Fabrication and Redesign of a Meso-Scale Six-Axis Nano-positioner System

by

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ABSTRACT

The industry's need for low-cost nano-positioners led MIT's Precision Compliant Systems lab to design a system of 10 six-axis meso-scale nano-positioners. They devised a system that could revolutionize the nano-scale industry, by making massive parallel positioning at the nanometer/micro-radian possible at a low cost. In order to test the design, the alpha prototype was built and tested. The fabrication and the assembly processes provided insight into possible redesign changes that would facilitate future manufacturing, as well as improve the performance of the nano-positioner. The fabrication of the prototype also allowed for the exploration of the accuracy of conventional machining methods and their effect on the device performance. Traditional manufacturing was necessary in order to achieve the lowest cost possible. The design was also analyzed from a business perspective and modified to begin the transformation from prototype to profitable product. The construction of the prototype and the proposed changes to the design are important to the development of the project.

Thesis Supervisor: Prof. Martin Culpepper
Title: Associate Professor of Mechanical Engineering

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Chapter 1: Background

The purpose of this thesis is to present how the fabrication and assembly a meso-scale six-axis nano-positioning system influenced the redesign of the system. By analyzing the current design shown in Figure 1, through the fabrication, assembly and business perspective, changes were made that led to an improved design in terms of each of these areas. The resulting design enables the team to eventually produce a system that can be sold as a consumer product. The proposed design advances the project one step closer to revolutionizing the nano-positioner industry, by providing the first system that can do massive parallel nano-positioning in the nanometer/micro-radian level at a low cost.

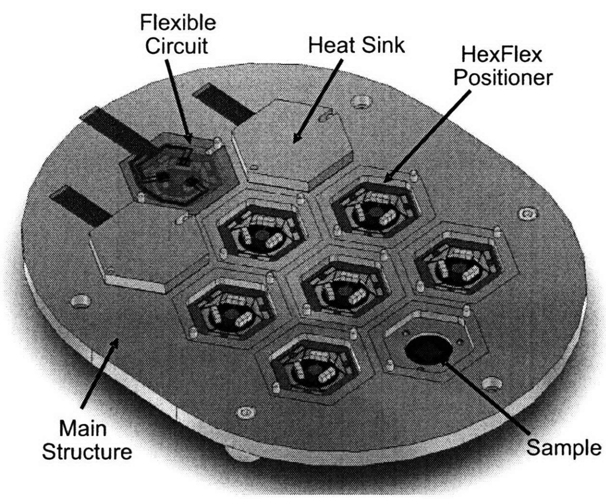

Figure 1. SolidWorks model of the complete original design [1].

Nano-positioners are an important tool in the fast growing nano-scale industry. A nano-positioner is used to move or to position a tool, sample, part, probe, or device to a desired position with nanometer accuracy and repeatability [2]. They are used in range of applications from high-speed confocal imaging to wafer stepping to precision machining. Due to this wide assortment of uses, the challenge has become to be able to design a nano-positioner that can meet the needs of each different function, at an affordable price. For this, a new generation of faster, more accurate, and especially less expensive nano-positioners is needed.

Herein positioner technology is evaluated on 3 different aspects: position noise, accuracy, and resolution. Current state-of-the-art systems are in the macro-scale and cost hundreds of thousands of dollars. They operate in serial positioning mode, and are capable of about 8 nm of resolution. The cost of these nano-positioners can exceed $900K, when the positioner can manipulate several stages at a time, making it hard for research institutions to afford them [3]. Currently there isn't a product out there that can do massive parallel positioning of probes for interacting with nano-scale structures.

The meso-scale positioner designed by MIT's PCS Lab arose from the specific application brought forth by researchers at Ohio State University. They were looking for a nano-positioner that could be used in their Dip Pen Nanolithography (DPN) process for writing on DNA strands. This process is not efficient enough if it is done one AFM tip at a time, thus the team created silicon chips that hold 40,000 tips. The next step was to find a way to position these silicon chips accurately so that they could be used to conduct massive parallel sensing and writing on DNA strands. This required that the team be able to manipulate a multiplicity, in this case at least 9 chips containing 40,000 tips each, of the silicon chips with nanometer/micro-radian resolution in 6 axes [3].

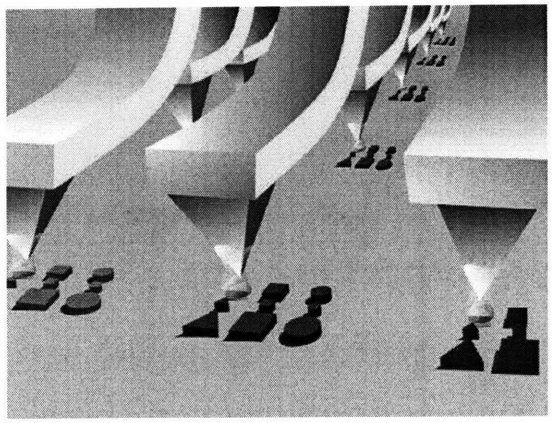

Figure 2. Simulation of 2D Dip Pen Nano Print Array Lithography [4].

MIT's Precision Compliant Systems lab committed to delivering an arrayed nano-positioner (ANP) that is capable of closed-loop positioning of an array of at least 9 chips for parallel DPN on a corresponding array of DNA strands. In order to achieve this, the first step was to design and fabricate an alpha prototype that could be used to do some open-loop testing of the mechanical elements of the ANP. The characteristics that this device is to be tested on are its stability, resolution, range, and dynamic properties; the results are then to be compared to the predicted values and the requirements for the project.

Chapter 2: Introduction

Creating a positioning device that can locate several chips containing 40,000 AFM tips with nanometer/micro-radian resolution in 6 axes at a low price is complex. The solution the team came up with for meeting this challenge was to work in the meso-scale (centimeters) as opposed to the macro-scale. The majority of current nano-positioners are in the macro-scale, making them bulky and expensive. By making a meso-scale nano-positioner the team would be able to achieve a viable bandwidth of kilohertz, and keep the cost $10s/device, while achieving the desired thermal stability and a nanometer resolution [1]. All this is possible in part because of the size of the positioner; a smaller positioner means lower costs of the mechanical components, as well as a higher natural frequency and therefore a higher bandwidth. Finally the improved thermal stability is also due to the decrease in material which is available to strain due to changes in temperature. The only disadvantage to working in the meso-scale is that the product is more difficult to fabricate and assemble. In this project it was necessary to use as much traditional machining as possible to keep the cost down. Given conventional machining tolerances, in some cases specialized manufacturing processes were needed in order to achieve the desired device performance.

The alpha prototype design was based around the micro HexFlex design that had been previously developed by the Precision Compliant Systems Lab. This design uses flexures to enable for controlled movement in six-axes. The flexure design has already been proven to provide accurate and repeatable positioning at the nano-scale. The central stage of the HexFlex is manipulated in 6 axes of freedom by manipulating the three actuator paddles. The symmetry of the geometry makes the stage stable by making it insensitive to thermal growth. The HexFlex was carefully designed to have a predicted inherent stability and repeatability, with a range of errors limited to 10s to 100s of nanometers [1].

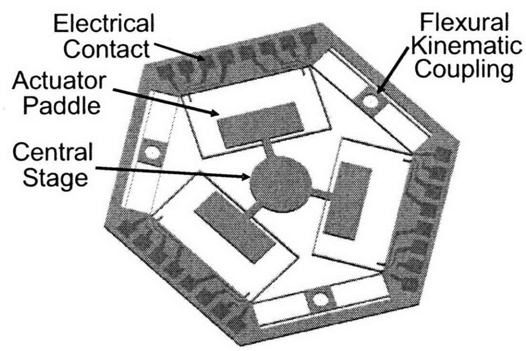

Figure 3. HexFlex design developed by the PCS Lab [1].

With a completed design, the next step was to create a prototype to be used for testing. This was the focus of this thesis, to fabricate and assemble the alpha prototype of a positioning device consisting of 10 meso-scale nano-positioners. The experience of fabricating and assembling the prototype provided key insight to possible redesign changes that will facilitate the fabrication of future systems. It also provided an opportunity to test what could be made using conventional machine tools, and what parts required higher tolerances. Calculations on parts of the model have shown that .0254 mm (.001") of inaccuracy can translate to about 25 microns of inaccuracy in the performance of the device. Manufacturing the current design while researching other possible uses for this type of nano-positioner allowed for the chance to see the design from a different viewpoint, and make design changes that will make the positioner a product that can be used in industry as well as research institutions. The proposed redesign will help the project continue to improve and will guide the final product design.

The fabrication process as well as the assembly process will be related in great detail. Focusing on how each step highlighted problems in the original design which led to an optimized redesign. The advantages of each proposed change will be described as well as to what extent they are relevant. Possible uses for a device that can do parallel positioning of different arrays of probes in the nanometer level will be explored. Finally the designed will be analyzed from a business model perspective, to note any possible modifications that will help the prototype become a product. The hope is to develop the design while the research is ongoing to ensure that a technology like this reaches is full potential by growing beyond the original scope of the project, and perhaps develop into a system that can be sold.

Chapter 3: Development Prototype

3.1 Fabrication of Prototype

The first step towards achieving a beta prototype of the meso-scale nano-positioner was to create a prototype of the original design. The finished prototype was necessary in order to test its accuracy, resolution, and position noise, and to ensure that it met the needs for the Dip Pen Nanolithography project. The performance data can also be used to determine what other uses this nano-positioner can be applied to. Experiencing the fabrication process was essential to the redesign. Understanding the challenges and constraints as well as the time it took to make each part allowed for changes to be made so that the beta prototype could be made more efficiently, with improved performance. Since the original design was made based mostly on modeling and past experience, it still had to be shown that it could be fabricated to meet the specifications. The design could then be modified to simplify the steps to get the machine made, also to make it as easy to mass produce the product as possible.

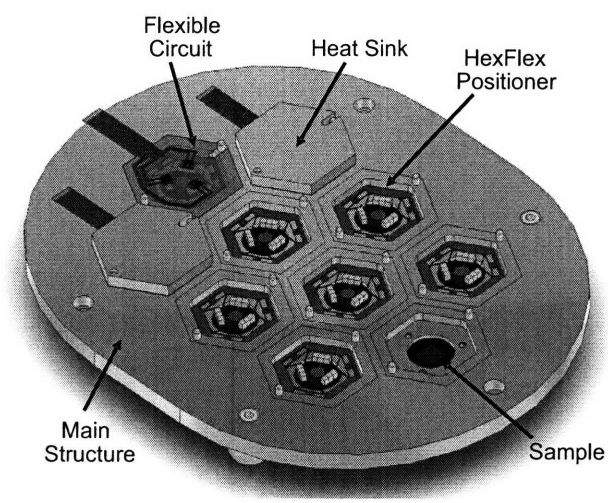

Figure 4. SolidWorks model of the complete original design [2].

Perhaps the most complex parts of the nano-positoner were the meso-scale HexFlex flexures. The HexFlex geometry of this flexure has been shown, in several other nano-positioners from by the PCS Lab, to have errors of approximately 10 nanometers. As show in Figure 5 the flexure has small details, making it hard to be machined with traditional machining methods. This is hard to do when the flexure is only 4.15 cm in diameter, 400 micrometers thick and the thinnest beams are 125 micrometers thick. In order to create these flexural beams, a process that would not put any stress on the material had to be used. As a result, these had to be done out of house because of the limitations of the available machine shop. Processes that can create micrometer details include an EDM, electro discharge machining, or microfabrication process. Both of these solutions create accurate parts without stressing the material, however they are time consuming and expensive compared to most traditional machining processes. Wire EDM cuts pieces by a series of rapidly recurring electric arcing discharges between the charged wire and the part which is submerged in dielectric fluid [5]. Since the wire never actually touches the part, chemical reactions erode away the material; there is no stress on the part allowing for fine details to be cut. The main limitation to this process is that only electrically conductive materials can be cut using EDM. This was the process that was used to make the flexures for the alpha prototype because it is faster, and cheaper than a microfabrication process.

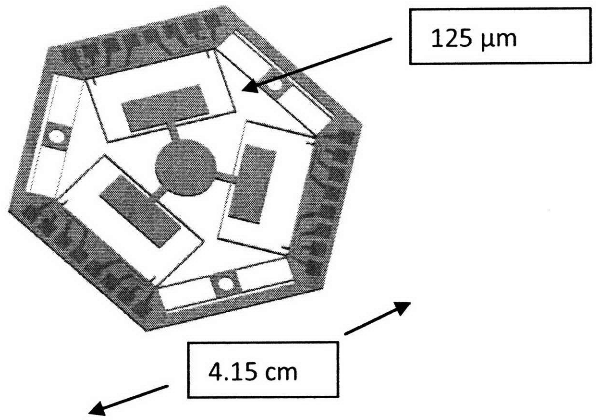

Figure 5. Hex Flex geometry with dimensions.

For the final product, the flexures will have to be made using a microfabrication process because they must be made out of silicon, which cannot be cut using EDM. This material and process will allow for piezo resistors to be printed on the thin beams of the flexures. The resistors are critical because otherwise there is no way to measure the displacement of the central stage. The performance of the current flexures will be measured by attaching a post to the central stage, and then taking measurements off it. This method will provide enough information about the displacement in the x, y, and z axes, but is unable to measure the yaw, rolls or pitch of the stage. The data collected from the flexures without the piezo resistors will be enough to understand the behavior of the alpha prototype, but is inadequate for the final design. Adding the piezo resistors will also give the product the ability for a feedback loop. The feedback loop works by taking readings of the resistance across the piezo resistors and comparing these readings to the applied current, and then adjusting the current to achieve the desired resistance and thus the desired displacement.

The challenge for the team was to produce a flexure that would be as close to the final flexure as possible but which was made by EDM. Given this requirement, stainless steel was chosen for the flexures because it has a similar Young's Modulus as silicon, 180 GPa compared to 210 GPa for silicon. This meant that both flexures would deflect similarly under the same loads. The alpha prototype was needed to test how the nano-positioner performed as an open loop system. One of the first and most important tests the team wanted to run was to check that the open loop system worked. A stainless steel flexure was good enough for this because a load can be applied to the flexure and then using a cap sensor a measurement can be made on the z-axis displacement. By attaching a post to the stage and then using a cap sensor measurements can be made on the x and y axis. These measurements are enough to understand how the open loop system is behaving.

From the product design perspective the challenge is to find a process that can keep the fidelity of the flexure design but is quicker and less expensive. If more stainless steel flexures were needed, possible alternatives to the wire EDM would be stamping and plunge EDM. Stamping would be the best solution in terms of manufacturing because it is quick and efficient. However it is not a viable solution given the geometry of the part. The stamping process is not precise enough to create the thin beams, more importantly it puts too much stress on the part while making the cuts. Using a plunge or cavity EDM would be similar to using the wire EDM process. They both use the principle of electro discharge to cut the parts, thus being able to create incredibly small and precise details without any stress on the part. The difference between them is that a plunge EDM uses a stamp-like tool instead of a wire as an electrode, to cut a pattern out of a material. This allows for a tool to be created that could cut more than one flexure at a time, which would speed up the manufacturing process. It also removes the need to stop the machining process every time a new contour has to be cut. This is necessary with wire EDM given the wire has to be cut and threaded through previously made holes every time a new closed contour is cut. The only downside of plunge EDM is the cost of making the tool and how quickly these tools wear; the cost would not be a problem if many flexures were needed as the cost would be spread over all the flexures.

Unfortunately there is no other process that could be used to make the silicon flexures. So these will have to be made via microfabrication processes. These are processes that are currently used for mass manufacturing so it is plausible to make the flexures efficiently enough to create a consumer product.

In order for the flexures to actuate Lorentz force coils had to be embedded in printed electric circuits. Running a current through the coil creates a force on the magnets attached to the actuator paddles and the beams flex. This circuit had to be outsourced as well, given the limitations of the machine shop available. The expertise of the out of house source allowed for the circuits to be made fast and cheaply. Forty circuits took about a month to build and to have the connectors surface-mounted onto them.

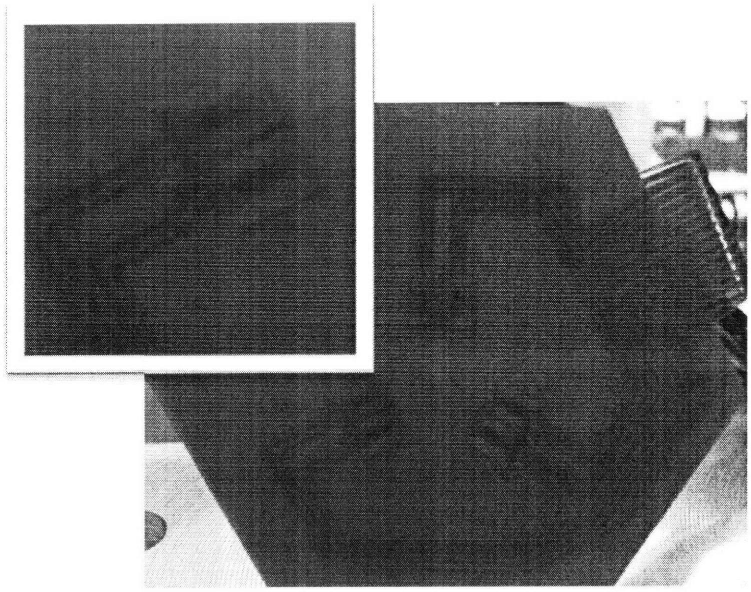

Figure 6. Printed electric circuit with a close-up view of a Lorentz force coil.

The first part that was machined in house was the hexagonal pieces used on top of each nano-positioner. These serve as heat sinks to which the printed circuits are attached. The only critical dimensions of the heat sinks were the width of the slot and the diameter hole. Both of these had to be a snug fit around a 3.97mm (5/32") dowel pin that would hold them in place on top of the base-plate. Since the outer geometry did not have to be super precise the parts were cut using a waterjet machine. To do this an OMAX file was created, shown in figure 6, making sure that both the slot and the hole were undercut so that they could be milled and reamed to their exact dimensions. The waterjet allowed for the parts to be cut quickly, which was important given that at least 10 had to be made. After they were cut the holes were reamed with a 3.99mm (.1572") reamer and the slot was milled using a 3.175mm (1/8") mill. The slot was cut using this mill because it was the one available; the process required a simple CNC mill program to be written.

The process was quick overall but the slot did have to be remachined because it was undersized. To solve this in future fabrication the slot should be milled using a 3.97mm (5/32") milled to ensure the slot is the right size. Not much of a redesign was needed for these hex pieces based on their fabrication. If the product was to be mass produced these pieces could be made using a mold and again reamed and milled afterwards. This would reduce the cost given that the waterjet process is expensive.

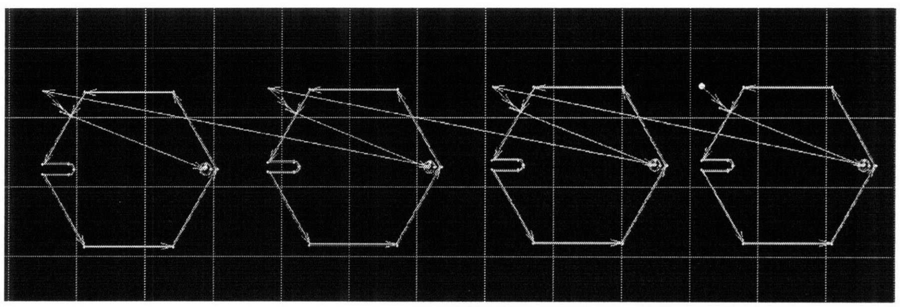

Figure 7. Layout of OMAX waterjet path, used to cut out the heat sink pieces.

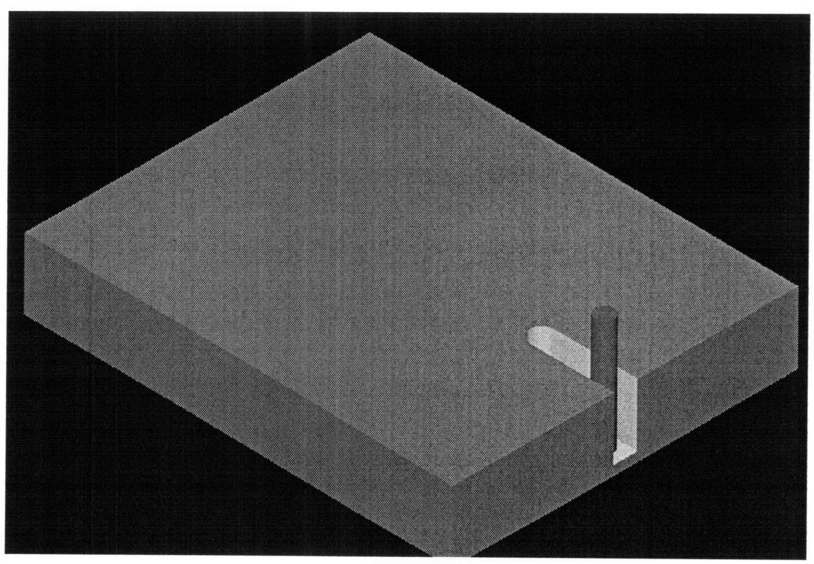

Figure 8. Picture of MasterCam Mill program, used to mill the slot in the heat sinks.

By far the most complicated part to machine was the base-plate. The base-plate is a large aluminum plate approximately 27.94cm (11") long by 20.32cm (8") wide, and 9.53mm (3/8") thick. The part has features on both sides and it gets to be as thin as 1.59mm (1/16"), which makes it extremely difficult to machine. The first redesign that was made even before it was machined was to make the base-plate a rectangle as opposed to an oval. Although the oval design is more appealing to the eye and uses less material it makes the fabrication of the part more complicated and it serves no real purpose. A rectangular base allows for the piece to be held easily in the vice of any machine. First the rectangular piece was cut using the waterjet; the outer holes were also cut in case the plate had to be bolted down to the table of a machine. It is important to note that these holes did not have to be exact with respect to the other features and thus could be machined separately from the other cuts. All features which had a critical placement in respect to other features were machined in one setup to ensure they remained true to each other. The base-plate was cut out of jig plate aluminum, because it was important for the piece to be as flat as possible so that the hex pieces would sit flat on the base-plate, otherwise with the tight fit around the dowel pins the hex pieces would not sit flat and the circuits would not be close enough to actuate the magnets.

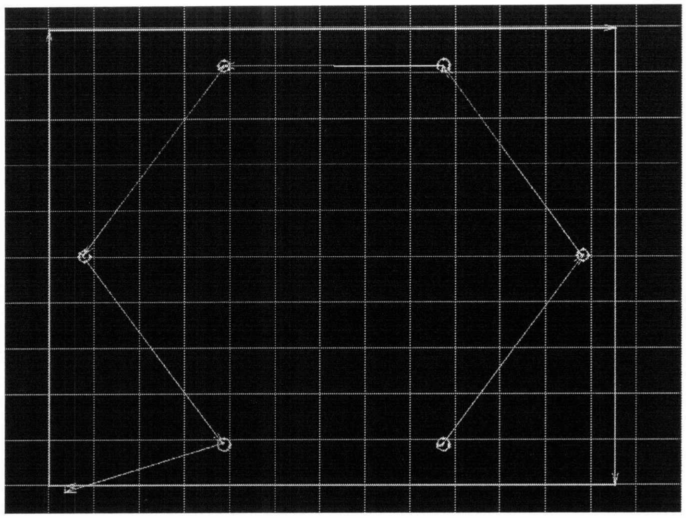

Figure 9. OMAX layout of waterjet path used to cut the outer perimeter and outer holes of the base-plate.

Once the base-plate outer perimeter had been cut, it could be held in the CNC mill vice. Using MasterCam a program was created for both sides of the plate, as shown in Figures 10 and 11. It was necessary to use CNC because of the complexity of the machining and the high accuracy needed for everything to fit together. CNC machining also greatly speeds up the manufacturing process. Care was taken in the order the cuts were made to ensure the best finish possible. The first side to be machined was the top side which is the one with the hex pockets. This was done because all the key features were on the top side of the base-plate, the backside only required a clearance pocket that was simple to machine. It was also important to machine all the cuts that had to be exact relative to each other before flipping the plate over to ensure accuracy. Thus it was important the order that the steps were laid out in the program. First all the holes were made, followed by the hex pockets, and finally the through holes in the middle of the hex pockets. Machining the holes first allowed for any burs to be removed during the milling processes. Once that was finished the plate was flipped and the square pocket in the back was machined. The machining of the base-plate was time consuming, but was necessary to ensure that the accuracy specifications were met.

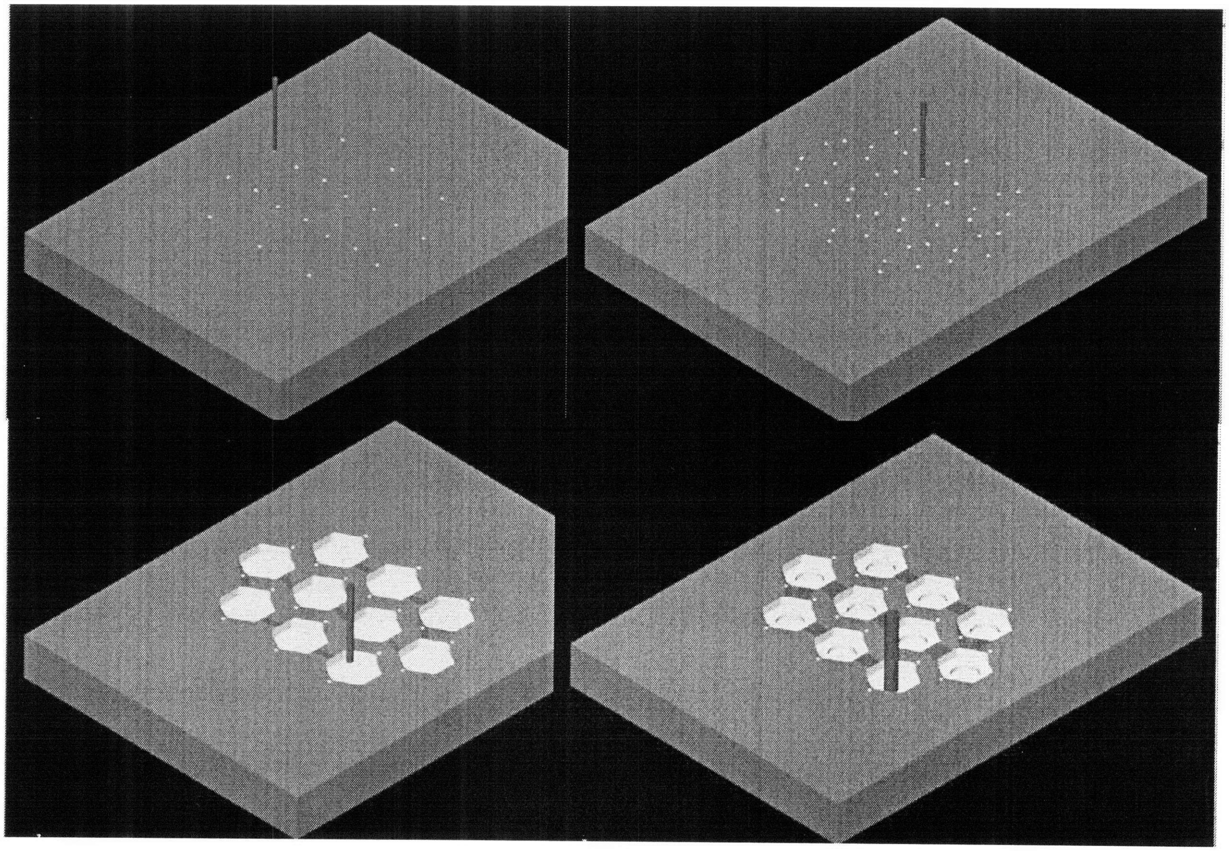

Figure 10. Pictures of the 4 steps in the MasterCam Mill Program for the top side of the Base-Plate.

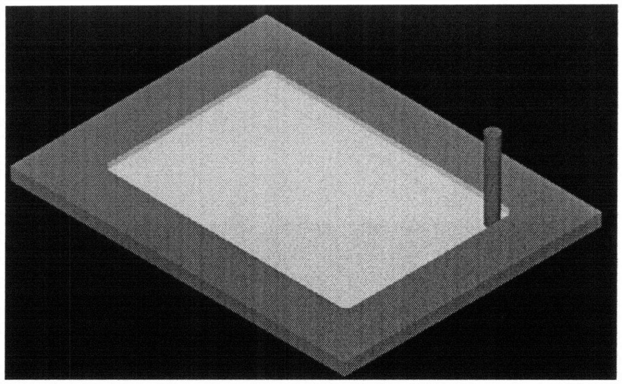

Figure 11. Picture of MasterCam Mill Program for the bottom of the base-plate.

One of the issues that became apparent during the fabrication of the base-plate was just how thin the piece became in some places and how this weakened the part. As a result even though the plate was originally perfectly flat, the plate bowed a couple thousands after the machining was done. This should be kept in mind in the redesign and accounted for. One possible solution would be to start with a slightly thicker aluminum plate of approximately 12.7mm (1/2"), this way the plate would be stronger at the end with its thinnest part being 4.76mm (3/16") thick. This is not a viable solution for the DPN application of the nano-positioner because in this case the flexure needs to be a maximum of 4mm from the array containing the DNA samples. This measurement drove the design of the base-plate, causing the thin hexagonal pocket to be a mere 2mm thick. The designed thickness allowed for 4 mm balls to be placed in each of the 3 holes inside the hex pockets. The balls stick out on both sides of the base-plate, becoming the supports for both the hex-flex and the DNA tray. They also serve as alignment features for both of these pieces. For other applications were the two parts can sit more than 4mm apart then the design could be altered to make the plate thicker overall, making it easier to fabricate the details and less delicate.

Another solution to the base-plate bowing is to support the plate better during machining. When the prototype was made the plate was held using only the vice, so the center of the plate had no support. As the machining occurred and the plate was milled thinner and thinner, the stress and the lack of support led to the slight bowing. For future fabrication the base-plate should instead be bolted to the machine's table which provides support throughout the entire area of the plate.

The base-plate machining was actually pretty quick once the MasterCam program has been written. This code can be used to make all future base-plates, and can easily be modified with any minor design changes. This part has to be CNC machined to guarantee that all critical dimensions are achieved; making a mold for this part would not create a part with the given tolerances. With future manufacturing the code can be optimized to run as quickly as possible and still create useful pieces.

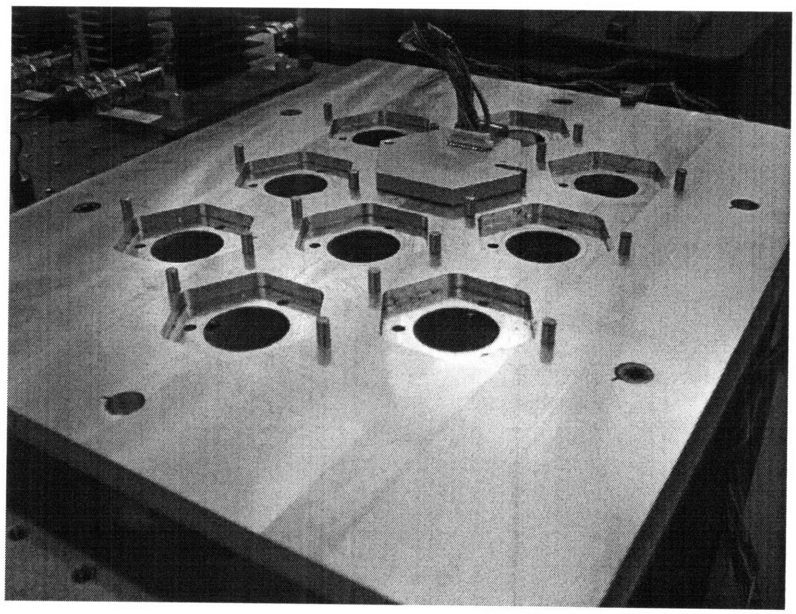

Figure 12. Picture of machined base-plate.

3.2 Assembly of Prototype

Once all the fabrication was finished the next step was to assemble the alpha prototype. During the assembly process the goal was to learn more about how the design could be improved both from a beta prototype perspective and from the perspective of building a consumer product. The redesign of the nano-positioner took into consideration how the assembly process could be simplified. The assembly involved putting each of the nano-positoners together and then assembling them as a whole onto the base-plate.

The first step in the assembly process was to attach the printed circuits to one side of the hex heat sinks. Before this was done the heat sinks were slipped into the dowel pins on the base-plate to ensure they were machined correctly. At this point it was discovered that the heat sinks did not sit flat on the plate, and were in fact hard to place on the dowel pins. This problem was due in part to the fact that the heat sinks had been cut out of a regular aluminum plate, as opposed to a jig plate like the base-plate. Thus the heat sinks were not completely flat, which prevented them from making uniform contact with the base-plate. This was a problem because the circuits that are attached to the heat sinks must sit close enough to the magnets for the magnets to be in the electro-magnetic field of the coils embedded on the circuits. The solution was to fly cut one side of each of the hex heat sinks, to guarantee that it was perfectly flat. For future assemblies this can be solved by either cutting the hex pieces out of a jig plate of aluminum or ensuring that they are fly-cut before assembly is begun.

Although fly-cutting the hex pieces greatly improved the problem, there was another factor that made it hard to slide the heat sinks onto the dowel pins. In the original design the holes for the dowel pins were only 1/8" deep. As a result when the pins were press fit they weren't completely straight since the hole was not deep enough to ensure that the pins could not be pressed at a slight angle. This was taken into consideration for the redesign and the dowel pin holes were made through holes. The through hole does not affect the other side of the plate as long as the pins do not protrude past the plane of the plate. The dowel pins can be press fit up to the plane of the plate, giving them more support that will ensure proper alignment. It is important to note that longer dowel pins will be needed if this is done. A slight chamfer on the holes was also added to help guide the dowel pins during the press fit.

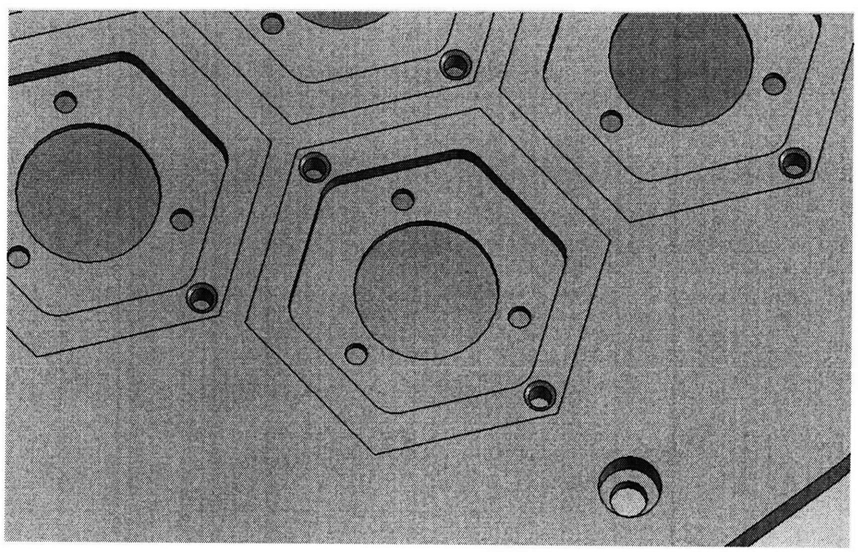

Figure 13. Detail of SolidWorks Model of the changes made to the dowel pin holes.

With the issues resolved the hex heat sinks were now ready to have the circuits attached to them. The circuit was attached to the side that had been fly-cut which guaranteed that the circuit would sit flat on the base-plate. Originally a small setup had been made that consisted of two dowel pins attached to a plate at the same dimensions as each set of dowel pins is placed on the base-plate. The goal was to use this setup as a guide to glue the circuits to the heat sinks. However it was found that it was easier to use the base-plate dowel pins as guides as these were more precise. The circuits were attached using double sided tape, being careful that the circuit was not wrinkled or bent. The connector tail of the circuit was glued to the other side of the hex piece so that if the wires were pulled the thin circuit connectors would not be pulled and break. This was simply a way to keep the connectors out of the way and it also protected the printed circuit.

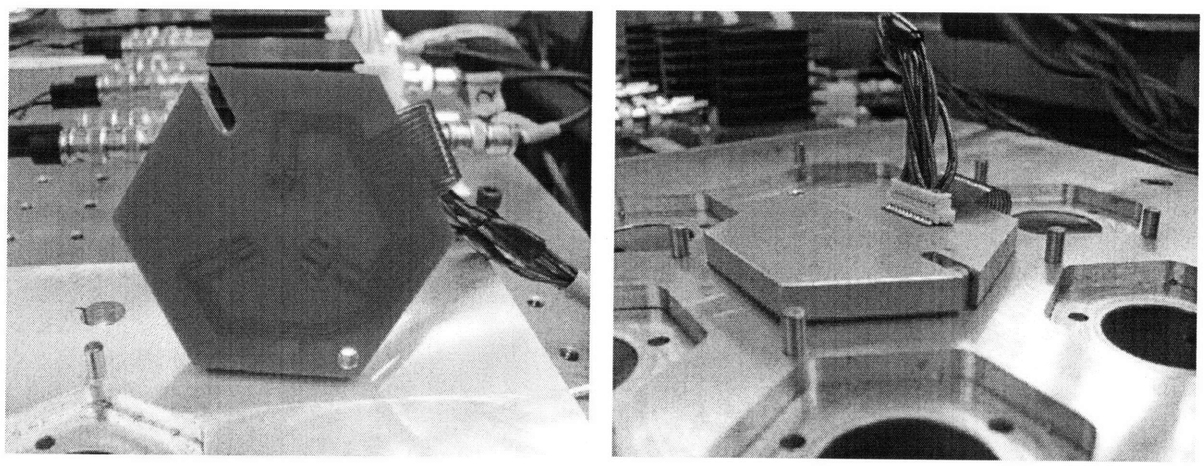

Figure 14. Printed circuits attached to the hexagonal heat sinks.

The next step was to attach the magnets to the flexures. To actuate the nano-positioners, a current is run through the coils, which in turn creates an electro-magnetic field which attracts or repels the magnets that are attached to the flexures. Three magnets had to be attached in a North-South-North configuration onto each of the actuator paddles, to ensure control in all 6-axes. First the magnets' North poles were marked, then they were aligned using a plastic straightedge. The set of magnets were carefully placed using plastic tweezers onto the paddles that were coated with Loctite 409 instant adhesive.

The final step of the assembly was the most complicated. As mentioned before the 3 holes on the hex pocket were designed to hold three 4 mm balls that would serve as support and alignment for the hex-flex and the arrays. The idea is that if the same 3 points of contact are used for the two pieces, they will have an absolute alignment to each other, as long as they are touching the three balls. This meant that the three points of contact will be 4 mm away from each other, given the diameter of the ball is 4mm, which meant that the two pieces would be parallel to each other.

To ensure that the two pieces would be as parallel to the base-plate as possible, the balls had to be press fit to the same depth. To do this a couple assembly jigs had to be made. The key piece, known as the assembly cylinder and shown in Figure 15, was used to make sure that all three balls were press fit the same amount. The other piece was used simply to hold the stage flat during the press fit. These parts had to be extremely precise in order for the assembly to be successful. The groove in the assembly cylinder had to be 1.524mm ± .0254mm (.0600" ± .0001"). This tolerance came from the fact that the balls are only 4 mm in diameter and the holes to hold them are approximately 2 mm deep. This gives for 2mm of room to play with. So the groove had to be as close to the 1.524mm (.0600") as possible to ensure that the balls stuck out enough on either side of the plate. This level of accuracy made it hard to machine this piece; luckily this piece only had to be made once for the assembly of several prototypes, unless the redesign calls for different measurements. Once the balls are press fit at the right depth and glued there is no need to redo this step. The hex-flex and the array can be placed and aligned over and over again using the 3 permanent balls. The balls were hand press-fit, because their size made them hard to manage on any machine, and not much force was needed to fit them.

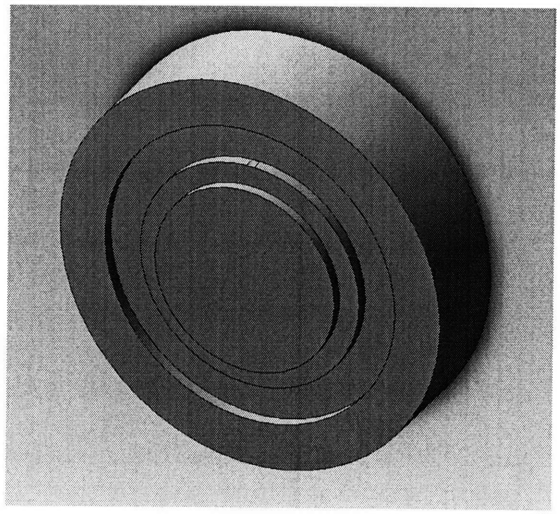

Figure 15. SolidWorks Model of cylinder used to press-fit the alignment balls to the correct depth

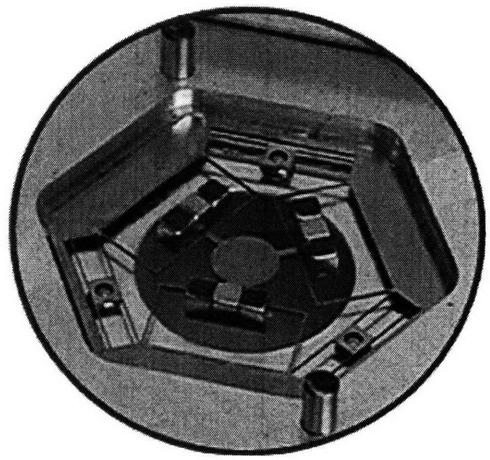

Figure 16. Picture of base-plate with dowel pins, press-fit 4mm balls, and flexure.

The design allows for the flexures, circuits, and arrays to be removable as opposed to a permanent assembly. This gives the system incredible flexibility in its uses. The current prototype calls for a silicon chip containing 40,000 AFM tips to be attached to the center stage, however there are hundreds of different probes, tools, samples, or devices that can be attached to the stage. The only requirement being that these are not too heavy that their weight cannot be supported by the flexure causing the flexural beams deform. Or too big that the nano-positioner can't exert enough force to move them. Luckily most things that have to be positioned in this scale are usually pretty small, and it's important to keep in mind that one part does not move, so in any given process the larger piece would be stationary while the smaller piece would be positioned. For example this might mean that the part moves relative to the tool as opposed to the other way around.

As a consumer product the base-plate would be sold with the balls attached and glued and the dowel pins pressed; ready to hold the flexures, the arrays and the hex heat sinks in the correct positions. The customer could then buy flexures with different attachments and replace these as often as needed. If a circuit was to fail, it could be replaced quickly and in fact the machine could continue to run with the other 9 nano-positioners functioning normally. These are all key features that make this system one that can be used in industry, given that it keeps the down time of the machine short and makes maintenance and repair simple and cheap.

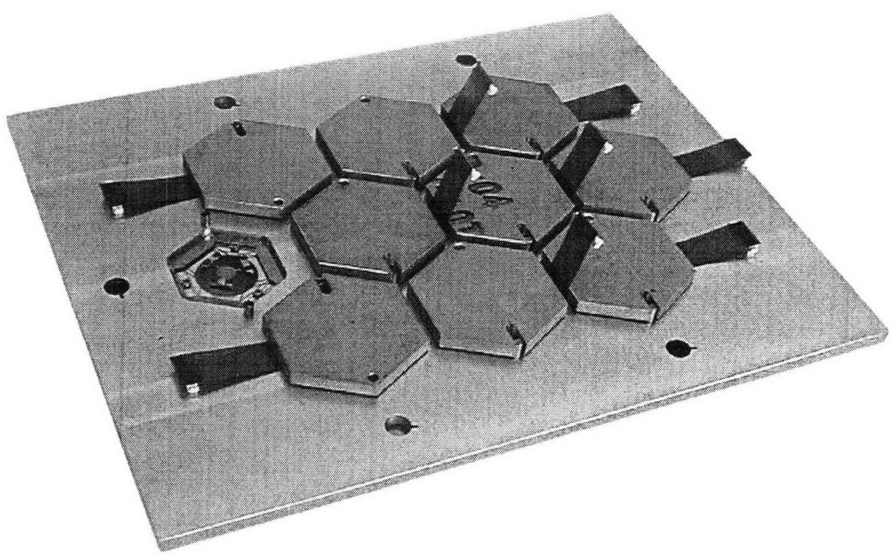

Figure 17. Picture of completely assembled system. The nano-positioner without the heat sink shows the HexFlex sitting on the three alignment balls.

Chapter 4: Possible Applications

Nano-positioners are used in a wide range of applications from the laboratory setting to the manufacturing industry. Their uses can be divided into two broad categories: position-and-hold nano-positioners and scanning nano-positioners. Position-and-hold applications require that the nano-positioner take something to a certain position and then maintain this position for an extended period of time. This requires that the positioner have a high thermal stability and little position noise. Scanning nano-positioners are optimized for travel speed and precision. Meaning that the positioner needs to reach a certain point quickly and accurately, it should also be able to settle down in short amount time, so that it can start moving to the next position. This ability is affected by the resonant frequency of the mechanical system and its controllability [2].

The HexFlex meso-scale nano-positioner serves both of these categories extremely well. For the position-and-hold applications, the meso-scale positioner has a high thermal stability because less material is available to expand and contract, the geometry of the hex-flex also guarantees that the position of the central stage will not affected by the thermal growth because of the symmetric nature of the design. The flexure design also takes care of a lot of the noise in the system because there are no motor actuators; instead Lorentz force actuators were used. These qualities allow for the positioner to hold an exact position for an extended period of time. As for the scanning applications, the hex-flex can move in six-axes at the same time, as opposed to serial positioning. This cuts down on the time to achieve a position, because the stage can be manipulated in all six-axes at any given moment. This is all possible thanks to the Lorentz force actuators used in the design, that can magnetically manipulate the flexure by creating an electrical field which induces a force on the magnets attached to the flexure, causing it to bend to the necessary position. It is important to note that the geometry and dimensions of the HexFlex's flexural beams can be altered to achieve a different range, resolution, and dynamic performance for the nano-positioner; allowing for the product to be modified depending on the needs of the application [1].

The main benefit of the proposed design is that it can position 10 different things at once. This makes it especially advantageous when dealing with manufacturing. The design is not as valuable, for example, for a microscope or an application where only one object is being dealt with at a time. However for applications such as DPN where hundreds of thousands of DNA strands have to be altered the ability to position 400,000 AFM tips quickly and accurately is essential to the process being able to be done quickly enough to be cost effective. These are the types of applications where this design will really make a difference.

Thinking about the design from the different uses perspective, the system will be most successful in a variety of industries if it is able to adapt to the needs of each application. To do this the positioner will most likely need to be able to position different things besides AFM tips. Thus it would be advantageous if the hex flex could have different attachments. However it would be hard for the consumer to switch such small attachments and secure them properly to the flexure. It would make more sense to change the whole flexure whenever a different attachment was needed. If the flexures are easy to change and cheap they can become disposable and thus every time the system was needed for a new application the HexFlex flexures would be replaced with those with different attachments. This idea works extremely well with the current design because of the alignment mechanism that has been integrated into the base-plate. The three balls that are glued to the main structure guarantee that whenever a flexure is switched it aligns with the arrays because these rest on the same 3 balls. As for the circuits these always sit in the same position thanks to the dowel pins, so whenever the flexures were changed and the circuits then placed back on top of them the two pieces would align. With the final flexures that will include the piezo resistor sensors, the whole system can easily be replaced if there is any failure.

Being able to replace the entire flexure would facilitate the use of it for the consumer. The nano-positioner would be able to be used for a range of applications without having to worry about cleaning it or buying a whole new positioner for a different use. A user would be able to place the 10 flexures with whatever attachment they needed, such as AFM tips, probes, tools, or others, on the base-plate. In the future if applications require it, the flexure geometry could also be modified to meet the needs of new applications. By modifying the flexure the positioner would be able to attain a different range, resolution, and dynamic performance which might be needed for the alternate use.

Some of the current uses for nano-positioners that would benefit from a system that has 10 six-axis nano-positioners working in parallel include, but are not limited to: AFM, fiber positioning, high resolution optical alignment, lithography, nanometrology, photonics packaging and equipment, disk drive testing equipment, semiconductor testing equipment, wafer stepping, mask and wafer alignment, and precision machining. These have a wide range of requirements and specifications, which the modular design of the proposed nano-positioner would be able to meet.

Chapter 5: Nano-positioner as a product

Looking at the product from a business perspective, the first step is to recognize what would be the source of income. The nano-positioner has already been designed and redesigned to meet the customer needs so that it can be assumed that given a market the product would be bought. The two main markets that have been identified are the research institutions/laboratory market, and the industry market. Both of these have a need for a nano-positioner that can position more than one tool, probe, or sensor, quickly and accurately in the nanometer/micro-radian scale for a fraction of the cost of the currently available systems. The meso-scale nano-positioner creates value for them by speeding up their process by at least 10 times, allowing for these processes to become much more cost effective and in some cases plausible. Using the DPN application as an example, this process would not have been cost effective for Ohio State University researchers with currently available positioners. The MIT developed nano-positioner will provide them with a system that meets their requirements and costs only a fraction of the cost, allowing them to write on hundreds of thousands of DNA strands at a time.

The business model that seems to make the most sense given the applications is to use a razor/razor blade model for this product. As explained the ability to change the flexure with the center stage attachment would be useful for several applications. Most importantly thanks to the three-point ball alignment and the dowel pin alignment the flexure can be changed while the alignment with the actuators and circuit is maintained. The replaceable flexures create a clear source of income; disposable flexures with the different attachments would be the main source of income. The base-plate or main structure would be a permanent one-time sale, which makes sense given the complexity of its fabrication. The cost of the main structure could be partially absorbed by the provider if the consumer committed to buying a certain number of disposables a month. This would help research institutions by keeping the upfront cost of the equipment down. The flexures with the sensors and attachments would be sold by the manufacturer, creating a constant source of income for the company.

There are multiple advantages that this business model provides for both consumer and manufacturer. The disposable cartridges would allow the consumer to use the same nano-positioner for several applications. For example they could use it for DPN while it was needed, and then instead of buying flexures with AFM tips, they could buy a flexure with a probe attachment and use the nano-positioner for scanning. This modularity would also make damaged equipment easy to replace. For applications dealing with dangerous substances everything that touched the substance (flexure and tips) would be thrown away after each experiment thus making the process safe and simple. All of this allows the consumer to use the positioner with a range of different substances and materials, depending on the application.

For the manufacturer this business model allows for them to have a continuous source of income from the disposables which would create cash flow which can then be used for future research and development or marketing. Also making the flexures in mass production would greatly decrease the cost of these which benefits both customer and manufacturer. The manufacturer could start by offering only one type of flexures and then expand to different attachments to the HexFlex (tips vs. probes). Eventually the manufacturer could provide flexures with different geometries to make it possible to use the nano-positioner in a wider range of applications.

A rough marketing strategy would be to first introduce the product to the research market. The company could launch the system in different labs by providing the main structure at a discount in exchange for being able to test the prototypes. This would allow the company to have a lot of feedback from the first prototypes, without having the pressures of industry to deal with. The low upfront cost would also make it a great solution for many laboratories. The research environment would really expose the different uses the nano-positioner can be applied to and from which the company would be able to capitalize. It would also get the company great exposure by being part of leading edge research in different institutions. Once the prototypes have been tested in different settings and proven, then it would be significantly easier to enter the industrial market. For this market the consumer wouldn't have as many cost limitations and thus no upfront cost would have to be absorbed by the manufacturer. At the same time the product would continue to be used in research applications considering how important it is for the development of a lot of new nanotechnology. The laboratories would also continue to be a great place for the company to do future research and development.

Once the company is ready to introduce the product to the industrial market, the packaging would include the main structure, with the circuits and computer program to control the positioners. This would be accompanied by a catalog with the different options of HexFlex flexures and attachments so that the customer would be able to chose which one works best for their application.

Market research has to be done to support the proposed business model. It will be important to understand the current state and growth of the nano-positioning industry in order to be able to accurately predict the future of this positioner as a product. More information needs to be collected from future users to have quantifiable data on their needs and possible applications. These numbers as well as a detailed study on the costs of each part of the business model would be used to support the proposed business model, as well as the proposed design changes that stemmed from this model.

Chapter 6: Conclusions and Recommendations

Once the nano-positioning system had been fabricated and assembled, its performance had to be tested. Given that the stainless steel flexures did not have the piezo resistors attached to them, the only displacement that could be easily measured was the z-axis displacement. This was done by attaching a cap sensor to a post that was glued to the center stage of the flexure, as shown in Figure 18. Increasing currents were run through the Lorentz force actuators and the displacement of the central stage in the z-axis was recorded. Two different trials were performed and their results were plotted on Figure 19.

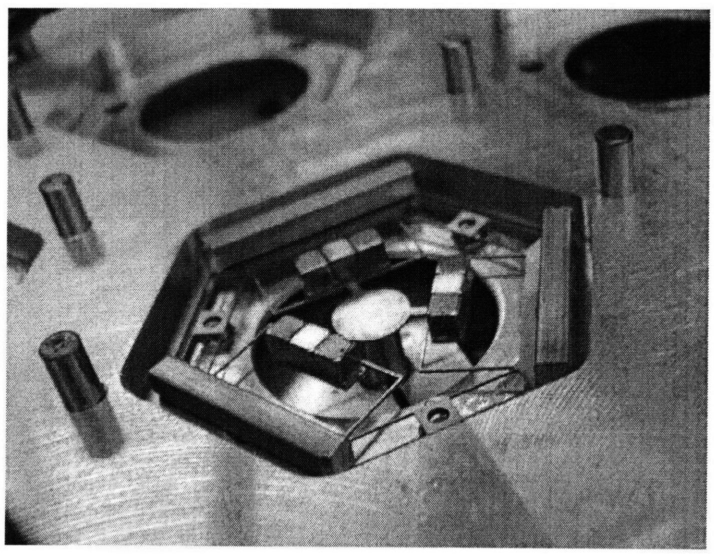

Figure 18. Flexure with cap sensor.

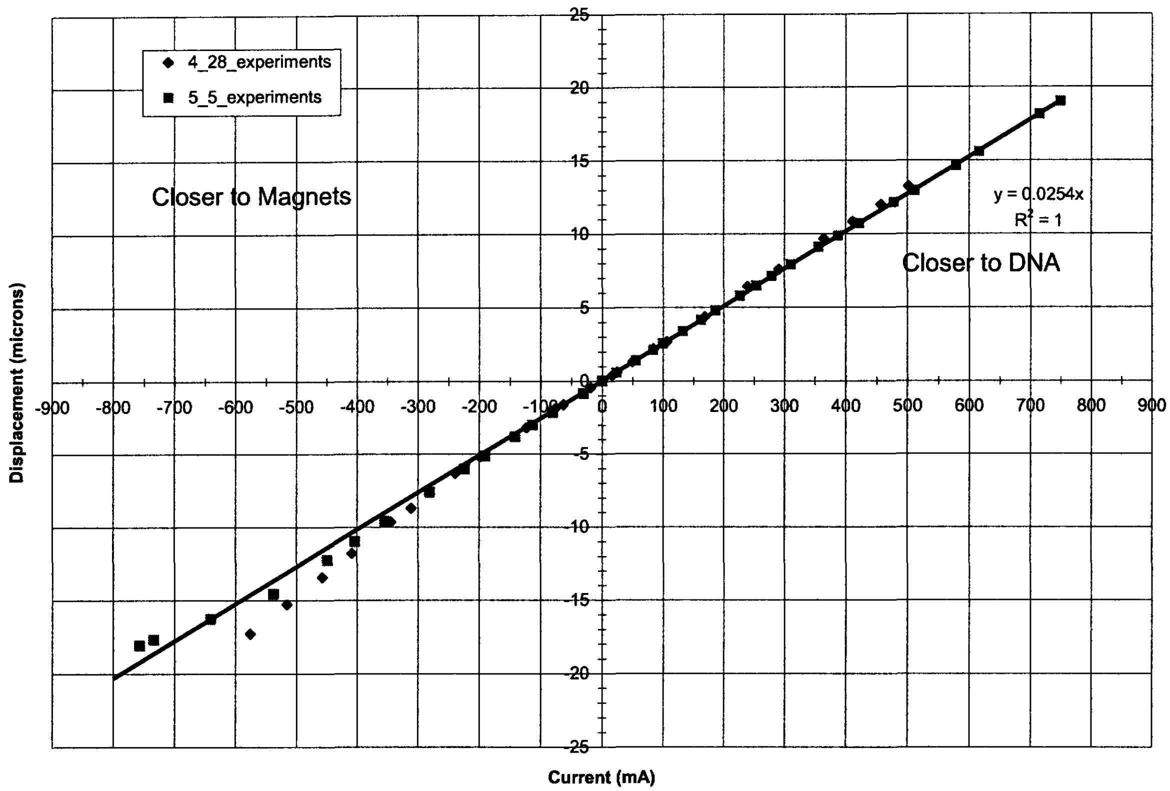

Figure 19. Plot of the data of the two trials showing current vs. z-axis displacement of one of the flexures.

As the graph shows there is a tight correlation between the two sets of data points. This indicates that the displacement of the system is predictable and repeatable, which is key to any nano-positioner. Future data will qualify the displacement in the other 5-axes and will allow for a model to be created that predicts the displacement based on the current applied.

These results place the team one step closer of achieving the goal of a low cost nano-positioner system. The final redesign created by this work, enables the project to advance even further by guiding the fabrication of the beta prototype. The original design has been optimized to ensure more efficient manufacturing and assembly, as well as to create a consumer product that could launch a company. By developing a rough business model and adapting the design to it, it is now clear how to proceed in order to revolutionize the nano-positioner industry with a low-cost device that is able to do massive parallel positioning in the nanometer/micro-radian level.

The next steps in the project will be to use the prototype that was developed to gather data on the performance of the system. The collected data could call for a redesign of any given part of the system, if the desired results are not achieved. As for the design in terms of the fabrication perspective, the beta prototype has to be built with the proposed changes. It will be important to create the flexures out of silicon so that their performance can be compared to that of the stainless steel flexures. The beta prototype will also test if the proposed changes facilitate the fabrication and assembly processes enough for the product to be mass manufactured.

Finally a business plan should be developed if this product is to launch a small company. The business plan would detail the business model and would provide monetary values to support the model. The help of someone with a strong business background would be necessary in order to create detailed product and marketing strategies. Research into the nano-positioner market would give a better insight into potential sales of the system. A complete business plan is necessary in order to receive any venture capital support, as well as small business grants.

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