

Design, Fabrication, and Testing of a Three-Dimensional
Monolithic Compliant Six-Axis Nanopositioner

by

James Labuz

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Mechanical Engineering


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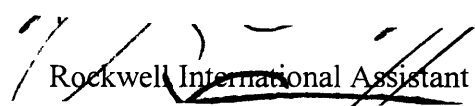
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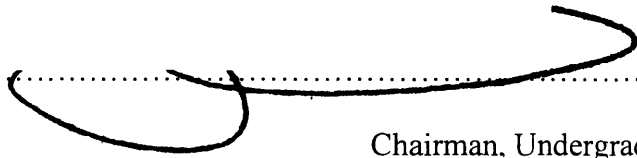
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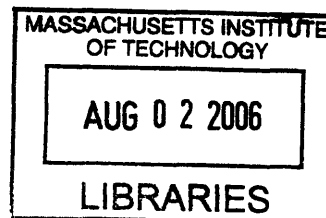
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ABSTRACT

The purpose of this research was to demonstrate the feasibility for creating a three-dimensional monolithic compliant six-axis nanopositioner. Much of this work was based off of the original two-dimensional HexFlex manipulator created by Prof. Martin Culpepper and a three-dimensional design by Samuel Korb. The compliant mechanism was manufactured from a single sheet of 1/8 inch 5052 Aluminum. The mechanism was designed to be fabricated on the non-precision, abrasive water-jet and to be formed using bending processes.

The fabrication process was successful. The entire machining process was on the order of one hour. The forming process was repeated multiple times without failure of the mechanism in all cases. The formed mechanism was tested to characterize its ability to manipulate the positioning stage both in- and out-of-plane. The transmission ratio for in-plane was measured at 6.4 while the out out-of-plane ratio was 6.3. The input deflection vs. output deflection curves display a linear relationship, but there was .0003 inches of hysteresis seen in the out-of-plane data after a max deflection of .0009 inches. This amount of hysteresis is undesirable and leaves further testing to determine its causes.

Thesis Supervisor: Martin L. Culpepper III

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CHAPTER 1

1 INTRODUCTION

1.1 Purpose of this research

The primary purpose of this research is to demonstrate the feasibility for creating a three-dimensional monolithic compliant six-axis nanopositioner. With the advent of nano-technology, laboratory automation has to meet the demands of faster, smaller, and cheaper solutions. Current precision manipulators cost tens of thousands of dollars. The designs usually include many individually machined pieces which each need to conform to tight tolerances to maintain such high accuracy. Research has proven that much more inexpensive manipulators with comparable resolution can be created from compliant mechanism. However the ranges achieved by mechanisms are much smaller, and research has suggested that a three-dimensional compliant mechanism can create much larger out of plane deflections. Figure 1.1 depicts a proposed solution.

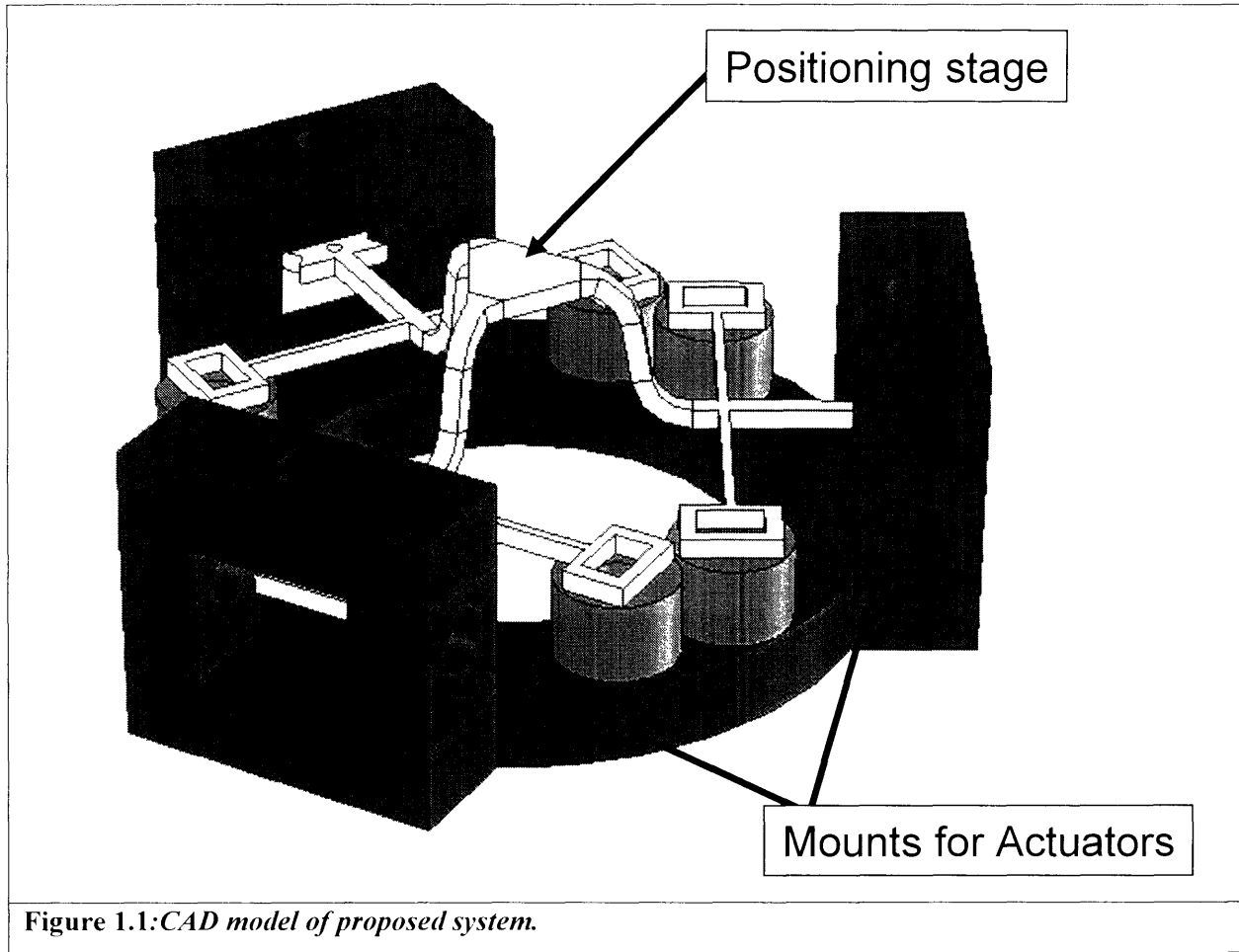


Figure 1.1: CAD model of proposed system.

1.2 Background

A common method of achieving six-degree of freedom positioning is through the use of a Stewart-Gough Platform. Traditionally, two planes are separated by six different legs. Holding the bottom plane fixed and actuating the legs in different known amounts yields a known position and orientation at the top plane. Many different configurations exist, referring mostly to how the legs meet the planes. For example, Figure 1.2 depicts a configuration where the legs share, in pairs, three points on the base and a different three pairs on the top.

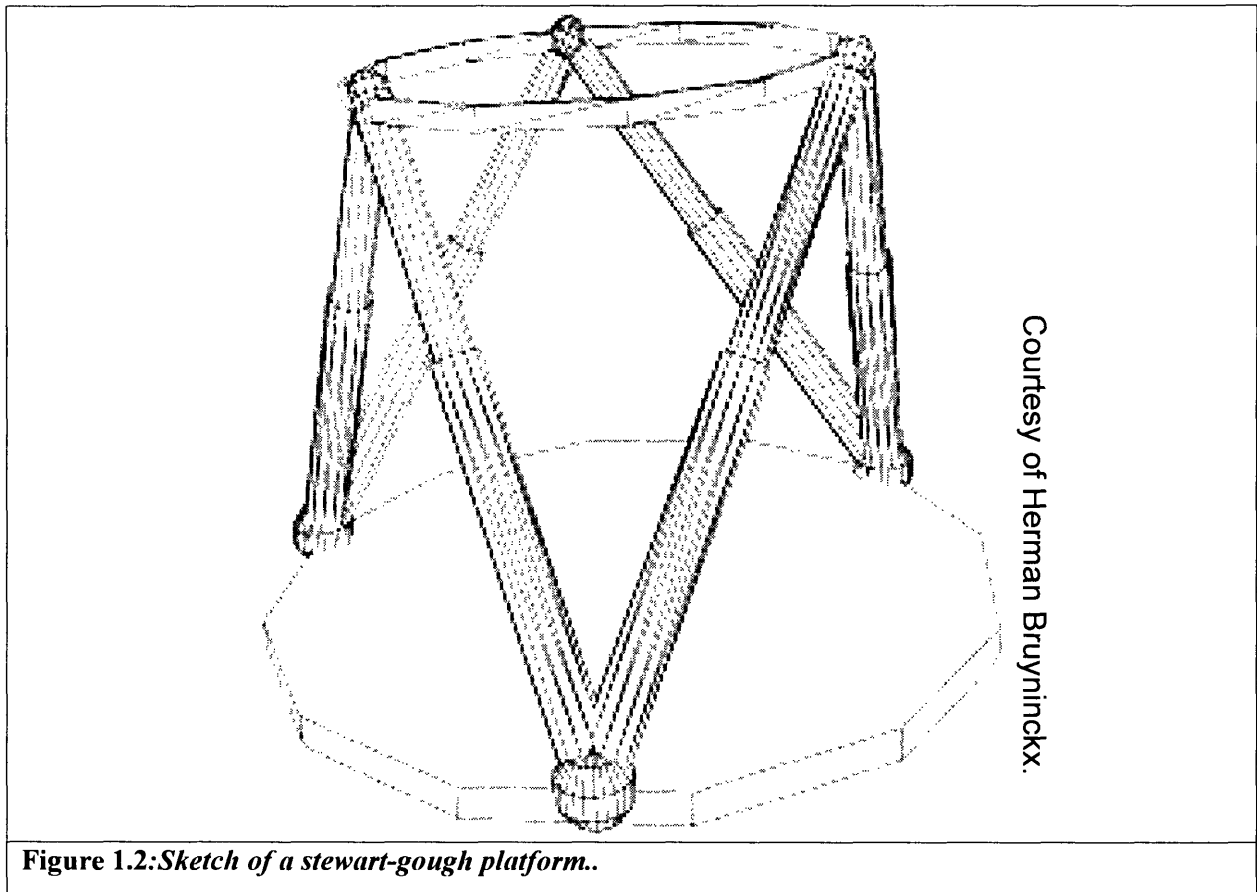


Figure 1.2: *Sketch of a Stewart-Gough platform.*

The Stewart-Gough platform design is manifested in a wide variety of positioning devices. These ‘hexapods’ are used from amusement rides to flight simulators. An example of smaller scale use is found in manipulators for micro-photonics. The photograph below in Figure 1.3 is a hexapod made by Physik Instrumente and is used for adjusting satellite dishes. As a response to complex mechanisms like these, Professor Martin Culpepper of MIT began researching the possibility of replacing a mechanism composed of many parts and complex joints with a single compliant mechanism. Compliant mechanisms are much simpler and therefore cheaper to manufacture. They are often made from one piece of material and rely on the elastic behavior of their material to create the desired degrees of freedom. In a multi-part mechanism,

the interface between parts is a large reason for lack of precision. Using a compliant mechanism

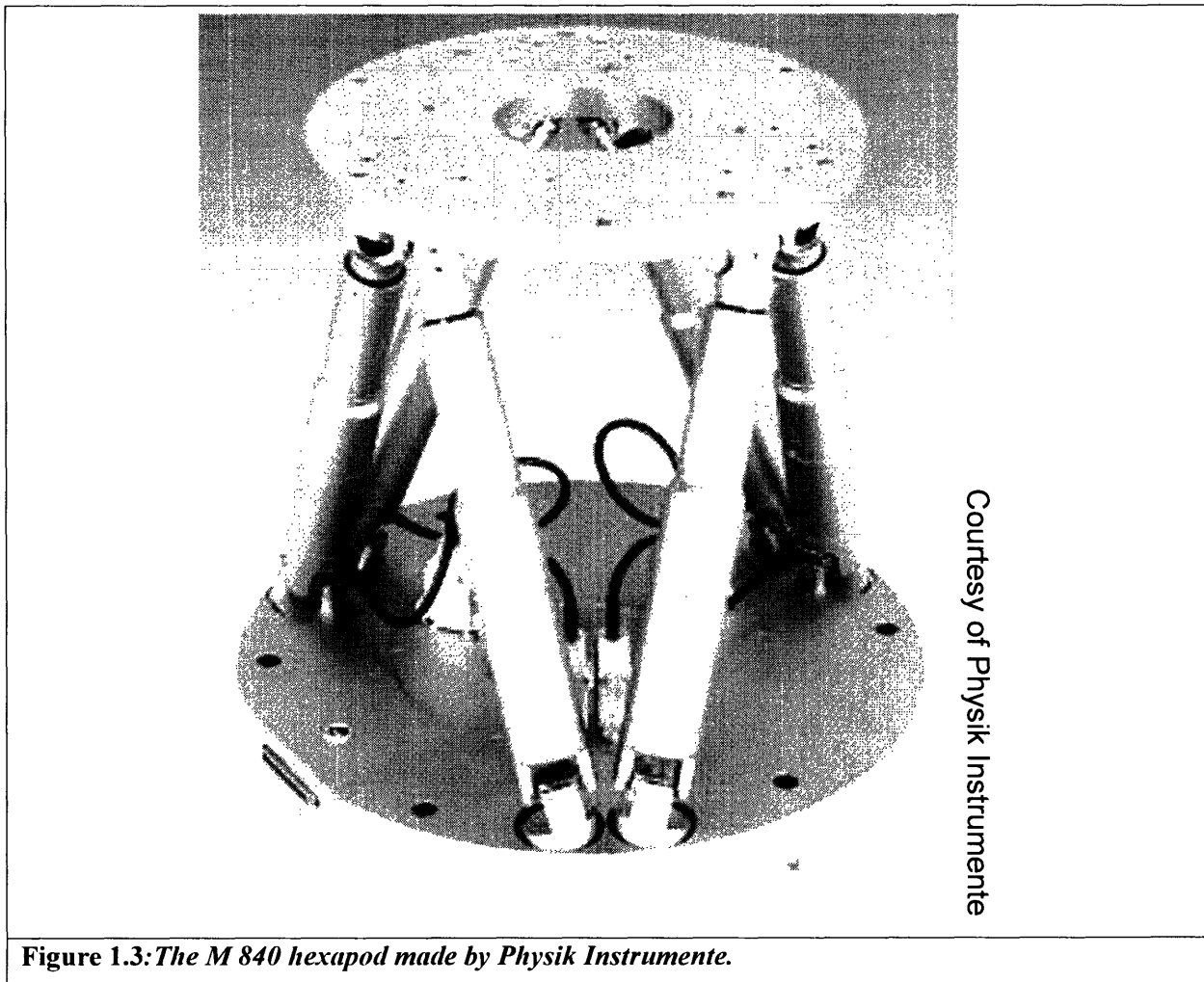


Figure 1.3: *The M 840 hexapod made by Physik Instrumente.*

removes the need for these joints. The result of Culpepper's work was the HexFlex Nanomanipulator [1,2]. Pictured below in Figure 1.4, the HexFlex system relies on a symmetrical compliant mechanism. The three tabs which extend radially from the center serve to actuate the positioning stage (the central triangle). Pushing the tabs either in-plane or out-of-plane creates a change in position of the center stage. Altogether, actuating the tabs in two dimensions creates six degrees of freedom for the stage. The resulting system won an R&D 100 award in 2003. It achieved a resolution better than 3 nanometers and was manufactured for only \$2,000.

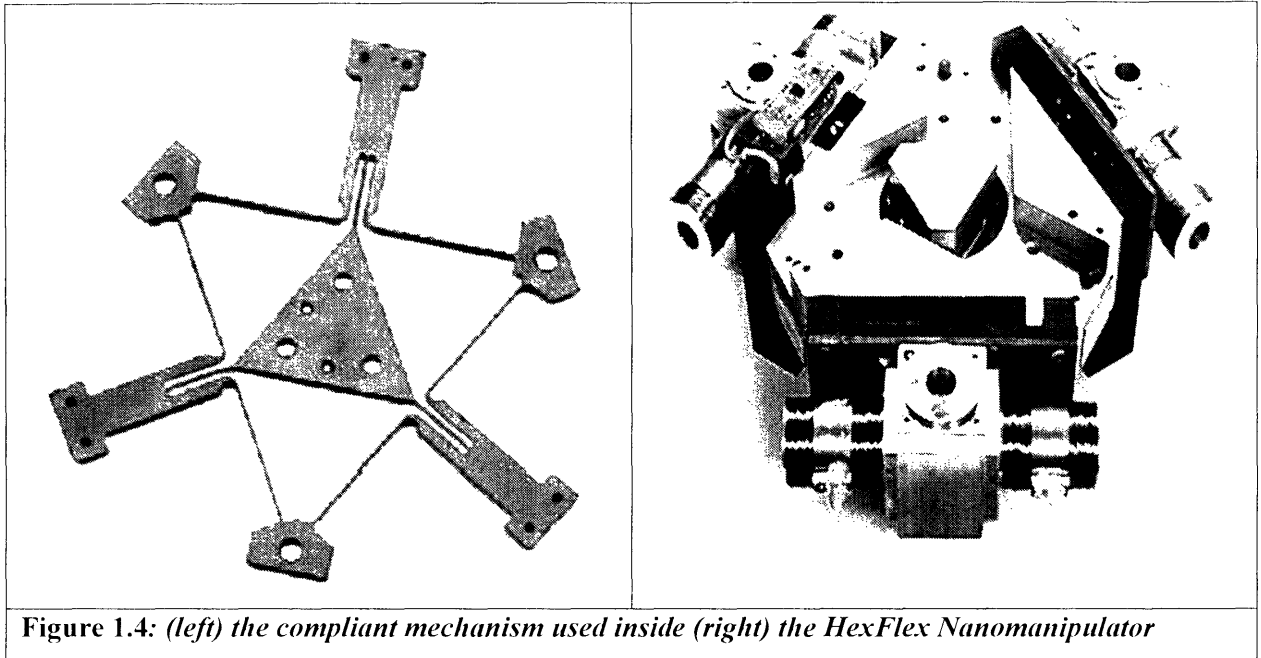


Figure 1.4: *(left) the compliant mechanism used inside (right) the HexFlex Nanomanipulator*

As a progression from the HexFlex flat 2D design, an undergraduate thesis on the design of a 3D HexFlex was written by Samuel Korb at MIT in 2004. Korb's work sought to create a two-dimensional figure on the abrasive water-jet and then press the positioning stage out of plane [3]. His resulting product can be seen in Figure 1.5. His design is similar to the HexFlex in many respects. However, the legs between the flexural beams and the positioning stage are drawn as double-curved structures in the two dimensional shape. This allowed them to be drawn into upward pointing beams when the manipulator was set in a fixture and pressed on the arbor press. While the desired shape was achieved the design had a few shortcomings. The method of drawing to achieve the third dimension often resulted in failure during the forming process. This could be attributed partly to the method of forming and partly to the material choice – 6061

Aluminum. Another drawback was the low natural frequency of the mechanism, making it vulnerable to external vibrations.

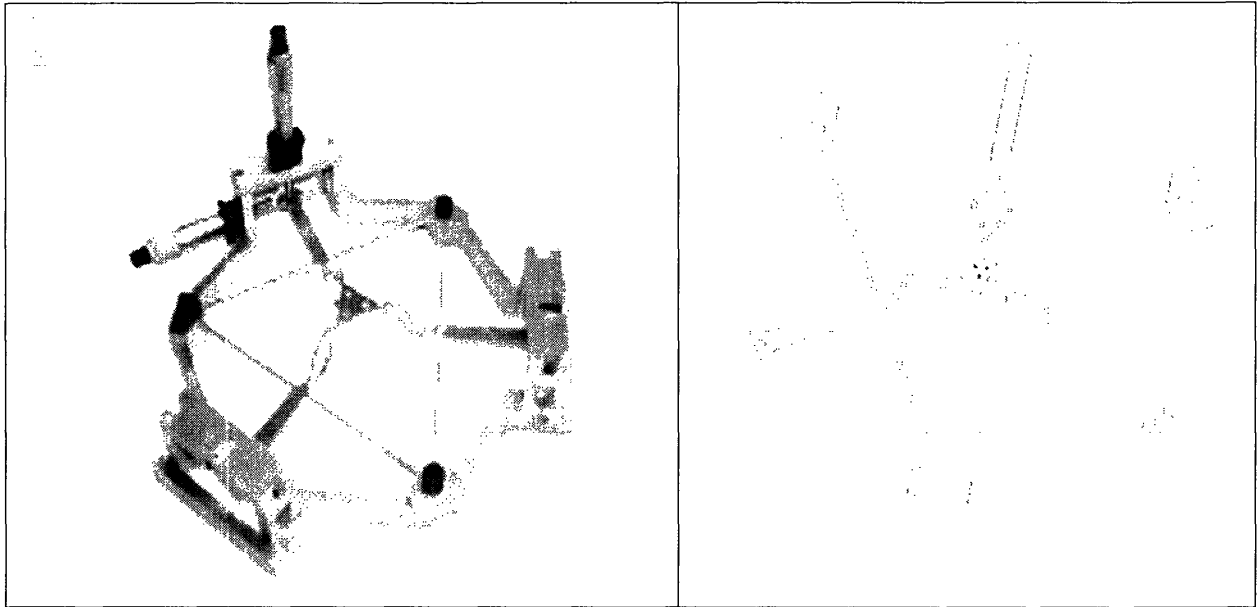


Figure 1.5: (left) photograph of Korb's 3-D HexFlex. (right) 2D shape of the mechanism.

The thesis that follows is mostly centered on improving on the groundwork laid in Korb's bachelor thesis. Time will be spent discussing the reasoning behind the proposed design, the methods and success of manufacturing, and a brief amount of testing demonstrating the mechanism's linearity.

CHAPTER 2

2 Design Requirements

The functional requirements for this nanopositioner are a function of previous HexFlex achievements, existing nanomanipulators, and intended applications. As discussed in the introduction, there are a number of products on the market which offer six-axis nanopositioning. A few examples and their capabilities are compared below in Table 2.1, along with the HexFlex.

Table 1.1: Comparison of existing manipulators.

Manufacturer	System Name	Work Volume (mm)	Linear Resolution (nm)
Physik Instrumente	F-206	X(12), Y(12), Z(12)	30
Aerotech	FiberMax	X(25), Y(25), Z(04)	10
EXFO	FR 3000	X(25), Y(25), Z(25)	0.1
	HexFlex	X(0.1), Y(0.1), Z(0.1)	3

It is apparent that while the resolution of the HexFlex is comparable, the range is noticeably smaller. The major limiting factor on the range of a compliant mechanism is the need to avoid plastic deformation at all times. However, this is not a problem for many of the applications in nanositioning. These devices are used largely for precision alignment in optical applications, and the original HexFlex demonstrated the ability to align two fiber optic strands.

Work done by Sam Korb developed a three-dimensional version of the HexFlex. The range and resolution attained were similar to the HexFlex. Most of the requirements for this device will refer to the prior characteristics of Korb’s device. A summary of that device’s achievements and the goals for a new design are presented below in table 2.2.

Table 1.2: Korb’s achievements and design requirements.

Korb’s Design	New Design Goals
75x75x75 micrometer range	Double
5-50 nanometer resolution	Maintain
8 inch diameter device size	Shrink to 4 inch
Formed using drawing	Use only simple beam bending

The device will be made from a single sheet of 1/8 inch Aluminum. A water-jet will be used to machine the initial two-dimensional structure of the manipulator. Korb’s work then used a forming process relying on a drawing process to achieve the third dimension. This was a major source of difficulty in the manufacturing of the device. It is the goal to create a design that relies only on simple beam bending in the three-dimensional forming. As a result the material must be chosen to be conducive to bends of up to 90 degrees.

This design will serve mostly as a proof-of-concept; therefore, in light of costs and time actuation will be done manually. The design will include interfaces for micrometer heads. The positioning stage will be designed to be large enough to interact with a dial caliper. A mount will be designed to hold the manipulator in place and interface the actuators.

CHAPTER 3

3. Manipulator and Mount Design

3.1 Manipulator Design

As the device is intended to be first machined on a water-jet, the design process began with a two-dimensional CAD drawing. The material will be 1/8 inch 5052 Aluminum to allow for the bending of the structure. The annotated drawing in Figure 3.1 depicts some of the major design consideration.

Upon analyzing Korb's design, it was decided that a limiting factor on possible three dimensional configurations was the fact that the device is mounted at three points, leaving all of the flexure beams to create a continuous perimeter. Thus, the first major design change is to create 6 anchoring points. This allows each of the three actuating tabs to be formed independently, using only simple beam bending. However, one major benefit of the 3-point anchoring is lost – precise knowledge of the location of those points. As there will be some error

in the bending process, the exact location of each of the 6 mounting points will be ambiguous to some degree. As a result the 1/4 inch mounting holes were replaced with 1/4 inch wide slots.

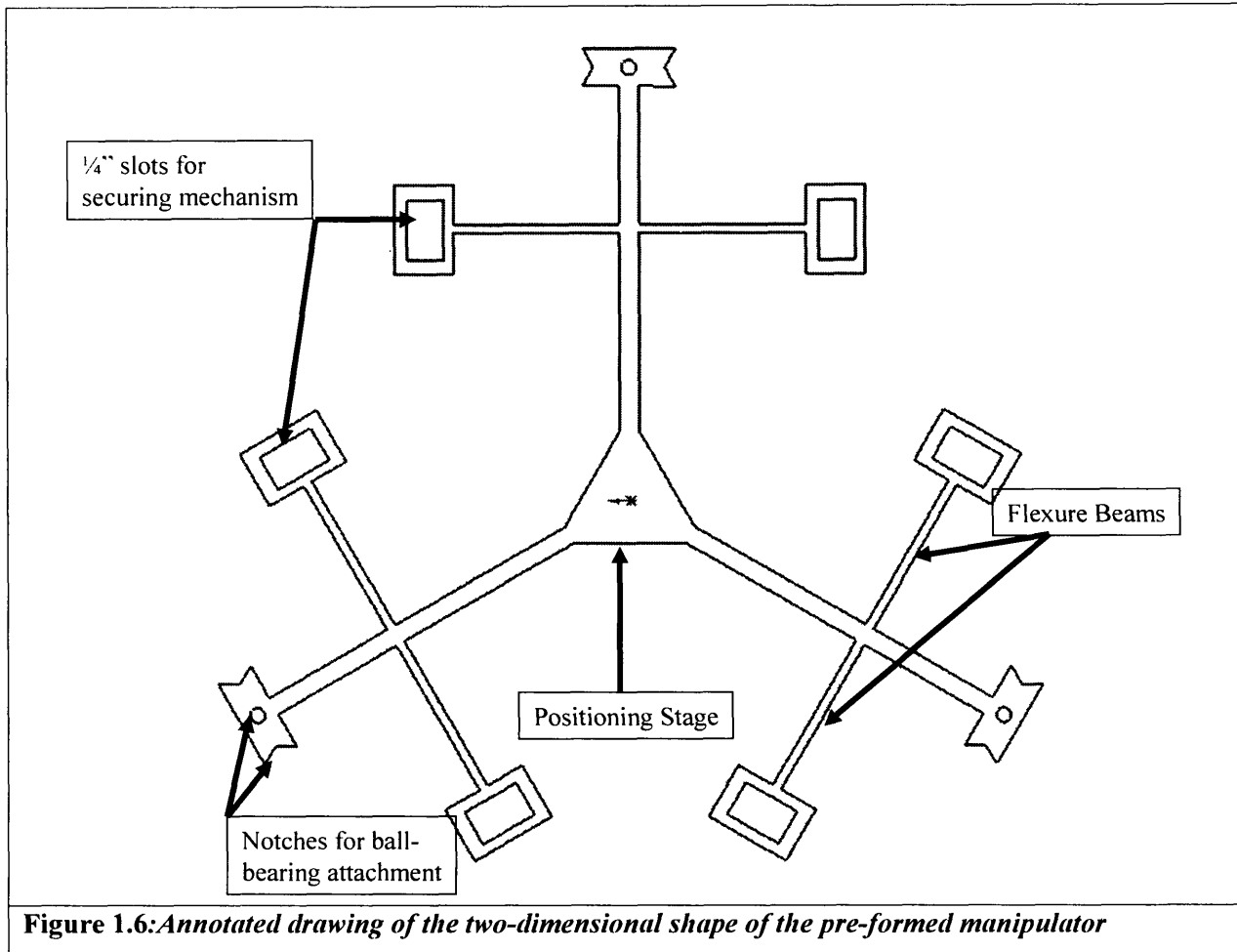


Figure 1.6: *Annotated drawing of the two-dimensional shape of the pre-formed manipulator*

Many of the other aspects of Korb's design remain. There are notches in the input tabs to allow for ball bearing to be placed. These will serve as interfaces for the micrometer heads and should decrease the amount of friction between the two surfaces. The flexure beams will be 1/16 inch in width. Combined with the 1/8 inch thickness dimension, the beams will have a propensity to rotate as opposed to bending down when an out of plane deflection is applied. The

overall size of the mechanism is just over 4 inch in diameter, satisfying one of the major design requirements.

The center triangle serves as the positioning stage. The tabs extending from this stage until the flexure beams are 1/8 inch in diameter. This section of the tabs is where the bending will take place in creating the 3-dimensional shape. A model of the desired three-dimensional configuration appears in Figure 3.2.

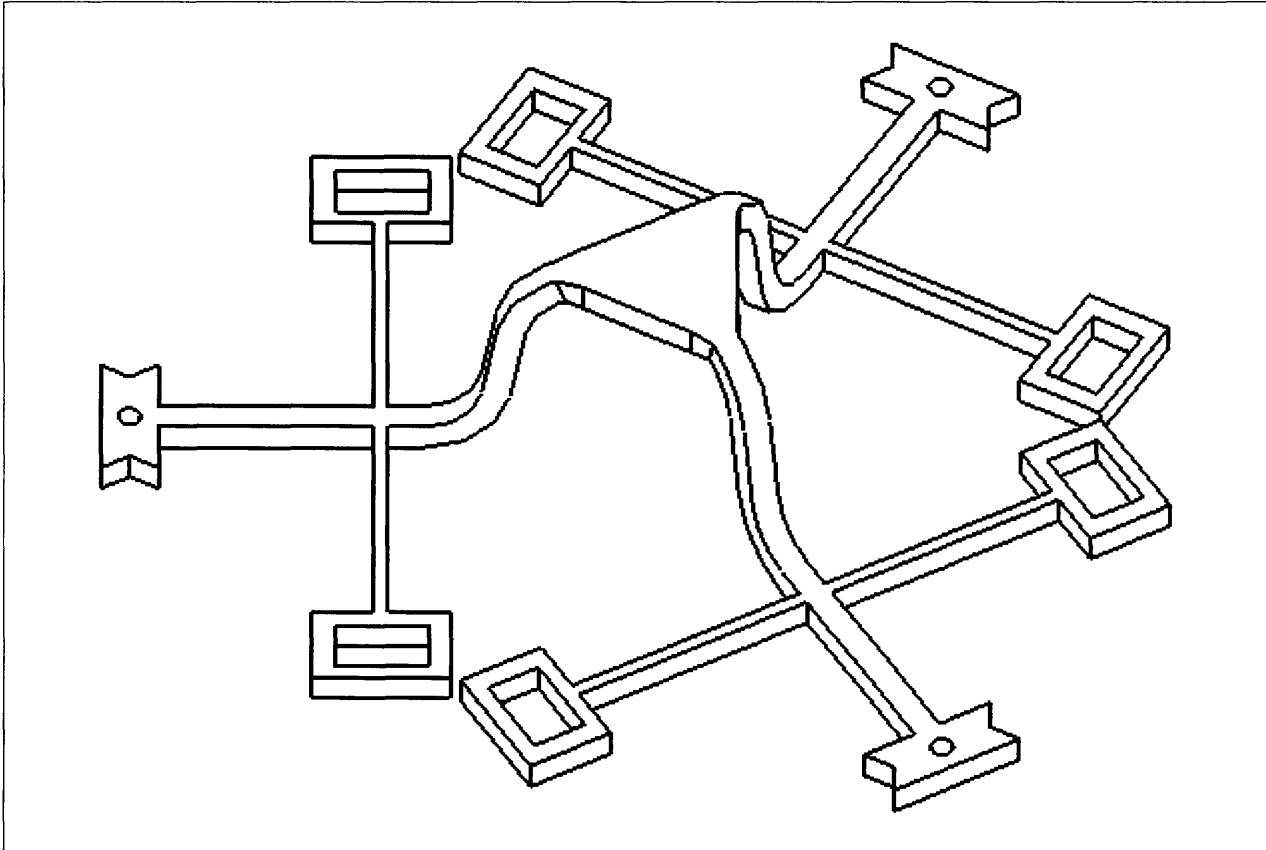


Figure 1.7: *Computer drawing of the desired three-dimensional manipulator.*

Figures 3.1 and 3.2 were derived from models designed in SolidWorks. The part was first drawn in the two-dimensional form, extruded as a sheet metal part, and then bent. The COSMOS FEA package was then used to analyze the expected deflection of the mechanism. A

picture of the deflection due to two equal and opposite in-plane inputs is shown below in Figure 3.3.

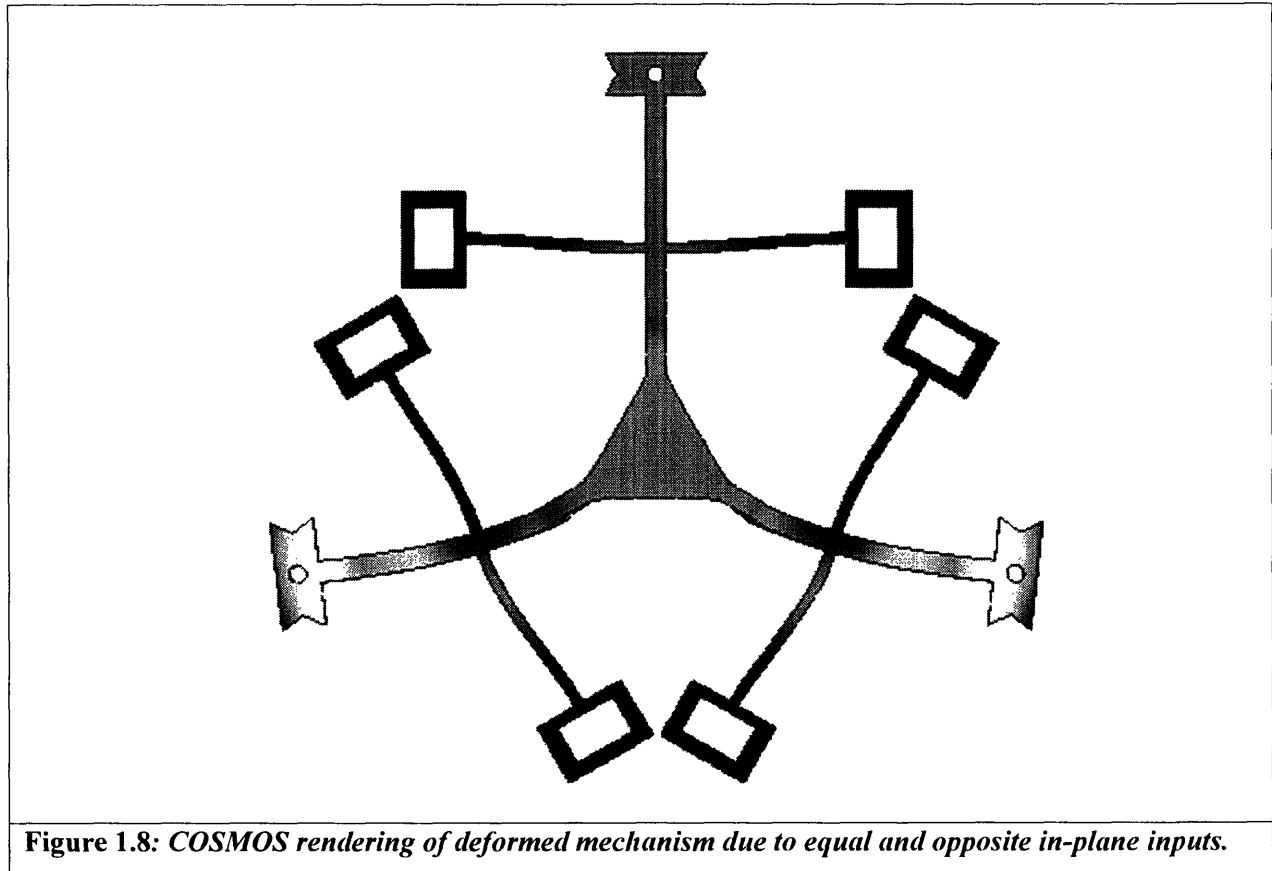


Figure 1.8: *COSMOS rendering of deformed mechanism due to equal and opposite in-plane inputs.*

3.2 Testing Mount Design

In order that the manipulator can be fixed in one place and manually actuated a mount was designed. Each part was designed to rely on the water-jet for all machining. To give the system a little more stability, the mount components were all cut out of ½ inch 6061 Aluminum. The goal was to create as small a part as possible while maintaining room for all of the needed

components. In total 16 (4 unique) pieces were designed. Figure 3.4 below depicts the system in two steps.

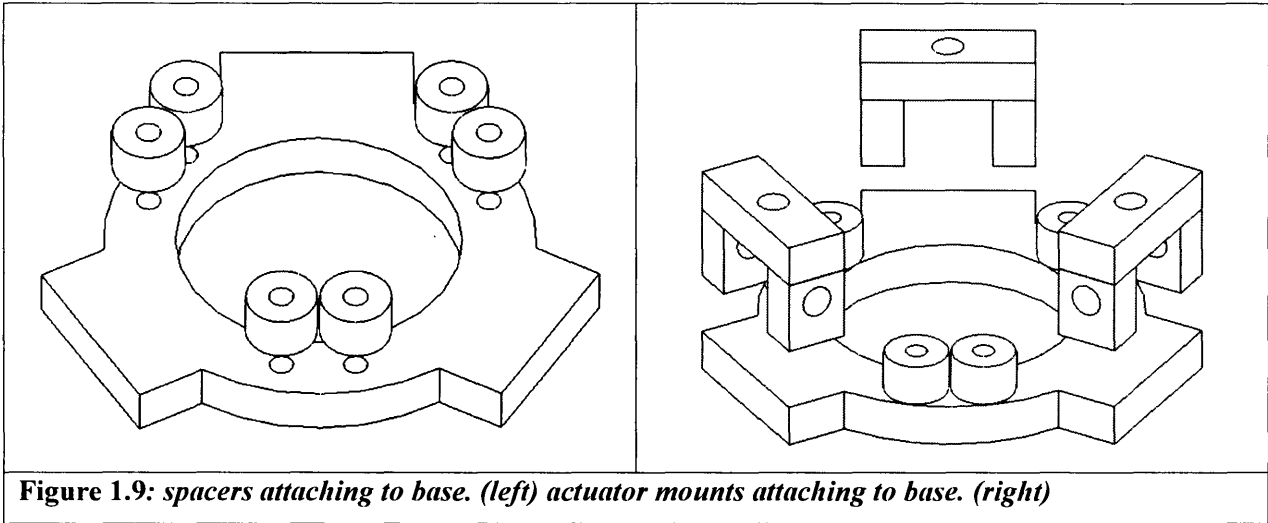


Figure 1.9: spacers attaching to base. (left) actuator mounts attaching to base. (right)

The base is composed of a 4.5 inch diameter ring with 2 inch wide tabs protruding at 120 degrees intervals. To ensure that actuation tabs of the manipulator have room to deflect downward, 6 half-inch spaces are employed. Finally blocks were designed to hold micrometer heads (Figure 3.5) for actuation. The vertical parts will be drilled and tapped so that they can be mounted by bolts to the base. The horizontal blocks will be glued to the verticals due to a lack of space for bolts.

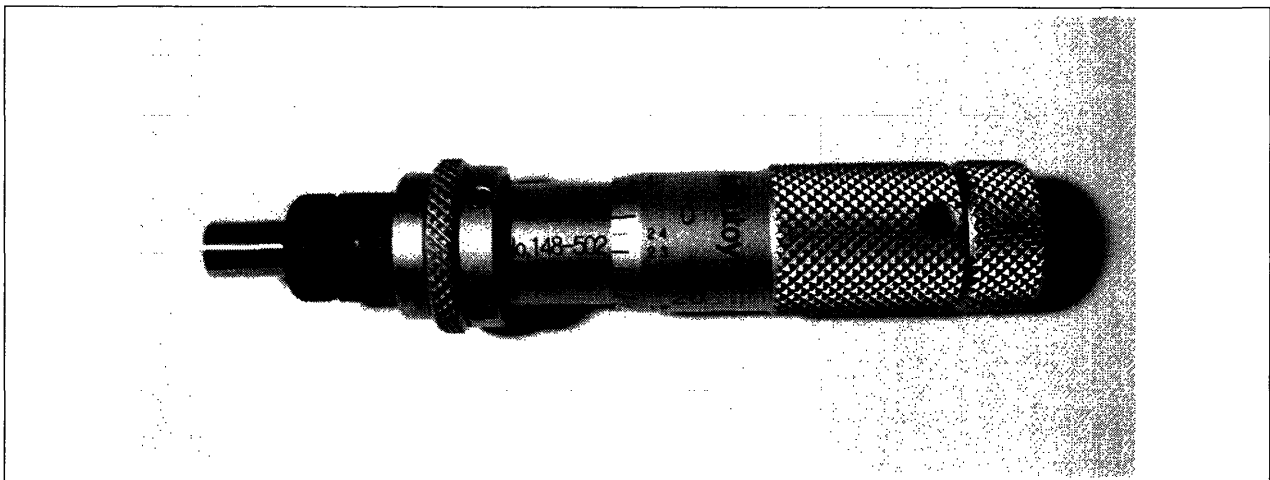


Figure 1.10: Photograph of Mitutoyo micrometer head (No. 148-502)

To control the motion of the positioning stage, the actuation tabs must be deflected both in plane and out of plane. In order to precisely input these deflections, Mitutoyo 148-502 micrometer heads were employed. They have a 0.5 inch range and 0.0001 inch accuracy. A set screw was used to hold each in place within the mounting holes. For testing purposes at most three micrometers will be in use at once. A photograph of one micrometer is presented above in Figure 3.5.

CHAPTER 4

4 Manufacture and Assembly

A large portion of this work was dedicated toward designing for ease in manufacture and assembly. Indeed, most of the cost reduction in such a mechanism is seen at the manufacture and assembly level. This chapter details the process from water-jetting parts, to forming the manipulator, and finally assembling the pieces.

4.1 Water-jetting the manipulator and mounting components

While not a precision machine, the water-jet is an ideal for this project. It is used to cut two dimensional parts quickly and easily. The parts were first drawn using the SolidWorks design package. Next, those files were converted into machine path files using the OMAX Layout and Make software. The water-jet does not give a perfectly vertical edge: across a 0.125 inch dimension the top surface measured 0.121 versus 0.131 on the bottom. This is equivalent to a 2.3 degree slope. For smaller parts, like the spacers and vertical mounting blocks, small tabs were drawn in to prevent them from falling to the bottom of the machine tank. The tabs were

later broken off with a rubber mallet. Once the parts are machined (a 35 minute process in total) they are sanded down to remove sharp edges and remnants of the previously mentioned tabs. A photo of the manipulator after water-jetting and sanding is shown below in Figure 4.1.

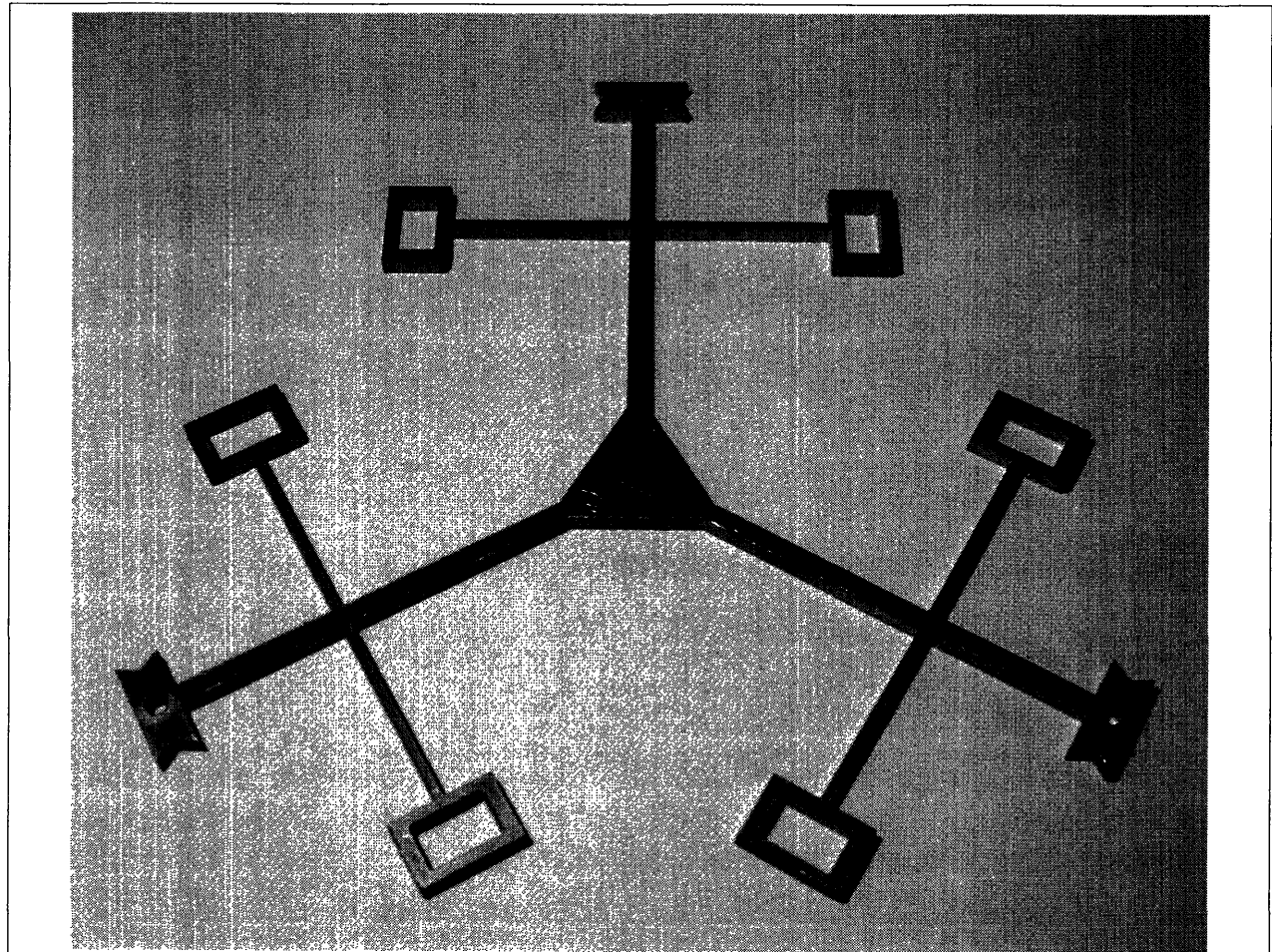


Figure 1.11:*Photograph of manipulator after water-jetting.*

4.2 Forming the Manipulator into a Third Dimension

The next manufacturing step was to bend the tabs of the manipulator to achieve a three-dimensional shape. A number of tools available around the lab were considered, but the small size of the manipulator and proximity of the bends to each other limited the options. In the end, the first three bends, closest to the positioning stage, were done using a 90 degree anvil and die.

The other three bends used a handheld set of wide duckbill pliers. The bends must be completed inside bend followed by outside bend, and repeated. The first three inner bends cannot be done at once, or else there is not enough room to use the handheld pliers to bend the rest. The solid model pictures below in Figure 4.2 illustrate this fact.

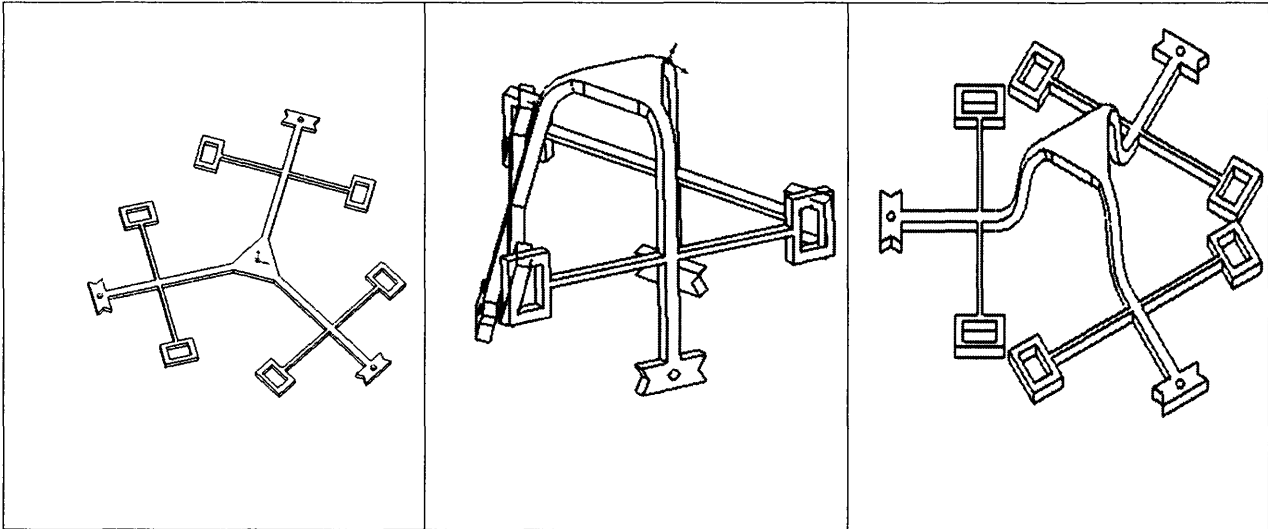


Figure 1.12: *Forming of the manipulator from 2D to 3D*

Using this non-precision method for bending, a desirable shape was still attained. As designed, the anchoring slots fit easily over the mounting holes on the base. There were a few undesirable notches on the corners of the positioning stage, due to the first bends, but they should not greatly affect the kinematics of the manipulator. Also, a number of methods could be employed to prevent these markings from occurring in the future. A photograph of the final formed manipulator is presented in Figure 4.3.

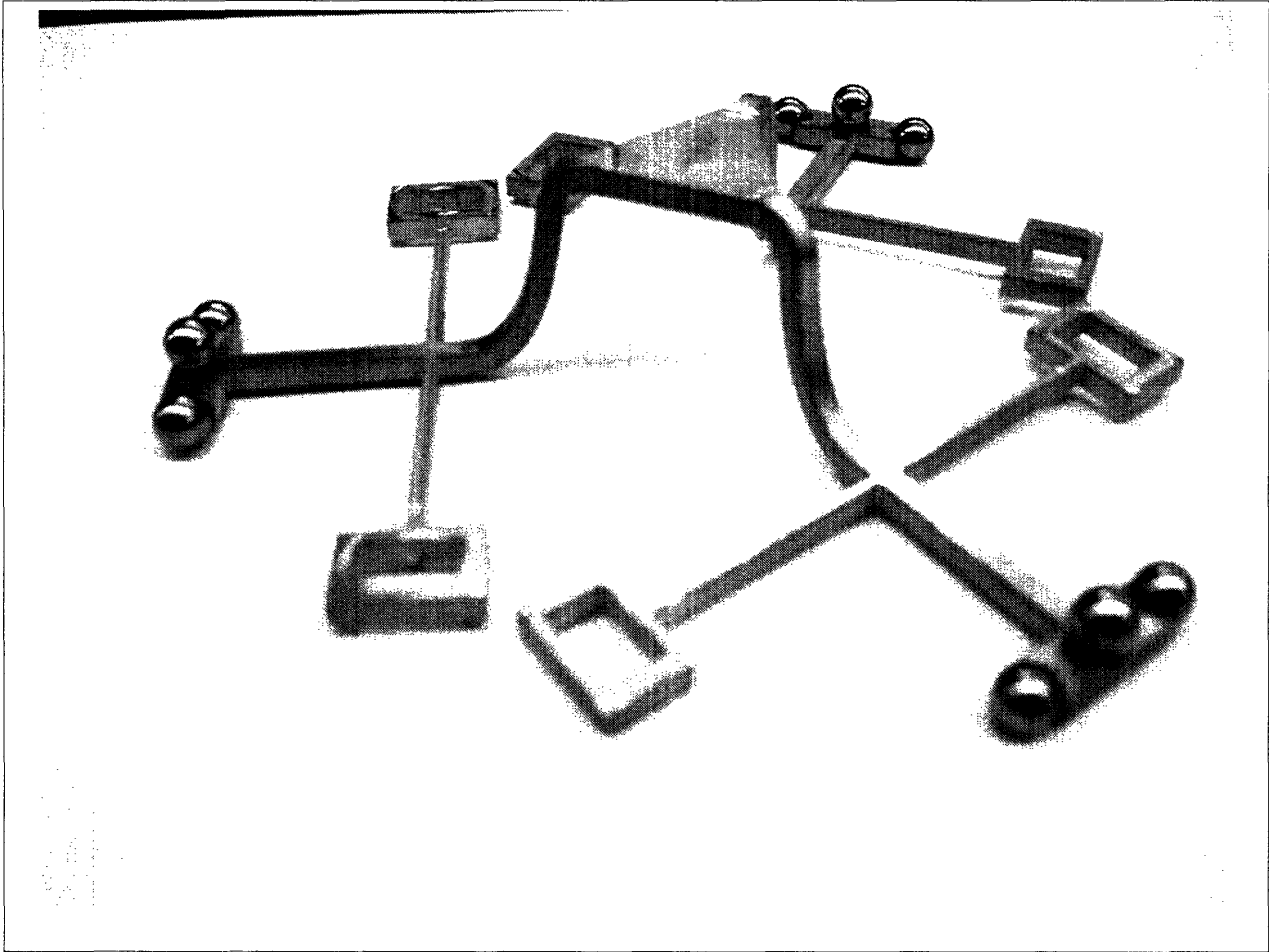


Figure 1.13: *Photograph of the 3D formed manipulator.*

4.3 Assembly

The assembly of the components occurred in the following manner. First a number of holes were still left to drill and tap. For holding the micrometer heads in place, these holes were designed for a 6-32 set screw. To secure the vertical mounting blocks to the base, $\frac{3}{4}$ inch, 8-32 bolts were used. Next the manipulator was set in place. While holding the spacers in between the base and manipulator, a $\frac{1}{4}$ inch bolt was passed through a washer, the three components, and then secured with a nut on the bottom. Currently, the bottoms of these bolts also form the

support feet when the assembly sits on the ground. Once the manipulator is fixed ball bearings were attached to the notches. Nine ¼ inch ball bearings were affixed using commercially available super glue. A photo of the system without the caliper mounting blocks is shown below in Figure 4.4.

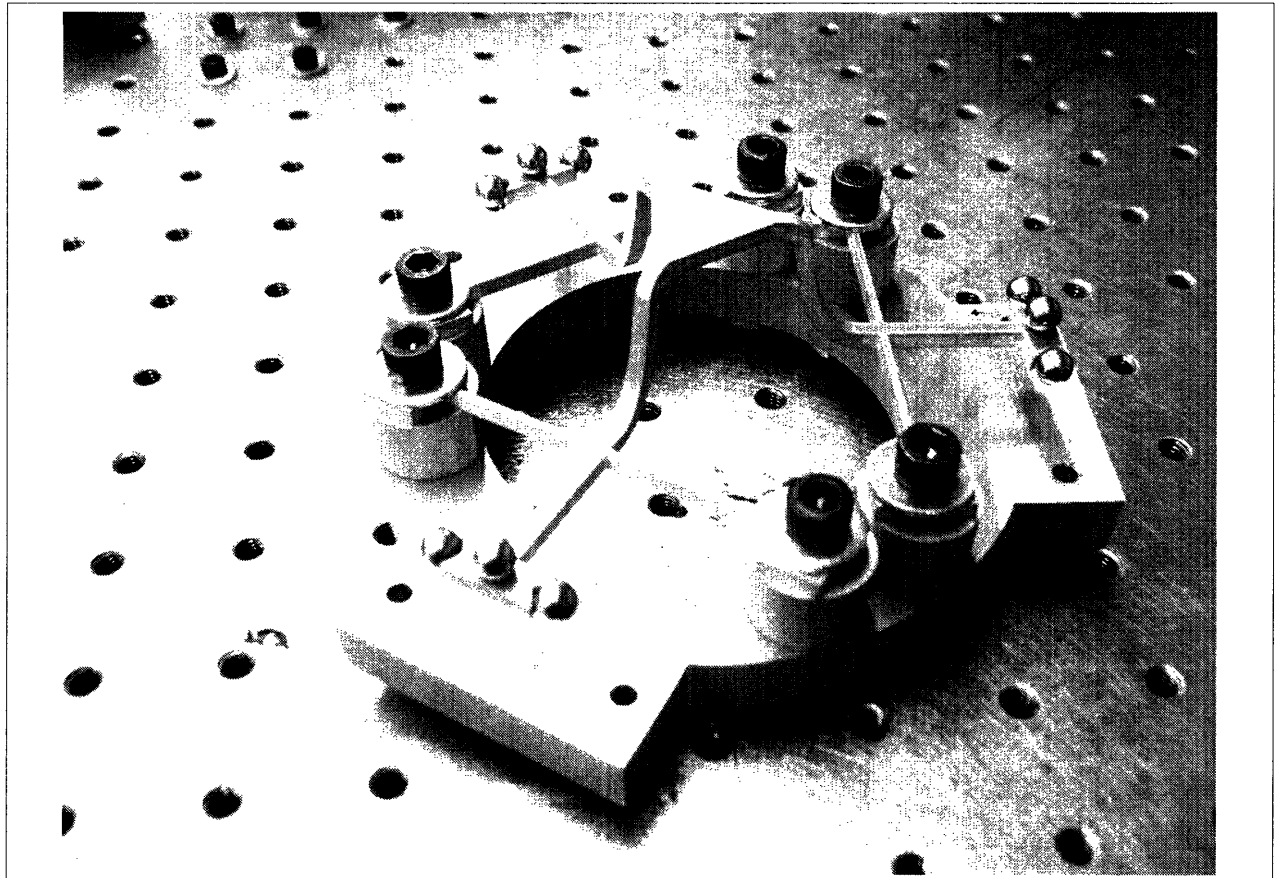


Figure 1.14: *Manipulator with ball bearings attached, without actuator mounts in place*

Finally, the horizontal mounting blocks were attached to their vertical counterparts using an aluminum adhesive. The system was then allowed to sit over night to ensure proper setting of the adhesives. Once set, the mitutoyo micrometer heads were placed in the desired positions and fixed using the 6-32 set screws. Two photographs of the completed system appear in Figure 4.5.

The first depicts the system set up for out-of-plane deflection, while the second illustrates the ability for a tab to be actuated both in-plane and out-of-plane simultaneously.

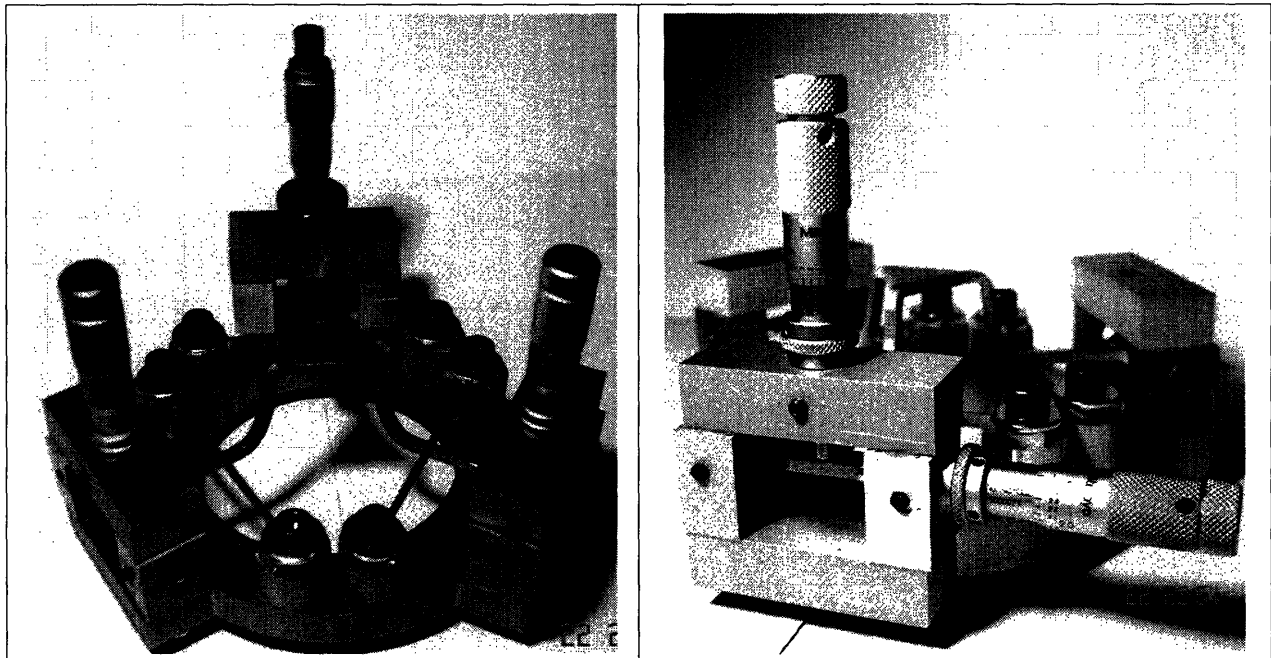


Figure 1.15: *photo of completed system set up for out-of-plane deflection, (left) photo illustrating the ability of the device to actuate both in and out of plane. (right)*

CHAPTER 5

5 Testing and Results

This chapter discusses the methods used for testing the positioning system. It details the steps in setting up the apparatus and recording the data. Also in this section, the collected data are presented.

5.1 Setting up the Testing Apparatus

The main goal of this testing is to vary the input deflection by the actuators and measure the corresponding deflection of the positioning stage. This experiment will be limited to two single axis tests: one in-plane, and one out-of-plane. While the mitutoyo micrometer heads will provide the input deflection, the output will be measured by a Mitutoyo electronic indicator. The model used was the Mitutoyo Absolute 543-558, with a range of two inches and increments of 0.00005 inches. The first test set up was for out of plane deflections. The three micrometers heads were each secured in their vertical positions. The electronic indicator was attached to a mount and suspended vertically above the positioning stage. The tip of the indicator was

lowered, and the indicator was zeroed. Each of the micrometer heads was adjusted until they just came into contact with the ball bearings, and the starting positions were noted. Next the micrometers were lowered 0.001 inches at a time, always in the same order and the corresponding deflection of the stage was recorded. A photograph of the testing apparatus appears below in Figure 5.1.

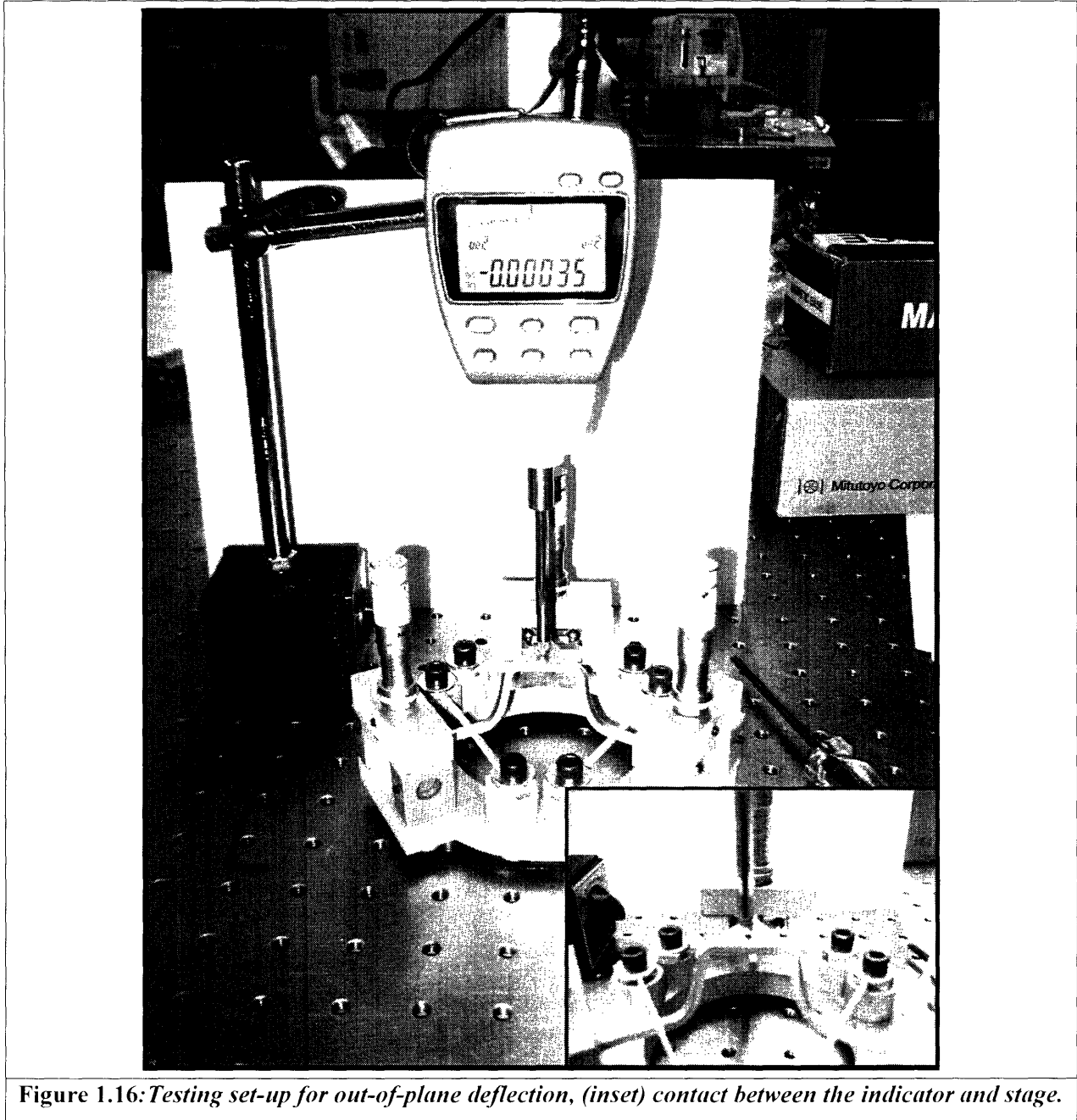


Figure 1.16: *Testing set-up for out-of-plane deflection, (inset) contact between the indicator and stage.*

A much similar procedure was repeated for the in-plane testing. The first step was to move two of the micrometer heads to new positions. In order to generate a simple in-plane deflection of the stage, the micrometers were placed in opposite directions. The third micrometer was not used at all in this test. Next the electronic indicator had to be adjusted to

read deflections in a new direction. As can be seen in Figure 5.2 below, the tip of the indicator was rested against the side of the positioning stage. The 1/8 inch thickness of the stage was a sufficient surface with which to interface the indicator.

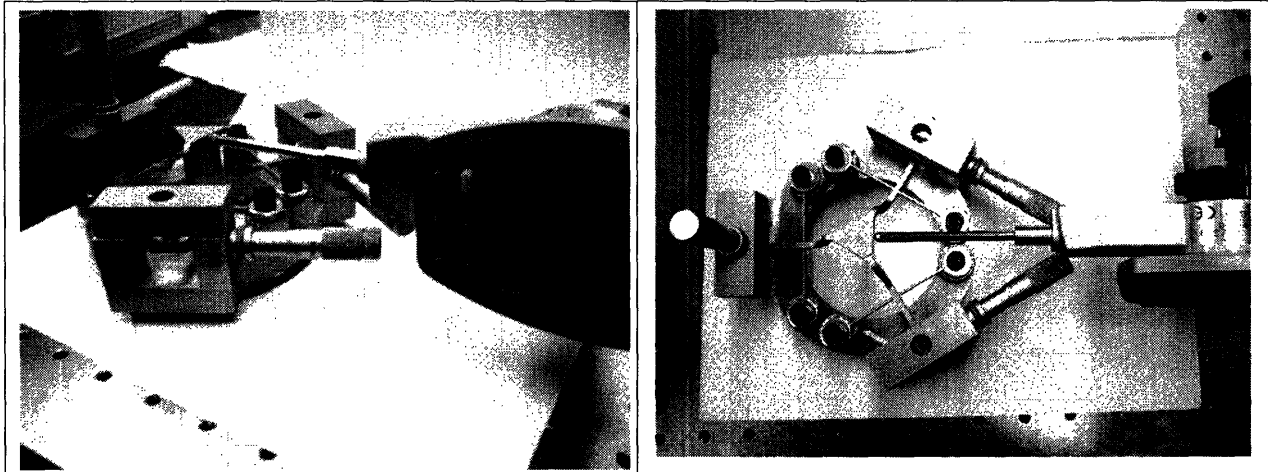
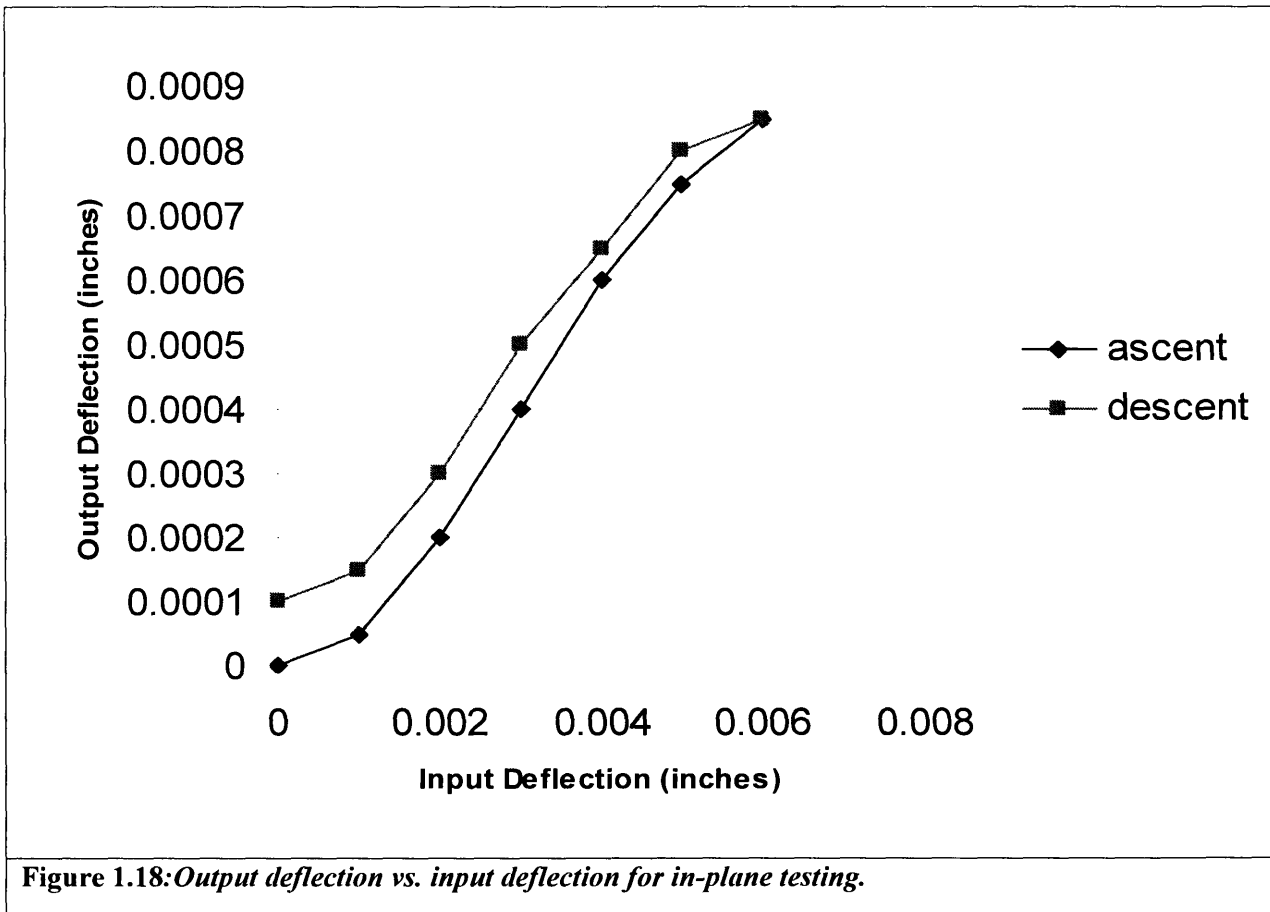


Figure 1.17: *The testing set-up for in plane deflection.*

5.2 Results

Presented below are the results of the testing of the mechanism. The graphs show two sets of data. These represent the ascent and descent data. As the micrometer heads increased the deflection at the input tabs, the ascent data was recorded. Once a certain point was reached, the deflection was decreased in the same increments, and the descent data was collected. The most extreme deflection point is shared by the two. The ascent data always starts at (0,0), and the descent data may or may not end there due to hysteresis.

Figure 5.3 shows the data collected from the in-plane testing. Clearly, the descent data



are always higher than the ascent points. This shows that there is some form of hysteresis at work. There are a number of places outside of the mechanism that may be causing this trend. The accuracy of human interaction with the micrometer heads is obviously in question, and the presence of hysteresis within the micrometers themselves is a possibility. The interface between ball bearings and micrometers is also a place where friction may be at work. Another characteristic to note in the data is the change in slope between the first two pairs of data points. This trend is apparent both in the ascent and descent. This can be attributed, most likely, to the

micrometer heads not being set exactly in contact with the ball bearings when the experiment began. This would result in lower deflections than expected in the first data point. Despite these shortcomings, the data does demonstrate a linear, predictable behavior.

The data collected during the out-of-plane testing is presented in Figure 5.4. While the general shape is similar to that of the in-plane testing, there is a strikingly much larger amount of

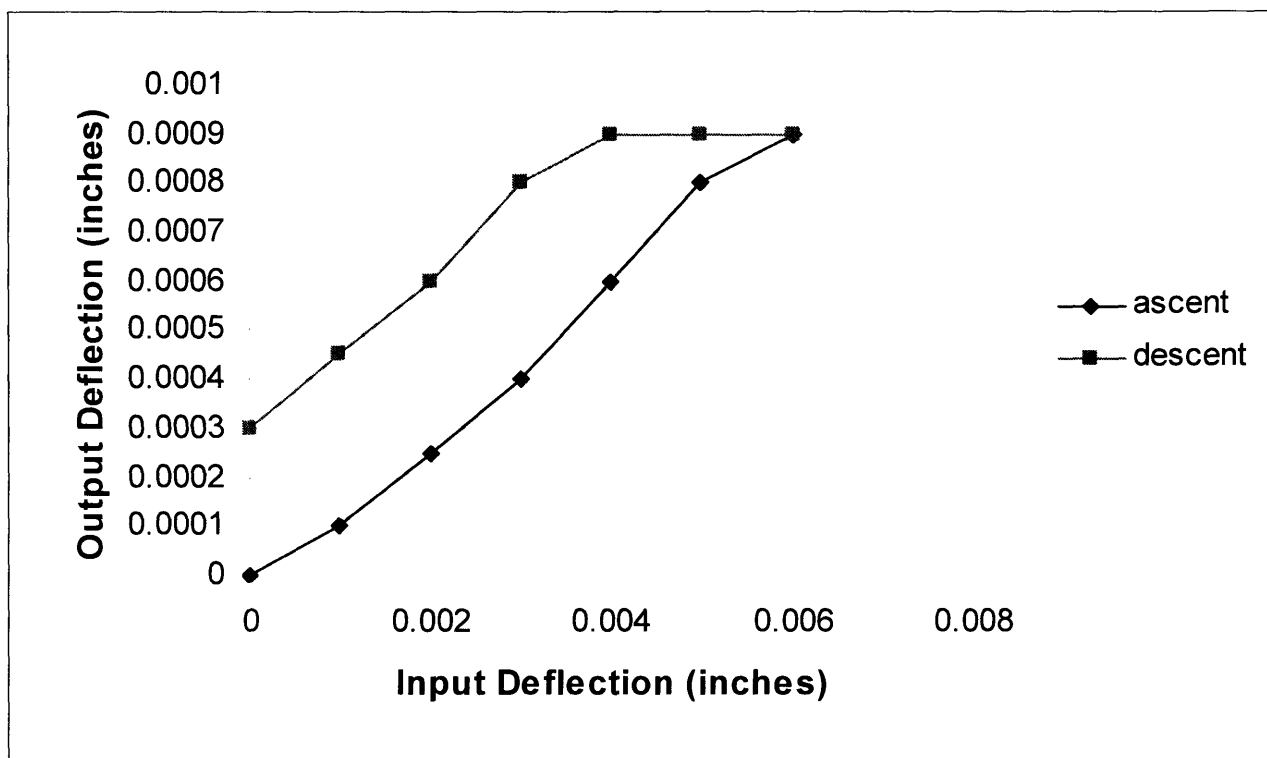


Figure 1.19: *Output deflection vs. input deflection for out-of-plane testing.*

hysteresis. In fact, the measured output deflection did not change for two straight data points, across which the micrometer heads changed 0.002 inches. When the ascent-descent cycle was complete, the stage was measured to be 0.0003 higher than where it originally started. It is possible that some amount of plastic deformation was incurred during the forming process, even

though care was taken to restrict the location of the plastic deformation. Again, despite the hysteresis, the data does show a linear trend both in the ascent and descent.

CHAPTER 6

6 Conclusions

This research had mixed results. On one hand it did not successfully double the range seen in previous work by Korb, and the results from the out-of-plane testing showed a startling amount of hysteresis. On the other hand, a design was created that no longer relies on drawing in curved beams, but rather employing simple one dimensional bends. In addition this design cut the size in half and demonstrated successful abilities in manipulating in-plane motion.

Table 1.3 Comparison of Design Characteristics

Characteristic	Korb's Design	New Design
Hysteresis	Minimal	1/3 of max deflection
Forming	Drawing curved beams	Bending straight beams
Size	8 inch diameter	4.5 inch diameter

A number of other important observations can be taken away from this research. First, the method of slotting the anchoring points on the manipulator is inherently flawed. Although it allowed sufficient room to mount the manipulator to the base, the points of actuation were designed relative to the base, and therefore an uncertainty existed regarding the interface of input tabs and actuators. One possible solution is offered. First, leave the anchor points as ¼ inch through holes. Next the base should be redesigned as three separate pieces each mounting across one flexure beam and two anchor points. Each of these pieces would have the actuator mounts directly affixed to them, and would be precisely positioned around the actuation tabs. Lastly, these three base parts would be mounted onto a single sheet which will be slotted to allow for uncertainty in the forming process.

Another suggestion would be to try some other tempers of Aluminum. While the 5052 was sufficient, there were still some signs of stress near the bends. It may be desirable to try 1100 as it is known for its workability. In regards to the actual forming process, the two step process could be replaced by creating a fixture to make all 6 bends at once. This would greatly increase repeatability and decrease production time.

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2. Culpepper, M., & Anderson, G., Design of a low-cost nano-manipulator which utilizes a monolithic spatial compliant mechanism. Precision Engineering 2004; 28:469-482.
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Appendix A

The following are the raw data points taken during the testing. The first table was for three equal out-of-plane inputs, while the second was the result of two equal and opposite in-plane inputs. The first four columns are used for determining the input values on the micrometers. The last two columns display the deflection of the stage resulting from the given input.

Out of Plane Deflection Test

<i>micrometer positions:</i>	1	2	3	input	ascent	descent
start	4173	4438	4038	0	0	0.0003
10	4163	4428	4028	0.001	0.0001	0.00045
10	4153	4418	4018	0.002	0.00025	0.0006
10	4143	4408	4008	0.003	0.0004	0.0008
10	4133	4398	3998	0.004	0.0006	0.0009
10	4123	4388	3988	0.005	0.0008	0.0009
10	4113	4378	3978	0.006	0.0009	0.0009

ascent TR= 6.293266

In Plane Deflection Test

<i>micrometer positions:</i>	1	2	input	ascent	descent
start	5000	4700	0	0	0.0001
10	4990	4690	0.001	0.00005	0.00015
10	4980	4680	0.002	0.0002	0.0003
10	4970	4670	0.003	0.0004	0.0005
10	4960	4660	0.004	0.0006	0.00065
10	4950	4650	0.005	0.00075	0.0008
10	4940	4640	0.006	0.00085	0.00085

ascent TR: 6.435006