Test and Analysis of Rapid Prototyping
Through the Design and Assembly One DOF Surgical Wrists

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Summer Undergraduate Program in Engineering Research at Berkeley
(SUPERB) 2003

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Abstract
This paper describes functionality tests and subsequent evaluation of a desktop, rapid prototyping assembly procedure employed at UC Berkeley for the construction of millimeter-scale robotic devices. Details are given for the design and construction of an example device that can be built using this assembly process, a 7-mm outer diameter (5mm lower leg separation, 3mm upper platform diameter), one DOF surgical wrist intended for use on minimally invasive surgery instruments. Although such a wrist had been previously constructed by a more experienced operator (over six months training), the paper details tests of the rapid prototyping assembly procedure by an operator with three days training and compares the resulting device to the one previously made. It is noted that after only two iterations (total time is less than four days) of the rapid prototyping process, the device produced by the less experienced operator closely matches the one made by the more experienced operator. Furthermore, to mimic common prototyping, small changes were made to the wrist design as influenced by tests performed on the resulting prototype devices. The paper also provides a description of the fabrication of a test stand and attachment of the prototype wrists to voice coil actuators as well as the results generated from these tests. The final wrist prototype has a 5mm outer diameter (2.5mm leg separation, 1mm upper platform) and was tested to have over 90 degrees motion, a parallel stiffness of .003N/degree, and able to withstand approximately 98 mN before peeling of the flexures was obvious. A total of five prototypes were produced using the rapid prototyping assembly process, and they were all fabricated and tested in less than eight weeks. Finally, the paper concludes with some suggestions for improvement in the design of future wrist prototypes.

1 Introduction
The process of designing and constructing millimeter scale robots is currently bottlenecked at the prototype stage. This stage requires numerous hours of work under the microscope or costly manufacturing by specialized companies. Therefore many new ideas are overlooked in favor of more dependable designs. It is the purpose of this paper to test the process whereby the prototyping of a millirobot can be completed on the desk of the researcher. This is centered upon work done at UC Berkeley in the area of micro assembly [1], [2] and more specifically upon [3]. The aim of their work was to develop an efficient, reliable, and yet flexible fabrication technique. These criteria will be tested by the construction of a millimeter scale robotic device, specifically a one Degree of Freedom (DOF) surgical wrist. Since this design has successfully been constructed prior to this test, the prototyping assembly’s efficiency will be demonstrated through the reproduction of the device by a technician with less than a week’s worth of training on this equipment. The comparison between this construction and that performed previously will demonstrate the reliability of the system. Finally, the flexibility of the fabrication will be tested through improvements made on the wrist’s design, and the ability for these improvements to be implemented.

The one DOF surgical wrist is designed for the purpose of implementation upon a minimally invasive surgery instrument. This would allow the surgeon 90 degrees of motion (45 in each direction) in a one DOF field near the end of his/her instrument. Currently there exist such wrists that are 10 millimeter in diameter, however our final design is half of that size (5mm). While this design does not employ conventional machined mechanisms, it does involve multiple structures more able to be miniaturized (hollow triangular steel beams and polyester flexures); yet, due to their small size they are painstakingly difficult to position and
assemble. This difficulty includes all aspects of the construction, from the cutting of materials to the final wiring of strain gages. Through the use of such UC Berkeley rapid prototyping devices as the laser-cutting machine and the Ortho-tweezers, the milli-scale parts can be cut and positioned with extreme precision.

Although the wrist mechanism is not extremely complex, its assembly illustrates many of the micro assembly techniques. The cutting of stainless steel and polyester, the folding of triangular beams, the positioning of these structures, and finally their gluing are all rapid prototyping processes that the wrist employs. These techniques can applied to much more complex structures, such as Micromechanical Flying Insect (MFI) project [4]; however the wrist prototype is merely an introduction into the many facets of the micro assembly process possibilities. Therefore its assembly is a perfect example of the ability to rapidly prototype a millimeter scale robot.

In addition, this paper describes tests of the functionality of the wrist. This includes the design and construction of a test setup, as well as the physical testing. The wrist was attached to an actuator and cycled through multiple position changes. The criteria for these tests include the functionality, estimated strength and prospective life.

2. Rapid Prototyping Overview

While not completely automated the process of construction involves many automated steps, as well as many that are semi automated. The idea of rapid prototyping of milli structures is dependent upon the joining of these varying steps into a system that is easily preformed and produce modules that in turn can be used in the construction of multiple designs. The two main modules are the triangular beam and the flexure. Although this production is geared toward modular assembly, it is not limited to it. The processes whereby the modules are moved and also positioned are suitable for many applications. The description of the construction given in this paper is merely an overview given for the purpose of familiarizing the reader with the process. The equations and reasons for each process are given in a more complete description [3]. Figure 1 pictorially depicts the steps of the assembly process and illustrates how they are combined in the production of a one DOF wrist.

Figure 1: The assembly process begins with the cut out parts (flexure, beams, faceplates...) these are then aligned using the rubber molds and glued. Meanwhile the plastic shaft is constructed from the wax, rubber mold. Finally the two are combined into the wrist assembly. (Flow chart shows the construction of the final prototype.)
The first module of our milli robots is the triangular beam used for structural support. These beams are cut from 12.5µm-thick sheets of stainless steel using the laser-cutting machine. The folding lines are cut in a perforated fashion leaving pre-score lines. Once the sheets are then folded along the preformatted lines using a folding mechanism. This mechanism was designed for the purpose of providing clean crisp folds, which produce minimal spring back. Although it must be manipulated by hand, the mechanism provides an almost fail proof triangular beam. Once folded, the beam is glued and then ready for use in construction. The triangular beams provide not only sound structural support; they also contribute less weight than solid structures, in addition to providing three flat surfaces with which to attach flexures.

The second module, the flexure, is also cut using the automated laser machine. It is cut from polyester and is used as a hinge between two triangular beams, a beam and a flat surface, or even any two flat surfaces. Due to the transparency of the polyester, the flexure is easily attached to a surface using UV cure glue. While the glue is sticky when applied it does not solidify until it is placed in ultra violet light. This enables the assembler to slide the flexure around until properly aligned without fear of its premature attachment.

The alignment of the modules (or other structures) is the part of this procedure that has received the most work. With the use of the Ortho-tweezers it is possible to easily align the beams to within a hundredth of a millimeter. This is done by first attaching a handling block to the structure to be moved thereby eliminating the need for various specialized grippers. Since the Ortho-tweezers are designed to pick up blocks it can do so quite easily. (We used 200x200x100µm blocks.) The blocks are attached by simply immersing them in liquefied low melting point wax and setting them on the object to be moved. When the wax cools, it solidifies attaching the block to the object. Thus attached it can be grasped with the Ortho-tweezers and lifted, carrying with it the object to be manipulated, in our case a beam. When the beam is in place the block can be simply blown off with a heat gun.

One of the other main machines that aids in the rapid prototyping process is the wax printer, the Thermojet Printer from 3D Systems Inc. is a significant part of the production of the 1 DOF wrist. The printer is used to print wax molds that are then cast into rubber molds, which are eventual used to form the plastic parts of the design (see Figure 2). The process of producing the mold is quite simple. Once a design exist in a 3D drawing program such as Solid Works, this printer can print the piece out by applying thin layers of wax on top of each other. Thus enabling the production of molds for the plastic shaft of the wrist to be simply printed without the need for costly machining.

The procedures described can be modified to produce quite complex structures as shown in the MFI project. However the processes used are still simply combinations of the laser cutting; beam folding, placement and gluing of flexures. Not only has this proven to be an easy way to prototype the flies, it has also enabled them to reduce the weight of the MFI. (For more information on the MFI project visit http://robotics.eecs.berkeley.edu/~ronf/mfi.html)

3. Original one DOF wrist design

The one DOF wrist is, as described above, a joint intended to be implemented upon the end of a minimally invasive surgical instrument. This device would then hold the surgeon’s tool (i.e. cautery electrode, forceps, scalpel) and allow it to be positioned up to 45 degrees in the side-to-side direction. This would give the surgeon a
total of 5 DOFs for movement in their surgery, by adding one more degree of freedom.

Figure 3: The original wrist design with cautery electrode attached to the circular faceplate tilted to -45 degrees.

3.1 Design Overview

This wrist, as designed and described by [3], uses a circular plate resting atop a plastic fulcrum to perform a teeter-totter motion. (The circular plate is the location that the tool would be attached.) This motion is provided by pulling on the triangular beam leg attached via flexures to the circular plate. Each leg is constructed of two beams, one of a length of 4mm and another of 10mm; once again these beams are connected using polyester flexures. The actuation of the plate requires the two-beam assembly in order to allow for the motion of the plate. When the plate is tilted, the short upper beam (the one attached directly to the plate) is also tilted. This linked construction allows the bottom beam to remain straight, and in line with the shaft of the arm (see figure 4). The straight beams are then extended down some arm where the surgeon would be able to manipulate them.

In order to simplify the operation of this wrist one leg is attached to a spring. This then allows the surgeon to simply maneuver one leg to rotate the plate. In addition a faceplate is attached on top of the polyester flexure. The face plate is comprised of 4 pieces of 12.5µm steel that match the back of the beams, this servers as a clamp strengthening the assembly by sandwiching the flexure between this and the beams.

Not only does the plastic support provide a fulcrum line, it also serves as a main supporter of the weight/pressure applied to the circular plate (the area to which the forceps would be attached). The support is thus designed to be 1mm thick and 3mm wide (the width of the plate). Since the top of this support is rounded, the plate easily rotates over it, while continually maintaining significant contact. Therefore the beams are relieved of much of their load, no matter what position of the rotation it is in. Consecutively to insure that the plate stays centered atop the support, it is attached using polyester flexures.

Figure 4: Configuration of beams for platform orientations ranging from -45 to 45 degrees in 10-degree increments.

3.2 Wrist Construction

The assembly of the wrist involves all of the steps of the rapid prototyping procedure. This construction is preformed by first cutting out the stainless steel for the triangles and also for a faceplate. This is done while the steel is on Gel-Pak, a material with a sticky surface. (The Gel-Pak is used to hold the steel in place so that it will not shift during the cutting process.) The
faceplate is left attached to the Gel-Pak while the rest of the steel is peeled away. Meanwhile the folding of the beams occurs. Following this the polyester is glued to the faceplate, taking care to avoid getting glue on the section to be bent. The beams are then laid out in their proper spacing and faceplate/flexure combination is glued to the beams. Finally the assembly is placed in the plastic shaft and flexures are attached to hold the circular plate to the shaft.

*Figure 5: Exploded view of wrist assembly depicting the various placements of components and glue.*

After a brief introduction to the various tools used in the rapid prototyping process, I attempted the construction of a wrist. The plastic shaft of the wrist proved to be the easiest portion to produce. The process of printing the wax mold, making the rubber mold and finally the molding of the plastic required very little experience. The next easiest part of the construction involves the cutting of the steel. All of the flat parts were cut using the laser cutting machine, by simply lining up the material and having the machine follow a computer sketch. A little more tedious procedure included the folding of the triangular beams, although through the use of the folding mechanism this was made simple enough it could be accomplished without the aid of a microscope.

Once the beams were constructed and the rest of the materials were cut out, I began the assembly the modules with the aid of the Ortho-tweezers. At first I had some difficulty controlling them, due to my inexperience with their controls and operation. However I quickly mastered them and they proved to be extremely efficient in the positioning of the various parts. By attaching a block to the polyester flexure I was able to lift it and set it directly unto the UV, cure glue coated faceplate, and ultimately line it up perfectly. I was then able to cure the glue by simply shining UV light onto the assembly.

With the help of the Ortho-tweezers I was able to precisely position the beams in a slot in a rubber holder. With the beams lined up, I was able to simply place the faceplate assembly on top of the arranged beams and glue them together. This is the area that I had the most trouble due to the fact that I used super glue rather then UV cure glue. This selection was made because of the impenetrability of stainless steel with UV light. However with the super glue I was limited on the amount of time that I was able play with the alignment of the two sections. In spite of this difficulty I was successful in attaching them. The final step before placing this assembly in the plastic holder, was to attach flexures to the under side of the circular plate for the purpose of attaching the assembly to the holder. Once again UV glue was used and a piece of stainless steel was glued over top of the flexures to clamp them to the circular plate. The assembly was then placed in the holder and the flexures were attached holding the plate in place.

### 3.3 Testing

Upon initial macroscopic inspection, the wrist appears to function properly. The faceplate rotates as the triangular legs are pulled, without any difficulty. However when the wrist is then placed under magnification, it can be seen that the flexure gaps are of different lengths. One is the specified .25mm while the other is larger at 4mm. This appeared to have developed during the super glue stage of the construction. Although the beams were placed with extreme precision using the Ortho-tweezers, the gluing stage is performed by hand and without practice the beams are easily knocked out of alignment. In spite of this defect the plate is capable of 100 degrees of motion (\(-40^\circ\) to \(60^\circ\)) *(see figure 6).* Therefore the wrist seems to be capable of the assigned task.

*Figure 6: The original prototype shown in different configurations (a) \(-40^\circ\) (b) \(0^\circ\) (c) \(60^\circ\)*
In order to test the functionality of the wrist, a stand was assembled that allowed the wrist to articulate the required 90 degrees; a voice coil actuator was used to provide the motion. The actuator provided 16mm of travel, and the wrist only required 2.5mm. (2.5mm calculation based upon the desire of faceplate rotation from −45 to +45 degrees.) Therefore to limit the motion, a lever was attached between the actuator and the wrist. This lever rotated over a pin mounted in the test stand, thus decreasing the travel. The triangular leg of the wrist was attached using a .83mm wire; which was sanded in order to fit inside of the triangle. Finally to make this connection solid, low melting point wax was heated up and applied to the joint; thus making the connection able to be disconnected easily. As mentioned earlier, the other leg was attached to a small spring. This was done using the same wire also sanded and “waxed.”

**Figure 7:** Wrist in testing mechanism with spring attached to one leg, and the other attached to the lever.

The voice coil was attached to a Precision Micro Dynamics BTA-18-6A linear power amplifier, which in turn was attached to a function generator. (for more information on the Precision Micro Dynamics see [http://pmdi.com/](http://pmdi.com/)). For initial testing purposes the wrist was tested for simple motion abilities, in other words the wrist was tested unloaded. The function generator was set to apply a 450-mill volt sine wave signal at one hertz. As expected the wrist began oscillating. After finding the wrist was capable of this speed, the frequency of the signal was increased to 3, 5 and finally 10 Hz. Once the signal had reached 10 Hz, it was left to oscillate at this frequency for approximately 4 minutes. Upon completion of this test the wrist was examined and found to be in good working manner. Thus the wrist has preformed over 2500 maneuvers with out failure.

4. Alternate one DOF wrist design

As explained earlier in order to demonstrate some of the potential of this rapid prototyping system, the original design is to be modified and the prototype rebuilt. In an attempt to eliminate the spring in the assembly the new design will have only one leg. With this revision the design also becomes more easily miniaturized, and the diameter will be reduced to 5mm. The original design, while small was still 7mm in diameter. While these changes may seem miniscule, this represents the sort of changes that prototypes often meet, small changes that require, with the current means, long expensive processes. As in the old design, the new one is expected to reach +/- 45° and be able to support the applied pressure on attached tool. It should be noted that the final design was constructed as the 5 prototype, and the procedure described here is for that wrist.

**Figure 8:** Final design with a cautery electrode tilted to −35 degrees.

4.1 Design Overview

From an analysis of the basic link orientation of a one leg design, the wrist is capable of reaching the desired range of motion. Figure 9 shows the new design in its various configurations, showing that it will meet the −45 to +45 degree mark. This new wrist is designed using the same modular parts (triangular beams, flexures...), as was the original design. However this time, instead of both sides of the circular platform attaching to legs, one side will attach to a leg while the other will attach directly to the plastic fulcrum. Since the fulcrum is no longer required to remain in the center of the wrist, it
was repositioned from the center to the side without the leg.

Figure 9: Single leg wrist configurations for platform orientations ranging from -45 to +45 degrees in 10 degree increments.

4.2 Construction

To avoid the variance seen in the original flexure widths, v channel rubber molds (see figure 3) were constructed that had .25mm spaces between the ends of two beams. This enabled the one beam to be butted up against the spacer and the other to be butted against the other side, thus producing a .25mm flexure joints. In all other areas, the construction was preformed exactly as before.

Figure 10: Rubber mold used for the placement of beams to insure .25mm wide flexure joints.

4.3 Testing

Similar to the previous wrist, this one was also attached to the voice coil via the lever. Also the new wrist was tested on the same frequencies (1, 3 and 10 Hz), just like its predecessor it also operated well.

When the range of this new wrist was tested, it was found to be capable of 110 degrees of motion, 50° in one direction and 60° in the other. (It should be noted that the range of motion of the wrist was limited by the mechanical stops placed on the actuator rather than the capabilities of the mechanism itself.) Having found the wrist capable of this motion, its parallel (unloaded) stiffness was tested. This was found to be 3 milli Newtons per degree of motion. Thus a force of 164 milli Newtons produces a change in orientation of 55 degrees.

Finally the wrist was tested under load, a 10-gram weight was placed on the faceplate. The wrist was capable of moving this; however, it quickly began to peel the flexure away from the triangular beams. The beams appeared capable of supporting the weight, however the glue was not strong enough to hold the flexures to the beams. Thus without modifications the wrist is capable of withstanding 98mN of force on the faceplate.

5. Conclusion and Future Work

As mentioned earlier, the goals of the rapid prototyping process are to develop an efficient, reliable, and yet flexible fabrication technique. This process would then completely revolutionize the process whereby small robots are designed. Using conventional methods, such as machining, engineers are limited in the ability to design small robots by the drastic length of time required to prototype an idea. The prototyping of a machined wrist could easily take a week or more simply to build an idea. With the rapid prototyping system, we were able to have an inexperienced operator learn the machines and build the prototype in less than 3 days. This time was even more drastically reduced on the second attempt, where the wrist was built in less than one day. The efficiency of the system is thus clearly evident, due to the ease with which ideas are turned into prototypes.
When the wrist that we built using the original design, was compared with that of an experienced builder, the reliability of the process is made clear. The only difference between the two wrists is the variance of the length of our flexures. By the second prototype, the flexure lengths were uniform; when the final (fifth) rendition was completed the process was perfected. The rapid prototyping process proved to be quite useful and easy to perform. The fact that an inexperienced operator can assemble milli scale robots, with such ease, barely hints at the many potentials of such a process.

Although the wrist was capable of the required motion, the glue fails to hold the flexures to the beams under load. For future work carbon fiber beams could be used in place of the stainless steel. Carbon fiber would be more easily glued to, thus increasing the strength of the flexures.[5] If the steel beams are desired, tabs could be added to the faceplate which would wrap around the beams.

Final as mentioned in [3] compact actuation of the wrist should be attached. The original idea was to use shape memory, which should still be attempted. In addition, piezoelectric (pzt) stacks may prove to be a more dependable source of motion.

Acknowledgements

The authors would like to thank Srinath Avadhanula, Abraham Bachrach, Quan Gan, Jacoby Hickerson, Steven Jones, Erik Steltz, and Robert J. Wood for their useful discussions and assistance.

References


