

The Icarus Machine: A Kinetic Sculpture that Demonstrates Gyroscopic Precession

by

Laura E. Nichols

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

Bachelor of Science

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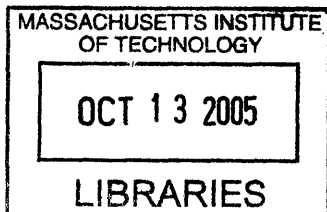
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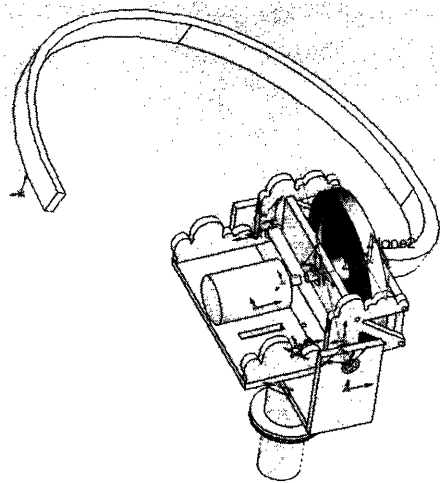
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ABSTRACT

Inspired by the desire to unite aspects of art and engineering into a comprehensive whole, I have designed and manufactured a kinetic sculpture that demonstrates gyroscopic precession. The aim of this project is to explore the interplay between two seemingly separate fields, art and engineering, and the effect of their union on perception and learning.



Thesis Supervisor: Woodie Flowers

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1. Introduction

For my bachelor's thesis in mechanical engineering, I have designed and built a kinetic sculpture that operates on the principles of gyroscopic precession. This project stems from a desire to unite the two areas of my life that I care most about: art and engineering. To some, art and engineering may seem like opposing ideals – art deals with feelings and engineering deals with functionality – but I feel that both are intrinsically linked to each other and add up to a greater whole. Neither one can exist without the other, but rarely are the two actually united. Robert M. Pirsig lays out the foundation of this dichotomy between art and engineering in his autobiographical novel, *Zen and the Art of Motorcycle Maintenance*. By dividing the human mode of thought into two categories, classical understanding and romantic understanding, he explores the conflict between the two. “A classical understanding sees the world primarily as underlying form itself,” whereas “[a] romantic understanding sees [the world] primarily in terms of immediate appearance.”¹ Engineering falls under classical understanding; art falls under romantic understanding. Engineering and art come into conflict because of this difference. The main reason for this conflict lies in the way that each mode of understanding is viewed by the other.

The classical style is straightforward, unadorned, unemotional, economical and carefully proportioned. Its purpose is not to inspire emotionally, but to bring order out of chaos and make the unknown known. It is not an esthetically free and natural style. It is esthetically restrained. Everything is under control. Its value is measured in terms of the skill with which this control is maintained.

To a romantic this classic mode often appears dull, awkward, and ugly, like mechanical maintenance itself. Everything is in terms of pieces and parts and components and relationships. Nothing is figured out until it's run through the computer a dozen times. Everything's got to be measured and proved. Oppressive. Heavy. Endlessly grey. The death force.²

It is my hope that by uniting a scientific concept with the aesthetics of a sculpture that a larger audience can be reached than could be reached by a scientific demonstration or a piece of art alone. To use Pirsig's terminology, people with a classical mindset can appreciate the mechanics and the underlying form of this type of sculpture while people with a romantic mindset can appreciate the immediate appearance of it. Through this dual understanding, classically minded people can learn to appreciate the role of aesthetics in design, and romantically minded people can be introduced to otherwise intimidating scientific concepts in a way that is comfortable and familiar. By introducing scientific concepts in a form that is aesthetic as well as functional, I also hope to demonstrate that science and technology can be an effective tool towards an artistic end, that for artists, technology can be exciting and inspiring instead of being what Pirsig claims is “the death force”.

¹*Zen and the Art of Motorcycle Maintenance*. p. 16

²*Zen and the Art of Motorcycle Maintenance*. p. 61

2. Background

2.1 Motivation and Inspiration

Kinetic sculptures are not a new idea; numerous other artists, such as Arthur Ganson, Ulrich Westerfroelke, and Moto Ohtake, to name a few, have produced sculptures that attempt to unite art with science and engineering. I was first introduced to the idea of a kinetic sculpture several years ago by the Arthur Ganson exhibit at the MIT museum. The exhibit fascinated me; I had never experienced anything like that before. Ganson's use of interaction with the observer combined with quirky use of found objects, such as wishbones and artichoke leaves, made quite an impact on me. Afterwards, the idea of kinetic sculptures stayed with me. This new experience spawned my own research into the field of kinetic sculptures, allowing me to discover artists such as Ulrich Westerfroelke and Moto Ohtake. From each of these artists, I learned what I did and did not like, in addition to learning what was possible. Westerfroelke incorporates interaction with the observer and environment along with an elegant simplicity that I find appealing. Ohtake shies away from interaction with the observer, and instead makes sculptures that interact with the environment, mainly wind, and that use gyroscopic effects to produce interesting motion. Even though these artists inspired me to explore the possibilities of kinetic sculptures, I still had no inspiration as to what kind of kinetic sculpture would be appropriate for me to design and build.

When Elizabeth Streb, a MacArthur grant winning choreographer from New York City, visited MIT in the fall of 2004, she showed pictures of a “flying machine” that had been made for her dancers. This machine utilized a weight on an arm to counterbalance the weight of a dancer, which allowed the dancer to spin around a vertical axis. The counterbalance was slightly less than the weight of the dancer, though, so the dancer was continually falling and re-attempting to “fly.” Streb talked of her fascination with forces and the inspirations behind the “flying machine.” While listening to her give her talk, I was struck with the idea of using gyroscopic forces to propel the dancer around.

Further exploring this idea, I realized that although I knew the equations governing gyroscopic motion and the basic motion they produced, I still had no real intuition about how gyroscopes behaved. I believe that this lack of intuition results from there being a lack of readily observable, every-day gyroscopic phenomena in our lives. If this lack of intuition was noticeable in myself, a person with almost four years of formal education in science and engineering – including a class that focused on gyroscopic phenomena and angular dynamics – then this lack of intuition must also exist for the majority of the population. It was with this in mind that I came up with the idea for the Icarus Machine, in hopes that through building a kinetic sculpture focusing on gyroscopic motion, I would gain intuition on the subject as well as inspire people who might otherwise find gyroscopes intimidating.

2.2 The Icarus Myth

The myth of Icarus begins on the island of Crete with the inventor, Daedalus, and his son, Icarus, attempting to escape from their imprisonment in the labyrinth that had once held the

minotaur. Since Daedalus had built the labyrinth, he was able to find his way out, bringing Icarus with him. Once they had escaped, Daedalus decided that they must flee Crete, or else experience the wrath of King Minos, who had imprisoned them to begin with. Escape via land was not an option, due to Crete being an island; escape via sea was also not an option, due to the fact that King Minos controlled all the waters surrounding the island. Air was the only route left to the two fugitives, so Daedalus made wings out of wax and feathers for his son and himself. Daedalus warned Icarus not to fly too close to the sun, else the wax of the wings would melt, and not too close to the sea, else the water would make the wings damp and make it hard to fly. During their escape, Icarus became too caught up in the exhilaration of flying and grew careless. He flew higher and higher, causing the wax of his wings to melt and sending him to his death in the Aegean Sea.

3. Methods

3.1 Design

To start with, I first made the Icarus figure that would be the focus of the sculpture. The body of the Icarus figure was made out of 16 awg. copper wire which was twisted into the shape of a human. His wings were made of 13 ga. copper plate which was roughly cut into the shape of wings and then cold-worked with a hammer, anvil, and dishing stump. The wings were then wired to the body and welded in place.

From here, I designed the gyroscope that would be responsible for the precession of the sculpture. The equation $w_p = mgR/Iw_s$ is the equation that governs the precession rate of the gyroscope, where w_p is the angular precession rate, mgR is the net moment placed on the gyroscope, I is the moment of inertia of the gyroscope's flywheel, and w_s is the angular velocity of the flywheel. From this equation, I used an iterative approach using an approximate net moment of 2.5 ft.-lbs. to find a range of values for w_s and I that gave the desired precession rate in the range of $\frac{1}{4}$ to $\frac{1}{2}$ Hz, slower precession rates being preferred. It was discovered that a motor speed of between 1000 and 4000 rpm and a flywheel with a moment of inertia of 3 – 6 lbs.*in.² would be most appropriate for the gyroscope's needs.

An 18VDC motor with an unloaded speed of ~5000 rpm was decided upon to drive a brass flywheel with a weight of 1.75 lbs. and moment of inertia 5.9 lbs.*in.² (Figure 1). When loaded by the flywheel, the motor speed drops to ~1500-2500 rpm, which gives a precession rate in the right range when combined with the flywheel and dropping the motor voltage to a fraction of the motor's rated 18VDC. In addition to controlling the precession rate by the motor voltage, the decreased voltage will keep from overdriving the motor when the sculpture is run for extended periods of time. The flywheel is held via a set screw on a $\frac{1}{4}$ " dia. steel axle mounted between two flanged ball-bearings 1 $\frac{1}{4}$ " apart. The flywheel's axis is connected to the motor via a flexible coupling to allow for angular and linear misalignments without harming the motor's own bearings. The bearings are each held by an plate that mounts between the two plates which serve as the gyroscope's frame. The motor is also mounted to this frame via a hose clamp that goes through two slots in a plate that is bolted onto the underside of the frame (Figure 2). Rubber is placed under the motor and between the motor and hose clamp to prevent slipping due to the torque of the motor running, as well as to add damping for the vibration of the motor spinning.

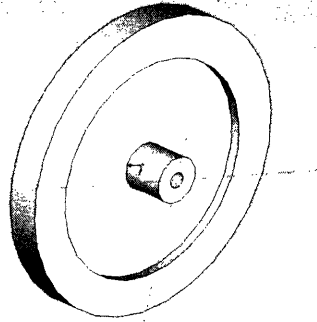


Fig. 1 – Flywheel

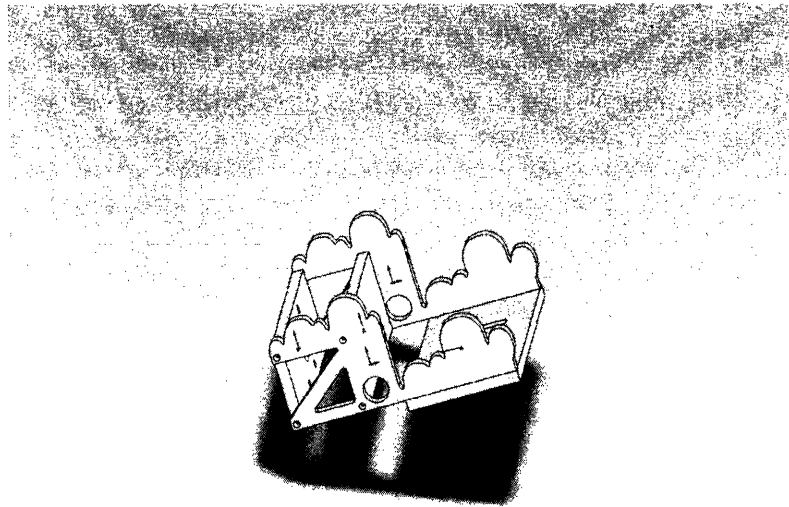


Fig. 2 – Frame with bearing and motor mounts

For the vertical axis, I decided that a bicycle rear hub and axle would be cost effective and have better bearings than what I could make, given time and machining constraints. Because I desired the sculpture to run off of wall power, not a battery, I chose a hub with a hollow axle for the wiring to run through. To keep the wires from becoming twisted during precession around the vertical axle, I used a mercury contact rotating electrical connection

that was within the size constraints. I designed the contact to have one flexible connection and one hard connection to the sculpture to allow for tolerances and slight misalignments without unnecessary stress on the electrical contact's bearings. From here, I designed the electrical contact cover (Figure 3) that also serves to connect the pivoting axis to the rotating hub of the vertical axis. The electrical contact cover is held to the hub via screws through the former spoke holes. There is a set screw at the top of the electrical contact cover to fix one end of the contact and to constrain it to rotate with the hub.

The gyroscope is mounted to the vertical axle via a horizontal steel axle running through brackets that screw into a horizontal bar that is centered on the vertical axis and bolted to the electrical contact cover (again, Figure 3). The horizontal axle also runs through the two plates that serve as the frame for the gyroscope. As this axle will only be serving as a pivot point, bronze bushings (see Figure 4) were used instead of ball bearings. These bushings were press fitted into the plates. To keep the horizontal axle in place, e-clips were used.

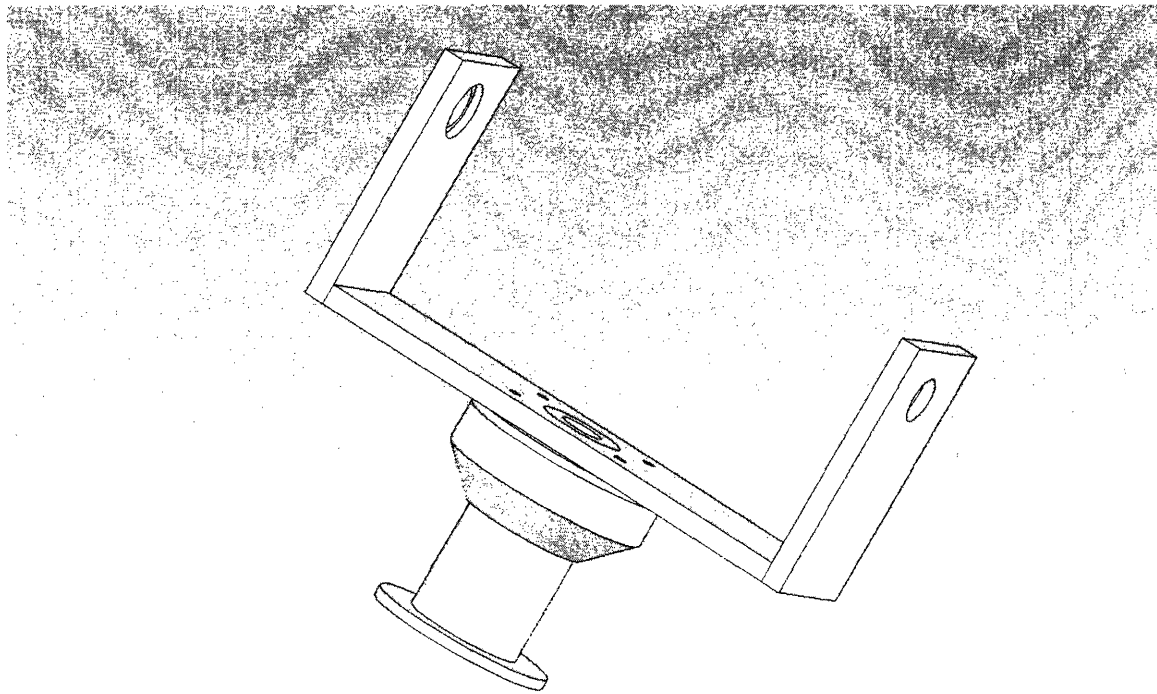


Fig. 3 – Electrical contact cover and brackets for pivot axle

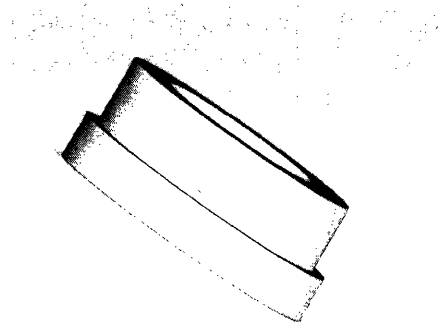


Fig. 4 – Bronze bushing

The mount for the vertical axis to the base is a flanged cylinder which holds the axle with a set screw to hold the axle and which is bolted onto a flat plate. The plate is mounted to two horizontal bars which bolt onto an small, old table.

The final thing that was considered was mounting the man, Icarus, to the frame of the gyroscope. This was done by a tapering out of plane spiral with the larger end welded to a plate that bolts onto the outermost bearing mount (see Figure 5). Icarus is connected to the tapered end via 16 awg. copper wires that wrap around and down the spiral.

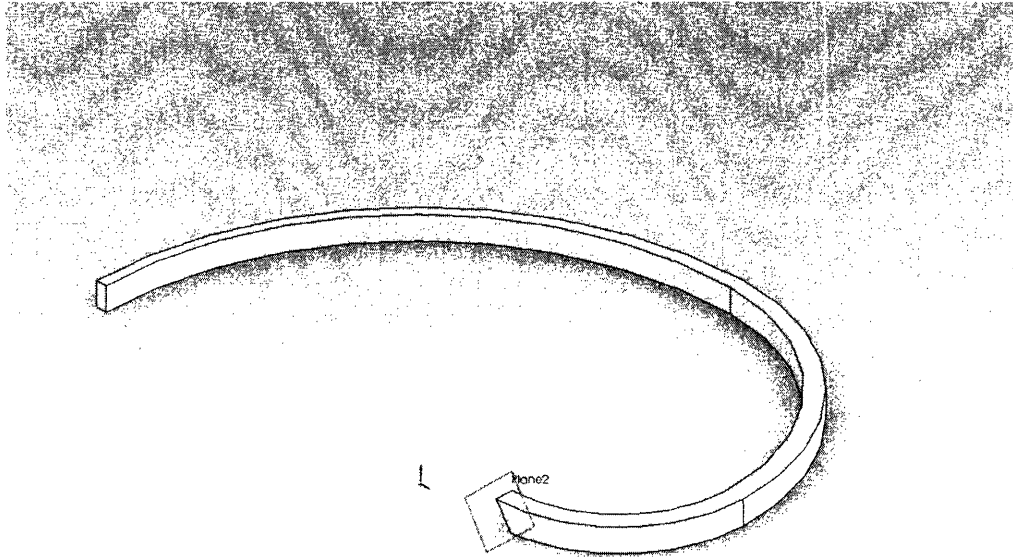


Fig. 5 – Spiral arm

3.2 Material Choice

Copper was chosen for the Icarus figure because of its ability to be easily formed by cold-working. Because the figure would not be under any mechanical stress, deformation after forming was not an issue. For the flywheel, high-lead naval brass was chosen due to its high density and machinability. The bushings for the pivot axle were made of bronze due to its frictional properties against the steel axle. Steel was chosen for both the pivoting axle and the gyroscope axle due to its high strength. For the rest of the sculpture, except for the pre-made bicycle rear hub and axle, aluminum was chosen due to its high machinability and low density.

3.3 Aesthetic Considerations

Because this is designed to be a sculpture, aesthetics were taken into account, in addition to the mechanical and material considerations. I took the theme of Icarus and built the aesthetics around that. From the top, down, I wanted a feel of man to machine then back to something more earthy. Icarus is made of beaten and twisted copper, which instead of having hard lines, has an organic feel. The wires that Icarus is made of wrap around the spiral that is supporting him. The spiral is a golden spiral, a form seen often in nature, but which is very mathematical. I felt this choice of spiral represented the idea behind the sculpture well. Towards Icarus's end, the spiral is tapered and more rounded, which grows toward a more boxy and mechanical feel the closer you get to the gyroscope. The brass flywheel of the gyroscope is supposed to represent the sun, which, in mythology, is the cause of Icarus's downfall. The "sun" is inside the frame that was cut on the water jet in the shape of clouds. The farther down on the sculpture, the more square and mechanical it feels. The vertical axis and brackets supporting the frame are obviously machined parts, cold and mechanical. The bolts used are black cap-end screws, which give an industrial feel to the sculpture. Because I wanted the sculpture to inspire curiosity about gyroscopic phenomena, I elevated the base on two clear plastic parallels so that it is obvious that there is no motor forcing the sculpture to go around in a circle. The base is mounted onto an old, worn wooden table which gives earthy roots to the entire sculpture. I felt that the progression from man to machine to earth represented man's relationship with technology. We came from earthy roots, used tools to make machines, which, in turn, allowed us to fly, to reach towards new heights. Icarus was chosen as the figure to serve as a small warning to any who choose to push technology into unknown territory; we might be able to "fly" with this new technology, but sometimes things happen that are unexpected and unexplained at the time. In Icarus's case, the sun melted the wax on his wings and he plummeted to his death, even though he was warned against such a thing happening. I do not intend Icarus to be a statement against the use of technology, only to warn towards a more ethical approach, to encourage the careful consideration of the ramifications of any technology we may seek out.

4. Conclusions and Recommendations for Future Work

Through this project, I have learned a great deal about the design process and about gyroscopic phenomena. The original idea grew and developed throughout the course of designing and building the sculpture due to the realizations and inspirations that came along

with the process. As it is, there are a couple of small aesthetic changes, such as cleaning up the wiring, that I would like to do in the near future, but these are secondary to the overall function of the sculpture. If I were to modify the overall design of this sculpture or to make another similar sculpture, there are a few things I would like to change. The first thing I would like to change is to be able to control the angle loss due to friction, the second is to allow for more interaction between the observer and the sculpture, and finally, I would like to demonstrate a wider range of gyroscopic phenomena than precession alone.

Adding a control system is a practical solution to allow the sculpture to run for long periods of time unattended. To do this, I propose adding a control mechanism to account for the angle loss of the gyro that occurs because of friction losses. A simple way to do this would be to force precession in the direction of precession, or in other words, to induce precession in the vertical plane. One solution would be to have a spinning rubber wheel that would catch the arm once the angle dropped to a certain degree and propel the sculpture around until the angle loss was compensated for. Another solution would be to have an electric control system that would turn on once the arm dropped past a certain angle and that would drive the sculpture around until the arm tilted past a small overshoot angle.

Adding interaction between the observer and the sculpture will contribute greatly to my goal of aiding the understanding of the underlying scientific concept. I believe that interactions lead to a more thorough understanding, a physical intuition, of a phenomenon than observation or equations alone. As for aesthetics, I believe that interactions with art aid the observer in becoming more involved in what is being shown. One way to go about doing this would be to have mechanisms such as cranks and brakes that would affect the precession rate, and thus the tilt of the sculpture. In implementing interaction, I feel that it is imperative that the interaction is physical, and not just adjusting voltages and flipping switches to slow down and speed up precession rate. It is the physical knowledge gained from such interactions that is important to the growth of intuition.

By demonstrating a wider range of gyroscopic phenomena, I would hope to further inspire curiosity about gyroscopes. Nutation – gyroscopic vibration – would be a good phenomenon to demonstrate. The way a gyroscopic system responds to impulses and vibrations is unexpected to someone who had never seen such an occurrence. At low precession rates, nutation can be quite beautiful. To implement a demonstration of nutation, the design of the current sculpture would have to be modified quite a bit; a wide range of motion is necessary, as well as a large degree of vibration stability. As it is, I believe that neither the sculpture nor the base is stable to withstand the forces that would come with large-scale nutation. If I were to try to implement nutation, I would redesign the vertical axle with bearings that could withstand large moments being placed on them as well as making the base heavier and with a larger footprint.

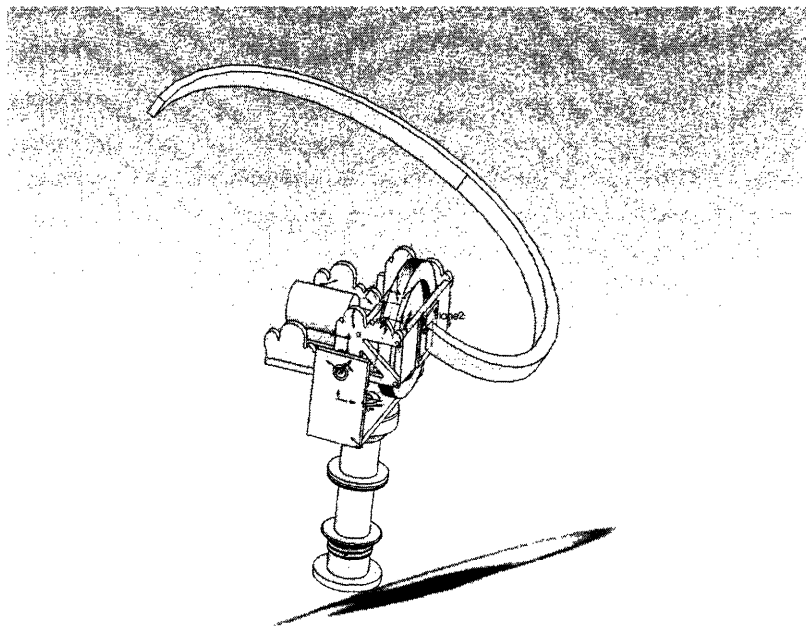
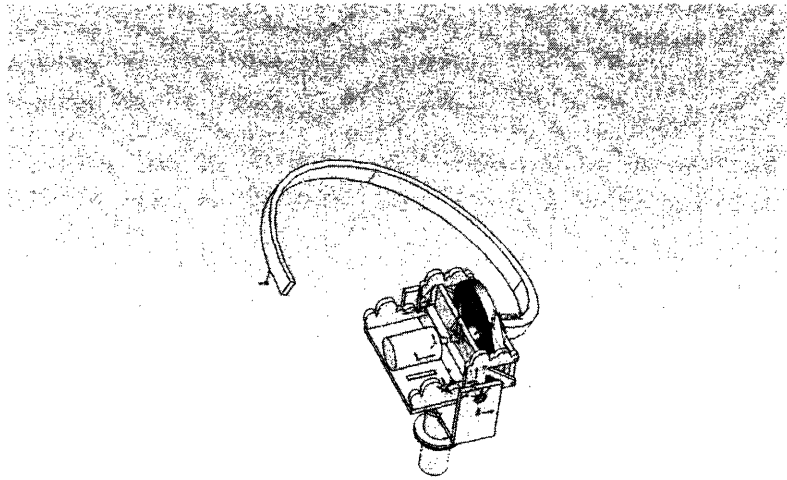
All in all, I consider the sculpture successful at fulfilling my original design goal of having an aesthetically pleasing sculpture that demonstrates gyroscopic precession. Through doing this project, I have gained a feel for how gyroscopes react, a better sense of the overall design process, and an idea of the challenges that await anyone who tries to unite art and engineering in such a way that is educational for the observer. I feel that this sculpture was a very worthwhile endeavor and is just the beginning of my exploration of sculptures along these lines.

Appendix

5.1 References

Pirsig, Robert M. *Zen and the Art of Motorcycle Maintenance: An Inquiry into Values*. New York: Bantam Books, 1981.

5.2 Additional Figures



Figs. 6 & 7 – Gyroscope assembly

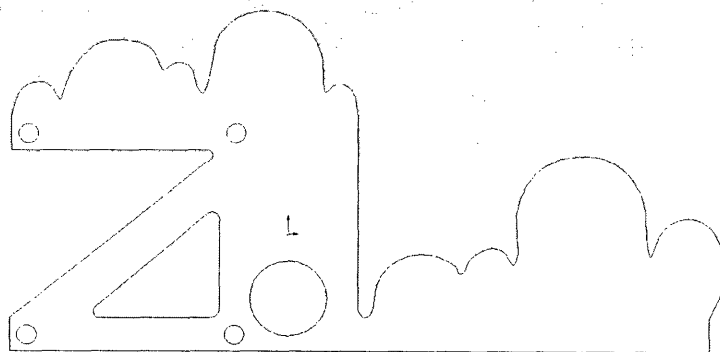


Fig. 8 – Detail of frame

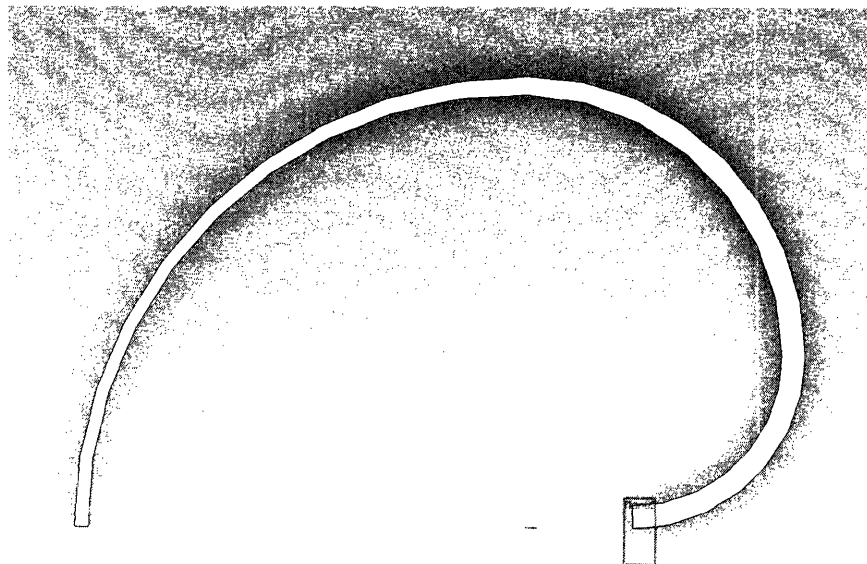


Fig. 9 – Top view of spiral arm