# Hybrid Deposition Manufacturing: Design Strategies for Multimaterial Mechanisms Via Three-Dimensional Printing and Material Deposition

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*This paper describes a novel fabrication technique called hybrid deposition manufacturing (HDM), which combines additive manufacturing (AM) processes such as fused deposition manufacturing (FDM) with material deposition and embedded components to produce multimaterial parts and systems for robotics, mechatronics, and articulated mechanism applications. AM techniques are used to print both permanent components and sacrificial molds for deposited resins and inserted parts. Design strategies and practical techniques for developing these structures and molds are described, taking into account considerations such as printer resolution, build direction, and printed material strength. The strengths of interfaces between printed and deposited materials commonly used in the authors' implementation of the process are measured to characterize the robustness of the resulting parts. The process is compared to previously documented layered manufacturing methodologies, and the authors present examples of systems produced with the process, including robot fingers, a multimaterial airless tire, and an articulated camera probe. This effort works toward simplifying fabrication and assembly complexity over comparable techniques, leveraging the benefits of AM, and expanding the range of design options for robotic mechanisms.* [DOI: 10.1115/1.4029400]

## 1 Introduction

Advances in rapid-prototyping (RP), such as 3D printing, or AM, have enabled the efficient fabrication of complex components that would otherwise be very difficult to make through conventional means. To date, this has had the most profound impact on the iterative design process for prototypes, but researchers have also applied RP processes toward producing functional assemblies [1,2].The limited selection of material properties has been the primary limitation of AM, especially for the more widely available FDM machines, which are restricted to thermoplastics such as acrylonitrile butadiene styrene (ABS), polyactic acid (PLA), polycarbonate, and nylon. In order to expand the utility of current desktop AM processes, we present a technique that uses AM printed components as both structural parts retained in the final system, as well as sacrificial mold features within which additional materials and embedded parts are deposited. Through this process, called HDM, complete systems including multimaterial components of a wide range of durometers, embedded electronics and actuators, and articulated joints can be easily produced via simple extensions to inexpensive and widely accessible AM processes.

Previously described methods, such as shape deposition manufacturing (SDM) and others (described in detail in Sec. 2), have been used to produce similar heterogeneous structures, combining embedded components and/or multiple materials to produce more complex, integrated components than traditional fabrication techniques. HDM seeks to improve upon some of the limitations of SDM, namely, making the fabrication process less labor-intensive, faster, and practical with a greater range of materials. Previous work by this paper's authors [3,4] had combined AM and casting techniques to fabricate functional robotic and prosthetic hands, demonstrating that such methods can create functional and robust mechanisms for use in real-world applications, not just limited prototypes. This paper builds from that initial work to present a thorough investigation and description of the HDM process, including a set of design strategies and recommendations for fabricating articulated, heterogeneous structures, specifically for use in robotics and mechatronics applications. Section 2 begins by summarizing relevant work and discussing the limitations of common AM processes. Section 3 will then overview the general concept and process for the HDM technique. Section 4 details design strategies for successful HDM components and systems, including a study of the interfaces between AM and casted subcomponents. Finally, Sec. 5 presents several functional examples of mechanisms created with this process.

## 2 Background and Related Work

**2.1 Injection Molding and Derivatives.** A number of commercial injection molding techniques [5] can be used to accomplish a subset of the capabilities of SDM and HDM. The examples most relevant to HDM include reactive injection molding (RIM), soluble core technology (SCT), and over-molding.

RIM [6,7] combines chemical reactions and molding to inject mixed compounds into low-temperature and low-pressure mold cavities. Polymerization may be initiated by either mixing, for polyurethanes, or heat transfer, for select epoxies and polyesters. This process can produce larger components than traditional

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injection molding, but often requires additional release agents, precise flow control, and additional curing time to sufficiently mix and activate the chemical reactions. This process is similar to many of the steps performed in HDM with regard to the mixing and molding of two-part compounds in open molds.

SCT [8] exploits the lower melting point or sacrificial nature of temporary plugs and inserts to generate parts with internal voids. Manufacturers can also use this method to produce scaffolds for carbon fiber lay-ups [9] for the fabrication of hollow composite parts. The process is limited by the methods by which the core is removed from the final product. HDM utilizes a similar method of dissolvable core structures to create voids and internal cavities.

Over-molding adds additional layers of material, usually thermoplastics, on top of previously created components, hereby integrating multiple materials. The process is frequently used in compliant, ergonomic features on tools, or ruggedized and durable housings for electronics [10]. As each subsequent layer is molded over prior layers, either through slide movements within the same mold or through a set of larger mold cavities, the latter must withstand the temperature required for the injection of the former, which limits the selection of workable materials. Also, the geometries are limited to nondie lock arrangements for both the mold cavities and the core slides.

**2.2 SDM.** SDM [11,12] or layered shape manufacturing alternates deposition and material removal steps to generate multimaterial geometries. Suggested materials for SDM are similar to those used in RIM, as molds for deposited resins are typically open. Functional examples created via SDM include compliant legs for the Sprawlita family of walkers [2], the passively adaptive SDM hand [4], and transmission components for light-weight unmanned aerial vehicles (UAVs) [13,14]. The resulting heterogeneous structures can accommodate integrated electronics and allow for more impact-resistant joints through the use of flexures in place of revolute joints. Although researchers have established systematic approaches to producing any arbitrary multimaterial geometry [15], the majority of proven, functional designs have been relatively simplistic and planar, requiring just one or two cycles of the SDM process.

The material removal step in SDM commonly uses traditional CNC milling to level the top of the mold between deposition steps. This establishes a primary build, or growth, direction [16] that designers must accommodate in their designs. CNC milling may not be appropriate for certain materials, specifically softer and more compliant urethanes that may entangle on the tooling. Some researchers have suggested either using alternative material removal tooling, such as fly-cutters, or softer sacrificial materials, such as wax [17], which can be removed via a water jet or pressurized air.

Due to the SDM process's handling of undercut features, each deposition step typically adds new material onto a flat plane, such that the final component may exhibit structural weakness between deposition layers, much like parts produced via FDM. Kietzman et al. evaluated the structural integrity of parts created by the SDM process in different growth directions, showed that the tensile strength depended on the chemical compatibility between successive deposition layers, and suggested that a monolithic part would consistently out-perform a layered counterpart [18]. Some relevant work [19] has proposed creating assembled molds to accommodate more complex shapes, allowing for a single-shot deposition of a contiguous structure with undercut features. Since the mold is discarded later, its structural integrity only needs to withstand the casting process.

Functional examples of SDM have commonly used two-part polyurethanes for deposition, due to their low-temperature requirements and initially low viscosity, allowing designers to bypass the cost and complexity of an industrial injection molding setup. However, the cure time for many of these materials are in the range of 10–20 hr, so the fabrication time for complex components with overhanging features can quickly become excessive, limiting the scalability of the process.

**2.3 FDM.** Although various forms of AM exist, this paper will focus on FDM, which is the most widely accessible and inexpensive method thanks to the open-source RepRap movement [20]. FDM produces three-dimensional objects by extruding layers of material, usually a thermoplastic such as ABS. An actively controlled extruder mechanism, either a pump or set of rollers, pushes the material as a solid, usually via spools of cylindrical filament, through a heated, liquefying chamber with an exit nozzle. Standard desktop 3D printers [21] utilize solid filament of diameter of 1.7–1.8 mm and extrude through nozzles with diameter of 0.4–0.6 mm at layer heights between 0.005 and 0.02 mm.

Freeform fabrication through FDM has been a significant boon to prototyping and iterative design, but groups have also recently showed its use in functional end products [3,22]. The technique has not only found a role in industrial tooling practices [23] but can also capably produce more than just discrete, solid pieces of varying geometries. Researchers have developed methods for embedding electronics midprint [24] and creating complex, articulated mechanisms in a single print [1,25,26], reducing assembly requirements.

In terms of utilizing an AM process within the proposed HDM framework, a number of considerations and process properties need to be considered. Although the extrusion of thermoplastics in FDM utilizes a longer cooling time than injection molding, part warping can still be an issue if the design includes sharp corners or step changes in part thickness. Also, unlike parts created through molding, components made via FDM will exhibit different structural properties depending on the orientation in which it's printed [25,27]. In comparison to parts made with similar freeform fabrication techniques, like selective laser sintering (SLS) or stereolithography (SLA), the extrusion paths on each layer also influences the final product [28]. This limitation requires careful consideration during the design process to maximize durability of the printed components. Parts are generally most susceptible to shearing failure between printed layers. For example, components for revolute joints should be printed with the axis of rotation parallel to the print direction, whenever possible. A basic summary of suggested best practices can be found in Ref. [25].

To handle more complicated geometries in single-material printing while maintaining flexibility in selecting the primary build direction, temporary structures using the same material as the model may be added, either manually in the model file or automatically by the printing software, to support features with undercuts. Both open-source and commercial software packages can generate thin-walled scaffolds in tessellating patterns beneath overhanging features. Breakaway supports must be sparse to ensure removal and mainly serve to enforce a maximal bound on the size of printed bridges when printing features requiring supports. These supports require sufficient clearance for mechanical removal after printing is complete and may limit the surface quality of printed parts.

Unlike SDM, where parts are built upward layer-by-layer, not all undercut features require support structures during deposition with AM processes. For FDM, depending on the extruding nozzle diameter and the layer height, a ramp of up to 45 deg from vertical [24] can be reliably printed without any additional support structures. Layers sometimes may also bridge across open space, if there are prior supports at both ends. However, prints with overhang features cantilevered too far outward, or bridges that span an excessive distance will deform and sag. These failures may be mitigated by more precisely tuning the extruder temperature and feed rate such that the extruded layers cool and solidify as quickly as possible [29].

In multimaterial printing, the secondary material is often a soluble material used to build the automatically generated support structures. Using a secondary, dissolvable material allows for more flexibility in support geometry. Sufficient adherence between the model and support materials is the primary restriction on material selection. Common support materials for FDM include polyvinyl alcohol (PVA), which dissolves in water, high impact polystyrene (HIPS), which dissolves in limonene, and Stratasys SR-20/2030/100, which dissolves in a sodium hydroxide bath.

The Stratasys INSIGHT software enables users to explicitly print subpaths of the object with support instead of model material. This allows for more unique and efficient approaches to creating removable core structures in heterogeneous robotic structures, as we will describe in Sec. 3.

**2.4 Fill-Compositing of FDM Parts.** It has been shown in Ref. [30] that parts produced on low-cost, FDM printers that utilize ABS and PLA can be mechanically functional under select conditions, but may still be structurally limited by material selection. A technique called fill-compositing [31] has been developed to reinforce 3D-printed components by taking advantage of FDM's ability to produce bridges, overhangs, and variable infill patterns within the part geometry. This process involves the injection of high-strength resins into voids created internally to the printed part. The hardened resins act like an internal reinforcing structure without the need for molding or altering of the part surface geometry. The authors have shown that this technique can increase part strength by up to 45% and mitigate many of the negative effects associated with the build layer construction of FDM components. Since fill-compositing only is intended to enhance strength and stiffness of printed components internally, additional features like grip pads, or flexible joints will need to be manufactured using another casting or molding process.

**2.5 Other AM Processes.** This paper will focus on the use of FDM as the AM process of choice due to its relative prevalence in research and academic settings. Other methods, such as SLS, SLA, and inkjet photopolymerization, which also build parts layer-by-layer, can be used in its place, but designers need to note the variations and limitations of these alternative methods. SLS [32] fuses each layer out of a homogeneous bed of thermoplastic powder and requires no support structures, but is restricted to a single-material selection. Similarly, SLA [33], a common type of photopolymerization, produces parts out of a vat of curable liquid resin, requiring breakaway supports for overhanging features. Inkjet photopolymerization, such as object polyjet printing, may be the most similar to FDM, as successive photopolymer layers are deposited via a series of nozzles and cured by ultraviolet light. This method produces support features out of a soft material that can be removed with a water jet [34]. A more complete comparison of various AM processes can be found in Refs. [35] and [36].

## 3 HDM: Combining Casting and AM

Leveraging the principles of FDM and SDM together allows researchers to bypass many of the design constraints of both processes and then efficiently fabricate heterogeneous structures with more complex geometries. Like SDM, the HDM process described in this paper is a variation on a combination of traditional casting and molding techniques.

**3.1 Process Summary.** Figure 1 presents the basic steps of the HDM process and can be summarized as follows:

(1) Printing parts: Initially, component pieces for the mold or solid bodies for the final mechanism are printed. The mold as a whole can be printed as a single monolithic piece or each subcomponent may be printed in an independent build direction that optimizes structure integrity or print duration. The printed pieces may require temporary support structures to facilitate the FDM process or they may include user-defined support structures for use in the later deposition stages.

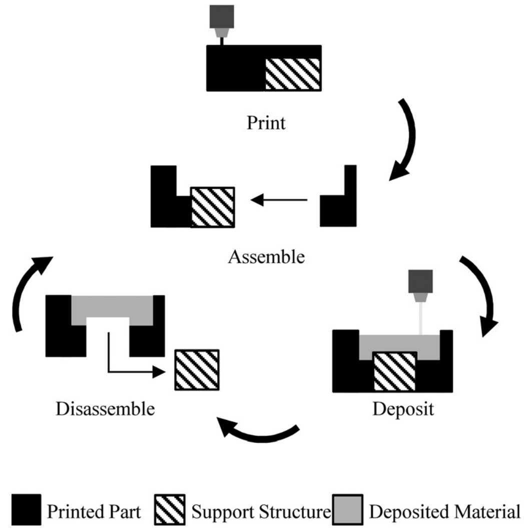


**Fig. 1 Summary of how 3D printing and resin casting can be combined to create novel mechanisms and structures through the HDM process, which may include multiple assemble-deposit-disassemble cycles**

(2) Assembly: Mold components are assembled in preparation for the deposition stage. This step may include embedding electronics or fixturing additional elements onto temporary scaffolds.

(3) Deposition: The appropriate material, usually a low-temperature, two-part urethane or epoxy resin, is deposited into the cavities of the mold. This may constitute a compliant flexure joint, provide a soft overmolding, or secure embedded components in place. Depending on material selection, this is often the primary manufacturing bottleneck that limits scalability, similar to SDM and RIM.

(4) Disassembly: After curing completes, the mold is taken apart to release the part. The resulting product of this stage may then be included as part of another assembly step for a more complicated mold requiring multiple deposition steps.

**3.2 Sacrificial Mold Features.** Fabricating the appropriate mold cavities is a limiting factor in processes like SDM. The selected build direction and number of overhanging features can greatly increase the complexity and length of the fabrication. Freeform fabrication techniques help eliminate the geometric constraints of traditional material removal processes. Also, as the mold does not necessarily need to meet the same robustness requirements as the final component, the structural limitations of parts created through FDM are not as impactful. In fact, while printed features may be part of the final product, they are especially useful as temporary cavity walls and boundaries that are removed later. Figure 2 shows an example of how portions of a single 3D-printed part can be used as a sacrificial mold that is removed after casting to create a functional finger, and Sec. 4 describes in detail more methods and strategies by which these sacrificial features can be created.

**3.3 Multimaterial Interfaces.** In heterogeneous structures, each material is generally deposited independently, and the chemical adhesion properties at the boundaries between different materials are often insufficient for components subject to external loads and disturbances [18]. Creating mechanical "root" or "dogbone" shaped anchors [37] with protrusions that effectively interlock the two bodies will increase fatigue life at interfaces between rigid and soft materials that expect large strain during operation. Reference [14] suggested elastomer anchors comprised both a

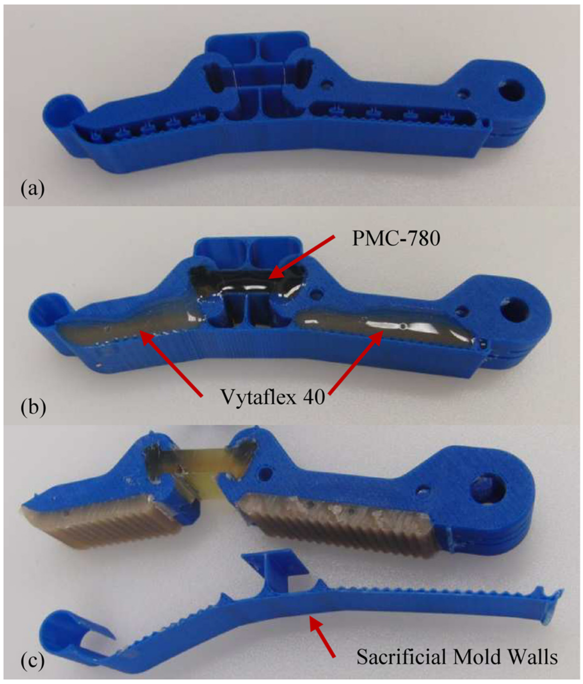


**Fig. 2 Steps to create an exemplar finger via the process described in this paper. (*a*) Mold component is printed with both sacrificial walls and core parts as a single monolithic part, (*b*) resin is deposited into the appropriate cavities, and (*c*) sacrificial features are removed with a file after deposited resins cure.**

protruding anchor and a void around which the rigid body is cast, but this design is not always an option given its geometric requirements. To avoid stress concentrations, past work [16] suggests using rounded features and avoiding sharp corners. In practice, the authors have primarily used two forms of anchors: (1) urethane anchors for flexure joints formed by printed cavities and (2) printed anchors around which softer urethane materials and pads are cast. The smaller, printed anchors in the latter case are often more appropriate for features with low profiles such as grip pads for fingertips. Figure 3(*b*) illustrates the difference between *flexure* and *pad* interfaces.

To evaluate the performance of these types of interfaces, tensile tests were conducted on samples with varying anchor parameters, as shown in Figs. 3(*a*) and 3(*b*). Urethane flexure anchors utilized PMC-780 [38] and the printed anchors utilized Vytaflex-30 [39]. These material selections are consistent with the preferred urethanes for the Yale Openhand project [3], an open-source robotic hand design designed with HDM principles. All tests were run on an Instron® 5569 universal testing system [40]. For the urethane flexure anchors, the diameter and overall width of the dog-bone feature were varied. The overall contour was rounded to avoid sharp corners and stress concentrations in the printed body. For the pad anchors, the number and dimensions of the individual ABS hook anchors were varied. A total of 34 test samples, 16 flexure samples, and 18 pad samples were evaluated. All test samples had a depth of 10 mm and utilized PMC-780 and Vytaflex from the same batch mixtures.

The experimental results, detailed in Figs. 4(*a*) and 4(*b*), suggest maximizing the overall resin anchor sizes to withstand the maximum tensile loads. Figure 4(*a*) shows that the pad interface as a whole did not fail altogether at the same time. The printed ABS hooks divide the pad material into multiple Vytaflex hooks, and each drop in measured stress indicates an individual resin hook failure as it disengaged from the interface. For the largest flexure anchor width values, the test sample remained intact for the entire allowable travel of the Instron® system, but hysteresis in the urethane flexure was evident. 3D-printed components did not show any signs of failure or deformation in any of these tensile tests. All interface failure conditions were due to the urethane component breaking free from the printed bodies, not mechanical failure in the elastomer.

## 4 Mold Design Strategies for HDM

In order to fabricate effective multimaterial components with the HDM process, a number of considerations regarding the creation of the molds should be observed. Those include amount of material used, accessible openings for material deposition, and amount of necessary postprocessing.

**4.1 Thin-Walled Mold Cavities.** The most straightforward mold design with HDM is to combine thin walls for the mold voids with the printed bodies, creating both permanent and sacrificial areas as a monolithic part. These walls are integrated into the overall print, shown in Fig. 5, and are manually removed in postprocessing, usually with a bandsaw or hand file, after the deposited resin fully cures. The minimal feature size that an FDM machine can produce is limited by the number of contour widths (usually a minimum of two) and the nozzle diameter. For the Stratasys uPrint and Fortus machines, the authors measured a minimum feature width of 0.7 mm, approximately twice the standard nozzle diameter. Despite this small feature size, the walls' printed contour lines will run continuously with the outer contours of the

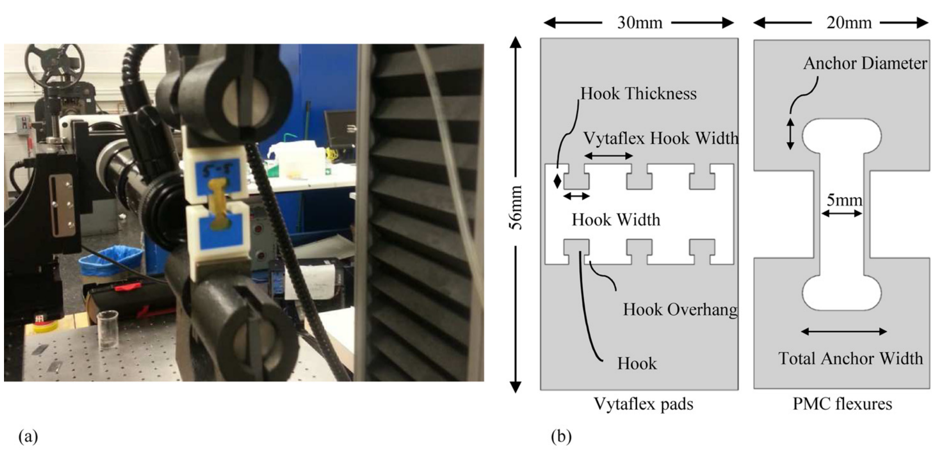


**Fig. 3 (*a*) Instron setup to test the tensile strength of various resin anchors in combination with printed ABS bodies and (*b*) parameters of the test samples for both Vytaflex 30 pads and PMC-780 flexures**

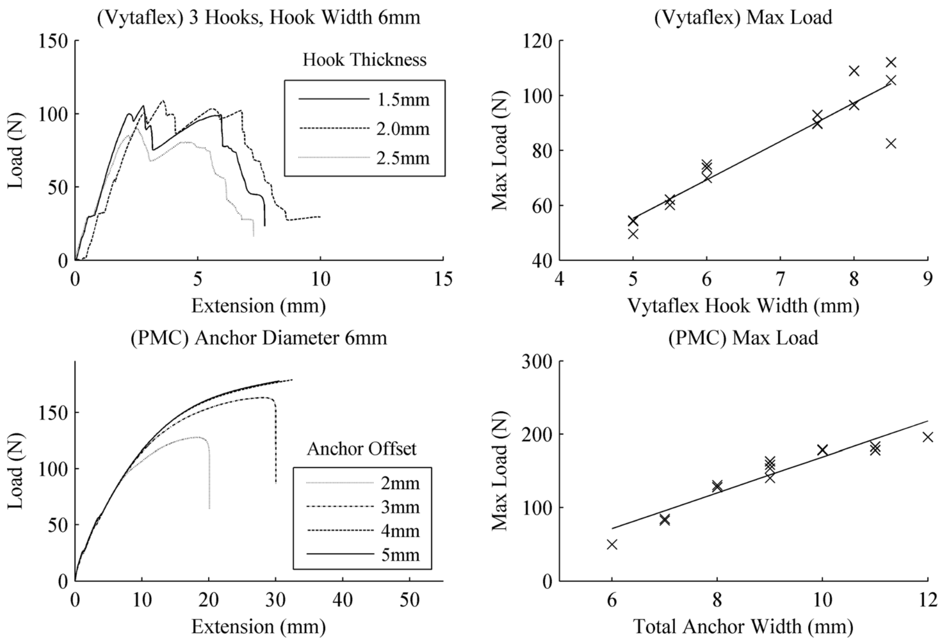


**Fig. 4 Tensile test results to determine failure points of various anchor designs. Results suggest maximizing the overall resin anchor protrusion size.**

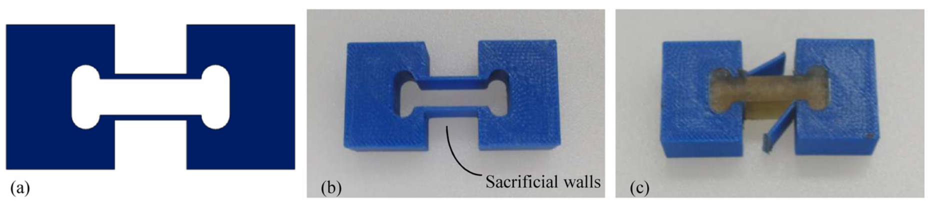


**Fig. 5 Mold cavity created with thin, sacrificial walls. The walls are manually removed, usually with a bandsaw or file, after the deposited resin cures.**

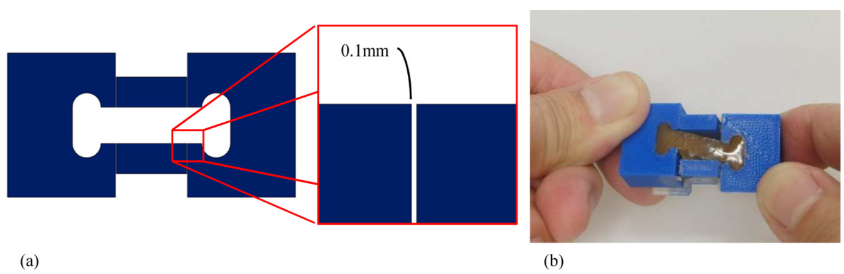


**Fig. 6 Regions printed side by side as separate contours can produce dissolvable or breakaway molds. In this example, the 0.1 mm gap separation is guaranteed to be smaller than the standard FDM printer's nozzle diameter (~0.4 mm). The optimal gap separation will depend on printer performance.**

overall piece as long as the printer g-code generation software recognizes the walls as contiguous with the overall geometry. Contrary to the design of printed or cast bodies, it may be beneficial to incorporate sharp corners and abrupt changes in thickness for sacrificial thin walls, because the resulting stress concentrations will better facilitate wall removal.

Snap-off sacrificial mold features that can be broken apart by hand can be generated by demarcating separate physical regions separated by a gap smaller than the printer's nozzle diameter. Although this produces independent, closed contours for each region, the final printed part will be monolithic, albeit with weakened structural integrity at the boundaries between each independent part region. Figure 6 shows an example of such a breakaway mold design. Modulating the size of these gaps will determine how easily these sections can be broken away. The authors suggest a gap separation 0.25 times the nozzle diameter (typically ~0.4 mm on a standard desktop FDM printer) or ~0.1 mm gap separation between the two independent parts.

**4.2 Dissolvable Mold Walls.** These sacrificial cavity walls may also be printed with dissolvable support material. This may simplify wall removal during postprocessing, as the entire mold can be placed in the heated lye bath or use the same support material removal process as any standard printed part, according to the printer manufacturer's suggested guidelines. Dissolvable

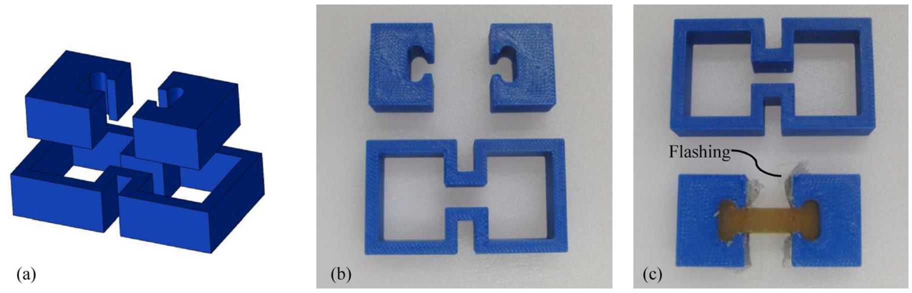


**Fig. 7 Example of snap-together, multipart molds that can be reused instead of destroying the temporary mold features**

components in molds are especially useful for multistage molds [41] where support structures and sacrificial features may be difficult to remove otherwise. Soluble portions of a mold can expose cavities not easily created through traditional material removal. Section 5 describes an exemplar part with inner features that would be difficult to manufacture without dissolving the inner core as an intermediary step between depositions. The deposited urethanes and resins need to withstand the high $p$H (9–11) and temperature (60–80 °C) conditions of the lye baths for support material removal.

The dissolvable features are separate bodies from the rest of the print and must be large enough to be free-standing. These features may be printed in place with the rest of the part or separately and then joined with adhesives at a later step. While wall removal may be easier, the required dissolve time may be prohibitively long, depending on the density of the support structures and the amount of surface area exposed to the bath solution. For example, sections of support material with limited exposure to the part's outer surface require a significantly greater duration of time to dissolve.

**4.3 Multipart, Reusable Molds.** More traditional, reusable, snap-together molds can also be produced (Fig. 7). While there is a higher initial material cost, postprocessing can be simplified considerably. According to basic design guidelines from printing service vendors [42], gaps of 0.1 mm and 0.3 mm should be used for tight- and loose-fit interfaces, respectively. From our experience and as noted in Fig. 7(*b*), it is useful to have a snap-fit, retainer piece that holds the other pieces in place. From trial and error, the authors suggest a minimum thickness of 3 mm for features designed for reuse in molds.

The resolution limitations and surface finish of 3D-printed parts is the primary concern with this design approach, as it is difficult to achieve a seamless seal between mating parts. This can result in undesirable flashing during the molding process, shown in Fig. 7(*c*), due to the urethane or resin leaking before fully curing. Flashing can be reduced by using urethanes with a lower initial viscosity. Incidental gaps in the assembled mold may need to be sealed with adhesives or other elastomers prior to the deposition step.

Another advantage of multipart molds is the freedom to select an optimal build direction for each subcomponent. Whereas monolithic molds with sacrificial, breakaway, or soluble walls are printed in place, restricted to a single build direction, components of a multipart mold may each be fabricated to optimize for strength, cost, or other design parameters independently of others.

**4.4 Mold Component Surface Finish.** Layered manufacturing techniques produce surface imperfections, in particular a "stair-stepping" texture in the build direction, and this may produce undesirable features in the casted resin part. For flexural parts that undergo a high degree of cyclic loading, surface defects may introduce a susceptibility of crack formation during use. In general, it is suggested that the mold should be designed such that its build direction is perpendicular to the cast flexure's primary loading direction, but the mold's surface texture can also be improved through postprocessing [36] methods such as abrasive sanding or the application of sealant and adhesives.

**4.5 Variations for Alternative AM Techniques.** Many of the techniques utilized in HDM are based on carefully selected part geometries while others are based on voids created through dissolvable inserts or portions of the part. Although any AM technique can be utilized for creating generic parts/molds with the correct external geometry, only FDM printing (to date) has the ability to create custom dissolvable mold segments. With this in mind, numerous multipart mold steps can replace the need for many of the requirements of dissolvable mold components within the HDM process.

## 5 Case Studies

In refining HDM, the authors identified a number of suggested design parameter limitations, listed in Table 1. These parameter guidelines were used in the following case studies:

**5.1 OpenHand.** The authors have designed and documented an open-source robotic hand [3] with 3D-printed fingers fabricated by the process described in this paper, showing that HDM can be used to fabricate a functional and robust mechanism. It extends the underactuated design first introduced in the SDM hand [4] and leverages 3D printing through the use of parametric source files, making it easier for nontechnical users to fabricate hands with dimensional properties best suited to their tasks. Using the principle of passive "mechanical intelligence," the physical properties of the fingers directly impact the hand's adaptive grasping performance. A commercial product [43] has been developed based on the design principles established by this initiative.

The OpenHand designs use cast flexures in place of revolute joints, driven by tendons. Their fabrication is facilitated by the thin-wall method described in section 4.1. The straight beam with rectangular cross section, shown in Fig. 8(*b*), is the most basic flexure joint, and its behavior in comparison with a revolute joint is described in Fig. 9. The travel of the proximal link relative to

**Table 1 Suggested HDM design parameters**

| Feature parameter | Value (mm) |
|---|---|
| Minimal printed feature size | 0.7 |
| Minimal printed void size | 1.0 |
| Minimal printed structural feature size | 3.0 |
| Minimal printed anchor protrusion size | 1.0 |
| Minimal resin anchor protrusion size | 3.0 |
| Minimal flexure thickness | 2.5 |
| Gap separation for break-away parts | 0.1 |
| Commonly printed layer thickness | 0.25 |
| Common FDM nozzle diameter | 0.4 |

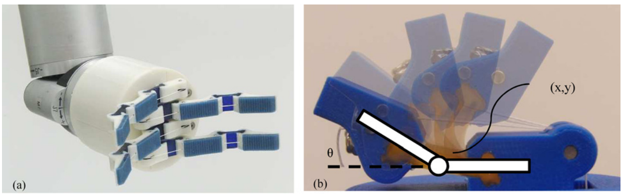


**Fig. 8 The OpenHand design (*a*) uses cast flexure joints and 3D-printed finger bodies and (*b*) tendons are routed across idler pins and pulleys to actuate the fingers. Its motion can be approximated as a revolute pin joint in certain configuration ranges.**

the base was tracked via a series of images taken for a set of tendon actuation inputs. As implemented in OpenHand, a flexure joint's effective center of rotation is most stationary in the joint range [1.0, 1.5] rad. Alternate flexure beam designs, such as variable cross-sectional profiles, embedded fibers for increased strength, and curvature along the major axis will perform differently.

An example of the build process for one of these finger designs with thin, sacrificial mold walls of thickness 0.7 mm is shown in Fig. 2. The proximal and distal finger bodies were printed along with thin mold walls as part of a monolithic mold, as shown in Fig. 2(*a*). The thin walls were removed with a bandsaw after resin deposition and curing. The bottom of the mold was sealed with tape to prevent leakage during material deposition. The top of the mold was left open to promote degassing and avoid internal air voids in the cast urethane. As stated in Sec. 3, Vytaflex 30 (30 Shore A) was deposited in the mold cavities for the finger pads, and PMC 780 (80 Shore A), a stiffer urethane, was deposited in the mold cavity for the finger flexure joint. The printed parts have mechanical features, illustrated in Fig. 3(*b*), to help retain the urethanes after deposition. A complete set of documentation and build instructions can be found online as part of the Yale OpenHand Project [44]. Though this hand was initially designed for FDM, the parts and mold features can be fabricated via any AM process, since they are based entirely on external part geometry.

**5.2 Lightweight Prosthetic Finger With Embedded Components.** Figure 10 shows a lightweight, prosthetic finger design, where the proximal and distal digits were deposited around the embedded components, including the joint flexure and finger pads. This is an example, where the primary part bodies do not necessarily have to be printed, and electronic components can be embedded within parts created through HDM. The printed components instead facilitate the use of alternative deposited materials for the main, solid bodies. Multiple printed molds and deposition steps were used to produce the functional finger shown in Fig. 10(*c*).

First, the finger pads and flexure joints were prepared in their own dedicated, independent two-part molds, similar to traditional injection molding. In this case, half of the mold pieces were printed with dissolvable material to ensure the parts could be

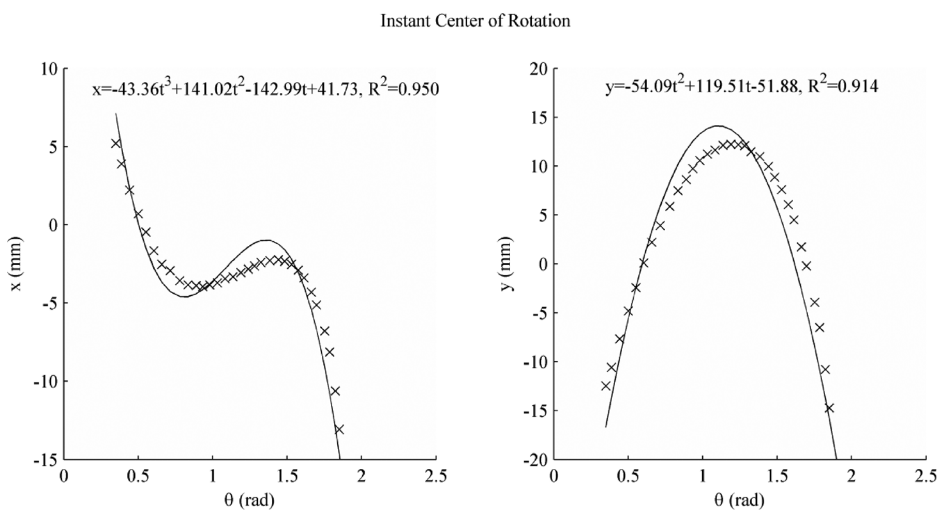


**Fig. 9 Flexure joints can be approximated as revolute joints under certain operating regimes. Buckling behavior of the flexure shifts its effective center of rotation at the upper and lower limits of its driving tendon's actuation space. Mechanisms utilizing flexural joints should be designed with this behavior in mind.**

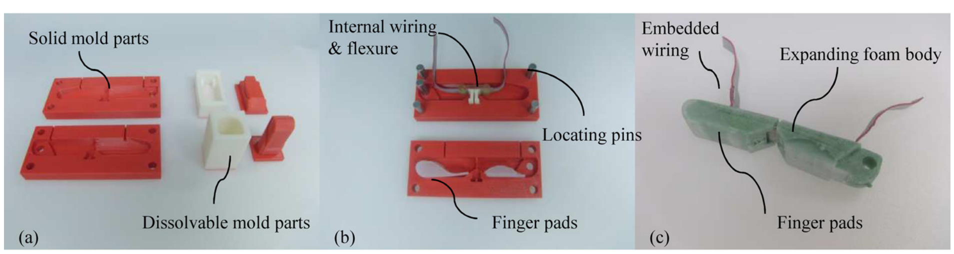


**Fig. 10 Finger design where the proximal and distal digits are deposited around embedded components. (*a*) Multiple mold pieces are printed separately with both ABS and dissolvable material to facilitate the fabrication of urethane components, (*b*) internal components are positioned in the larger finger mold before the finger links cavities are filled with expanding foam to create the final product (*c*).**

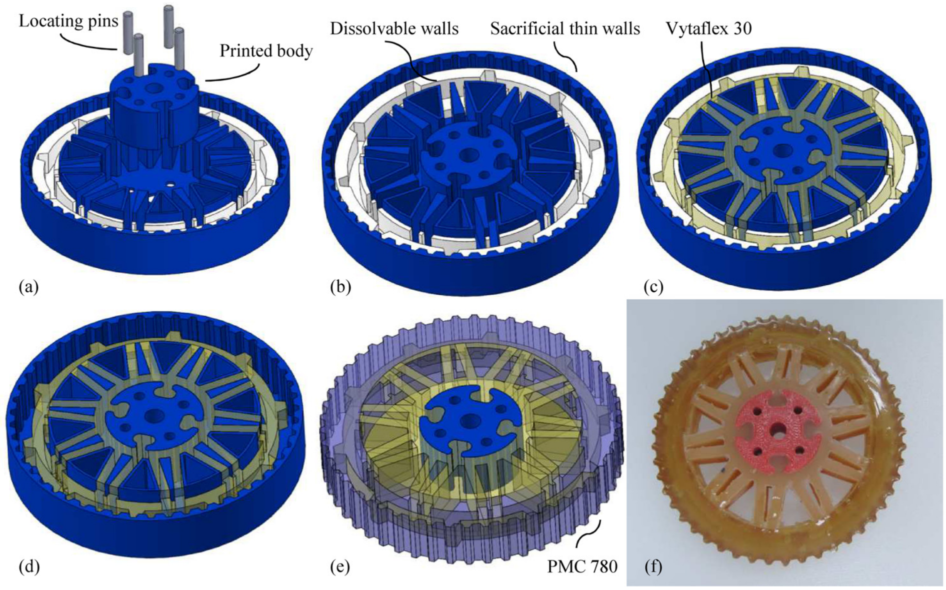


**Fig. 11 Example of the airless tire, a compliant tire created with compliant spokes and a soft rim. The spokes must be anchored within the outer rim. The components are initially (*a*) printed and (*b*) assembled. (*c*) The spokes are first deposited with Vytaflex 30, and then (*d*) the dissolvable components are removed through the use of a lye bath. In the final step (*e*), the outer rim is deposited, and the outer mold features are broken apart to produce the finished wheel (*f*).**

removed from the mold regardless of the finger pad geometry, shown in Fig. 10(*a*). Molding them without dissolvable components would have made it difficult to eject the elastomer from the mold. Consequently, it is preferable to print these mold components with soluble material in FDM rather than SLS or resin-based AM processes. The joint flexure material was deposited around an internal cable, so that the wiring could run within the finger itself. Notched features were included in the printed mold parts to consistently position and secure embedded components prior to deposition.

The internal components were then assembled and fixed within a larger two-part, finger mold, shown in Fig. 10(*b*). Steel locating pins are used to help precisely align the two mold halves during assembly. In this example, the proximal and distal links are fabricated with a urethane expanding foam epoxy, Foam-iT!®15 [45]. The epoxy foam has an expansion ratio of $4x$, and the pressure due to expansion served to ensure a seamless integration of the embedded components with the main finger body. A similar casting process was used to create the fingers for the i-HY hand, complete with integrated tactile and joint sensors [46].

**5.3 Airless, Compliant Wheel Frame.** An "airless" tire is a wheel with compliant spokes, as shown in Fig. 11, designed to deform and passively adapt to traversal over rough terrain. The wheel maintains its round form on level ground to enable high speeds while also increasing the vehicle's ability to maneuver over ground obstacles. This example demonstrates how to generate robust interfaces between contiguous regions of cast elastomers. The spokes and outer rim are made with cast urethanes Vytaflex 40 and PMC 780, respectively, via a two-stage deposition procedure. Figures 11(*a*)–11(*e*) detail the fabrication steps for this component.

This design requires dissolvable inner cores to allow for multiple deposition steps. Although the main mold has both solid ABS and dissolvable material, it was printed as a single part so that it would not need to be disassembled and reassembled between deposition steps. The central, printed wheel hub was secured to the main mold body with a set of steel, locating pins. The Vytaflex spokes (shown in yellow in Figs. 11(*c*)–11(*e*)) were first deposited in the initial mold cavity bound by the dissolvable walls. After the urethane spokes finished curing, the mold was put in the lye bath to expose a new, secondary cavity, in which PMC 780 was deposited, for the wheel's rim. The remaining thin mold walls were then broken apart to eject the completed, compliant wheel.

Due to the low interurethane adhesion between the Vytaflex and PM 780 materials, the outer rim was deposited as an envelope around the spoke frame to maximize the strength of the interface between the spokes and rim. This requirement increases the geometric complexity of the secondary mold cavity, making it preferable to use a dissolvable or easily removable material. However, if a multipart mold could be constructed such that pieces can be manually removed to expose the secondary cavity, then AM processes other than FDM can also be used.

**5.4 Articulated Camera Arm.** Sometimes, components fabricated through HDM can augment the capabilities of existing devices. Continuum and snake-like robots have applications in robot-assisted surgery, surveillance, and locomotion in unstructured environments [47]. The construction of such highly articulated mechanisms may involve numerous precision-machined parts and fasteners or specialized in mold assembly steps [48].

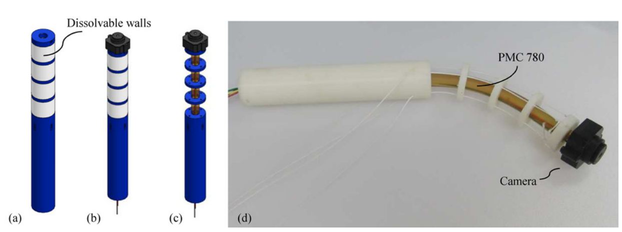


**Fig. 12 Example of a tendon-driven, snake-like camera probe. (*a*) The initial frame is printed with alternating solid (blue) and dissolvable (white) sections around a central core cavity, (*b*) the camera wires are positioned such that they route through the center core, and (*c*) The central core is filled with urethane, and the dissolvable sections are removed via the lye bath before the camera is attached.**

Figure 12 shows a tendon-actuated, continuum probe with a camera integrated at the end, for use in surveillance applications. The wires to the camera are embedded in the cast urethane spine at the center.

The overall frame (Fig. 12(*a*)) was printed in a single process, with alternating solid and dissolvable sections around a central cavity. The frame was designed in such a way that the dissolvable sections did not need to be specified explicitly. Instead, the design relies on the basic support material contours automatically created with the default toolpath generator. With the camera wires running through the central cavity, PMC 780 was deposited to secure the camera in place. Removing the dissolvable sections then produced a segmented, tentacle structure. A set of three tendons were then routed through the remaining, interspersed ABS discs around the urethane core to actuate the articulated arm.

## 6 Conclusion

The HDM process, in which AM augments layered manufacturing methodologies, such as SDM, can extend the application and simplicity of the processes to allow the creation of multimaterial and embedded mechanisms for use in robotics and mechatronics applications. As a form of freeform fabrication, AM reduces the number of manufacturing constraints and enables the fabrication of a more diverse set of component geometries, particularly ones with overhangs and internal voids. This methodology can greatly reduce the manufacturing time, necessary amount of manual labor, amount of waste material, and complexity of assembly versus other processes.

The authors have demonstrated the viability of HDM components and systems in robotic mechanisms through the design of a functional robotic hand and other examples. The mechanical strength of interfaces between elastomers and printed parts was measured, and guidelines for the fabrication of these heterogeneous structures were provided. Design strategies and practical notes for the production of molds and cavity walls were also presented. All examples and suggested practices are achievable with a desktop FDM machine such as the Stratasys uPrint [21] and standard ABS material.

Future work in this direction will analyze other material selections and alternative joint designs to enable more complex mechanisms. While the authors briefly touched upon embedding electronics during the deposition process, more can be done to formalize that process and produce a set of best design practices. A prospective long-term extension of this methodology would be an integrated and comprehensive manufacturing cell capable of autonomously fabricating articulated and instrumented mechanisms from start to finish.

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