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## FABRICATION OF A ROBOTIC HAND USING RAPID PROTOTYPING

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### ABSTRACT

In this paper, the application of Rapid Prototyping in the fabrication of a robotic hand is presented. Using the Selective Laser Sintering Sinterstation 2000 of DTM Corporation of Austin, TX, prototypes of mechanical joints were fabricated experimentally. The designs of these component joints were then used to fabricate the articulated structure of one four degree of freedom finger of a five-fingered robotic hand. This robotic finger and joints have been fabricated in one step, without requiring assembly while maintaining their desired mobility.

Keywords: Rapid Prototyping, Stereolithography, Selective Laser Sintering, Robotics, Hands.

### INTRODUCTION

Rapid prototyping of parts and tools is a rapidly developing technology with many advantages: a) time and money savings, b) quick product testing, c) expeditious design improvements, d) fast error elimination from design, e) increased product sales, and f) rapid manufacturing (Ashley 1995 and 1998). Its main advantage is early verification of product designs. Rapid Prototyping is quickly becoming a valuable key for efficient and concurrent engineering. Through different techniques, engineers and designers are now able to bring a new product from concept modeling to part testing in a matter of weeks or months. In some instances, actual part production may even be possible in very short time. Rapid Prototyping has indeed simplified the task of describing a concept to design teams, illustrating details to engineering groups, specifying parts to purchasing departments, and selling the product to customers.

Robotic systems have been used as part of a rapid prototyping process (Tse and Chen, 1997; Vergeest and Tangelder, 1996). However, the application of Rapid Prototyping in robot design and fabrication has been very limited. One of the first works to rapidly fabricate robotic systems was made by Professor Gosselin and his group at Laval University who used a Fused Deposition Modeling Rapid Prototyping machine (Laliberte, Gosselin and Cote, 1999). Several mechanisms were fabricated such as a six-legged six degree-of-freedom parallel manipulator. These rapidly manufactured mechanisms required assembly after Rapid Prototyping of the mechanism parts.

Recently, our group at Rutgers University has fabricated a three-legged, six degree-of-freedom Rapid Prototype of a parallel manipulator in one step, without requiring assembly (Alam, Mavroidis, Langrana and Bidaud, 1999; Won, DeLaurentis and Mavroidis, 2000). To do this, a set of joints that includes revolute, prismatic, universal and spherical joints, was fabricated using the Stereolithography (SL) machine model SLA 190, from 3D Systems, CA. These joints are shown in Figure 1. Through a trial and error process, different features such as clearance, part size and support structure generation were optimized to produce working mechanical

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joints. Of these features, determination of clearances was very important in successful part fabrication. The optimum clearances between two near surfaces, were determined to be 0.3 mm for flat surfaces and 0.5 mm for circular surfaces. Also, the size of these parts is in the order of a few centimeters. This was done to determine the limits of the available apparatus as well as to conserve processing time and material.

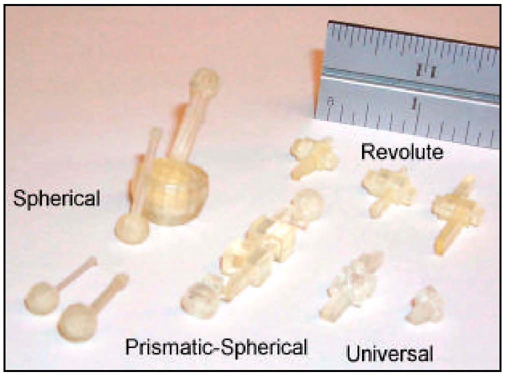


**FIGURE 1. Stereolithography Joint Fabrications**

A three-legged 6-DOF parallel manipulator was chosen as the first mechanism to be fabricated with the Stereolithography SLA 190. The leg of the parallel manipulator consists of two spherical joints, one at each end, and a prismatic joint at the middle of the leg. Each leg of the three-legged platform connects two triangular links. In Figure 2, pictures of the fabricated rapid prototype of the parallel manipulator are shown in two different configurations. This prototype was built overnight during a 12-hour period. To the authors' knowledge, this is the first successful fabrication of a multi-joint, multi degree-of-freedom robotic system that was Rapidly Prototyped without requiring any assembly.

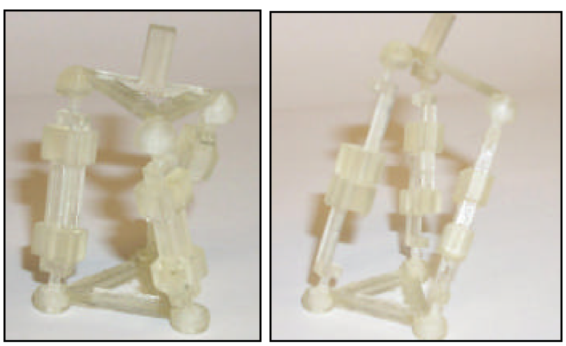

**FIGURE 2. Three-Legged Parallel Manipulator**

The use of Rapid Prototyping in the fabrication of non-assembly type robotic systems is further explored in this paper. The main focus of this investigation is the successful design and construction of articulated structures using another prototyping technique known as Selective Laser Sintering (SLS). Prototype joints similar to those fabricated with the Stereolithography process are Rapidly Prototyped using the Selective Laser Sintering Sinterstation 2000 of DTM Corporation of Austin, TX. In addition, one four degree of freedom finger of a robotic hand with four fingers, a thumb and a palm is constructed as one non-assembly type mechanism. Rapid actuation of the joints of the rapidly prototyped systems is outside the scope of this paper and

## RAPID PROTOTYPING

Rapid Prototyping 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; Crawford and Beaman, 1999). Also referred to as Solid Freeform Fabrication, Rapid Prototyping 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 (Wohlers, 1999). Its main advantage is 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 (Bylinsky, 1998). In this work, Selective Laser Sintering (SLS) is used and is described briefly in this section.

Selective Laser Sintering (SLS) is a three-dimensional building process based on the sintering of a metallic or non-metallic powder by a laser. The SLS process involves the heating of the powder using a $CO_2$ localized laser beam. This localized heating raises the temperature of the powder enough to cause solidification by fusion without melting. The model is built on a platform that is situated within a horizontal platen. The build platform, which is initially flush with the platen, is lowered a depth equal to that of the slice thickness. A powder is then rolled, scraped or slot-fed onto the platform and then the laser draws the 2-dimensional cross-section. This lowering, powdering and lasing process is repeated until the part is complete.

No support structures are necessary in this process since the part rests on and within the non-sintered powder. Post-curing is not necessary except in the case of ceramic parts. Available materials include polycarbonates, nylons, polyamides, elastomers, sand casting materials and steels. A schematic of the process and the main physical process components are shown in Figure 3 (Dolenc, 1994). The fabrication of prototype parts used in the present investigations was through a professional Rapid Prototyping service provider for SLS manufacturing. The machine used is the Selective Laser Sintering Sinterstation 2000 of DTM Corporation of Austin, TX.

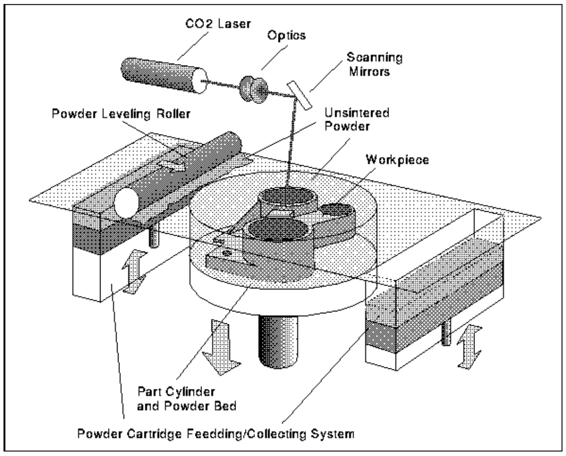


**FIGURE 3. SLS Process (Dolenc, 1994)**

## JOINT FABRICATION WITH SLS

Joints of robotic finger were built using the Selective Laser Sintering (SLS) Sinterstation 2000 of DTM Corporation of Austin, TX. The basis material chosen was a polyamide. Clearances similar to that established for joints fabricated using the Stereolithography SLA 190 process were used as trial values. These values are conservative as the Sinterstation 2000 has a greater level of accuracy, $\pm$0.005"-0.0075" versus $\pm$0.0075", and a smaller layer thickness, 0.005" versus 0.006", over that of the SLA 190.

When building joints at an oblique configuration, instead of a vertical one (upright configuration), a special effect appears called the "step effect" or "staircase effect". 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. In SLS, the thinner layers reduce considerably the "staircase effect" in rounded joints.

Two different types of joints were fabricated with the SLS machine: a revolute joint and a spherical joint. Both joints are parts of a rapid prototyped robotic hand that is presented in Section 4. Because of their use in a robotic hand the joints needed to satisfy specific design criteria.

The revolute joint, that connects the ends of two links, is restricted to approximately 100° 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 Figure 4, this rounding allows the links to clear each other in revolution only through the desired range of motion.

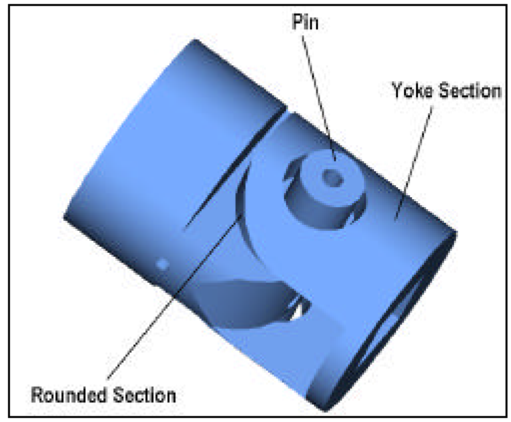


**FIGURE 4. Revolute Joint**

The spherical joint, which serves as the "knuckle" at the finger-palm interface (see Figure 8), is to have approximately 90° of revolution and about $\pm$15° 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 5a.

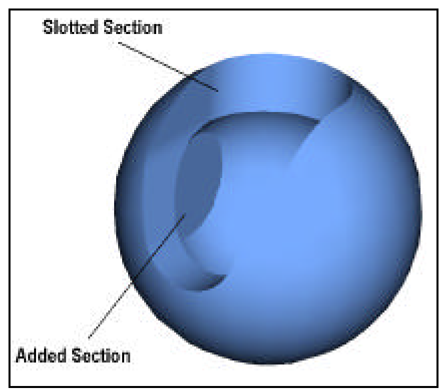


**FIGURE 5a. View of Modified Socket**

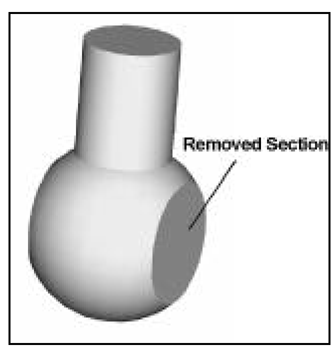


**FIGURE 5b. View of Modified Ball**

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 5b). The combination of the modified ball and the slotted socket (Figure 6) will not fully restrict but will serve to limit the range of twist to approximately $\pm 10°$; a value acceptable in preliminary prototypes.

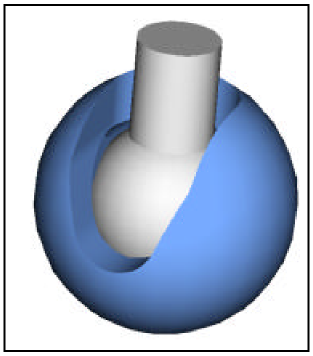

**FIGURE 6. Modified Spherical "Knuckle" Joint**

As seen in Figure 7, using the SLS process to build non-assembly type joints proved successful. Both parts exhibited good mobility through the desired ranges of motion. Also, the presence of the "staircase effect" was reduced due to the Sinterstation process' thin layer thickness. The fabrication of these two joints is the first verification step in the robotic hand construction.

The improvement in rounded surface quality has important consequences in the design of these joints. First, the decreased "step effect" means that the clearances between moving surfaces can be reduced to a lower value. Another important effect is the diminished importance of part orientation during the fabrication process in rounded as well as in flat and sloped components. Selective Laser Sintered parts do not require any computer or manually generated support structures. This is an important process advantage. Parts do not have to be designed with the consideration of support structure placement in part orientation during the build cycle and in addition, the task of support removal is eliminated.

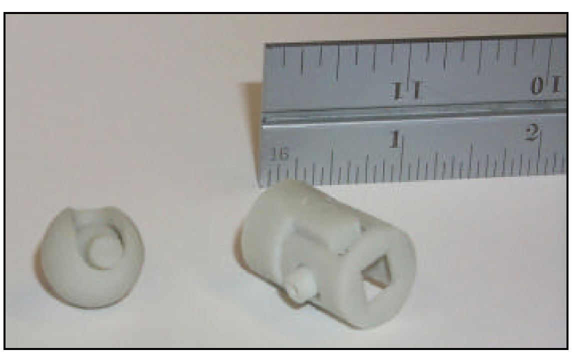

**FIGURE 7. SLS Fabricated Joints**

## ROBOTIC HAND FABRICATION

A robotic hand with five fingers and a palm, all constructed as one non-assembly type mechanism, is currently being designed and fabricated (Figure 8).

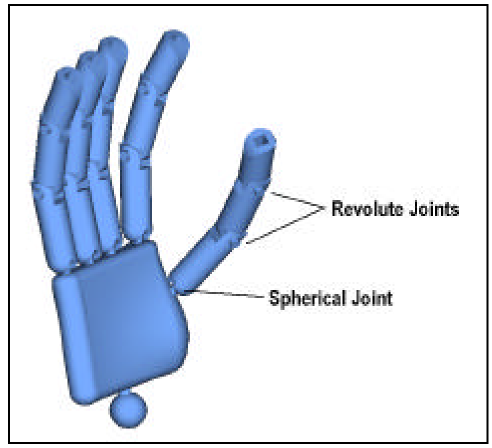


**FIGURE 8. CAD Rendering of Robotic Hand**

This robotic hand is designed with the future purpose of using a Rapidly Prototyped robotic hand as a possible replacement for mechanically driven prosthetic hands. The fingers are composed of three cylindrical links connected by two revolute joints (Figure 9). Each of the fingers is to be attached to the palm section by spherical joints.

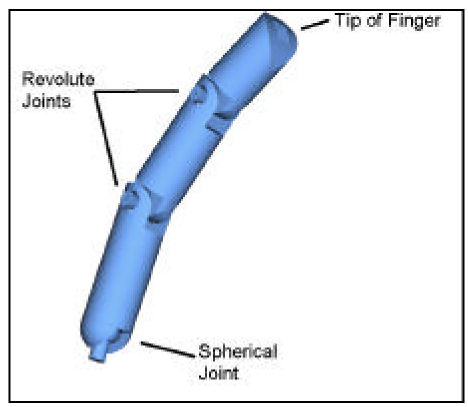


**FIGURE 9. A Robotic Finger**

Rapid Actuation of the robotic hand is to be achieved through a combination of cables and Shape Memory Alloy artificial muscle wires. Shape Memory Alloy (SMA) wires are characterized by a reduction in length when resistive heat is generated through the length of the wire by the flow of electricity. The SMA wires to be used in this design have a wire diameter of approximately 150 microns (0.006"). The cables will be connected close to the pivot points of the revolute joints and will run through the incorporated "pathways" (Figure 10) within the length of the fingers. The cables will be crimped to SMA muscle wires proximal to the palm. It is necessary to run the cables through the hand rather than the SMAs themselves as the activation temperature of the SMA is 70 - 90°C and the melting temperature of the SL material is 85°C. (The melting temperature is not a consideration with the SLS material as its melting temperature is 185°C.) The use of SMA wires will be the first attempt at actuating a Rapidly Prototyped system at Rutgers University.

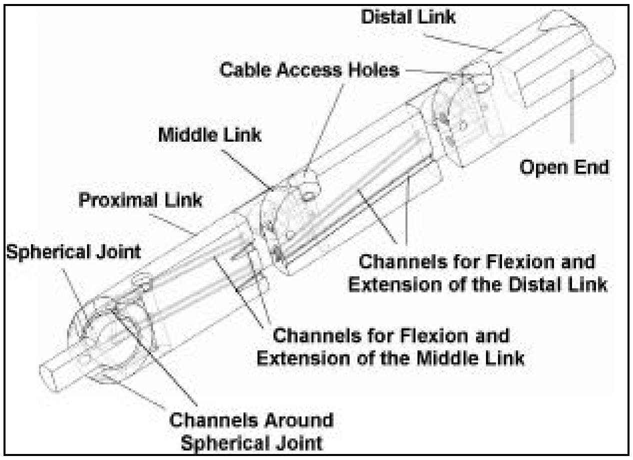


**FIGURE 10. Cable Channels in SLS Finger**

Figure 10 shows a cutaway view of the channels within the finger for routing of the cables used for actuation. These pathways, 0.1 inches in diameter, were designed to guide the cables through the finger links so as to decrease stress on the cables while maintaining the required tension. One channel through the middle link appears in a diagonal pattern, as seen from this side view, for the above-mentioned purpose. In addition, the cables intended for flexion and extension of the distal link travel over top of the revolute joint between the middle and proximal links so that the movement of these two revolute joints is uncoupled. The channels through the proximal link fan out around the ball and socket (which could be seen from a dorsal view). Two cable pathways, one for flexion and one for extension of the modified spherical joint, run through the socket on the palmar and dorsal sides to allow for $90^{O}$ rotation during actuation. Currently, abduction and adduction movement at the finger spherical joint is passive.

Another important design consideration in this robotic hand prototype is to be able to have the same range of motion and be similar in size to that of an average human hand. The former guiding design feature necessitated the use of modified joint designs to partially restrict some of the degrees of freedom. The design features and fabrication of these joints was presented in Section 3.

Presently, a single robotic finger has been fabricated using the SLS process as shown in Figure 11. The SLS procedure here was similar to that of the revolute and spherical joints described in Section 3. The SLS process produced a quality, fully assembled finger with good joint mobility, clearances, and ranges of motion. The SLS glass filled nylon material used for this assembly provided for less joint friction than the previously polyamide fabricated single joints. The clearances are such that there is some additional movement in the joints than desired, so it would be possible to reduce these tolerances in the future. As in the previous SLS constructions, the joints fully reach the designed range of motion. Additionally, all the pathways and cable assembly holes were clear of material. The Selective Laser Sintering process successfully fabricated this multi-joint, multi-degree-of-freedom robotic finger.

**FIGURE 11. Robotic Finger Built With SLS**

## DISCUSSION

The joints and systems fabricated using the Stereolithography machine model SLA 190 as well as the SLS Sinterstation 2000 produced quality plastic parts. Joints fabricated using both of these prototyping methods exhibited good overall movement characteristics and near-surface clearing.

The joints fabricated using the Stereolithography SLA 190 included spherical, revolute and prismatic type joints. These joints were designed with clearances of 0.3 mm and 0.5 mm for flat and circular near surfaces, respectively. An essential design consideration in the SL process is the support structure requirement. In addition to an initial base support structure necessary prior to initial part fabrication, additional supports provide structural stability and a starting point for overhangs and new layers to initiate layering. The SL joints showed good smoothness and evenness in flat vertical and horizontal surfaces. For rounded or oblique sections, the parts showed acceptable surface agreement with CAD models.

The joints fabricated using the Selective Laser Sintering Sinterstation 2000 included spherical and revolute type joints. These were determined to be of a higher quality in overall part prototyping. This can partially be attributed to the Sinterstation 2000's greater level of accuracy in planar detail and resolution in layer thickness over the SLA 190. These advantages directly lead to a number of machine advantages.

Due to a reduced staircase effect, the sliding-friction in the joints was reduced in the SLS fabricated parts over the SL fabricated parts. Also, the SLS process produced joints with smaller clearances and smoother rounded surfaces. These improvements are the result of a more accurate Rapid Prototyping machine in the Sinterstation 2000 over the SLA 190. In contrast, the SL produced parts showed much greater smoothness and regularity over the SLS parts. Another important advantage is that the Selective Laser Sintered parts do not require any computer or manually generated support structures. Parts do not have to be designed with the thought of support structure placement in part orientation during the build cycle as well as manually performing the task of support removal.

Both Rapid Prototyping processes constructed joints with the desired ranges of motion and size, however the SLS process showed more apparent advantages over the SL process in a number of regards. It is important to note that the majority quality advantages of the SLS parts over the SL parts cannot be solely attributed to the Rapid Prototyping processes alone. To make a more competitive comparison between the two RP processes, a higher-end model of the Stereolithography should be used in SL part fabrication. This would provide a better basis for comparison on areas such as step effect, overall surface quality and minimum clearances. The model SLA 190 is no longer in current production. 3D Systems produces models ranging from the SLA 250 to the fifth-generation design SLA 7000. The third-generation Sinterstation 2000 is currently one of two systems offered by DTM Corporation

From the comparison conducted using the two somewhat unequally matched RP machines, there are a number of differences between the RP processes themselves, which will be present regardless of the machine model variation. For example, the SL process is based on the photo-polymerization of a liquid resin whereas the SLS process in based on the sintering of powders. These differences will produce parts with varying mechanical properties due to build material choices. Post-processing considerations play an increasingly important role in complicated mechanisms and robotic systems. As previously mentioned, the SLS process does not require the generation of support structures. This provides an advantage in part design freedom and prototype orientation during the fabrication process.

As Rapid Prototyping technologies continue to improve, mechanisms and robotic systems built using this methodology will compete with and eventually surpass those of traditional fabrication techniques. Ideally, the clearances necessary to effectively compete with assembled components and mechanisms need to improve by an order of magnitude. Avenues to approach this need may be currently possible through the use of system technologies, which are currently under development. For example, MicroTEC of Duisburg, Germany has developed a micro-stereolithography process that can produce parts with layers as thin as 1 μm (0.00004") (Wohlers, 1999). This is a 150-fold reduction over the SLA 190’s 0.006" minimum slice thickness.

## CONCLUSIONS

Rapid Prototyping has been shown to be a viable means of simple and quick fabrication of prototypes for the articulated structures of robotic systems. Several joints and robotic systems have been fabricated using this framework. The successful fabrication of the robotic finger gives further confidence in this Rapid Prototyping framework. In the future, actuation of rapidly fabricated prototypes will be investigated through the use of Shape Memory Alloy artificial muscles or other types of smart materials.

## ACKNOWLEDGMENTS

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## REFERENCES

Alam, M., Mavroidis, C., Langrana, N. and Bidaud, P., 1999, "Mechanism Design using Rapid Prototyping", *Proceedings of the 10$^{th}$ World Congress on the Theory of Machines and Mechanisms*, Oulu, Finland.

Ashley, S., 1995, “ Rapid Prototyping is Coming of Age”, *Mechanical Engineering*, Vol. 117, No. 7, pp. 63-68.

Ashley, S., 1998, “RP Industry’s Growing Pains,” *Mechanical Engineering*, Vol. 120, No. 7, pp. 64-67.

Bylinsky, G., 1998, "Industry's Amazing Instant Prototypes", *Fortune*, Vol. 137, No. 1.

Crawford, R. and Beaman, J., 1999, "Solid Freeform Fabrication: A New Manufacturing Paradigm," *IEEE Spectrum*, February 1999, pp. 35-43.

Dolenc, A., 1994, "An Overview of Rapid Prototyping Technologies in Manufacturing", Helsinki Univ. of Technology, http://www.cs.hut.fi/~ado/rp/rp.html.

Laliberte, T., Gosselin, C. and Cote, G., 1999, "Rapid Prototyping of Mechanisms", *Proceedings of the 10$^{th}$ World Congress on the Theory of Machines and Mechanisms*, Oulu, Finland.

Tse, W. C. and Chen, Y. H., 1997, "A Robotic Systems for Rapid Prototyping," *Proceedings of the 1997 IEEE International Conference on Robotics and Automation*, Albuquerque, NM, pp. 1815-1820.

Vergeest, J. and Tangelder, W., 1996, "Robot Machines Rapid Prototype," *Industrial Robot*, Vol. 23, No. 5, pp. 17-20.

Wohlers, T., 1999, *Rapid Prototyping and Tooling State of the Industry: 1999 Worldwide Progress Report*, Wohlers Associates.

Won, J., DeLaurentis, K. and Mavroidis, C., 2000, “Rapid Prototyping of Robotic Systems,” *Proceedings of the 2000 IEEE International Conference on Robotics and Automation*, April 24-28 2000, San Francisco, CA.