Research article

Rapid fabrication of a non-assembly robotic hand with embedded components

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Keywords

Rapid prototypes, Robotics, Assembly

Abstract

The application of rapid prototyping in fabricating a non-assembly, multi-articulated robotic hand with inserts is presented in this paper. The development of robotic systems that have all necessary components inserted, with no assembly required, and ready to function when the manufacturing process is complete is quite attractive. Layered manufacturing, in particular stereolithography, can provide a means to do this. Stereolithography produces a solid plastic prototype via a manufacturing procedure where three-dimensional solid models are constructed layer upon layer by the fusion of material under computer control. An important aspect of the rapid prototype method used in this research is that multi-jointed systems can be fabricated in one step, without requiring assembly, while maintaining the desired joint mobility. This document presents the design and techniques for part insertion into a non-assembly, multi-articulated, dexterous finger prototype built with stereolithography.

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Assembly Automation
Volume 24 · Number 4 · 2004 · pp. 394–405

· ISSN 0144-5154
DOI 10.1108/01445150410562606

1. Introduction

Rapid prototyping (RP) allows the fabrication of complex three-dimensional structures, which could not be produced with conventional fabrication processes. This has made it easier to incorporate and attach sensors, actuators and transmission elements within the structure and joints of the robotic system. Furthermore, RP permits one-step fabrication of multi-articulated, multi-link systems as a whole, without requiring assembly of their structural members and joints after fabrication. These structures are called non-assembly robotic systems. Finally, the addition of components during the building phase to this one step fabrication technique can provide rapid production of fully functional and mobile robotic systems, and offers an alternative manufacturing process.

Over the years, major improvements in the overall quality of prototyped parts have been achieved through enhancements in accuracy, material choice and durability, part throughput, surface texture, and alternative RP processes. These improvements have led to an evolution of the functionality of RP prototypes (Crawford and Beaman, 1999; Bylinsky, 1998). Evolution of the techniques and applications of RP is a continually developing and expanding field. Current research is leading to a more functional rapidly prototyped part with an increasing number of applications and part feature enhancements.

Layered manufacturing has been widely used for the rapid fabrication of physical prototypes of functional parts, patterns for molds, medical prototypes such as implants, bones and consumer products (Bylinsky, 1998). Robotic systems have been used as part of a RP process in (Tse and Chen (1997) and Vergeest and Tangelder (1996). However, the application of RP in robot and mechanism design and fabrication has been very limited. Professor Gosselin and his group at Laval University, using a fused deposition modeling RP machine, fabricated several mechanisms such

Received: 18 May 2004
Accepted: 9 July 2004
This project was supported by a CAREER grant (DMI-9984051) from the National Science Foundation. Furthermore, this material is based upon work supported under a National Science Foundation Graduate Research Fellowship (recipient Kathryn J. De Laurentis) and a Selected Professions Engineering Dissertation Fellowship from the American Association of University Women. Any opinions, findings, conclusions or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the National Science Foundation.

as a six-legged six degree-of-freedom parallel manipulator (Laliberté *et al.*, 1999, 2000, 2001). These rapidly manufactured mechanisms required assembly after RP of the mechanism parts.

Professor Cutkosky and his group at Stanford University using a different RP process called shape deposition manufacturing developed planar, non-assembly mechanisms and robotic systems with embedded sensors and actuators. These components were inserted in the multi-articulated structure during its fabrication as opposed to their integration in post-fabrication assembly phases. Their focus is the development of biomimetic structures to illustrate their techniques (Cham *et al.*, 1999; Bailey *et al.*, 2000). More recent research explores embedding flexible materials during the build process of multi-material layered prototypes. A procedure is outlined for part design and for the insertion process, since embedding flexible elements poses particular challenges concerning the protection of the elements (Hatanaka and Cutkosky, 2003). This group also proposed methods for performing the systematic design, error analysis and optimal pose selection for these mechanisms (Rajagopalan and Cutkosky, 1998, 1999; Goel *et al.*, 2000; Binnard and Cutkosky, 2000).

Additionally, researchers at the Georgia Institute of Technology, proposed methods to develop complex devices that maintain the intended functionality and have embedded components using the stereolithography (SLA 250) technique. They performed many experiments for both embedding objects during the build process and for determining tolerances for working prototypes. Detailed guidelines are given for part design for functionality and component insertion, and component preparation for insertion (Kataria and Rosen, 2000; Geving and Ebert-Uphoff, 2000). Another rapid prototype example is a hand developed at Georgia Tech. It utilizes shape memory alloys for actuation and rapid fabrication for the shell of the fingers and palm. It has nine DOF, with each finger capable of approximately 50° range of motion, and nine SMA actuators. This near human size hand has the potential of illustrating the concept of a mass-customizable, non-assembly build process (Diez, 2004). However, no sensors are added and no parts are embedded during the build.

Further research has been done in prototyping compliant mechanisms in a collaborative effort between Raytheon Systems Company and Brigham Young University. Mechanisms that have flexible members, present a challenge in fabrication. This research proposes four methods most suitable for this type of manufacturing, namely CNC milling, laser cutting, electrical discharge machining, and abrasive water jet cutting; and finally suggest that a combination of the methods be used. This is a hybrid approach, one that combines conventional and layered manufacturing methods. Furthermore, an outline of the required procedure for manufacturing is given independent of method (Mortensen *et al.*, 2000).

Our group has studied the fabrication of non-assembly robotic systems using two different RP processes: Stereolithography (SL or SLA), using the SLA 190 and the Viper si2™ SLA® System machines, and selective laser sintering (SLS). Several non-assembly mechanisms and robotic systems have been developed, all beginning with the production of the joints to assure mobility. Results of this work have been extensively presented in Alam *et al.* (1999), Won *et al.* (2000a, b) and Mavroidis *et al.* (2001); in particular, the details of part tolerances, and build and processing procedures for the non-assembly mechanisms can be found in Mavroidis *et al.* (2001). To the authors' knowledge, the work sited in Alam *et al.* (1999) and Won *et al.* (2000a) was the first successful fabrication of multi-joint, multi degree-of-freedom, spatial robotic systems and mechanisms without requiring any assembly using the SL and SLS processes.

In the current project, the concept of non-assembly robotic systems is carried a step further, by incorporating component parts, such as sensors and cables, into the mobile joints during the build process. This paper discusses some techniques for accomplishing this goal as it pertains to building the fingers of a robotic hand prototype using both the SLA 190 and the Viper.

2. Rapid prototyping

RP or layered manufacturing is a fabrication technique where three-dimensional solid models are constructed layer upon layer by the fusion of material under computer control. This process generally consists of a substance, such as fluids, waxes, powders or laminates, which serves as the basis for model construction as well as sophisticated computer-automated equipment to control the processing techniques such as deposition, sintering, lasing, etc. (Dolenc, 1994; Wohlers, 1999). Also referred to as solid freeform fabrication, RP complements existing conventional manufacturing methods of material removing and forming. It is widely used for the rapid fabrication of physical prototypes of functional parts, patterns for molds, medical prototypes such as implants, bones and consumer products (Dolenc, 1994). Its main advantage is

Assembly Automation
Volume 24 · Number 4 · 2004 · 394–405

early verification of product designs. Through quick design and error elimination, rapidly prototyped parts show great cost savings over traditionally prototyped parts in the total product life cycle (Wohlers, 1999). Currently, there are over 30 different types of RP processes in existence, such as stereolithography, which is used here and described below.

Stereolithography is a three-dimensional building process, which produces a solid plastic model. In this process, an ultraviolet (UV) laser traces two-dimensional cross-sections on the surface of a photosensitive liquid plastic (resin). The laser partially cures the resin through low energy absorption of laser light thus producing a solid. The first cross-sectional slice is built on a depth-controlled platform, which is fully submerged under the first thin layer of resin. This and each successive thin layer of liquid resin has a depth equal to that of the vertical slice thickness of the part. After each slice is traced on the surface of resin, the platform lowers by a depth equal to that of the slice thickness. Successive 2D slices are cured directly onto the previous layer as the part is built from bottom to top.

Support structures are needed to maintain the structural integrity of the part and supports overhangs, as well as provide a starting point for the overhangs and for successive layers on which to be built. These supports are constructed from a fine lattice structure of cured resin. After the part is fully built, the support structures are removed and the part is cleaned in a bath of solvent and air-dried. The prepared parts are then flooded with high-intensity UV light in a post-cure apparatus (PCA) to fully cure the resin. The Department of Mechanical and Aerospace Engineering of Rutgers University is equipped with two stereolithography machines from 3D Systems, CA. The model SLA 190 uses Cibatool® SL 5170 resin for part building. The second machine is the Viper si2™ SLA® System. The resin used in this machine is Accura® SI 40 Nd, though other basis photo-polymer resin epoxies with various physical properties are available for this machine.

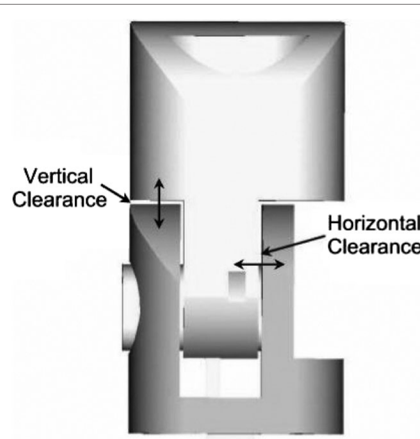
3. RP fabrication: mobility

The first step in building mobile robotic systems with a RP machine is to be able to successfully fabricate joints. Different types of non-assembly mechanical joints such as revolute, spherical, prismatic and universal joints were fabricated with the SLA 190 machine (Alam *et al.*, 1999).

Through a trial and error process, different features such as clearance, part size and support structure generation were optimized to produce working mechanical joints. Of these features, determination of clearances was very important in successful part fabrication. The optimum clearances for the SLA 190 (Cibatool® SL 5170 resin), between two near surfaces, were determined to be 0.3 mm (0.01182 in.) for flat surfaces and 0.5 mm (0.019685 in.) for circular surfaces. The clearances for the Viper si2™ SLA® System (Accura® SI 40 Nd resin) at normal resolution are: 0.222 mm (0.00875 in.) for circular surfaces, and 0.381 mm (0.015 in.) for vertical flat surfaces and 0.3175 mm (0.0125 in.) for horizontal flat surfaces (Figure 1). An important note is that these tolerances for the Viper refer to parts in the 25.4-38.1 mm (1-1.5 in.) range. Clearances for larger parts have not yet been determined.

The tests to determine these clearances were performed for both machines at a layer thickness setting of 0.1524 cm (0.006 in.) for the SLA 190 and 0.01016 cm (0.004 in.) for the Viper. The trials were systematic in that the initial clearances for both flat and circular surfaces began at 1 mm and were decreased by 0.1 mm for each successive build until the joint was no longer mobile for the SLA 190. The clearances were then increased by 0.05 mm until the joint was clear and freely moving. Note that for the Viper, this process was somewhat different and not as lengthy because much experience had been gained from the initial SLA 190 builds. The process began with the SLA 190 determined clearances; building four parts at once and adding or subtracting 0.127 mm (0.005 in.) for gross tolerances and 0.0635 mm (0.0025 in.) for fine tolerances. Finally, the optimal joint clearances were found when there was enough space between the surfaces of the joint to allow free movement yet not too great that supports were built between the surfaces to prevent movement. Furthermore, in all cases

Figure 1 Flat surfaces clearances for the Viper si2™ SLA® system



supports were removed between joint surfaces when necessary to ensure mobility. The above tolerances have consistently given the same results regardless of build angle for identical parts as well as a variety of different parts, with similar overall dimensions, made over the past 4 years. Further details can be found in Alam *et al.* (1999), Won *et al.* (2000a, b) and Mavroidis *et al.* (2001).

One of the test mechanisms produced, a classical cross-type assembly universal joint shown in Figure 2, consists of two different constitutive components, two yokes and a connecting cross hub. Utilizing previously built joints as a design reference; this universal joint was fabricated with the appropriate circular surface clearances. This mechanism was fabricated in the upright position along its length as indicated in the CAD rendering shown in Figure 2. The completion of this build cycle took approximately 8.4 h.

As a consequence of all this testing, the preferred build orientation for the SLA 190 machine was determined. When building joints at an oblique configuration, instead of a vertical one (upright configuration), a special effect called the "step effect" or "staircase effect" appears. This effect can reduce the quality of fabrication of the joint. This is the result of approximating a continuous curved surface in the vertical direction with a discrete set of horizontal thin layers. Obviously, the thinner the layer or building the part in an orientation closer to a vertical configuration reduces this effect. However, this is not necessarily so for the Viper, since it has a feature called "Z smoothing". This ensures the roundness of curved geometry by eliminating roughness on layer lines. Parts can then be built at angles. An example of a finger prototype built at 35° angles about both longitudinal and joint axes is shown in Plate 1. Because of this type of building, no supports were created in the joints (generally no supports are built on parts with angles greater than 30°), while the surfaces remained round and the joints mobile.

In summary, through the experimentation with the joint fabrication some important issues became apparent from which a general approach was formulated. The methodology of

Figure 2 Universal joint built with SL

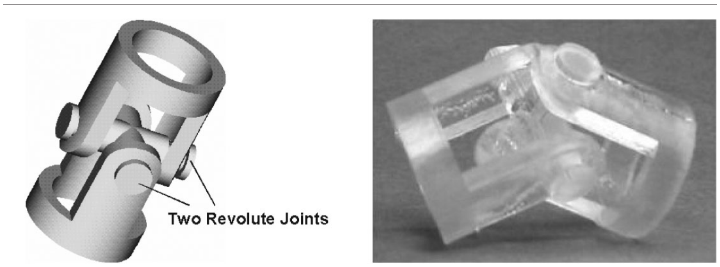
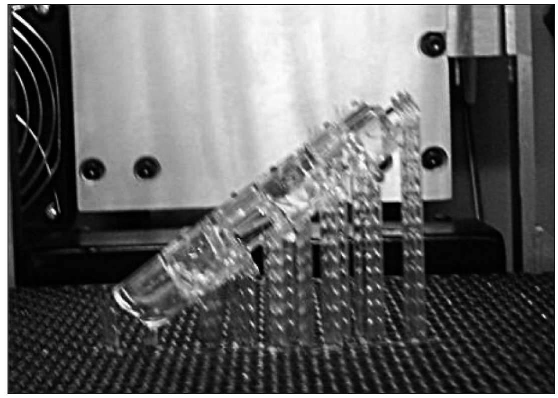


Plate 1 Finger prototype built at angles to eliminate joint supports

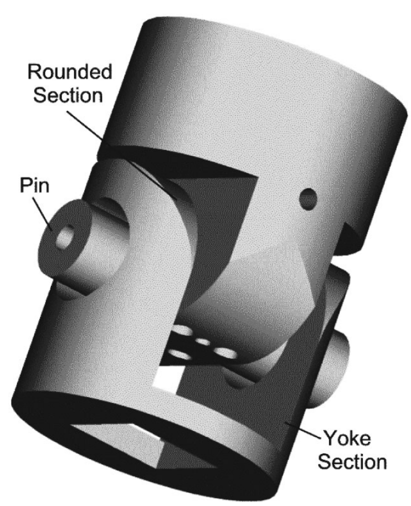


(1) specifying joint clearance;
(2) defining build direction;
(3) utilization of support structures;
(4) elimination or venting of trapped volumes; and
(5) developing novel design strategies, all provide the basis for this type of mobile, non-assembly fabrication.

Upon completion of the joint builds and testing, a mechanism with multiple joints, such as a finger, could be built. This process began, similar to above, with the fabrication of the specific joints of the finger. Two different types of joints were fabricated with the SLA machine: a revolute joint and a spherical joint. Because of their eventual use in a robotic finger and a hand the joints needed to satisfy the specific design criteria.

The revolute joint, shown in Figure 3, connects the ends of two links of the finger. The range of motion for this joint is restricted to approximately 95° of revolution. This limitation on the range of motion was accomplished through the rounding of just one side of the yoke section of the fixed link side. As can be seen in the figure, the other side

Figure 3 Revolute joint

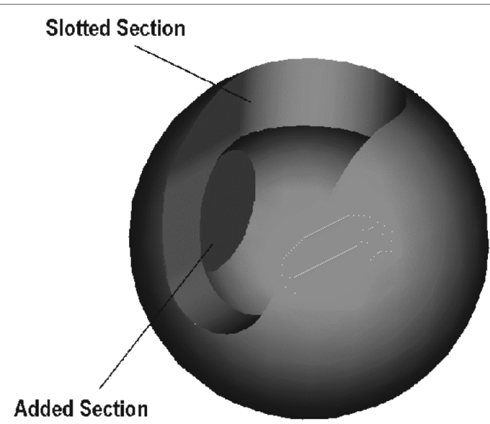


Assembly Automation
Volume 24 · Number 4 · 2004 · 394–405

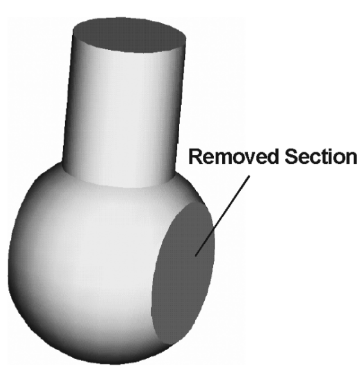
was not rounded to act as a stop. (Often, revolute joints provide a full 180° range of motion.) Thus, this rounding allows the links to clear each other in revolution only through the desired range of motion.

The spherical joint, which serves as the "knuckle" at the finger-palm interface is to have approximately 90° of revolution and about $\pm 12°$ of side-to-side freedom in the fully extended configuration and 0° of side-to-side freedom in the fully contracted configuration. This is an approximation on the range of motion present in an average human finger. The limitation on spherical range of motion was achieved by slotting the socket section in a shape as seen in Figure 4(a). Another restriction was that of minimizing the range of twist about the extended-finger axis. This was accomplished by removing material from diametrical hemispheres of the inner ball and adding material to the inner section of the socket resulting in a modified spherical joint (Figure 4(b)). The combination of the modified ball and the slotted socket (Plate 2) will not fully restrict, but will serve to limit the range of twist to approximately $\pm 12°$; a value acceptable in preliminary prototypes.

Figure 4 View of: (a) modified socket and (b) modified ball

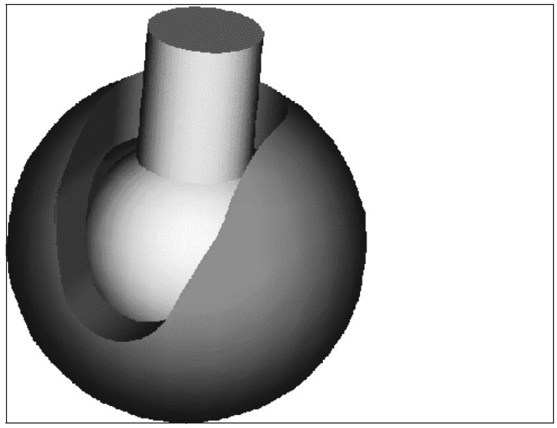


(a)



(b)

Plate 2 Modified spherical "Knuckle" joint



The building of these non-assembly type joints proved successful. Both parts exhibited good mobility through the desired ranges of motion. The fabrication of these two joints is the first verification step in the robotic hand construction.

The next fabrication was a whole finger constructed as one non-assembly type mechanism, leading to the creation of the hand. The fingers are composed of three cylindrical links connected by two revolute joints (Figure 5). Each of the fingers is to be attached to the palm section by modified spherical joints (Figure 4(a) and (b)). An important design consideration for this robotic finger demonstration model is to have the same range of motion and similarity in size to that of an average human finger and hand. The former guiding design feature necessitated the use of modified joint designs to partially restrict some of the degrees of freedom.

One of the benefits of using RP fabrication techniques is in the provision of spaces for actuators and sensors into the design to simplify final assembly. One fabricated hand part was the thumb. The thumb design (Figure 6) has been modified to a two link, two joint assembly to more closely resemble the size and "appearance" of the

Figure 5 CAD view of a robotic finger

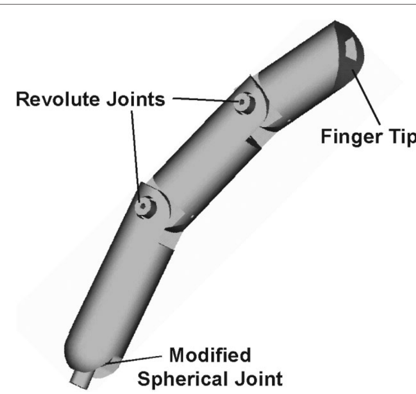


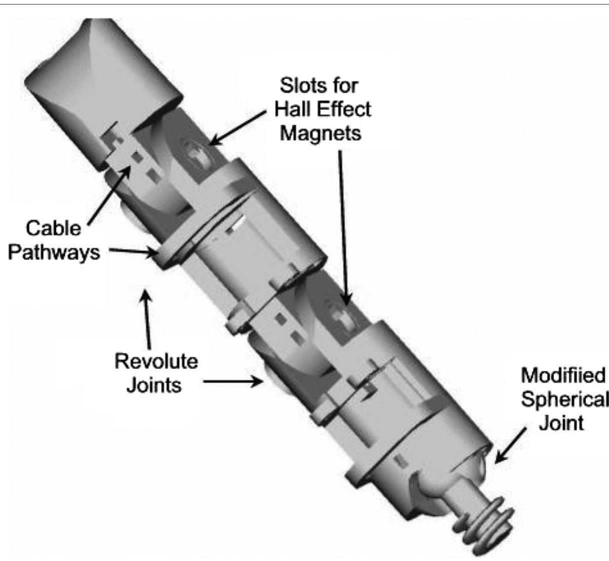
Figure 6 Robotic thumb built with SL

human thumb. As can be noted from Figure 6, slots for sensors have been incorporated. The SLA 190 machine successfully fabricated this prototype with tight fitting, smooth moving joints.

This next prototype was one of the first built using the Viper si2™ SLA® System (Accura® SI 40 Nd resin). This finger incorporates the previously shown ideas of joint clearances, cable routing pathways, and spaces for sensors. This prototype is modular and allows for several different configurations that can include springs or other cables for passive movement or joint coupling. The spherical joint is threaded for easy attachment to the palm. See Figure 7 and Plate 3.

Figure 8 shows the palm design and SL fabricated part. The palm is hollow to allow for passage of cables and sensors, and it includes loops and slots for passage ways or attachment points. It also has a threaded end for easy connection to a forearm structure. Because fabrication of the separate structures of the robotic hand has been successful, the entire hand can now be built as one non-assembly prototype or assembled via threads as shown in Figure 9.

Figure 7 CAD of new robotic finger built with SL



4. RP fabrication: insert procedure

Though intriguing, the concept of embedding parts during the rapid prototype process does present some challenges. Each RP method offers different challenges as well as advantages. For example, with SL there is the problem of laser shadowing once the part has been inserted (Goel *et al.*, 2000). One way to avoid this is to adjust the part orientation for the build. Other challenges that are more non-specific to technique are determining:

(1) component reaction to the basis material and/ or post-processing;
(2) tolerances between the embedded components and the build part;
(3) whether to utilize or delete supporting structures;
(4) build orientation; and
(5) insertion points.

Owing to prior research on articulated non-assembly mechanisms, a basis was formed for developing a method for finding the clearances, build orientation and support structure utilization associated with the SLA 190 and Viper. Some experiments were completed to find the tolerances of various parts inserted during the SLA 190 build. Through a trial and error process, previously built SLA parts, and plastic and metal parts were inserted either before or during the build process to accomplish this task. The findings are shown in Table 1. As a consequence of attempting to find the build clearances, the build orientation that is best suited for the SLA 190 machine was determined.

The clearances were found by measurements taken from previously built SLA parts along with a trial and error process of embedding plastic and metal parts during the build. The findings are shown in Table I under the heading "Other-Resin". Note that at this time part insertion during the build has been done only for the SLA 190. The column "Other-Resin" for the Viper refers to metal or plastic parts placed in the prototype after the build. Also shown in the

Plate 3 Finger built with SL and actuated with SMA wires

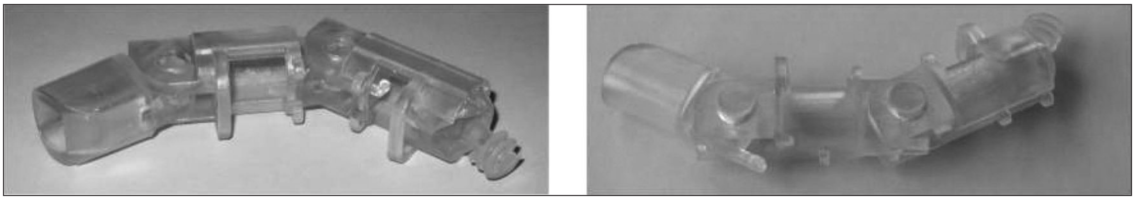


Figure 8 New robotic palm built with SL

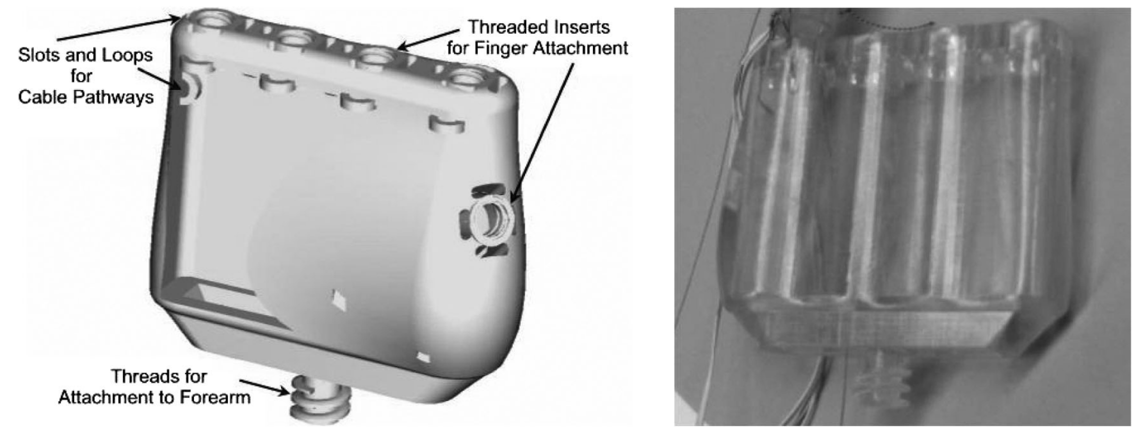
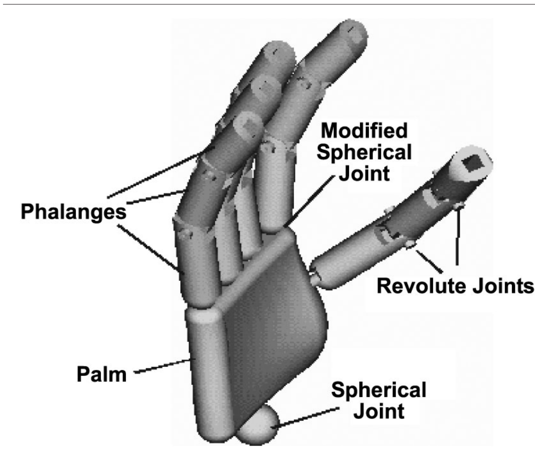


table are the previously mentioned clearances for mobility, listed under "Resin-Resin".

In addition to the clearances listed in Table I, there are more specific tolerances for the Viper shown in Table II, depending upon the desired level of part-to-part "tightness" for nonmoving entities. The values listed are for post build insertion only and pertain to both resin to resin and metal/plastic to resin parts. Examples of utilization of these various clearances are: loose fit – refers to the slot made for the Hall effect sensor, so that it could be repositioned while in the finger; moderate fit – refers to such things as the screw holes in the back forearm actuator bracket; and tight fit – refers to the clearances for the Hall effect magnet so that it could be placed in the slot, but would not fall out.

Figure 9 Pro/ENGINEER® rendering of a Robotic Hand



These experiments illustrated that not only are tolerances, supporting structures and build orientation factors but also the type of insert. Additionally, here the support structures were a problem for the fabrication, but it has been shown in Won *et al.* (2000a) that the SL supports can be used to one's advantage. Supports can be drawn into the part where necessary to maintain the structural integrity and to avoid interference with the insertion. Furthermore, each fabricated part needs to be assessed individually for all these characteristics, which are often interdependent. In addition to the above, experiments were completed to test the possibility of inserting sensitive components, such as motors, during the build cycle.

From all these experiments a basic insertion procedure was developed. In particular, the proper insertion point was determined by dividing the height (the distance from the platform to the proposed layer of part introduction) by the layer thickness, plus one (1) since the machine begins count at layer one:

$$\text{InsertLevel} = \frac{\text{height}}{\text{layer thickness}} + 1$$

This is more reliable and predictable than depending upon time of insertion. It is difficult to ensure the proper addition of all the various phase times such as pre-dip, z-wait, analyzing, and

Table I Clearances between various parts inserted during the build

Technology	SLA 190 (5170 resin)		Viper (SI 40 resin) (Normal resolution)	
Material categories	Resin-Resin (mobility)	Other-Resin (inserted)	Resin-Resin (mobility)	Other-Resin (inserted)*
Flat surface mm (in.)	0.3 (0.0118)	0.15 (0.0059)	Vertical: 0.381 (0.0150) Horizontal: 0.3175 (0.0125)	0.1245 (0.0050)
Radial surface mm (in.)	0.5 (0.0197)	0.2 (0.0079)	0.222 (0.00875)	0.1868 (0.0074)

Notes: "Other" materials refer to metal or plastic objects embedded or placed; * Moderate clearances shown here, for more detail see the next table

Table II Clearances between various parts inserted after the build

Technology	Viper (SI 40 resin) (normal resolution)		
Clearance designation	Loose fit	Moderate fit	Very tight fit
Flat surface mm (in.)	0.15 (0.0059)	0.1245 (0.005)	0.0254 (0.001)
Radial surface mm (in.)	0.222 (0.00875)	0.1868 (0.0074)	0.0254 (0.001)

drawing. Furthermore, it is helpful to have enough time for the proper placement of the component into the part being fabricated. This is accomplished by either stopping the machine (not recommended) or by adjusting the z-wait time length at not only the desired layer but also at the previous and successive layers. In summary, the key points to consider for inserting component parts are as follows:

(1) correct clearance for part/component types;
(2) proper build orientation;
(3) utilization of support structures;
(4) support configuration and/or style;
(5) elimination or venting of trapped resin volumes;
(6) appropriate selection of components to be embedded;
(7) protection or preparation of sensitive parts to be inserted;
(8) calculation of the right insertion layer level; and
(9) suitable adjustment of the z-wait time.

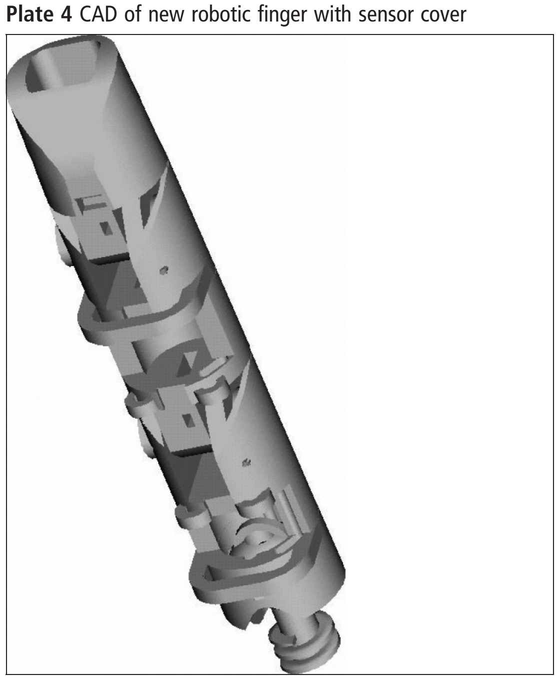
5. Demonstration example: finger prototype

Finally, a finger prototype was built, in the SLA 190 machine, to show that inserts could be added during the build into mobile joints. The process began with the finger prototype previously shown, however, the clearances were increased to accommodate part insertion and the revolute joint was modified to cover the inserts (Plate 4).

The standard SLA 190 circular clearances were used (0.5 mm), but the flat surfaces were increased (0.381 mm). Hall effect sensors and magnets, along with the joint cables were inserted (Figure 10). The cables were placed in a small box (top photo) made prior to insertion so that it would not float away in the resin. The exposed wires in the Hall effect sensors were coated with a thin layer of hot glue. The magnets were placed inside the partial pin (Figure 11) before the build and then this was embedded into the remaining pin. This was done so that the magnets would be placed correctly as described next.

The Hall effect sensors were placed in each revolute joint for recording rotational movement. The Hall effect sensors are from the SS490 series from Honeywell. The specific type to be used is the SS496A, which has a magnetic range of 840 Gauss. The magnets used with the sensors are Bonded Neodymium Iron Boron disks, 6 mm (0.236 in.)

Plate 4 CAD of new robotic finger with sensor cover



Assembly Automation
Volume 24 · Number 4 · 2004 · 394–405

Figure 10 Inserted parts during build

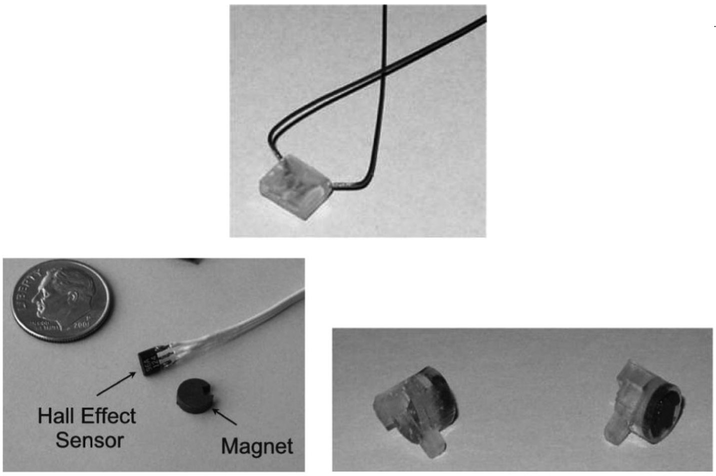
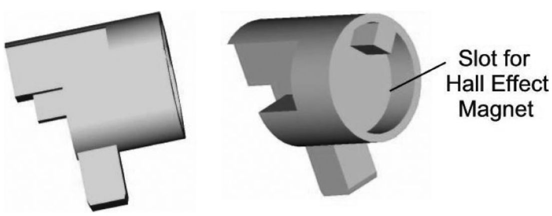
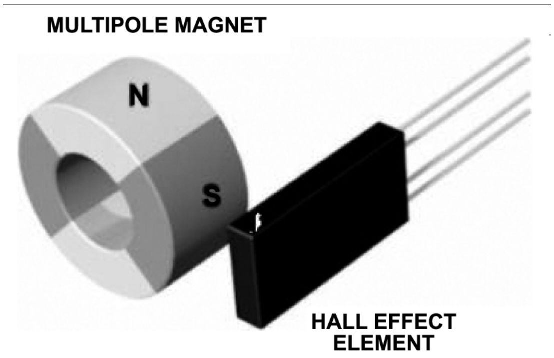


Figure 11 Partial revolute pin for magnet placement



diameter and 2 mm (0.079 in.) thick (length), from Dexter Magnetic Technologies (2004). They are magnetized across the diameter and have two poles. The maximum magnetic field varies between 7500 and 1000 Gauss depending on the size and distance to the sensor. This maximum is reached only at the North and South poles. The basic Hall effect principle consists of passing a current through a thin piece of semi-conducting material (Hall effect element) in a magnetic field, which is perpendicular to the element. A Lorenz force is exerted on the current distribution, which disrupts it producing a potential or voltage difference across the output (Figure 12).

Figure 12 Hall effect sensor concept



In order to achieve the desired Gauss of approximately 840 it was necessary to place the sensor a distance of 0.1524 cm (0.060 in.) from the magnet. After testing and calibration, this was adjusted to 0.1016 cm (0.040 in.) for a better reading range. Figure 13 shows the orientation of the magnet and sensor for this prototype. The sensor is placed such that it reads the changes in voltages in a range of approximately 120° within the poles.

Cavities were implemented into the CAD drawing for easy addition of the sensors. The design as shown in Figure 14 maintained the required distances.

The parts were inserted at their respective layers via the procedures outlined earlier. It was important that all the parts were added at the correct layers so that shadowing would not occur. Figure 15 shows the necessary insertions and placement.

Additionally, the finger was built at 20° about the y-axis (positive along the left side of the platform, front to back) in the negative x-axis direction (positive along the front of the platform

Figure 13 Hall effect sensor and magnet positioning

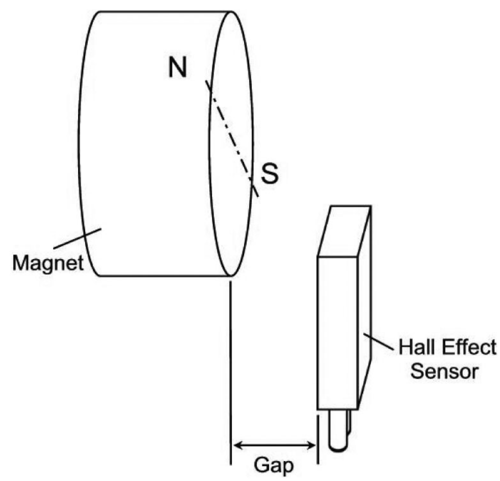


Figure 14 Slots included in the design for sensor addition

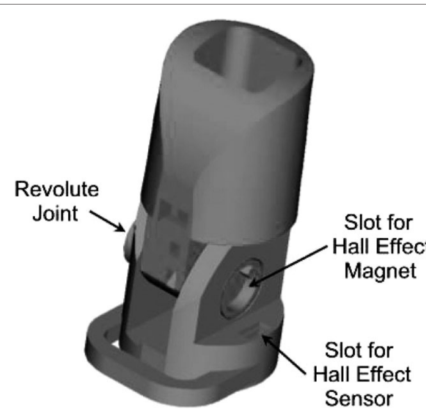
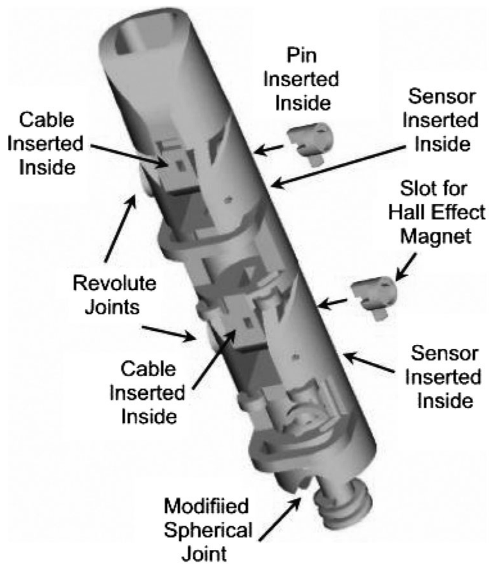


Figure 15 Insertion points for the embedded parts



from left to right). This provided a large enough angle so that supports were not built in the joints and allowed for all the joints to be made freely moving (Plate 5). See Plate 1 for further explanation of this concept.

Plate 6 shows the successful completed finger built with inserts, which took 16 h. The joints have complete mobility just as the previously built finger has (Plate 3). The sensors are functioning normally; the distal interphalangeal joint (joint closest to the finger tip) sensor ranges between 1.3 and 4.3 V, and the proximal interphalangeal joint (middle joint) sensor ranges between 0.8 and 3.2 V. No sensor was inserted into the spherical joint.

As a side note, this type of design allows for several assembly options. Plate 8 shows the addition of a spring across the distal interphalangeal joint, which can also be attached along all the joints. This is useful in eliminating a joint actuator. The springs and cables used in these types of configurations are shown in Plate 7. The cable shown here is 25 lb fishing line (Plate 8).

Plates 9-11 shows two options for wrapping a cable from the distal interphalangeal (DIP) joint across the middle phalanx and around the proximal interphalangeal (PIP) joint, where it is attached. This closely resembles finger anatomy. With this type of configuration flexion of the DIP ligament pulls the PIP into flexion, but more importantly, extension of the PIP joint pulls the DIP into almost complete extension.

Plate 5 Part oriented 20° about the *y*-axis

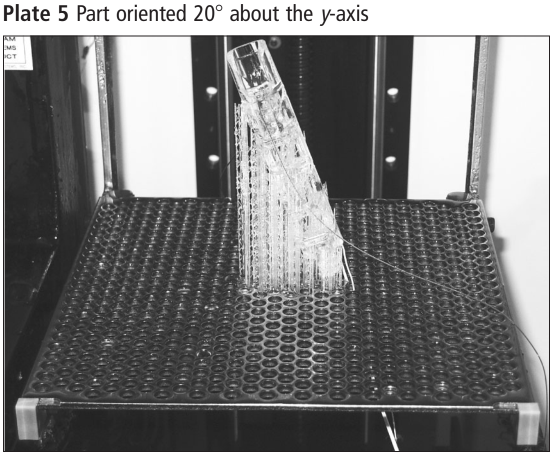


Plate 6 Completed finger with component parts inserted during build

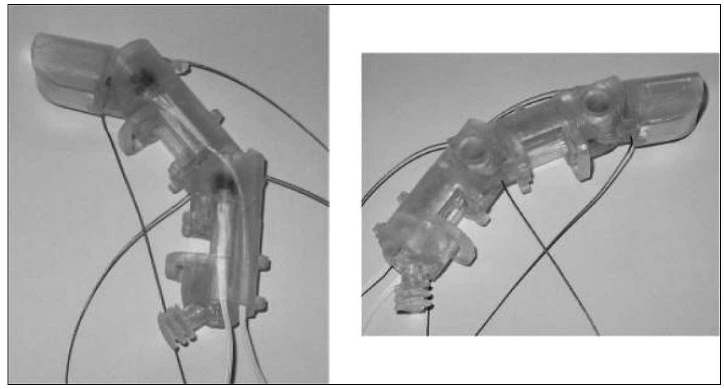


Plate 7 Springs and line used for varying finger configurations

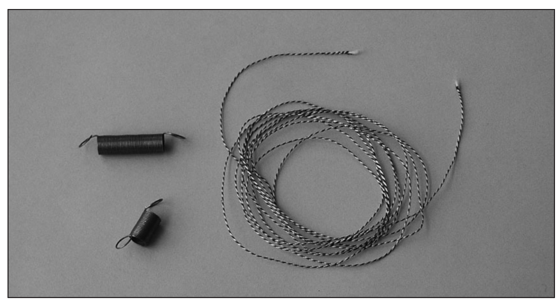


Plate 8 Spring across the DIP joint

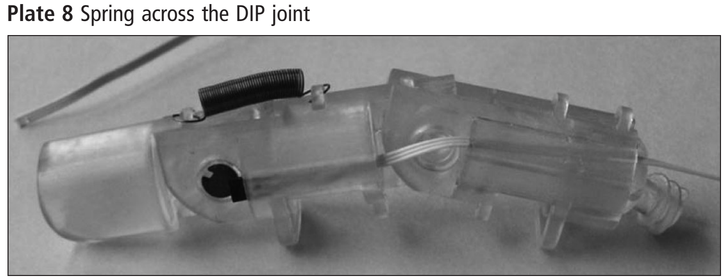


Plate 9 Cable across the middle phalanx

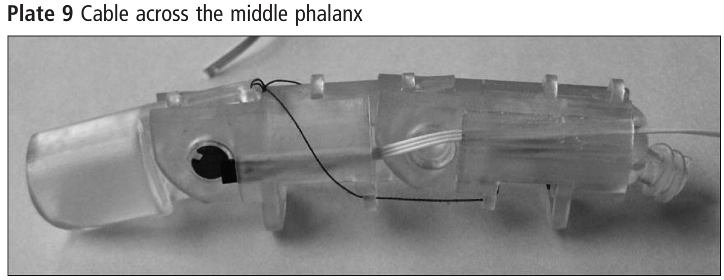


Plate 10 Cable wrapped under the middle phalanx

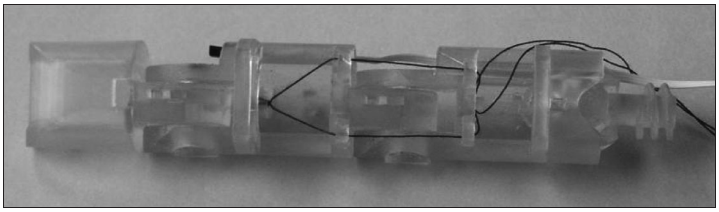
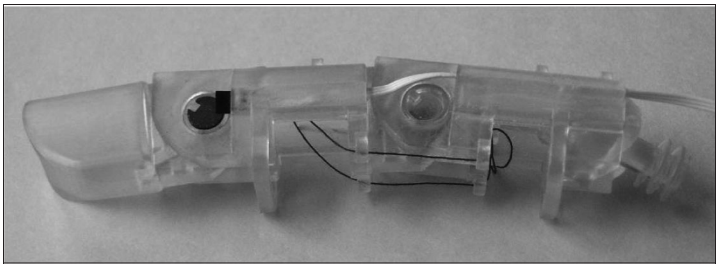


Plate 11 Cable wrapped around the PIP joint



With this type of setup, the finger is a modular unit. The finger was then attached to the palm as shown in Plate 12.

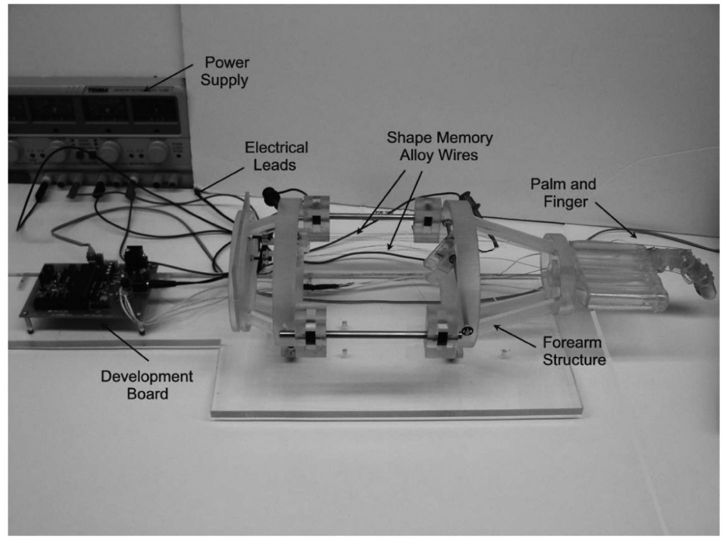
Finally, the supporting structure or forearm shaft, which serves as the mounting brace for the finger actuators was constructed. The palm with finger attached is screwed into the forearm. The full assembly (Figure 16) illustrates well the versatility and utility of RP techniques.

One finger weighs 0.017 kg (0.038 lbs), the palm is 0.079 kg (0.174 lbs), and the forearm is 0.514 kg (1.133 lbs). The RP hand alone is estimated to weigh 0.164 kg (0.362 lbs). The total hand (four fingers, thumb, palm and support structure) is estimated to be 0.907 kg (2 lbs).

There are several benefits to building the finger in this manner; the Hall effect sensors are covered, the cables are securely fastened inside the finger, and the entire prototype is assembled upon completion of the build. However, with this type

Plate 12 Finger with palm

Figure 16 Stereolithographic finger prototype



of design it took less time to build the part and then add the sensors. A cover could be made to enclose the sensors after the build if so desired. It was difficult to embed the parts in such a complex design. In particular the cable was problematic since it is so flexible. Additionally, during the cleaning process one has to be careful not to cut any of the cables. Though it would appear that in this case it is more time efficient to insert parts after the build, this prototype does illustrate that embedding objects can be accomplished in a one step non-assembly mobile part, so that when it is complete, it truly is a novel fully functioning mechanism.

6. Conclusions

RP has been shown to be a viable means of simple and quick fabrication of prototypes for the articulated structures of robotic systems. The various joints and the finger prototype were used to show the one-step, non-assembly, manufacturing process (not just a prototyping process). Additionally, the successful fabrication of the finger illustrates the use of RP as a means of manufacturing in which component parts are added during the build process. Both these techniques combined, provide a means of developing rapid prototyped fully functioning non-assembly type robotic systems and mechanisms with embedded component parts. The user can decide which parts to fabricate in this manner based on the part upon geometry and build time.

It is important to note that the embedding experiments to date have been performed using the SLA 190. The general process described can be modified for other RP machines, though the

Assembly Automation
Volume 24 · Number 4 · 2004 · 394–405

process may not be as easily accomplished. For example, the Viper recoating blade would need to be adapted, i.e. stopped, and/or the parts would need to be inserted closer to the build completion to achieve this part insertion concept.

In summary, the finger model illustrates well the fabrication processes for non-assembly, mobile parts with inserts. The methods described here do provide an alternative manufacturing technique that can be beneficial to those who desire a fully functioning, multi-articulated mechanism with embedded components. This is significant in and of itself, but it also offers a means for building customizable parts and complete systems. This also advances the development, in the future, of a procedure for the hardware system component of an automated robot design and manufacturing process.

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