A DISTORTION-MINIMIZING MICRO-MIRROR ARRAY WITH MICROACTUATORS FOR WIDE-ANGLE VIEWING

NSF Summer Undergraduate Fellowship in Sensor Technologies (SUNFEST)
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ABSTRACT

Mirrors of numerous shapes, including spherical and paraboloidal mirrors, have been employed for many different commercial and industrial uses, despite their tendencies to distort and warp images. When the object in consideration is planar and oriented normal to the optical axis of the mirror, the amount of distortion introduced by a paraboloidal mirror is less than the distortion introduced by a spherical mirror. Therefore, there must exist an optimal mirror shape that minimizes distortion of planar objects normal to the optical axis. This objective of this study was to fabricate a versatile device capable of simulating numerous mirror shapes to allow for determination of optimal, distortion-minimizing mirrors. Using an Excimer Laser, millimeter-scale mirror mechanisms capable of rotation about two axes were created. Electromagnetic actuation was tested and experimented with in order to determine its feasibility as a means of mirror manipulation. Piezoelectric actuation was also investigated. Although no actuation was achieved, the numerous attempts provided useful information as to why no motion occurred. This paper will delineate the findings of these actuation experiments and provide the groundwork for future research and experimentation.

1. INTRODUCTION

Curved mirrors, or catoptric mirrors, have numerous uses throughout the world today [1]. They can be seen on automobiles and in businesses. One new found application for catoptric mirrors is in omni-directional viewing cameras. The movement to develop omni-directional cameras has resulted in increased interest in catoptrics. An omni-directional camera is created when the optical axis of a catoptric mirror is aligned with the center of an orthographic video camera and mounted several inches from the lens [2]. The quality of the images obtained from such a camera varies with different catoptric shapes. For example, when a spherical mirror is used, the images are noticeably different from those obtained when a paraboloidal mirror is employed. The most important difference between the two catoptrics is the amount of distortion introduced into the images. A spherical mirror creates more distortion around the perimeter of an image than a paraboloidal mirror does [1].

This difference in distortion introduced by the spherical and paraboloidal mirrors indicates that an optimal mirror shape must exist that allows for wide-angle viewing with minimal distortion [1]. Determining the optimal mirror shape requires complex calculations. A further difficulty is the fact that different objects require different mirror shapes to minimize distortion. A planar object requires a specifically shaped mirror to be imaged correctly by an omni-directional camera; a spherical object requires a different shaped mirror.

To facilitate the calculations of these optimal mirror shapes, it would be ideal to have a mirror that was continuous and amorphous so that it could readily change shape. Such technology does not exist, though. The next best thing is a micro-mirror array. Composed of hundreds of discrete mirrors, all individually rotary about two axes, a micro-mirror array would allow for approximations of optimal mirror shapes.

2. METHOD

2.1 Fabrication of the Mirror Mechanism

The optimal starting point for developing a micro-mirror array was determined to be an individual working mirror mechanism created at a large scale. The first feature of the mechanism to be investigated was the overall shape of the device. In order to fabricate a large-scale model of the device, the Fused Deposition Modeling (FDM) machine was used in conjunction with Pro Engineer Software. The FDM takes a 3 dimensional Pro Engineer file, divides it into multiple layers, and builds the model up from the working surface by slowly depositing plastic filament in layers. After the Pro Engineer software had been learned, the FDM machine was used to create several design iterations. One of the first FDM iterations of the mirror mechanism design consisted of two platforms that were connected with four curved ribs (see Figure 1). Although it rotated about two axes, the axes were unknown—a detriment of the design that led to its abandonment.

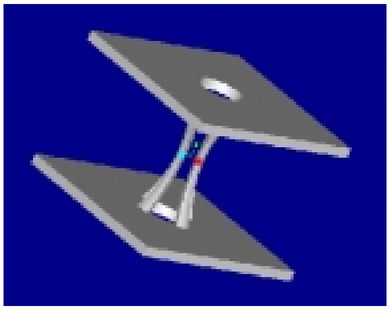

Figure 1: Mirror mechanism with four curved ribs.

A second-generation mirror mechanism design created using the FDM machine was composed of four serpentine springs that allowed for rotation in two axes (see Figure 2).

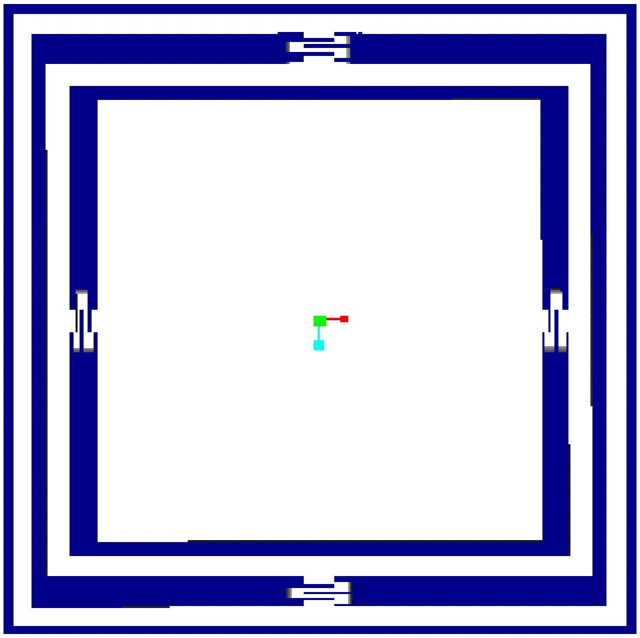

Figure 2: Mirror mechanism with serpentine springs.

This design improved on the initial design iteration in that the axes of rotation were known. It was determined that serpentine springs were the optimal way to allow for rotation of the mechanism without using multiple parts. The serpentine springs minimized actuation forces, and rotation axes were known [3].

Once the overall shape of the device was established, its size had to be reduced. After investigating several fabrication options, it was decided to use an Excimer Laser and CNC table in order to replicate the serpentine spring mirror mechanism on a smaller scale than was possible using the FDM machine (see Figure 3).

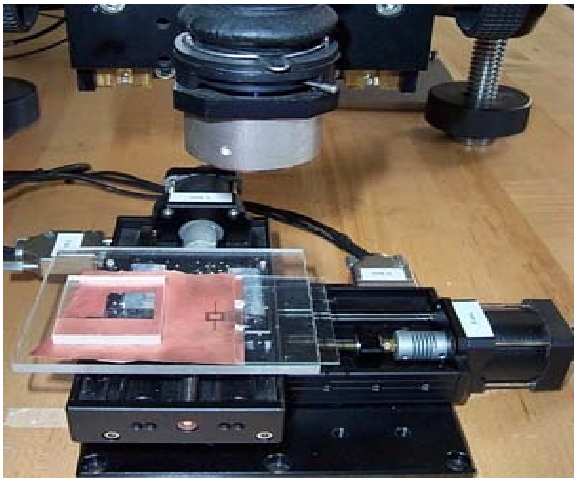

Figure 3: Excimer Laser and CNC table

Learning the software interface with the CNC table was difficult because the drivers for the CNC table required very specific inputs. For example, AutoCAD R13 was used to design the desired mirror mechanism, and the CNC drivers would only recognize lines drawn in the color green and a layer called “Profile.”

The width of the laser beam proved to be the limiting factor in the attempts to reduce the size of the mirror mechanism. With a diameter of ~50 μm, the laser beam limited the mechanism to sizes in the millimeter range.

After several experimental uses and satisfactory size reduction, the material being laser machined was switched from paperboard to Kapton-coated copper. Kapton-coated copper allowed complex circuitry to be etched into a single mechanism, along with torsion beams or serpentine springs. The laser was capable of removing fine lines of the thin copper layer, leaving Kapton to serve as an insulator.

One challenge that arose at this point was how to make the laser do multi-layer cutting. With one pass of the laser, the copper layer was cut through. With two passes of the laser, the entire thickness of the material, both copper and Kapton, was cut. It was discovered that using two AutoCAD R13 files was the best way to create a pattern that required multi-layer cuts, with some cuts through the copper and some cuts through the entire material. The first AutoCAD R13 file included all of the cuts through just the copper and all of the cuts through both the copper and Kapton. On the second AutoCAD R13 file, only the cuts intended to go through both the copper and the Kapton layers were included.

The first and second AutoCAD R13 files had to have exactly the same extents of the drawing. This was ensured by drawing corner brackets about the first AutoCad R13 drawing. Once the first AutoCAD R13 file drawing was completed, saving the file under another file name created the second file. Then the necessary modifications could be completed (removing the features to be cut through the thin layer of copper only).

2.2 Actuation

With a satisfactory-sized mechanism attained using the laser, methods of actuation were considered, including piezoelectric and electro-magnetic actuation. To simplify this stage in the development of the mirror mechanism, it was decided that actuation of a mirror mechanism capable of rotation about one axis would suffice. The mechanism was also simplified by selecting simple torsion beams as opposed to serpentine springs [3]. Although torsion beams introduced problems of their own, namely the increase in torsional rigidity, they possessed several advantages over the serpentine springs. The main advantage was the capability to easily etch electrical leads into the mechanism. A serpentine spring would have created the need for serpentine electrical leads requiring much larger mechanisms than were desirable for testing purposes.

2.2.1 Piezoelectic Actuation

Piezoelectric beams were investigated as a means of actuation. The intent was to place four piezoelectric beams underneath the four corners of the mirror mechanism. Through the application of varying voltages to the beams, the mirror angle deflection could be effectively controlled. After testing the piezo-beams, though, it was discovered that they were not easily controlled. Only with the application of 120 Volts DC was motion observed in the piezoelectric beams, and this motion was an instantaneous jump from the beam’s initial resting position to a final position. The capacitive properties of the beam made it impossible to achieve positions between the initial and final position.

2.2.2 Electomagnetic Actuation

By far the bulk of the actuation research was devoted to electromagnetic actuation. The tendency of a current-carrying wire to deflect in a magnetic field was the basis for this research. Considering Formula 1 below, the cross product of the current (I) through the wire with the magnetic field strength (B) creates a force (F) out of the plane [4].

$$F = I \times B \tag{1}$$

Therefore, when two wires are parallel, but their current is flowing in opposite directions as if the wires were in a loop, a torque will be created by the opposing resultant forces (see Figure 4) [4].

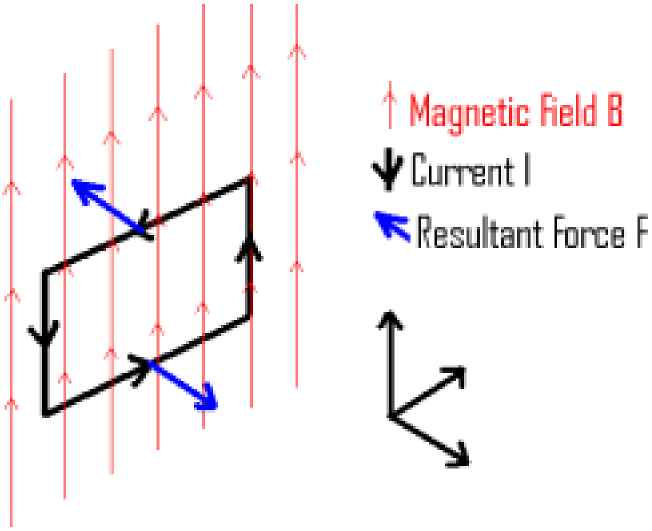

Figure 4: Illustration of deflection theory.

Formula 2 allows the torque (T) to be calculated using the loop current, the magnetic field strength, the area of the loop (A), and the sine of the angle (θ) between the magnetic field direction and the current [4].

$$T = IAB\sin(\theta) \qquad (2)$$

With this theory in mind, the Excimer Laser was used to create a mirror mechanism that incorporated several conducting wire meanders into the design. After considering the implications of the numerous wire meanders across the surface of the mechanism, it was determined that the wire, when doubled back upon itself as it was in the meanders, would create no net force and thus no deflection. A second iteration possessed a simple current carrying wire loop etched into the surface of the mirror platform. This design was selected because of its simplicity and its similarity to the idealized theory behind Formula 2. The square mirror platform of the mechanism was approximately .0075 meters per side and was supported by .001-meter-long torsion beams. Around the perimeter of the mirror platform, etched through the copper, was a thin wire conducting loop with positive and negative leads crossing from the mirror platform over one of the torsion beams to the anchors (see Figure 5).

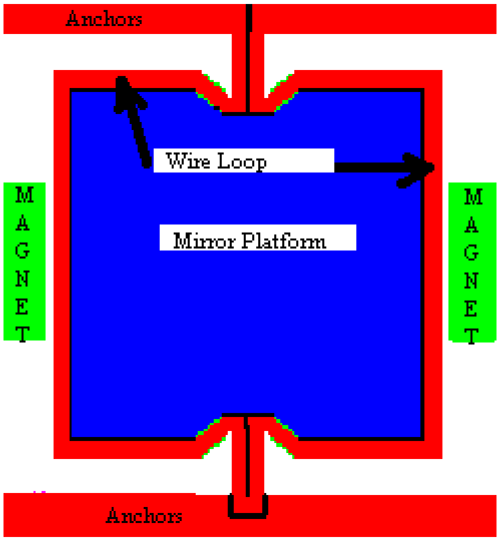

Figure 5: Mirror mechanism with wire loop, torsion bars, anchors, and magnets.

Because laser machining was so time consuming, the AutoCAD R13 patterns were limited to the most intricate details of the mechanism where manual cutting would be impossible. Any features that were large and easily cut with scissors, such as the anchors, were left for manual cutting. The mirror platform, torsion beams, and wire loop were all cut with the laser.

According to Formula 2, the wire loop, and thus the mirror platform, will rotate until the normal of the platform is parallel with the magnetic field [5]. Unfortunately, Formula 2 does not take into account the resistance to bend—the torsional rigidity—of the material. By taking the torque calculated in Formula 2, and substituting it into Formula 3, which accounts for the length of the arm in torsion (L), the torsional rigidity (K), and the Modulus of Rigidity (G), the angle of deflection (ϕ) is obtained.

$$\phi = (TL)/(KG) \qquad (3)$$

Formulas 2 and 3 were used to calculate the current required to obtain specific angles of deflection. To obtain one degree of deflection, it was determined that .129 Amps would be needed. To see ten degrees of deflection, 1.29 Amps were required. Calculations can be found in the Appendix.

Another limiting factor in the mirror mechanism made of Kapton-coated copper was its current carrying capacity. It was critical to know the maximum current flow achievable in order to avoid burning up the mechanism’s circuitry. The maximum current was determined by using Formula 4 and integrating it twice. Temperature (T), the distance from the anchors (x), the thermal conductivity of air (K_t), the cross-sectional area of the circuit (A), and resistance per unit length (R’) are all taken into account [6].

$$(\partial{}^\wedge 2T)/(\partial x^\wedge 2) = (-(I^\wedge 2)R')/(AKt) \qquad (4)$$

The above differential equation was solved with the boundary conditions $T = T_0$ at $x = 0$ and $T = T_0$ at $x = L$, where the length of the entire wire loop is (L). Using these values, the maximum current that could be passed through the circuit was found to be .385 Amps.

3. IMPLEMENTATION

After several recalculations to verify that the numbers were correct, it was decided to go ahead with the aforementioned method of electromagnetic actuation. With the mirror mechanism machined, electrical leads were soldered to the anchors. The mechanism was then placed upon a structure so that the mirror platform was centered over a cutout area. This cutout area allowed the mirror platform to rotate free from obstruction. Two permanent magnets, oriented so they were attracting one another, were placed adjacent to the mirror mechanism and mounted as close as possible to the two prominent edges of the wire loop (see Figure 6).

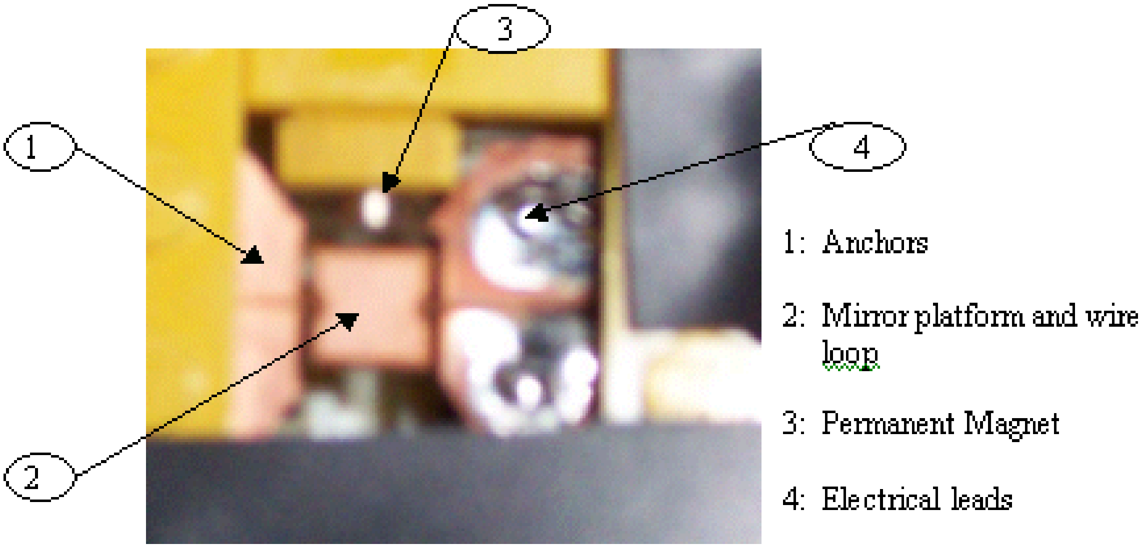

Figure 6: Actual setup of the mirror mechanism.

Once the mechanism was secured to the structure, the electrical leads were placed into the circuit. A proto-board was used to set up the required circuitry. A 6 Volt voltage source was used to supply the circuit with power. From the voltage source, the current was directed into a potentiometer. In series with the potentiometer further down the circuit, the mirror mechanism was attached. The potentiometer reduced the voltage to the delicate mirror mechanism (see Figure 7).

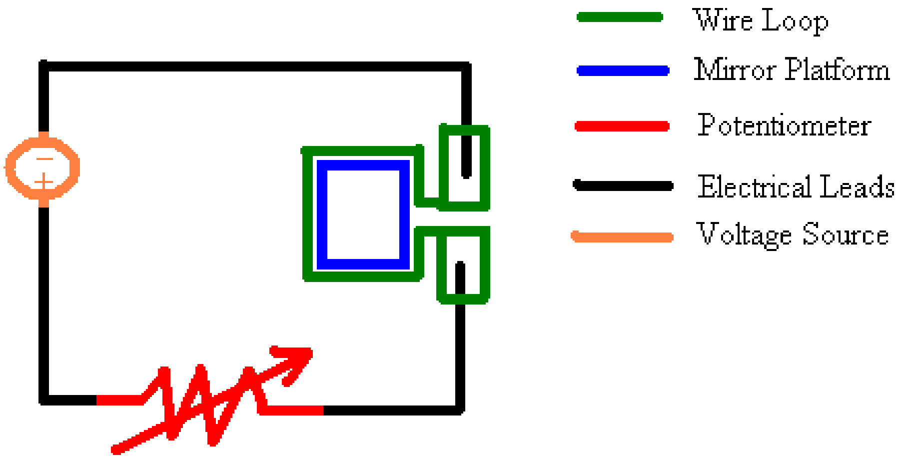

Figure 7: Wiring schematic.

4. RESULTS

The mirror mechanisms created by the Excimer laser were appropriate for a prototype. Aside from the glossy and reflective qualities of Kapton, which were desirable for a mirror, the mechanism itself required minimal force to deflect about its axis of rotation. Minimal actuation force was desirable to reduce the amount of force required of the microactuators.

The Excimer laser also allowed mirror mechanisms of adequately small sizes to be fabricated. Several square mirror mechanisms that were approximately three millimeters per side were fabricated out of paperboard. For actuation testing, though, larger sized mechanisms, approximately 7.5 millimeters per side, were used.

Actuation testing of the mirror mechanism, setup as described in section 3: Implementation, produced no results and was unsuccessful. Various voltages, resistances, and currents were tried in attempts to cause the mirror platform to magnetically deflect. Magnetic fields were also varied in strength by using several magnets of different strengths. Position of the magnet was also experimented with to no avail.

5. DISCUSSION AND CONCLUSIONS

The mirror mechanism sizes attained using the Excimer Laser were a success. Due to the diameter of the laser, mirror mechanisms with serpentine springs could not be created any smaller than three millimeters per side. Therefore, downsizing the mirror mechanism within the limitations of the Excimer laser was achieved. Using the micro-fabrication lab, further downsizing of the mirror mechanism is possible. Unfortunately, the micro-fabrication lab was unavailable for use throughout the summer.

Although motion of the mirror mechanism was not achieved, numerous valuable lessons as to why it failed to move were learned. After multiple attempts to induce the mechanism to move, attention was directed toward problems that were hindering its motion. It was observed that after handling and numerous uses, the fragile mirror mechanisms would cease to conduct current. Because of the nature of the small mechanism and the wiring preceding it and following it in the circuit, checks were done to determine the location of breaks in the line. Each electrical connection was probed by using a small wire hooked into ground at one end and free at the other end. If the voltage source registered a current flow, the break in the circuit could be assumed to be further along in the wiring. Once the probing wire reached a location where current was no longer indicated as flowing, the break in the circuit could be assumed to be located between that point and the positive voltage source.

If the break was located somewhere other than the mirror mechanism, the circuit was generally easily fixed. On the other hand, when the break was determined to be within the mirror mechanism itself, it could not be located with the naked eye.

In one instance, the circuit suddenly stopped conducting current. There had been no significant disturbance to the mechanism other than a minimal rotation about its axis caused by a probe. This sudden loss of conductivity merited a look at the mechanism through a microscope. At the corners at the base of the torsion beams, where they met the anchors, small cracks were propagating through the copper. One of the leads was severed by these cracks, resulting in the broken circuit. Although the initial setup of the mirror mechanism was difficult and often rough on the device, possibly creating the stress fractures, the repetitive twisting intended for the device’s operation appeared as though it would wear away at the torsion bar in time, as well.

Another problem was discovered when a mirror mechanism was wired improperly, yet still conducted current. The mirror mechanism was designed to be wired from two specific points—one of the anchors and the center of the mirror platform. Instead, it was accidentally wired the same way as all the other mirror mechanisms—with both leads attached at the anchors. In this configuration, no current should have been conducted. To the naked eye, it appeared as though there were no shorts that could complete the circuit as it was wired. Nonetheless, the circuit was complete and it conducted current. Once again, a look at the mechanism underneath a microscope was merited. The laser had, in fact, not completely penetrated the copper layer. What should have been a continuous line cut by the laser was actually a line of small holes. In between each pair of holes was a small section of copper that was untouched by the laser, bridging the insulating gap and creating a short circuit. This short resulted in the observed conduction of current. A quick look at the Excimer Laser log sheet showed that when this particular pattern had been cut, the laser had already been used extensively since the laser gas had been changed.

6. RECOMMENDATIONS

Given the difficulties encountered throughout the research and discussed above, the Excimer Laser and its CNC table should be investigated and subject to quality experimentation. A study exploring the gradual decrease in cutting quality between regular gas changes would be most helpful to anyone who intends to use the Excimer Laser for prototyping and production, especially if multi-layer circuit etching is required.

Another recommendation is to eliminate the torsion bars used to support the mirror platform and convey electrical leads in favor of serpentine springs. Employing serpentine springs will reduce the cross-sectional shear stress, perhaps eliminating the stress fractures that plagued the electrical leads of the torsion bars. At the same time, serpentine springs present the interesting challenge of how to connect electrical leads to the mirror platform itself.

One electromagnetic actuation method proposed but never fully investigated used pistons to control the angles of the mirrors. A piston would be centered underneath each edge of the mirror. Surrounding the piston would be a coil of wires, or solenoid, which would be fixed to anchors. Variances of voltage in the solenoids would cause the pistons to move either up or down. In this way, the angle of deflection of the mirror could be controlled. This idea should be seriously considered as a means for actuation.

7. ACKNOWLEDGMENTS

The research presented in this paper was supported by the National Science Foundation (NSF) through an NSF Research Experience for Undergraduates (REU) grant. I would like to thank Dr. Suresh and his team of graduate students for their support and advisement throughout the SUNFEST program. Dr. Hicks of Drexel University was also helpful and was the impetus behind this research. When difficulties were encountered in my research, I could count on receiving assistance and suggestions from not only Dr. Suresh and Dr. Hicks, but from all faculty who participated in SUNFEST, especially Dr. Engheta. Terry Kientz and his resourcefulness proved to be very helpful throughout the summer. Lastly, I would like to thank the SUNFEST program and Dr. Van der Spiegel for affording me the opportunity to participate in the University of Pennsylvania's summer research.

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APPENDIX

Angle of Deflection Calculations

$$k = ab\wedge3[16/3-3.36b/a(1-b\wedge4/(12a\wedge4))]$$
$$G = E/(2(\nu+1))$$
$$R = \rho L/A$$
$$T = IAB\sin\theta$$
$$\phi = TL/KG$$

Solve for k (torsional rigidity):

Dimension of torsion beam	a=.00025 m
Dimension of torsion beam	b=.0000275 m

$$k = ab\wedge3[16/3-3.36b/a(1-b\wedge4/(12a\wedge4))]$$

k=2.58076e-17

Solve for G (modulus of rigidity):

Modulus of Elasticity	E_{kapton}=3.2 GPa
Modulus of Elasticity	E_{copper}=110 GPa
Poisson's Ratio	V_{Kapton}=.34
Poisson's Ratio	V_{copper}=.34
% X-sectional area of beam	%Kapton=90.90%
% X-sectional area of beam	%Copper=9.09%

$$G = E/(2(\nu+1))$$

G=4.81645e9

Solve for R_{loop} (resistance of loop);

Resistance per unit length	ρ_{copper}=3.5e-8 ohm meters
Length of wire loop	L=.032 m
X-sectional area of wire	A=1.25e-9 m^2

$$R = \rho L/A$$

R_{loop}=.896 ohm

Solve for T (torque) in terms of V (voltage) and R (resistance):

Voltage	V
Resistance of potentiometer	R
Current	I=V/R
Resistance of loop	R_{loop}=.896 ohm
Area of wire loop	A=.000056 m^2
Magnetic field strength	B=.3 Tesla
Angle between B and I	θ=90 degrees

$$T = IAB\sin\theta$$

$$T = (.000017V)/(R + .896)$$

Solve for ϕ (angle of deflection):

Length of torsion beam	L=.001 m
Torsional Rigidity	k=2.58076e-17
Modulus of Rigidity	G=4.81645e9
Torque	$T = (.000017V)/(R + .896)$

$$\phi = TL/KG$$

$$\phi = (.136765V)/(R + .896)$$