Proceedings of DETC'03:
2003 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference
Chicago, Illinois USA, September 2-6, 2003

DETC2003/DFM-48166

PROCESS PLANNING FOR EMBEDDING FLEXIBLE MATERIALS IN MULTI-MATERIAL PROTOTYPES

Motohide Hatanaka and Mark R. Cutkosky
Center for Design Research
Bldg. 560
Stanford University
Stanford, California 94305 USA
Email: motohat@cdr.stanford.edu

ABSTRACT

We describe a set of techniques to permit the fabrication of multi-material layered prototypes with embedded flexible components such as reinforcing fibers, fabrics and electrical wiring. The main challenges are to maintain the shapes of the flexible elements during processing and to control precisely the geometries of adjacent regions of part material without either damaging the flexible elements or being hindered by them. The solutions involve sequences of controlled deposition and/or removal of part material and sacrificial "buffer" material. Functional considerations concerning strength and fatigue life may induce additional constraints on the processing sequence. Where conventional material removal is impractical, we present a new approach involving a hybrid of photolithography and shape deposition manufacturing. Alternative methods of achieving similar functions without cross-boundary embedding can ease fabrication and even improve performance. Design and process selection guidelines have been composed based on fabrication experience.

Keywords: Rapid prototyping, multi-material, component embedding, process planning.

INTRODUCTION

The early development of layered rapid-prototyping technology focused mainly on creating arbitrary three-dimensional shapes from CAD models – "look and feel" prototypes rather than functional machines. Subsequently, great strides have been made toward fully functional prototypes that feature high-strength materials, fine surface finishes, and compliant and multi-link mechanisms with controlled tolerances [1-5]. Recently, special process planning methods for prototypes with embedded components such as bearings, circuits, sensors and actuators have also appeared in the literature [6-8, 11, 15]. The details of the solutions depend on the specific rapid prototyping processes being addressed but common themes are to use sacrificial materials to temporarily encapsulate embedded components, preventing unwanted infiltration of part material, and to create custom, consumable fixturing for locating the parts to be embedded. However, a continuing challenge has been the incorporation of flexible materials.

There are several reasons for particularly wanting to embed flexible materials in prototypes. First, flexible high-strength fibers and fabrics of kevlar, glass, carbon and polyester provide a way to greatly increase the strength and stiffness of prototypes by turning them into composites. Fibers are also useful for creating flexural joints or hinges with high toughness and fatigue life. Other functional considerations include the transmission of electricity, light or fluids. For example, electromechanical prototypes require embedded wires or flexible circuits for transmitting power and signals among sensors, processors, etc. In addition, actuators may require embedded tubes for air, for hydraulic fluid, or for cooling. Springs are still other example of embedded flexible components.

In this paper we report on methods to embed flexible components in multi-material parts and *in-situ* fabricated mechanisms (i.e., mechanisms that are created pre-assembled during prototyping). We first describe the problem in general terms and then give four classes of solution, which we illustrate with examples.

The challenges associate with creating multi-material prototypes with embedded components are primarily:

- defining and precisely controlling the shapes and locations of flexible materials during processing
- selectively adding, removing or otherwise processing material around the flexible strands without damaging them or being hindered by them,

- preventing stress concentrations that could lead to early failure.

In the following section we discuss these issues in the context of a simple abstract example of an embedded flexible component that straddles the boundary between two different part materials as shown in **Figure 1**. In general, we assume that functional requirements for such a design imply a smooth and precise boundary between the two different part materials and good adhesion between the part materials and the embedded flexible element.

Figure 1. Prototypical two-material part with an embedded flexible element.

NOMENCLATURE

In the following discussions and examples we use a series of schematic diagrams for manufacturing process illustration. The diagrams are all overhead views of a part in process. The growth direction is perpendicular to the plane of the page. **Figure 2** is a diagram for color scheme explanation.

For generality we further assume that one of the part materials, B, is possibly a soft material for which controlled material addition or removal is impractical. Thus, material B can only be added or removed in bulk.

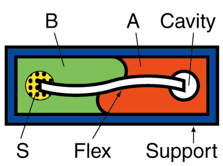


Figure 2. Generic in-process example with embedded flexible fibers: A = hard part material, B = soft part material, S = temporary (sacrificial) material, Flex = embedded flexible elements.

MATERIALS AND MANUFACTURING METHODS

In the following discussion we assume a rapid prototyping process such as a variation on Shape Deposition Manufacturing (SDM) [9] in which various materials can be deposited, and sometimes removed, to obtain the desired part. Sacrificial materials may also be used to provide support and to create temporary fixtures or boundaries. In the examples that follow, we have employed combinations of stiff and flexible polymers for creating the parts, and waxes or uncured polymers as the sacrificial support materials. Flexible components included fibers, fabrics, electrical wires and flexible printed circuits. CNC machining and a hot water jet were employed for selective removal of sacrificial materials, solvents were employed for bulk removal.

PARTIAL AND CROSS-BOUNDARY EMBEDDING CHALLENGES

We have encountered three main difficulties associated with creating parts with embedded flexible components: fixturing the flexible members, achieving good control of the geometry of part materials in the vicinity of the flexible elements, and avoiding stress concentrations. These difficulties are explained in the remainder of this section.

Fixturing challenges for flexible components

The functional requirements of a design determine how embedded components must be configured and located during manufacture. For rigid components, rapid prototyping methods permit the creation of custom temporary fixturing elements that are later removed. This approach is convenient for embedding discrete components such as bearings, electrical devices, etc. A number of specific fixturing techniques have been discussed in the literature [6, 11]. However, for flexible elements, fixturing is more problematic. It can be difficult to maintain the shape of the flexible elements as materials are added or removed around them. In addition, it may be necessary to hold the flexible elements under tension until they are encapsulated. When simple approaches involving temporary fixtures, adhesives etc. are not adequate, a method discussed in the next section is to precoat the flexible component in a thin sheath of soft part material. The soft material protects the fibers and makes the flexible element easier to handle without significantly reducing the flexibility or strength of the design.

Material deposition and removal challenges

The fundamental requirements in creating samples like the one shown in **Figure 1** are:

- to achieve precise control of the geometries of the constituent regions (A, B and embedded elements)
- to produce a strong part with good bonding among the constituents and without stress concentrations or poor finish that will produce fatigue failures.

To satisfy these requirements we may use any combination of controlled material desposition and removal. For example, in the case of fused deposition modeling (FDM) the part materials are deployed precisely to the desired shape; in the case of shape deposition manufaturing (SDM) controlled material removal or shaping is used to create the desired shape. These processes will be referred to as *selective* material addition or removal in the following discussion. The challenge in each case is (1) not to be hindered by the flexible material (i.e. to have access to all regions desired) and (2) to avoid damaging the flexible elements as a side-effect of the material deposition, removal or curing process.

A typical problem is to prevent castable materials (i.e., bulk material addition) from infiltrating regions where they are not desired. When flexible fibers pass through the boundary of a region, sealing can be especially difficult. On the other hand, removing material around a flexible component can lead to problems because the flexible element is unable to support itself as it becomes released. Photolithography can provide a way to alter material immediately adjacent to the flexible fibers without affecting the fibers themselves. However, in this case there is the problem that the fibers may shield or shadow the material underneath. Similar interference problems have been identified by other researchers [11].

Where selective material addition or removal is impractical in the vicinity of flexible elements, we may employ *bulk* material addition or removal. For example, we may cast a liquid polymer into a cavity or we may remove an entire region of sacrificial material by melting it or washing it away with solvent. A variation on this process is to combine SDM with photolithography in which a mask and UV light are used to define a geometric pattern, followed by bulk material removal with solvent. Examples of these methods are presented in the next section.

Stress concentration considerations

Stress concentration is one of the most important factors to be considered when designing structures that deform or bear cyclic loads. A stiff material may crack; a soft material may tear; delamination may occur at a material interface. An embedded component may also break when the surrounding matrix deforms.

Sharp-edged concave geometries are generally undesirable, both on the exterior of the part and on interior boundaries between dissimilar materials. Stress concentrations also occur where there is an abrupt change in the Young's moduli. In addition, microscopic defects on material surfaces – especially for soft materials that undergo large strains – should be avoided. For example, we have found that selective material removal for soft materials will lead to surface cracks and poor fatigue life. However, by modifying the process plan, the soft material (generic material B) can be cast into a smooth cavity that establishes its shape. Examples of linkages with flexures that have survived over 1 million cycles are presented in the next section.

SOLUTIONS

In this section we describe several approaches to creating multi-material parts with embedded flexible components that overcome difficulties described in the previous section. The approaches are illustrated with examples of mechanisms that we have created and their accompanying process plans.

The approaches all involve one step of selective material deposition or selective material removal. The various process sequences are illustrated schematically in **Figure 3** and are understood to represent partial process plans or plan fragments. In each case, we assume that the process starts with creating temporary or sacrificial fixtures and inserting the flexible material into them.

Selective material deposition

The most straightforward approach to achieving the configuration in **Figure 1** is to selectively deposit either material A or material B so as to create a defined boundary between them, while encapsulating the flexible component. This approach is labeled as sequence I in **Figure 3** and the manufacturing steps are depicted in **Figure 4**. Note that if selective addition of material A defines the boundary then B can be added in bulk (e.g. by casting) to obtain better bonding at the interface and with the flexible element. Following the addition of material B, the fixtures are removed and the cavities are filled with materials A and B if necessary.

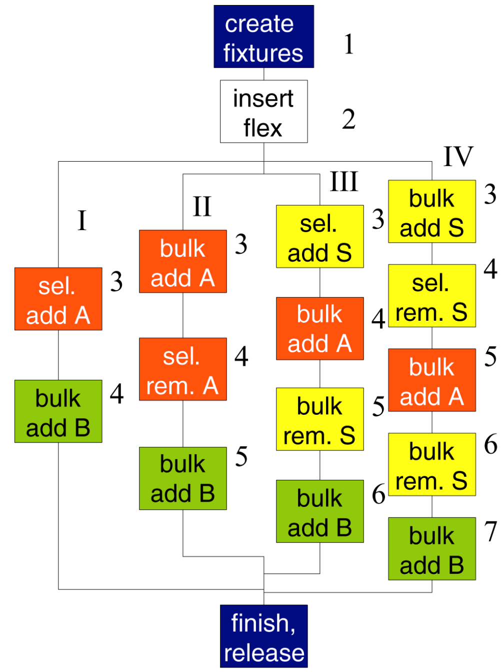


Figure 3. Process chart for the four main methods for partial and cross-boundary embedding: (I) selective material deposition, (II) selective material removal, (III) selective deposition of sacrificial material, (IV) selective removal of sacrificial material.

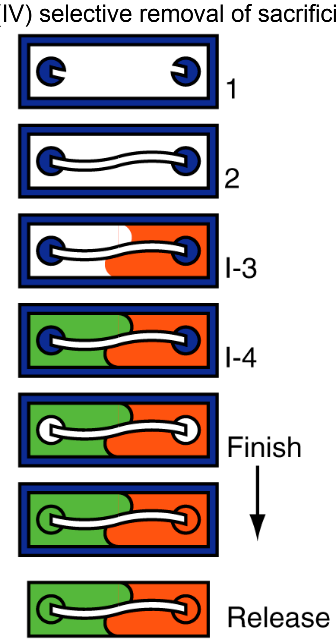


Figure 4 Selective material deposition (Process I, Fig. 3) for creating a two-material part with embedded flexible elements.

Unfortunately, this approach is particularly susceptible to all three of the general difficulties listed in the previous section. In particular, the materials, A, and processes that give best local control of deposition (e.g., FDM) often result in compromises on material porosity and on the bond strength with respect to the flexible component. Conversely, materials such as urethanes and epoxies with good surface wetting and high bond strength can be difficult to deposit selectively. Other options are available for selective deposition of non-fluid materials [12].

An alternative is to selectively deposit a sacrificial material that is subsequently removed to create a shaped cavity for adding part material in bulk. The corresponding sequence is labeled III in **Figure 3** and the modified steps are illustrated in **Figure 5**.

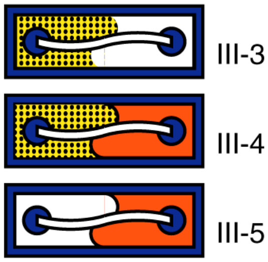


Figure 5. Selective sacrificial material deposition (Process III, Fig. 3)

. A technique that can be used to enhance the control with which either part or sacrificial material is added, is to temporarily create narrow shapes such as channels so that added material is kept in place by capillary action while still in the liquid state. This is the approach used for the string-suspended gimbals as shown in **Figure 7** and **Figure 6**. The flexible fibers in this case are 1.0 mm diameter strings of polyester yarn. A mold is first created in sacrificial material (wax) and the strings are stretched and held in place. Small amounts of additional sacrificial material are then added to encapsulate the strings at narrow gaps in the mold. Part material (castable urethane in this example) is then poured into place. After removal of the wax, the complete gimbals are as shown in **Figure 6**. Note that there is no second part material. Related techniques include creating temporary “dams” or spacers of sacrificial material to create a boundary for the part material.

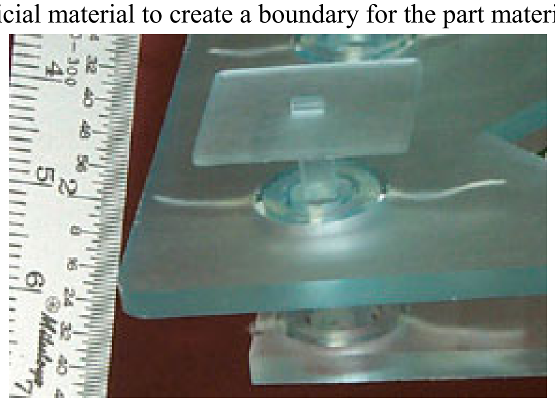
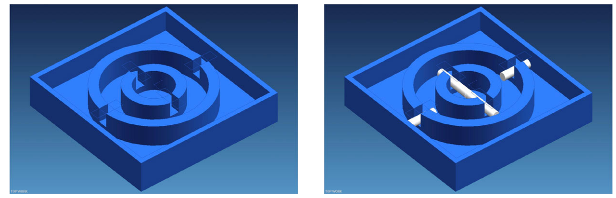


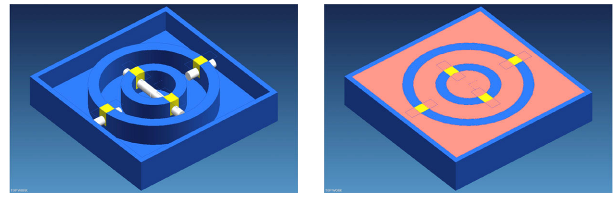
Figure 6. Finished mechanism with string-suspended gimbals supporting upper and lower plates.

Selective material removal

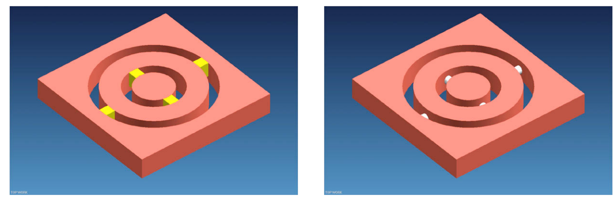
Where selective addition of part or sacrificial material does not give adequate control of the local geometry or surface finish, an alternative is selective material removal. The removal can be via CNC machining [9, 13] or can use methods such as laser melting or vaporization or a water jet. Selective removal of part material is listed as process II in **Figure 3**. When working with embedded flexible components, however, we more commonly employ selective removal of sacrificial material (process IV in **Figure 3**, modified steps in **Figure 8**.) to create a shaped cavity into which part material can be introduced without damaging flexible materials.



Prepare mold and fixtures by selective removal of wax support and place the flexible elements (strings).



Selectively deposit sacrificial material in thin grooves and bulk-deposit part material in remaining cavities.



Bulk-remove support material with solvent remove additional wax from strings with hot water jet.

Figure 7. An example of using selective addition and removal of sacrificial material: process steps for creating 2DOF gimbals with string flexures.

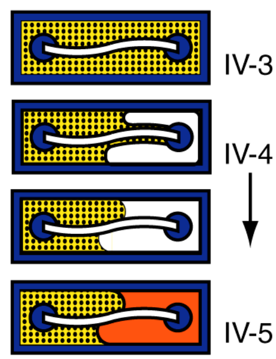
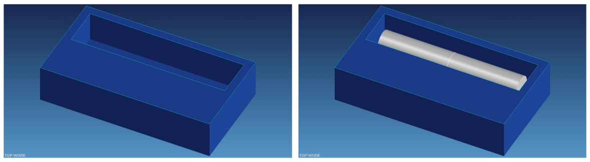
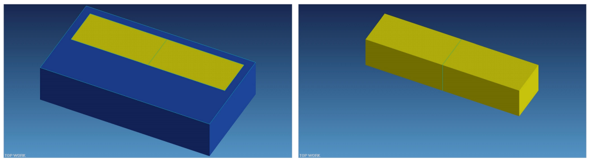


Figure 8. Selective sacrificial material removal (Process IV, Fig. 3) : initial selective removal with a conventional process such as CNC machining provides a smooth surface finish over most of the interface region; residual sacrificial material on the flexible elements is removed with a hot water jet or other process that does not affect fibers.

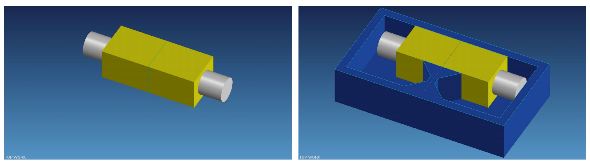
Selective removal of sacrificial material was employed in building the spring-loaded flexural hinge shown in **Figure 9**. The flexible insert in this example is a coil spring that is anchored in solid polymer at each end. The spring was first completely encased in sacrificial wax and then its ends were exposed by selectively removing wax. The remaining wax in the center protected the spring when solid polymer (material A) was cast around it. The completed product is shown in **Figure 10**.



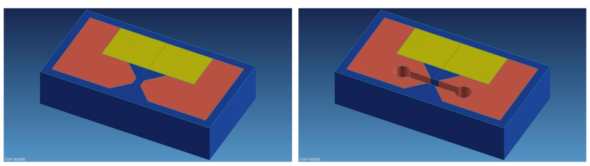
Machine mold in support material
and place coil spring in mold.



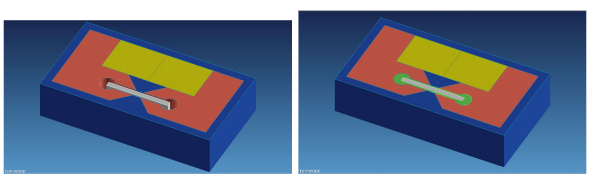
Bulk-deposit wax
and release wax-encased spring from mold.



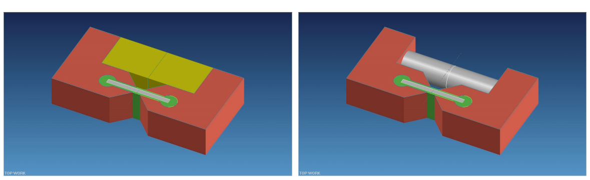
Selectively remove wax from ends of spring by hot water jet;
insert resulting part in new machined mold.



Bulk-deposit part material A in mold cavity and
machine slot in part material and mold for flexure
(rounded ends reduce stress concentrations).



Place polyester reinforcement fabric in slot and
bulk-add soft material B to encapsulate fabric.



Extract part from mold and remove protective wax
from coil spring.

Figure 9. Process steps for creating a durable spring-loaded hinge with a combination of hard and soft polymers and a fabric-reinforced flexure

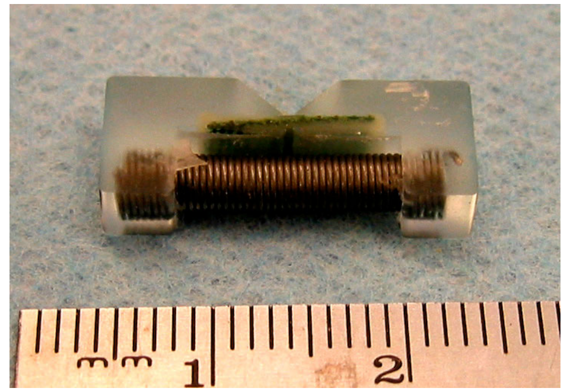
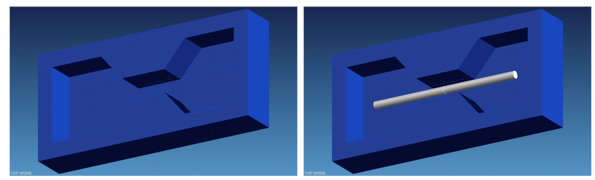
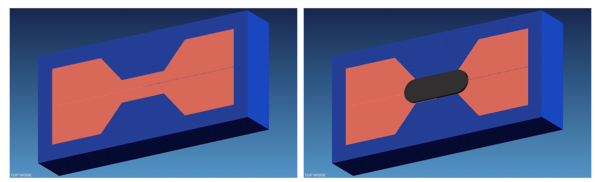


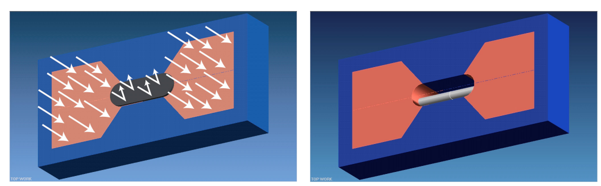
Figure 10. Photograph of the finished spring-loaded hinge with fabric-reinforced flexure



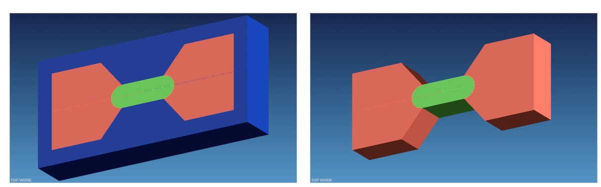
Machine mold in support material and place flexible insert.



Bulk add photocurable polymer (SU-8)
and position photomask over flexure region.



Expose in collimated UV light, bake and use solvent
to remove the unexposed polymer.



Bulk-add flexible polymer (material B)
and remove support material.

Figure 11. Process steps for creating a fiber-reinforced flexure with hard (SU-8) [14] and soft (silicone) materials.

For delicate fibers, it may be difficult to remove sacrificial materials selectively without causing damage. A useful variation in such cases is to employ a photosensitive material that is selectively exposed and then removed chemically. This method was used to create another flexural hinge with embedded fibers and fine electrical wires, following the process shown in **Figure 11**.

A photo-curable epoxy, SU-8 was employed as the rigid part material. Bundles of threads and wires were placed in a sacrificial mold, encapsulated in SU-8 and baked at low temperature to drive off the solvents, following the standard procedure for thick layers of SU-8 [14]. A mask was then positioned to block UV light from the region of the flexure. The sample was exposed to UV light and a solvent was applied to remove the unexposed SU-8. A soft solicone was then cast into the flexure region. After curing, the part was released from the sacrificial mold. An early finished prototype is shown in **Figure 12**. Subsequent steps for a part using this approach would be to machine the upper surface of the hard SU-8 material and then continue with additional SDM cycles to create more features

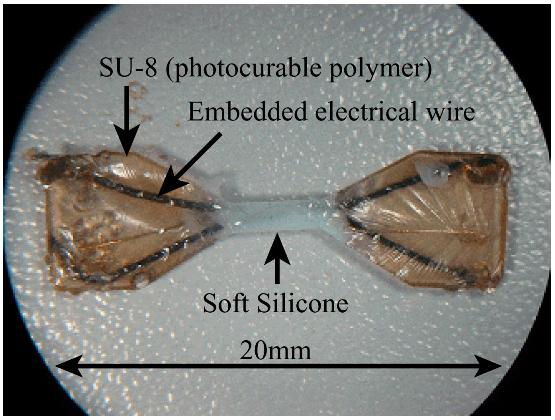


Figure 12. Finished flexure fabricated from SU-8 and flexible silicone. (Source: S. Bailey, Stanford CDR)

Summary of design and material selection guidelines

The design and material selection guidelines for the four major methods of cross-boundary embedding are summarized in **Table 1**.

ALTERNATIVE SOLUTIONS

Pseudo-boundary formation

Although selective material deposition and removal can be combined to create many multi-material designs, issues of obtaining access while also preventing damage to the inserts and ensuring a strong bond remain. Even the combined SDM-photolithography method has the limitation that if the flexible fibers are too dense they will shield the photocurable material beneath them, making complete removal difficult.

Therefore, a solution that we have used for creating in-situ fabricated linkages such as the ones in **Figure 13** is to create "pseudo-boundaries" of material. Essentially, we create a thin layer of soft material around the flexible fabric so that we do not have to worry about precise definition of the boundary between hard part material and fibers. Technically, the boundary between the hard material and soft material is altered from the original specification in **Figure 1**. However, the practical result is often indistinguishable.

Selective Deposition Design: Create geometry to provide clear access for deposition tool. Create mold features to facilitate control of material (e.g., by capillary action). Material: Use mold/part material combination with good wetting in corners and narrow passages. Deposit material with moderate viscosity and fast solidification to minimize reflow. **Selective Removal** Design: Create geometry to provide clear access for removal tool. Provide space and routes for waste material removal. Material: Use mold/part material combination with large difference in melting temperature or resistance to chemical, solvent or abrasive removal.

Table 1. Design and material guidelines for cross boundary embedding

The rightmost linkage in **Figure 13** consists of fabric-reinforced flexures that connect links of hard material. The linkage is a single element that replaces a pantograph with 31 assembled components, shown at left. Versions of the fabric-reinforced linkage have undergone a million actuation cycles without failure [7, 10].

The basic approach is illustrated in **Figure 14** sequence V and highlighted in **Figure 15**, and follows the same sequence as used to create the fabric-reinforced hinge in **Figure 9**. The fabric is encased entirely in soft material, including where it is nominally surrounded by hard material. This approach also helps to avoid failure of the flexible member at the original hard material/soft material interface because the soft material helps to distribute loads. Functionally, the modified design in **Figure 15** is very similar to the original specification in **Figure 1**. The stiffness of the hard material region is not seriously compromised if the thin inclusion of soft material is hydrostatically incompressible (e.g. silicone rubber or polyurethane with a Poisson's ratio of 0.5) because it cannot bulge or contract laterally, being restrained by the hard material above and below.

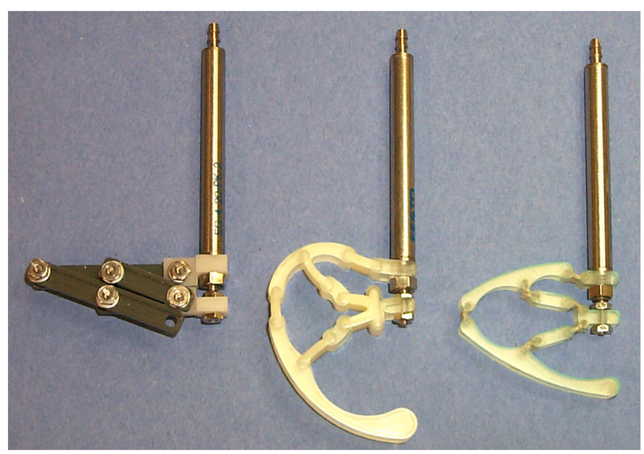


Figure 13. Linkages for extending piston stroke length in a legged robot. Left: original version with fasteners, pins and bearings has 31 components in addition to the piston. Middle: an early fabricated protoype with hard links and thick flexures of soft material. Right: improved linkage with hard links and thin but tough fabric-reinforced flexures encased in soft material.

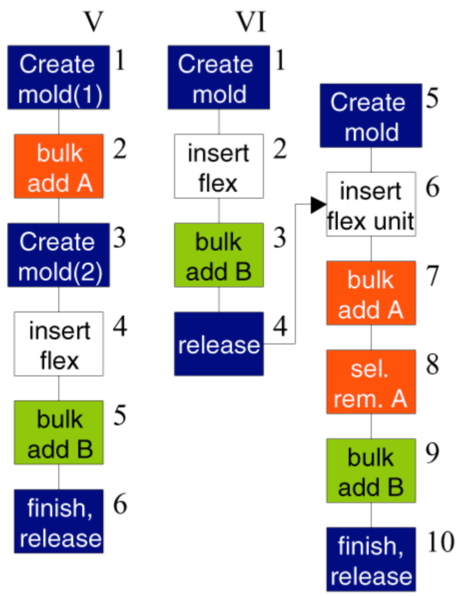


Figure 14 Process flowcharts for (V) Pseudo-boundary formation and (VI) pre-encapsulation. Note that steps 5-10 in the latter method are the same as method (II) in Figure 3. These steps can be replaced by any of the three other methods of fabrication.

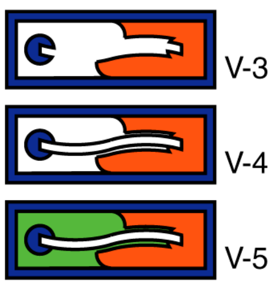


Figure 15. Pseudo-boundary formation (Process V, Fig. 14). The insert is placed only after the first material is cast.

Pre-encapsulation

A final variation on the same theme is to pre-encapsulate the flexible members in a thin shell of soft material. This method requires a few more processing steps but has some additional advantages. The thin layer of soft material provides the flexible members with better geometric definition and stability and makes them easier to fixture. The soft material also provides a buffer zone to prevent damage to the flexible fibers during selective removal of adjacent hard materials. The approach is shown in **Figure 14** as sequence VI and schematically in **Figure 16**.

Why choose these alternative methods?

The two alternative methods of embedding flexible components offer advantages and disadvantages as indicated in **Table 2**. Pseudo-boundary formation is easier and more reliable than real cross-boundary embedding. It also reduces stress concentration on the flexible insert. Hence, this process is the most favorable as long as the potential reduction in anchoring strength can be tolerated.

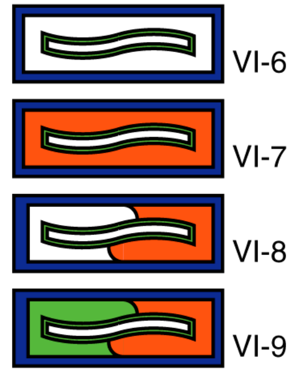


Figure 16. Pre-encapsulation of the flexible insert in a thin shell of soft part material. (Process VI, Fig. 14). This facilitates the fixation of highly flexible material with low geometrical definition.

Pre-encapsulation is to be used only when the flexible insert is too difficult to fixture or too sensitive to some of the selective processes. It is a preparation step for such delicate inserts which is to be avoided if possible in order to reduce work.

An exceptional case is when the second casting of part material (for example, step VI-8 and 9 in **Figure 14** or **Figure 16**) can be eliminated because the buffer material from step VI-3 in **Figure 14** serves as the second part material. Then this process becomes virtually equivalent to pseudo-boundary formation in advantages and disadvantages except that the fabrication precision is reduced by moving the pre-encapsulated insert from one mold to another. Hence, pre-encapsulation without a third material casting step is preferred.

	Pseudo-boundary formation	**Pre-encapsulation**
Advantages	• Requires no selective add/rem. processes -Is easy to perform -No risk of insert damage • Relatively low number of steps • Reduces stress concentration on insert • Controlled geometry	• Eases fixturing by: -increasing stiffness -providing predefined geometry. • Lowers risk of insert damage • Reduces stress concentration on insert
Disadvantag	• Weaker anchoring strength of insert.	• Weaker anchoring strength of insert • Relatively large number of steps • Requires selective removal process

Table 2. Advantages and disadvantages of alternative methods compared to direct cross-boundary embedding.

PROCESS SELECTION GUIDELINE

The process selection criteria between the four main methods of cross-boundary embedding and the two alternative methods were discussed in the previous paragraph. As seen in **Table 3**, process favorability ordering among the four main processes changes depending on the subject of comparison. The table can be extended to include more criteria as required to help the designer decide on the order of preference.

	Selective deposit (I)	Selective removal (II)	Sel.dep. sacrif. (III)	Sel.rem. sacrif. (IV)
Number of process steps	1	2	3	4
Time (tooling + curing)	1	2	2	4
Insert damage risk	1	3	2	4

Table 3. Process favorability. 1=best, 4=worst.

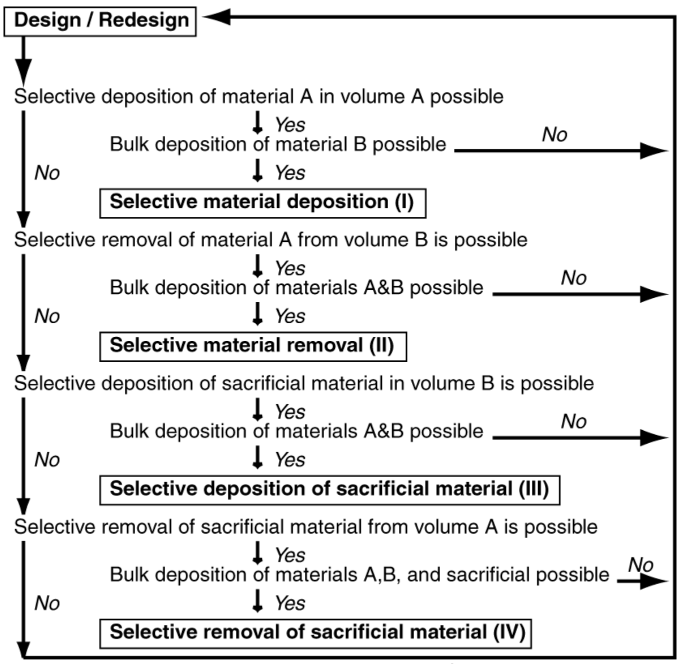


Figure 17. Process selection flowchart

Once the order of preference is decided, one can systematically select the best method available as shown in **Figure 17**. This particular flowchart has preference order (I), (II), (III), (IV).

CONCLUSIONS

Several methods of cross-boundary embedding were developed and tested. Three major difficulties were identified: fixturing the insert, selectively adding, removing or otherwise processing material around the flexible insert without damaging or being obstructed by it, and avoiding stress concentration, especially at the material boundary. Accordingly, methods of selective addition and removal of part material and sacrificial material were developed. Where conventional material addition or removal cannot prevent damage to embedded flexible components, an alternative is to combine photolithography with bulk material removal. In other cases, some alteration of the original specification can greatly simplify the process plan without significantly affecting functional properties, sometimes even improving them. Guidelines for design and process selection have also been established to help designers.

The variety of methods allows us to perform cross-boundary embedding of flexible components in multi-material parts. However, some of the processes require refinement. Reduction of manual labor in fixturing the components is a major area of future work.

ACKNOWLEDGMENTS

The photolithographic method was originally developed by Sean Bailey at Stanford CDR. Other members of the Stanford rapid prototyping community, including Byongho Park, Wonhyoung Ryu, Lewis Hong, and Prof. F.B. Prinz have contributed to the work presented in this paper.

This work was made possible by ONR MURI grant N00014-98-1-0669 and NRO 000-01-C-0311. The hybrid photolithographic/SDM method was supported in part by an NSF dissertation enhancement award for S. Bailey (0138436).

REFERENCES

[1] Mavroidis C., DeLaurentis K.J., Won J., and Alam M., 2001, “Fabrication of Non-Assembly Mechanisms and Robotic Systems Using Rapid Prototyping,” *Journal of Mechanical Design, Transactions of the ASME*, Dec, 2001, **123**, pp.516-524.

[2] Rajagopalan, S., and Cutkosky, M. R., 1999, ‘‘Optimal Pose Selection for In-Situ Fabrication of Planar Mechanisms,’’ *Proceedings of the 1999 ASME, DETC/DFM Conference,* Las Vegas, NV, Sept 12–15, 1999, Paper DETC99/DFM-8958.

[3] Rajagopalan, S., and Cutkosky, M. R., 1998, ‘‘Tolerance Representation for Mechanism Assemblies in Layered Manufacturing,’’ *Proceedings of the 1998 ASME DETC/DFM Conference,* Atlanta, GA, Sept 13–16, 1998, Paper DETC98/DFM-5726.

[4] LaLiberte T., Gosselin C., Cote G., 2001, “Practical Prototyping,” *IEEE Robotics & Automation Magazine,* Vol. 8, Issue 3, pp43-52.

[5] Kota S., Hetrick J., Li Z. and Saggere L., 1999, “Tailoring Unconventional Actuators Using Compliant Transmissions: Design Methods and Applications,” *IEEE/ASME Transactions on Mechatronics*, Vol. 4, No. 4, December 1999.

[6] Cham, J.G., Pruitt, B.L., Cutkosky, M.R., Binnard, M., Weiss, L., and Neplotnik, G., 1999, ‘‘Layered Manufacturing with Embedded Components: Process Planning Issues,’’ *Proceedings of the 1999 ASME DETC/DFM Conference,* Las Vegas, NV, Sept 12–15, 1999, Paper DETC99/DFM-8910.

[7] Clark, J. E., Xia, L. and Cutkosky, M. R., 2001, "An interactive aid for designing and planning heterogeneous layered prototypes " *Proceedings of the 2001 ASME DETC/DFM Conference*, September 9-12, 2001, Pittsburgh, Pennsylvania, USA.

[8] DeLaurentis K.J., Mavroidis C. and Kong F. F., 2002 "Rapid Fabrication of Non-Assembly Robotic Systems With Embedded Components," *IEEE Robotics and Automation Magazine*, 2002.

[9] Merz, R., Prinz, F.B., Ramaswami, K., Terk, M., Weiss, L., "Shape Deposition Manufacturing," Proceedings of the Solid Freeform Fabrication Symposium, University of Texas at Austin, August 8-10, 1994.

[10] Clark, J. E., Cham, J. G., Bailey, S. A., Froehlich, E. M., Nahata, P. K., Full, R. J. and Cutkosky, M. R., 2001, "Biomimetic Design and Fabrication of a Hexapedal Running Robot", Intl. Conf. Robotics and Automation (ICRA2001), Seoul, Korea, May 21-26 2001.

[11] Kataria A. and Rosen D., 2000, "Building Around Inserts: Methods for Fabricating Complex Devices in Stereolithography," *Proceedings of the 2000 ASME DETC/DFM Conference,* Baltimore, Maryland, September 10-13, 2000.

[12] Das S. and Santosa J., 2001, "Design of A Micro-Hopper Array for Multi-Material Powder Deposition," *Proceedings of the Solid Freeform Fabrication Symposium,* 2001, pp155-162.

[13] Liou F.W. et al., 2001, "Research and Development of A Hybrid Rapid Manufacturing Process," *Proceedings of the Solid Freeform Fabrication Symposium,* 2001, pp138-145.

[14] SU-8: a thick photo-resist for MEMS http://aveclafaux.freeservers.com/SU-8.html

[15] Ting F.P.Y., Gibson I. and Cheung W.L., 2001, "Study on Selective Laser Sintering Components with Electrically Conductive Channels," *Proceedings of the Solid Freeform Fabrication Symposium,* 2001, pp1-10.