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MECHANISM DESIGN USING RAPID PROTOTYPING

Munshi Alam[1], Constantinos Mavroidis[1], Noshir Langrana[1] and Philippe Bidaud[2]

[1] Department of Mechanical and Aerospace Engineering
Rutgers University, The State University of New Jersey
98 Brett Rd., Piscataway, NJ 08854, USA
Tel: 732 - 445 – 0732 and 732 – 445 - 3618, Fax: 732 - 445 - 3124
E-mail: mavro@jove.rutgers.edu, langrana@caip.rutgers.edu

[2] Laboratoire de Robotique de Paris, CNRS-UPMC-UVSQ
10-12 Avenue de l' Europe, 78140 Velizy FRANCE

Abstract

In this paper Rapid Prototyping techniques have been used to fabricate mechanisms and evaluate their design faster. Prototypes of revolute, prismatic and spherical joints have been built using the Stereolithography machine SLA 190 of the Department of Mechanical and Aerospace Engineering at Rutgers University. In addition, a three legged six degree of freedom rapid prototype of a parallel manipulator has been fabricated. These rapidly prototyped mechanisms and joints have been fabricated in one step, without requiring assembly while they maintained their desired mobility. As far as the authors are aware, this is the first time that multi-joint, multi-degree-of-freedom mechanisms have been rapidly prototyped without requiring any assembly after their fabrication.

Keywords: Rapid Prototyping, Design of Mechanisms

1 Introduction

The design of mechanisms and manipulators has been studied by many researchers and engineers. Mathematical methods have been proposed to find a mechanism's significant parameters to perform a task that is described using kinematic and dynamic specifications [Sandor and Erdman, 1984 and Erdman and Sandor, 1991]. Once a mechanism design is proposed, it is always desired to have a design evaluation before any full prototype is built so that design changes are made fast and cost effectively. Even though powerful three dimensional Computer Aided Design and Dynamic Analysis software packages such as Pro-Engineer, IDEAS, ADAMS and Working Model 3-D are now being used, they could not provide important visual, haptic and realistic workspace information for the proposed mechanism design.

Virtual Reality and Rapid Prototyping are two computer based disciplines that are developing very fast and that can be used for fast mechanism design evaluation. Recently, Virtual Reality has been proposed as a tool to evaluate mechanism designs [Furlong et. al, 1998, Nahvi et al., 1998]. Virtual Reality provides a three dimensional environment where a designer can input design positions using a combination of hand gestures and motions and view the resultant mechanism in stereo using head-mounted 3D glasses. The 3D nature of the design space makes Virtual Reality a very useful tool for evaluation of mechanisms in very realistic conditions. The virtual models developed in the Virtual Reality Software can be interfaced with haptic devices for tactile or force feed-back (Nahvi et. al., 1998). Workspace estimation, link interference, obstacle avoidance and singularities, and dynamic behavior are some of the parameters that can be evaluated using Virtual Reality.

Rapid prototyping of parts and tools is a rapidly developing technology [Ashley 1995, 1998]. Its main advantage is early verification of product designs. So far, the application of rapid prototyping in mechanism design has been very limited. One of the first works to rapidly fabricate mechanisms was made by Professor Gosselin and his group at Laval University [Gosselin, 1998] who used a Fused Deposition Modeling rapid prototyping machine. 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 mechanisms parts. In this paper, the application of rapid prototyping in mechanism design is explored. Prototypes of revolute, prismatic and spherical joints and a three legged six degree of freedom rapid prototype of a parallel manipulator have been fabricated in one step, without requiring assembly.

2 Rapid Prototyping / Stereolithography

Rapid Prototyping or Layered Manufacturing is a fabrication method where artifacts are constructed layer upon layer by depositing material under computer control. 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.

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.

The first step in rapid prototyping is to develop a computer model with any CAD modeler e.g. I-DEAS or Pro/Engineer. The volume of this model is then meshed or broken into small elements. Each element is described by the (x, y, z) coordinates of the end points and the outward normal. The file containing all these information about the mesh elements is known as .stl file. This file format is readable by most prototyping machines.

Having prepared the .stl file, there are different technologies available to build rapid prototyping models. But the following steps are common to all rapid prototyping methods. The .stl file is exported to the software that comes with the rapid prototyping machine. Then the model is reoriented by the user to find the best posture for ease in fabrication, support structures are created and edited and proper build parameters are chosen. Support structures are built to hold the part above the plate and they are needed to prop any overhanging part. The fabrication process starts with several layers of lattice-like support, then the machine builds the object layer by layer. When layer is built, the platform goes down in the vertical direction and another layer is built on the top of the previous layer.

Stereolithography is one of the technologies used in rapid prototyping. Stereolithography creates a tangible 3-D object from a CAD drawing by directing ultraviolet laser radiation onto a vat of polymer resin (liquid plastic). After being cured in an ultraviolet oven, each piece is then hand-polished and finished to specifications. The end product is an exact model of the 3-D drawing, giving designers, engineers, manufacturers, sales managers, marketing directors, and prospective customers the opportunity to handle the new part of product. In this way, design iterations can be made quickly and inexpensively, guaranteeing companies the best product, in the shortest time possible. The flow chart in Figure 1 shows the different steps that are involved in a Stereolithography process.

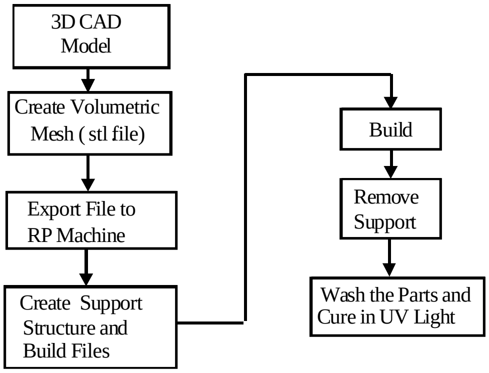

Figure 1: Building Parts in a Stereolithography Machine

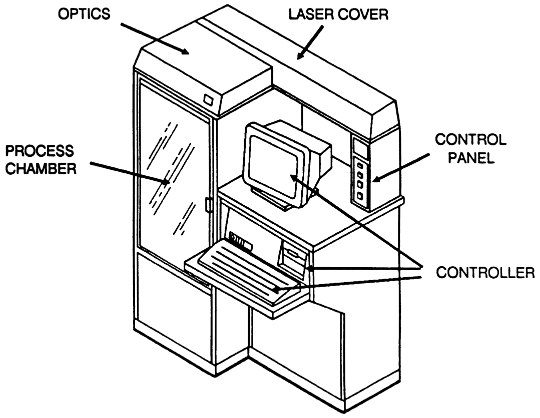

Figure 2. The SLA 190 Machine

The advantages of rapid prototyping are: a) money saving, b) quick product testing c) fast design improvement, d) time saving, e) fast error elimination from design, f) product sale and g) rapid manufacture

The Department of Mechanical and Aerospace Engineering of Rutgers University has a Stereolithography machine, model SLA 190, from 3D Systems, CA (see Figure 2). This machine has been used to fabricate prototypes of the mechanisms. The SLA is a computer controlled, electro-mechanical, scanning laser system designed to draw complex cross sections on the surface of a vat of photopolymer. The major components of the SLA 190 machine are: Laser, Process Chamber, Optical System, Control Panel, Vat, Controller. The SLA laser generates a beam under computer control, that is focused onto the surface of the resin. The SLA uses a helium-cadmium (HeCd), continuous multi-mode ultraviolet laser with a wavelength of 325 nanometers. Liquid resin is used to build parts in this machine. The laser beam when focused on a liquid resin, the resin solidifies by a process called photopolymerization. And thus the part is built layer by layer. The minimum layer thickness that can be achieved using this SLA 190 machine is 0.125mm (0.005 in). Once the part is built it is first washed with alcohol and then with water. Finally, the part is fully cured by ultra-violet light in a chamber. The SLA 190 machine comes with a software called *Maestro*. This is used for processing the .stl file that is obtained from the CAD modeler. A .stl file is a triangulated solid model. *Maestro* first analyzes the .stl file to check the integrity of the triangulated model. Then it creates supports for the overhanging parts of the models and finally slices the model in the vertical direction i.e. Z-direction. This sliced model is exported to the SLA machine. *Maestro* allows the user to choose proper layer thickness, waiting time between building two consecutive layers and many other fabrication parameters.

3 Application of Rapid Prototyping in Mechanism Design

The possible advantages and disadvantages of the application of rapid prototyping in mechanism design are summarized below:

Advantages

- Rapid prototyping can be used to obtain a very fast prototype of a mechanism which is going to be kinematically equivalent to the designed one.

- Several kinematic properties of the mechanisms can be evaluated. These are: a) workspace evaluation, b) identification of singular configurations including uncertain configurations where the mechanism has internal mobility, c) determination of link interference, d) visualization of joint limits. It has to be noted that it is very time consuming to evaluate these properties numerically.

- With this technology, free-form solids can be prototyped in a very short period of time. This type of technology is of particular interest for building larger scale prototypes of complex mini/micro mechanisms with highly complex shapes.

- If possible, no assembly will be required for the mechanism.

Disadvantages

- The parts built in a rapid prototyping machine are non-metallic which makes the prototype unsuited for any dynamic/force analysis or testing since the dynamic behavior of the real mechanism is completely different from the rapid prototyped mechanism.

- Clearance is a big issue when mechanisms are built in rapid prototyping machines. Clearance depends a lot on the accuracy of the machine, layer thickness and the orientation of the part while building. Clearance accuracy decreases when the part position is not perfectly vertical while being built.

- Support structures very often cause problems. The support structures need to be edited in the software called *Maestro* before the part is built. This editing has to be done judiciously. Sometimes, the removal of the support structures, after the part is built, creates problems particularly when the part size is small.

- Since the parts such as joints and links that are fabricated are small and weak, actuation of rapid prototyped mechanisms is very difficult. A lot of research needs to be done to find out a way to actuate the rapid-prototyped mechanisms.

We investigated the possibility of building a complex spatial multi-loop mechanism. We have selected a three legged, six degree of freedom parallel manipulator. One of the objectives was to build the mechanism in one go that is there is no need for assembly.

4 Joint Fabrication

The first step to build mechanisms with a rapid prototyping machine is to be able to fabricate joints. Different types of mechanical joints such as revolute, prismatic and spherical joints were fabricated with the SLA machine of the Department of Mechanical and Aerospace Engineering. Different sizes of joints were built to get the right clearance between the moving parts of the joints. Also another goal was to investigate how small a mechanism is it possible to build. This is important for reducing the time and cost of fabrication of the prototype. Different problems were encountered during the fabrication of the joints. The first problem when building small joints is that the removal of support structures becomes very difficult and tedious. Keeping that in mind, the part sizes have been optimally chosen so that the clearance between the moving parts is not too large and the removal of support structure does not pose a problem when a joint is built. After a few trial and errors, some fine mechanical joints were built.

4.1 Revolute Joint

Different sizes of revolute joints were built with the SLA machine. Two types of revolute joints were built: (a) non-assembly type i.e. requiring no assembly and (b) assembly type revolute joints i.e. joints that have to be assembled. In Figure 3 the CAD drawings and pictures of the non-assembly type are shown.

The main problems that were faced during the fabrication of the revolute joints are:

- Determination of the location of the support structures. Some of the software-generated support structures were not located at the places they should have been. Therefore some support structures were manually created in *Maestro*.

- Achieving a small clearance between two moving parts that allows a smooth motion. This problem was solved by trial and error. For the revolute joint in Figure 3, the clearance between the pin diameter and the link hole diameter is a very important issue for proper functioning of the joint. Too little clearance will glue the pin to the link and too high clearance will introduce extra degrees of freedom to the link.

- Identification of weak support structures. Some of the software-generated support structures were not strong enough to hold the part.

- Removal of support structures.

Note that, if more than required supports are created, then it becomes very difficult to remove them after the parts are built. So one has to be very careful in creating supports for the parts. This comes from experience and trial and error.

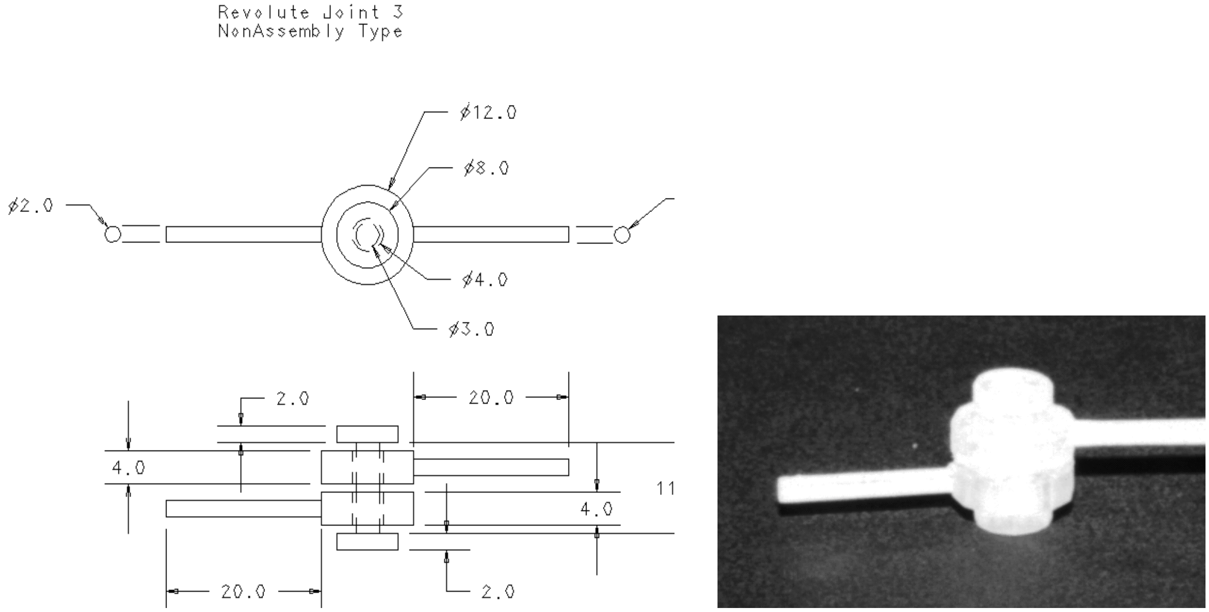

Figure 3: Non-assembly Type Revolute Joint (all dimensions are in mm)

4.2 Spherical Joint

Spherical joints with different sizes for ball and socket were built. Similar problems with the support structure and clearance were faced. Two slightly different designs of spherical joints were fabricated. In the first design, shown in Figure 4, the socket is chopped slightly from the bottom to create a way for the support structure to go through the hole and hold the ball in place otherwise the ball would get glued to the socket. This spherical joint was built having the ball and socket at the bottom in other words the SLA machine built the ball and socket first before building the link arm. The second type of design for a spherical joint is shown in Figure 5. In this design, since the ball and socket was built at the top, the ball did not need any support as it was supported by the vertical link itself. By trial and error, it was found that a 0.5mm radial clearance was very good to get a three degree of freedom motion from the joint.

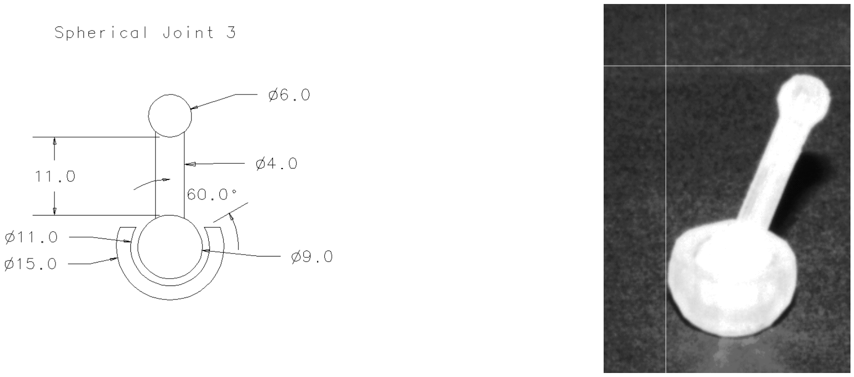

Figure 4. Type I of Spherical Joint (all dimensions are in mm)

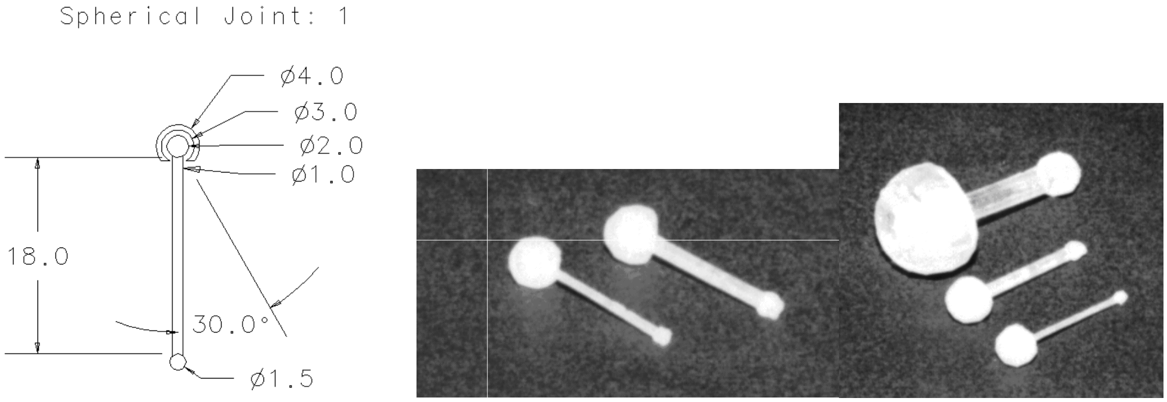

Figure 5. Type II of Spherical Joints (all dimensions are in mm)

4.3 Prismatic Joint

A prismatic joint or sliding joint was built with the SLA machine. Initially a cylinder-piston type prismatic joint was fabricated. But the size of the cylinder was very small and because of that, the trapped resin inside the cylinder could not be removed. Thus, the piston ceased to move after the ultra-violet curing of the joint. Then the joint was redesigned so as to avoid any closed cavities that trap resin. In Figure 6, the final design of the prismatic joint is shown. The joint is structurally simpler than a revolute or spherical. The clearance between the moving parts was 0.3 mm.

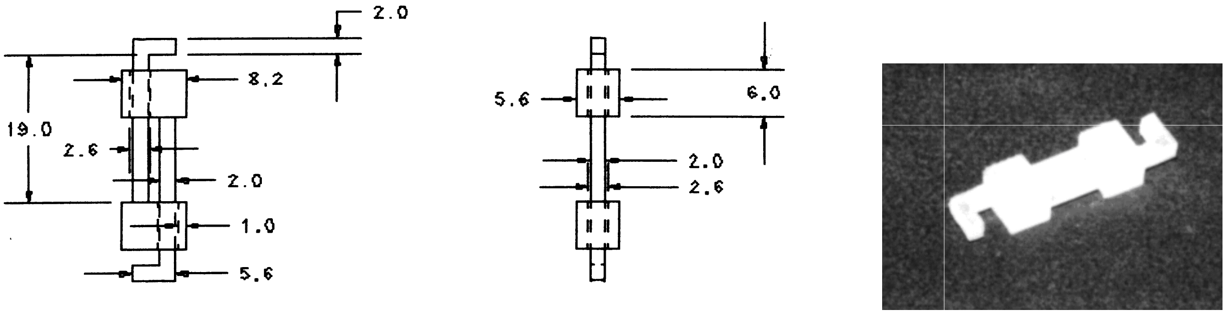

Figure 6. Prismatic Joint (all dimensions are in mm)

5 Three Legged Parallel Manipulator

In this section a non-assembly type three-legged parallel manipulator has been built using the SLA machine. First, one leg of the parallel manipulator was built to demonstrate the feasibility. The leg of a parallel manipulator consists of two spherical joints, one at each end, and a prismatic joint at the middle of the leg. The design of the joint presented in Section 4 were used. The CAD drawings and the fabricated model of the leg are shown in Figure 7.

After being satisfied with the quality of the leg, the final platform was built with three identical legs. The top and bottom platforms are two triangular ternery links (links connected to three joints) having the same dimensions of 1″ x 1″ x 1″ on three sides of the triangle and the thickness was 0.07874″ (2 mm). To save fabrication time, the triangular platforms were not completely filled. The stub on the top platform is meant for providing the input forces and moments for the platform motion. Since the fabrication of each joint was tested separately, the fabrication of the leg didn't have any special problems. In Figure 8 pictures of the fabricated rapid prototype of the parallel manipulator are shown at different configurations. This prototype was built overnight during a 12hour period. Additional information can be found in [Alam, 1999].

6 Conclusions

In this paper, Rapid Prototyping is used to fabricate multi-degree of freedom mechanisms. In our future work we will study the potential use of Rapid Prototyping in the performance evaluation of mini/micro mechanisms that will be used in practical applications such as in surgical and endoscopic mechanical systems.

7 Acknowledgments

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References

Alam M., 1999, *Task Oriented Kinematic Design of Mechanisms and Manipulators and Their Evaluation Using Rapid Prototyping*, Master's Thesis, Department of Mechanical and Aerospace Engineering, Rutgers University, January 1999.

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.

Erdman A. G. and Sandor G. N., 1997, *Mechanism Design: Analysis and Synthesis,* Vol. 1. 3rd Edition, Prentice-Hall, Englewood Cliffs, NJ .

Furlong T. J., Vance J. and Larochelle P., 1998, "Spherical Mechanism Synthesis in Virtual Reality," *Proceedings of the ASME Design Automation Conference,* Atlanta, GA.

Gosselin C., 1998, "Rapid Prototyping of Mechanisms", *Presentation at the Research Workshop on Task Oriented Design of Reduced Complexity Robotic Systems* held at the 1998 ASME Mechanisms Conference, Atlanta, GA.

Nahvi A., Nelson D., Hollerbach J., and Johnson D., 1998. "Haptic Manipulation of Virtual Mechanisms from Mechanical CAD Designs." *Proceedings of the 1998 IEEE.* International Conference on Robotics & Automation, Leuven, Belgium. May.

Sandor G. N. and Erdman A. G., 1984, *Advanced Mechanism Design: Analysis and Synthesis,* Vol. 2. Prentice-Hall, Englewood Cliffs, NJ.

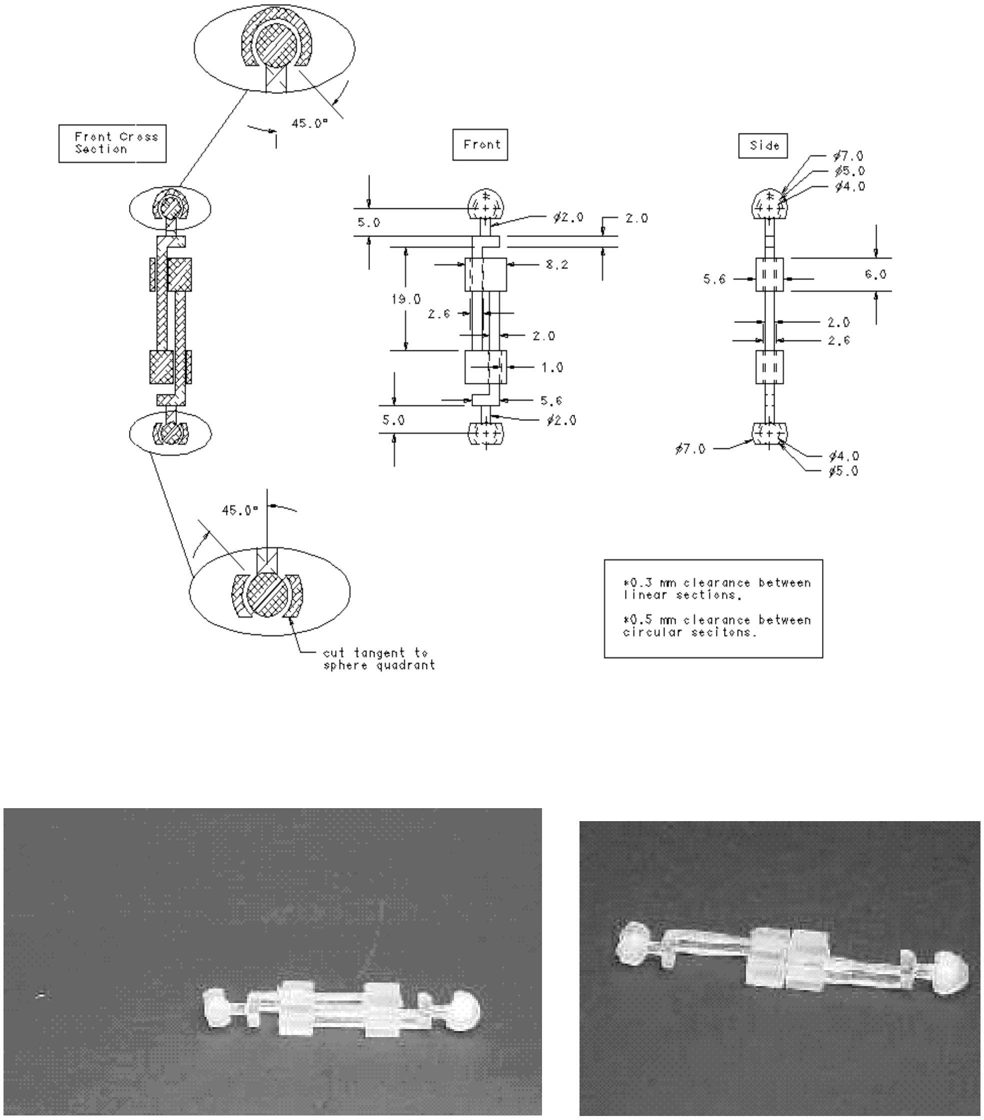

Figure 7. Leg of a Parallel Manipulator (all dimensions are in mm)

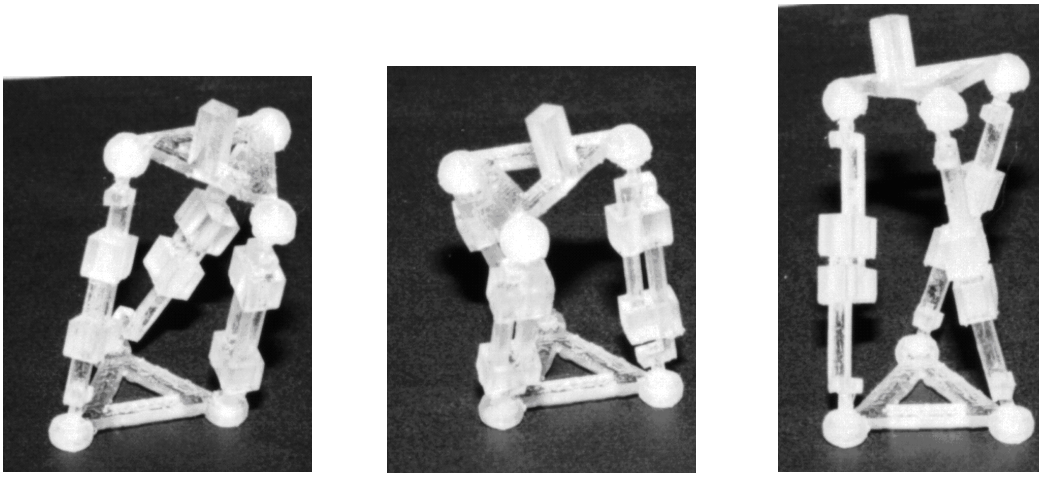

Figure 8. Three Different Configurations of the Parallel Manipulator