compliance or they can be functional components, such as sensors and actuators. Figure 3.1 shows how components can be embedded in the SDM cycle. In the example shown, high performance parts such as low-friction bearings and a steel shaft can be embedded into a pin joint as it is being built, instead of assembling the different components. By encasing the components inside the mechanism and optimally integrating them with the mechanism itself, we can create designs are not only more robust, but, in many cases, have increased performance.

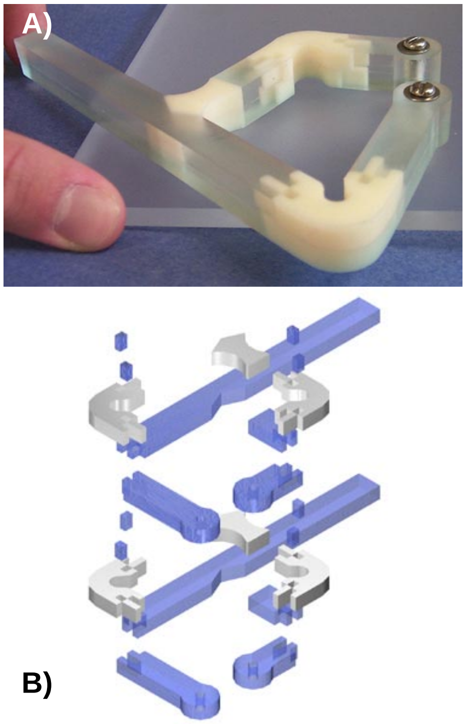


Figure 3.3 a) Prototype five-bar linkage with heterogeneous material properties, in which three of the joints have been replaced with flexures of a soft grade of plastic. b) Sequential order of layers for the linkage.

An example of this is a prototype robot linkage with an embedded pneumatic system, as shown in Figures 1.1 and 3.2. It consists of a linkage joined by an embedded steel spring that is actuated by an embedded low friction (glass and graphite) piston. The two valves that regulate air flow into the piston are also embedded as well as a pressure sensor and amplifier. The electrical connectors and tubing fittings are partially embedded, giving external access to the components. Figure 3.2a shows the finished part and Figure 3.2b shows the sequential order of layers used in the manufacture of the mechanism.

In this particular case, embedding the pneumatic components allows us to place both the valves and the pressure sensor as close as possible to the piston, which would not have been possible with traditional assembly. This results in a reduction of the volumes associated with tubing and fittings and therefore a reduction of the delays that limit the system bandwidth of pneumatic actuators. Indeed, for the limb shown in Figure 3.2, the time constant of the valves becomes the limiting factor in determining system response (Cham, 1999).

3.3 Heterogeneous-material Mechanisms

In theory, the deposition step of the SDM cycle is not limited to a particular material. The material deposited can be varied between deposition steps or even within one deposition step. This results in the capability of creating a mechanism whose structural properties can vary spatially to suit its particular function. For example, a prototype stainless steel part with embedded strain gages and thermocouples made of constantan and chromel was created with SDM (Golnas *et al*., 1998). Here, the strain gages were directly deposited between layers of aluminum oxide (to provide electrical insulation), and layers of copper for heat dissipation.

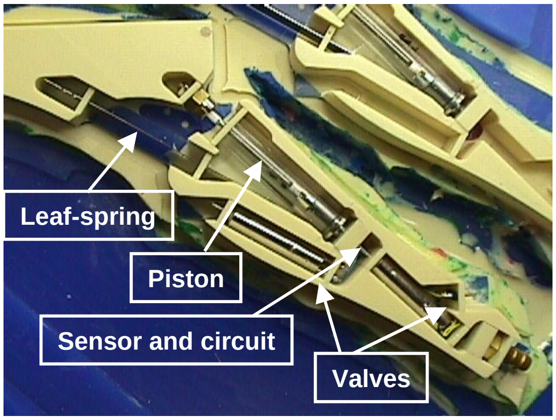


Figure 3.4 Embedded components are placed in the preceding geometry and temporarily encased to prevent infiltration during the next deposition cycle.

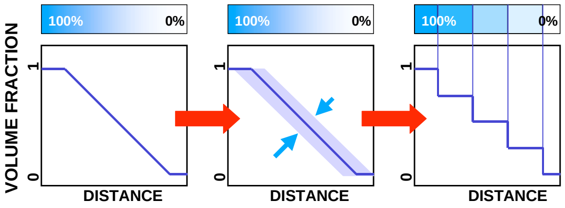
The use of plastics in the deposition process also results in interesting capabilities. As we have seen, properly chosen passive impedance can increase the robustness and simplify the control of robot mechanisms. Instead of assembling springs or dampers to achieve this passive impedance, we can arrange the materials of mechanisms in an almost arbitrary fashion to obtain the desired features. The wide range of material properties that can be obtained with plastics, from very stiff to very compliant, allows us to integrate a range of desired impedances into the structure of the mechanism itself.

An example prototype mechanism is shown in Figure 3.3. The mechanism is a five-bar linkage in which three of the joints have been replaced with flexures. The structural material of the linkage is a grade of polyurethane with high stiffness, while the flexure material is a soft, viscoelastic polyurethane. This design allows us to introduce compliance and damping into the mechanisms in a simple and robust way. If we were to create the entire mechanism out of just the stiff material, the flexures would have to be designed very thin in order to get the same amount of compliance, again reducing robustness.

3.4 Manufacturing Issues

While the capabilities discussed above resolve many of the limitations of traditional manufacturing, they also raise interesting process planning issues for SDM. Fundamentally, the inclusion of embedded components and heterogenous materials requires that more control be exerted over the cycle of material deposition and shaping than is necessary for parts of homogeneous material.

Issues found in embedding components are detailed in (Cham *et al*., 1999) and include positioning and fixturing



(a) Specified Continuous Material Map (b) Allowable Variability Tolerance (c) Discretized Geometry

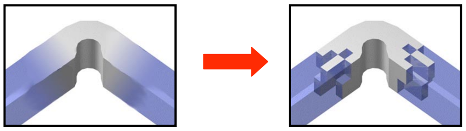


Figure 3.5. Constraints in the manufacturing process may require a discretization of the desired material property based on the constraints in the manufacturing process.

the components (see Figure 3.4), protecting the functionality of the components and connecting embedded components between parts. Solutions to these problems generally involve the deposition of a sacrificial material which partially encases critical parts of the components, but which is later removed.

Heterogeneous materials, their representation and manufacture with SDM are addressed in (Rajagopalan *et al.*, 1999). The issues that arise include ensuring that proper bonding occurs between the different materials and the fact that soft plastics cannot be machined easily, which places constraints on the order in which materials are deposited. For example, soft materials used in flexures can only be cast, since machining introduces surface imperfections that lead to fatigue failure.

In addition, some materials such as urethanes cannot be mixed in arbitrary ratios. A desired gradation in material properties must be discretized according to the constraints and variability of the manufacturing process. This discretization is shown in Figure 3.5 and was used to make the joints for the mechanism shown in Figure 3.3.

Such issues do complicate process planning for SDM, and must be addressed in the design of biomimetic structures. In fact, much of the success of the prototypes presented was due to the fact that the designers were also the manufacturers. However, if robot design is to be truly changed by this manufacturing technology, robot designers must have access to the technology without intimate knowledge of the process plans.

4. Discussion and Future Work

The capability to compose a structure with arbitrary geometry and varying materials results in a truly enormous design space. If we have m materials (including void, or empty space) that we can deposit in various mixtures, the product space becomes, as shown in (Rajagopalan *et al.*, 1999):

$$T = E^3 \times R^m$$

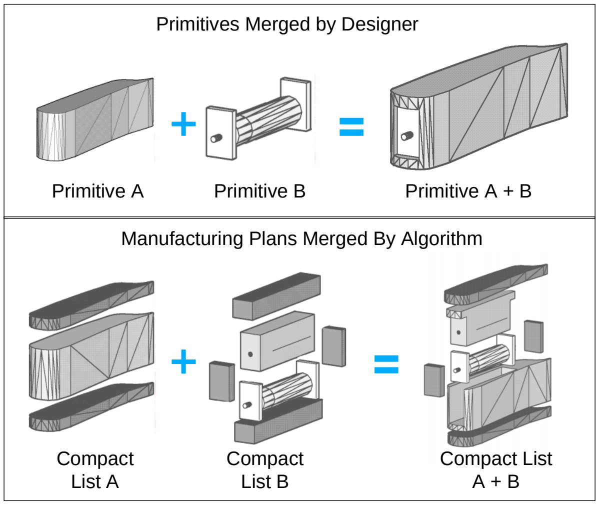


Figure 4.1 Design-by-Composition Interface. Here, designers compose designs from a library of "primitives". Meanwhile, the design interface merges the individual process plans for each primitive into a combined process plan.

For example, if we have a small shape + material optimization problem, we can imagine that the available space for the part is discretized into N cells or voxels. For a single homogeneous material, the number of possible designs is 2^N. (Of course, most of these may not be feasible for structural or other reasons). If we now assume that we have m materials (including void) that we can combine with a mixture resolution of one part in r, the number of possible designs grows to:

$$\left(\frac{(r+m-1)!}{r!(m-1)!}\right)^N$$

Clearly, if designers are to take advantage of this expanded design space, they will need better design and process planning tools than are available today for layered manufacturing.

In the near term, our solution is to create libraries of components and primitive elements that are accompanied by fragments of process plans. A designer can quickly compose new designs from combinations of primitives and library elements using Constructive Solid Geometries (CSG) operations, as shown in Figure 4.1. In this example, a solenoid valve is merged into a structural component. The process plan for the embedded component includes the sacrificial material used to protect the ports of the valves, as well as the addition of features used to locate the component. *Design-by-composition* software (Binnard 1999) automatically composes the overall process plan by merging the plan fragments associated with each element and enforcing additional ordering constraints. The software runs as a plug-in for commercial CAD systems. A prototype of this software is available for public download at the following location: *http://cdr.stanford.edu/interface/software.html.*

In other work, software is under development that will automatically decompose three dimensional shapes into primitive elements known as “compacts” (Ramaswami *et al.* 1997). In this way, new geometries can automatically be added to the design libraries.

Ultimately, we can envision a mechanical analog to the MOSIS project that revolutionized VLSI design in the 1980s with a combination of standardized design rules and design tools.

Of course, experimental validation of the robustness of mechanisms made with SDM is also needed. In addition, collaboration between roboticists and biologists continues in provide further insights into the advantages arthropod morphology, kinematics and dynamic properties.

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