THE DESIGN AND DEVELOPMENT OF

A GYRO MACHINE FOR

INDUSTRIAL APPLICATIONS

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SUMMARY

Gyroscopes have a number of applications in today's world. They have been used in different applications such as navigation systems, mixing different powders, mixing paints, automobile transmission systems. The property of the gyroscope to rotate the spinning mass about all three axes in order to maintain its equilibrium makes the top to stand on its end compared to similar machines. Current washing machines have only one axis of rotation, either horizontal or vertical. New modifications are mainly in terms of controlling the rotation of drum (or container) of the washing machine either in the clockwise or anti-clockwise direction. In this investigation, a revolutionary approach, namely, a machine based on the gyroscopic concept is proposed that will enable washing of the clothes efficiently by rotating the container in all three axes.

The original idea of developing a washing machine based on gyroscopic principle was developed by Dr. R. Komanduri in 1985. The container of the gyro machine in this investigation is spherical. This system was built by a previous group and it was modified and analyzed in the present investigation. The focus was mainly on obtaining more than two degrees of freedom at the sphere container using gyroscopic concepts. This innovative machine was further analyzed based on the motion obtained at the sphere for its promising application such as washing machines and mixers for powders or different kinds of materials.

The Gyro machine proposed here is based on the underlying principles of the gyroscope following the Flemings right hand rule. A hollow sphere was used as the main container, which was mounted on the inner gimbal, and this subassembly was mounted on the outer gimbal. This assembly was part of the existing setup. The diameter of the sphere is 12 ", that of the inner gimbal is 18 " and that of the outer gimbal is 24 ".

Different approaches such as rotating sphere manually or by using electric motor were investigated to arrive at the optimum. This approach is named the flywheel approach. In this, the sphere is energized and used as a flywheel. Based on this approach, the degrees of freedom concept and reverse engineering, the mechanism was developed using Pro-Engineering software. A Magnetic field was induced to spin the spherical container as well as to rotate the outer gimbal with a single input based on gimbal lock concept. To obtain optimum a magnetic flux density of 0.3 Tesla, 4 NdFeB bar magnets (2" x 1" x 0.5") (KJ magnetics) were arranged radially inside the outer gimbal at a distance of 0.2 " from the inner gimbal. Magnetic field analysis was carried out to determine the effect of magnetic field on the inner gimbal using COMSOL 3.2 Multiphysics software. Torsional springs and extension springs were used to energize the sphere after equal intervals and to restrict the inner gimbal to 90°. To spin the sphere continuously, the option of switching the polarities of the motor i.e. indirectly changing the direction of rotation of the outer gimbal was found to be more effective. The time gap between switching the polarities was found to be ~15 seconds. Based on this profile, the gyro machine was automated to switch the polarities and to control the speed of the machine by using a micro-PLC.

The performances of the gyro machine was analyzed based on the results obtained from the mechanism and the experimental results. A high-speed camera was used to observe the motion of the outer gimbal, inner gimbal, and different variations of the sphere, such as rotation and oscillation. Based on this, different cycles were identified and are studied in detail. Clothes (material) to be washed (mixed) can be loaded in the hollow sphere in order to get completely a new washing (mixing) experience. It may be noted the system we built is not a gyro washing machine but a prototype of a gyro machine to investigate the performance. The next version would be specific machine design to wash clothes.

The inner sphere is able to rotate in all possible directions due to relative motion between the sphere, the outer gimbal, and the gyroscopic effect on the inner gimbal. In the present investigation, dimensions of all the main components, such as the inner gimbal, the outer gimbal, and the frame of the gyro machine are obtained as a function of the size of the sphere using parametric relationship. Likewise, in the future, if the size of the sphere is changed based on the volume requirements, then the dimensions of all the components can be determined. Scaling of the machine would be easier due to the relationships developed.

Based on the analysis, different cycles can be programmed. These cycles are spin, rolling, oscillating, and drying cycles. Each cycle is discussed in detail, which explains different profiles generated by these cycles and their advantages in washing clothes in more efficient way. The advantages of the machines compared to the problems experienced by current commercial washing machines are also presented. Emphasis is also given to explain other industrial applications of the gyro machine apart from washing clothes.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The Gyroscope or Gyro is not a new instrument. Since the time of Greeks, Chinese, and Romans, this concept of the Gyroscope was known and was recognized and used for different purposes. In early times, people built a variety of toys with a spinning top (frameless gyroscope) which has the unique ability to maintain its axis of rotation while rotating. In countries, such as New Zealand humming top- like structures having a number of holes on the top were used for mourning ceremonies. Between the 16th and 18th centuries, different scientists, including Galileo (1564-1642), Christiaan Huygens (1629-1695), and Sir Isaac Newton (1642-1727) used these frameless gyroscopes to understand the rotation of both Earth and other planets and the laws of physics [1]. In mid-17th century, an English scientist named Serson observed a tendency of spinning top to remain at a level, even if the surface on which it is rotating is inclined. He was among the first to suggest the use of an artificial horizon based on this concept for sailors to find the direction while sailing. It was not until the mid-18th and early 19th century that the physicists started using these spinning tops as a scientific tool.

The concept of a gyroscope was known in the French schools since the 18th century. Such an instrument was used to explain the precession of the Earth's rotational axis. In 1817 the first gyroscope was designed by Gottlieb [1]. Friedrich von Bohnenberger was a professor of Mathematics, Astronomy, and Physics at the University of Tuebingen, Germany [1]. Bohnenberger didn't give a specific name to this instrument but called it a "maschinchen" or "Baby Machine" [2]. This instrument came to be known as the machine of Bohnenberger. The schematic and photograph of this instrument is shown in Figure 1. It can be observed from Figure 1, the Gyroscope was made with a heavy ball as a spinning mass instead of a wheel and the use of gyros with cardanic suspension. This type of gyroscope became famous with the name of a mechanical gyroscope or gimbaled gyroscope, meaning a gyroscope with rings. At that time, this instrument had no scientific application, but served as the basis for Foucault's study [1].

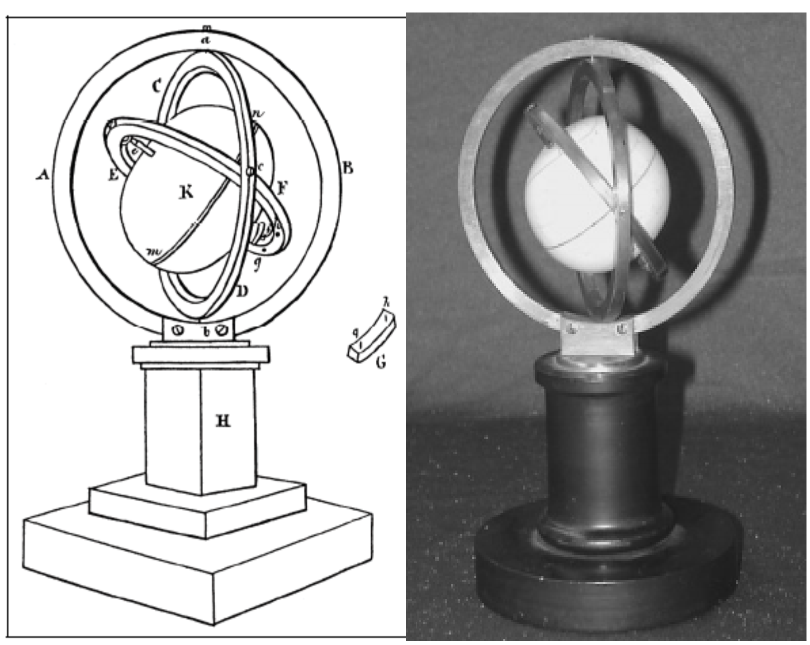


Figure 1 Schematic and photograph of a gyro with cardanic suspension after Bohnenberger [1]

In 1852, Léon Foucault used different techniques and methods to observe the rotation of the earth [1]. He used a long pendulum and set it to swing back and forth in the direction of the South and the North poles of the Earth while the earth was rotating. On a similar line, he developed a special type of instrument to study the rotation and precession of the Earth about its axis. Foucault's studies concentrated on gyros with cardanic suspension. He placed a spinning wheel supported by a ring so that the wheel would have independent rotation than that of a ring. As the ring was connected to the rotating Earth, the axis of the wheel remained pointed towards the direction of rotation of the earth, and likewise. He found the direction of rotation of the earth and concluded that the earth rotates in twenty four-hour periods [3]. Similarly, Foucault was the first to use the gyroscope for scientific applications to explain its effect on the behavior of objects traveling on the Earth's surface. Foucault named this instrument from two Greek words- "Gyros" which means circle and rotation and "Skopein" which means to view. Foucault was the first to recognize that blocking one degree of freedom of the suspension of a gyroscope can be used to develop indicators that can be used to measure different rotation of the components [4]. Since then many scientists and researchers started paying attention to the gyroscopic phenomenon. The focus was to use a gyroscope for unique applications.

In the 19th century, inventors found useful applications of the gyroscope as a gyrocompass. A German engineer and inventor, Hermann Anschiutz-Kaempfe recognized that the stable orientation of the gyroscope could be used in a gyrocompass. Normal navigation and orientation systems that were used at that time had limitations for undersea applications. Gyrocompass was developed as a solution to this problem. In 1904, German scientist Dr. Otto Schlick came up with an idea to employ gyroscope on the ships for steering applications in order to prevent a ship from rolling [5]. Schlick tested a gyroscope equipped with a rapidly spinning rotor in a German torpedo boat under different tilting conditions and found the gyroscope to be useful for this application.

1.2 BASIC PRINCIPLES OF THE GYROSCOPE

Gyroscope can be considered as a solid body capable of rotating at high angular velocities. It is a mechanical device armed with most important part of the system, namely, the flywheel. The flywheel is mounted with a heavy rim in such a way that, while rotating at high speed its axis of rotation can turn in any direction about the fixed point on that axis. Gyroscopic inertia and gyroscopic precession are the two most fundamental properties of the gyroscope.

1.2.1 Gyroscopic Inertia

In the case of the gyroscope, rigidity in space obeys Newton’s law of conservation of angular momentum. Namely, a body continues to rotate from its state of rest, unless otherwise acted upon by an unbalanced force. Therefore, when a flywheel is rotating it will continue to rotate in its plane of rotation, unless otherwise it has sufficient energy to rotate with the same angular velocity. However, when there is an unbalanced force acting on it, it obeys Newton’s third law of motion, namely, for every action, there is an equal and opposite reaction. So, the flywheel applies an opposite force on the third axis in order to maintain its plane of rotation. This phenomenon is called “gyroscopic inertia or rigidity”.

1.2.2 Gyroscopic Precession

A gyroscope consists of three axes, namely, spin, input, and output axes. Spin axis is the axis about which the gyro mass rotates; Input axis is the axis about which imbalanced force acts (also called the torque axis); and output axis is the axis about which a gimbal or a ring rotates (also known as the precession axis). When a gyro rotor rotates about the spin axis and torque is applied about the input axis then this unbalanced force moves the spin axis into the input axis and rotates the gimbal about the output axis or precession axis.

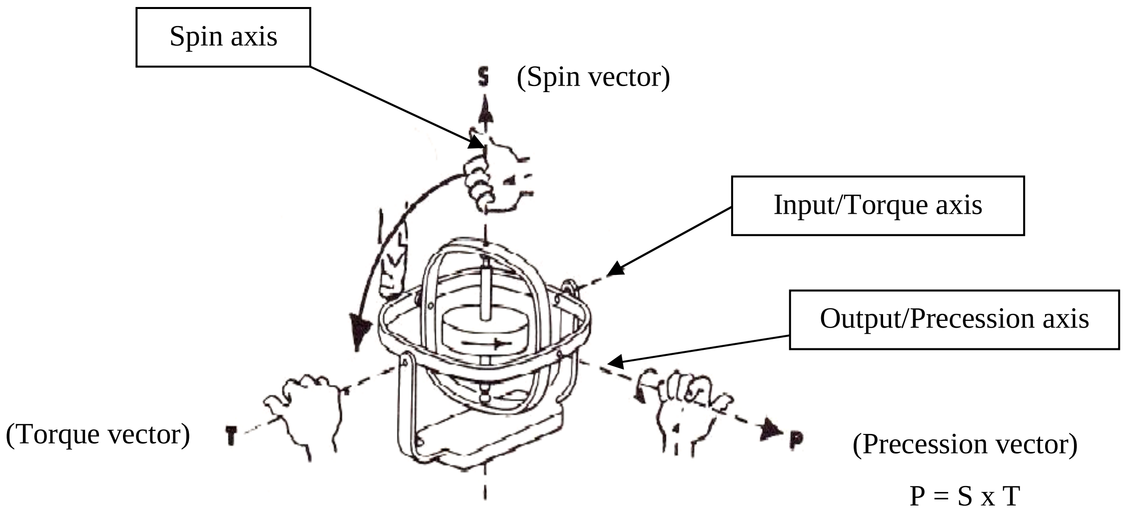


Figure 2 Vector representation of gyroscopic precession [6]

1.3 TYPES OF GYROSCOPE:

This subsection briefly reviews different types of gyroscopes that were developed and used for a variety of purposes. It also focuses on their advantages for a variety of applications. Mechanical, optical, and vibratory gyroscopes are the main types of gyroscopes. Their functions are outlined in detail in the following.

1.3.1 Mechanical Gyroscopes:

Mechanical gyroscopes operate on the principle of conservation of angular momentum. They consist of a gimbal and a spinning mass. The number of gimbals varies from two to three depending upon the application. Figure 3 shows a simple mechanical gyroscope. A spinning mass, in this case, a wheel mounted on the inner gimbal. This subassembly is mounted on the outer gimbal. Pin type contacts are used to rotate them with respect to each other. Normally, they are rested on bearings to achieve rotation with less friction. The outer gimbal has one degree of freedom as it can rotate only about the X-axis. The inner gimbal has dual axis motion as it can rotate about two axes X and Y, the spinning mass with three axes of motion as it can rotate about X, Y, and Z-axes.

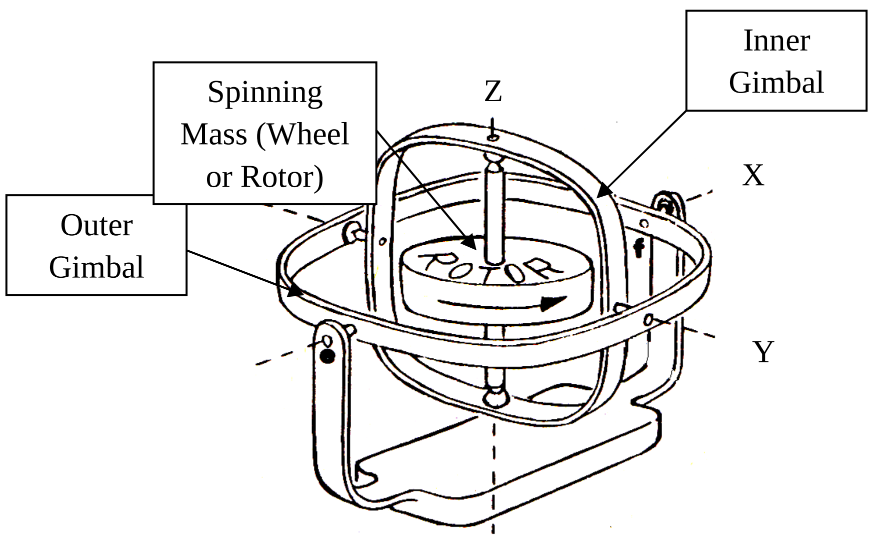


Figure 3 Schematic of a simple mechanical gyroscope [6]

An interesting aspect of the gyro system is that it can resist change in the orientation due to an effect, namely, the conservation of angular momentum. Mounting of the spinning mass makes it free to rotate about the axes perpendicular to its spin axis.

Spinning mass always remains aligned with respect to the way the whole set up is rotated. Mechanical gyroscopes are further classified into rate-gyros and rate-integrating gyros.

1.3.1.1 Rate-Gyro:

This type of mechanical gyroscope is an open loop system. If a torque is applied as an input on one of the axes perpendicular to a spinning axis, then there is a torque output generated in the form of precession on the third axes. So, for the rate gyro, rate in and torque out is the principle of operation [3]. In the case of rate gyro, spinning mass is rotated by a motor attached to a torsional bar. Torsional bar is used to constrain the rotation of the gimbal. The system works in accordance with the Newton's Second Law of Motion as there is a change in the rate of angular momentum. Modern gyroscopes that measure the angular velocity are listed in the category of rate-gyroscope. In mechanical gyroscopes, angular velocity is difficult to measure compared to rate-gyroscope. Angle pick off is a technique that is used in this case.

1.3.1.2 Rate Integrating Gyro (RIG)

This type of mechanical gyro is a closed loop version of the rate gyro. In RIG, a high precision ball bearing replaces the spring. Damping is accomplished with the help of a fluid. The resistance offered is directly proportional to the viscosity of the liquid. The rest of the working is similar to the rate-gyro.

1.3.2 OPTICAL GYROSCOPES

In optical gyroscopes, interference light is used to measure the angular velocity. The principle behind optical gyroscopes is that the light travels at a constant speed in an inertial frame through a given medium [7]. It was observed through several experiments that there is a change in the path length depending on the direction of rotation of the waveguide. Increase in the path length has been noticed if the waveguide is rotated in the same direction as the light path and decrease if rotated in the opposite direction. This is also called the Sagnac effect.

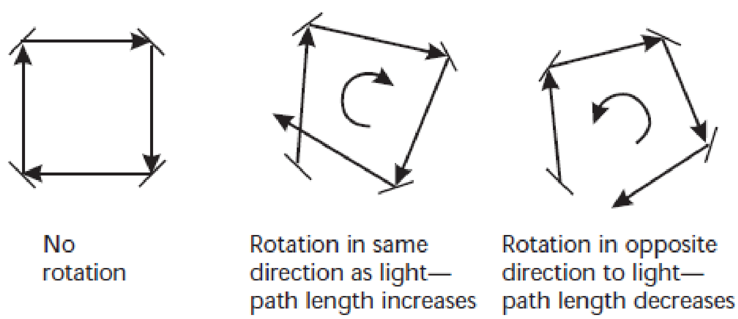


Figure 4 Effect of a closed loop waveguide rotation on path length after Groves [7].

There is a phase shift due to this effect, which results in the interference of these light beams. So, angular velocity can be easily measured from the intensity of a combined beam. The main application of this type of gyroscopes is in the sensors, which have numerous applications. Optical gyroscopes are classified into two categories, namely, ring laser gyro and Interferometric fiber optic gyro.

1.3.2.1 Ring Laser Gyro (RLG)

Figure 5 shows a typical Ring laser gyro. The principle of operation is based on the Sagnac effect. In the case of RLG, a laser beam is directed in a close loop tube with the help of mirrors placed in each corner. Laser beam is formed by the helium-gas mixture placed inside the tube and a high potential difference generated across a gas. The direction of rotation of laser cavity in the RLG is dependent on the type of lasing mode generated.

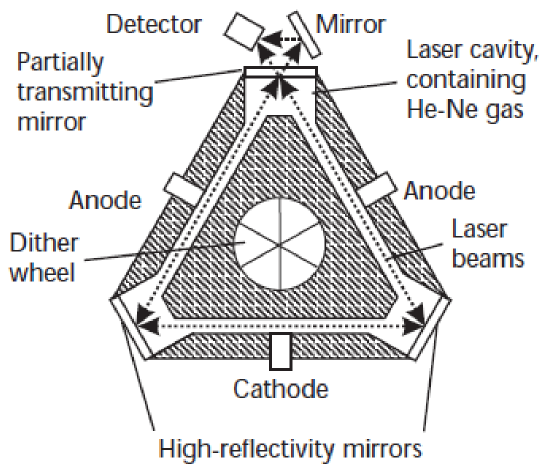


Figure 5 Ring laser gyro showing different parts of the system after Groves [7]

1.3.2.2 Interferometric Fiber-Optic Gyro (FOG)

In FOG, the angular velocity is measured using light interference. It consists of a fiber optic coil and two beam splitters. The Light source is split into two by the beam splitters. The two light beams have equal wavelengths. These beams are focused on the fiber optic coil. If the sensor is rotating, the Sagnac effect comes into play and once the beam exits they are combined and measured. It has been observed that the intensity of this combined beam is directly proportional to the angular velocity. Therefore, the angular velocity can be found out more accurately with the help of this gyro.

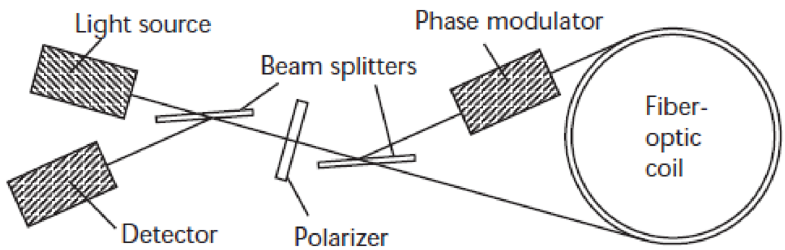


Figure 6 Schematic of Interferometric fiber optic gyro showing different parts of the system after Groves [7].

1.3.3 VIBRATORY GYROSCOPE

Figure 7 shows the principle of working of the vibratory gyroscope. A vibratory gyroscope consists of an element, which undergoes the simple harmonic motion.

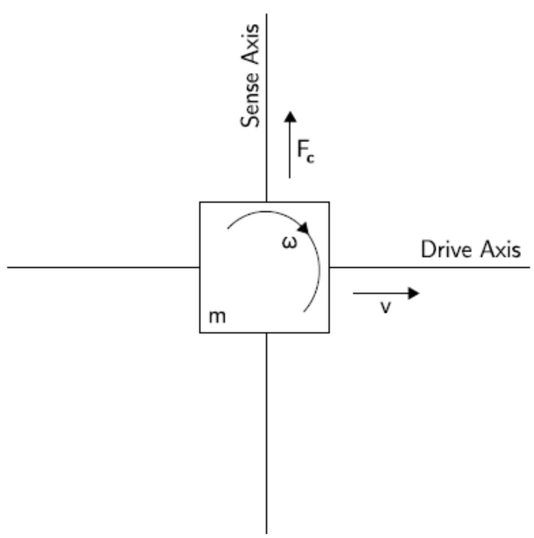


Figure 7 Principle of working of a vibratory mass gyroscope after Woodman [8]

When the gyro is rotated, the vibratory gyroscope detects the Coriolis acceleration of the vibrating element. Because of this operational principle, Vibratory gyroscopes are used in the applications such as spacecraft orientation, automotive etc.

1.4 MECHANISM

A mechanism is a mechanical device. It is a group of machine elements operating in a specific manner and creating a particular motion [9]. Mechanism is used to study motion of different machine elements linked to transfer motion from the source to the output. Mechanism includes design and analysis of several machine elements, such as links or bodies, cams, gears by considering their motion characteristics. Mechanisms are represented by a linkage system consisting of links in which at least one link is fixed. Varieties of connections are possible through different types of joints, such as pin, spherical. General mechanisms are classified into open loop and closed loop mechanisms. Figure 8 shows the differences between two mechanisms, namely, open loop and closed loop.

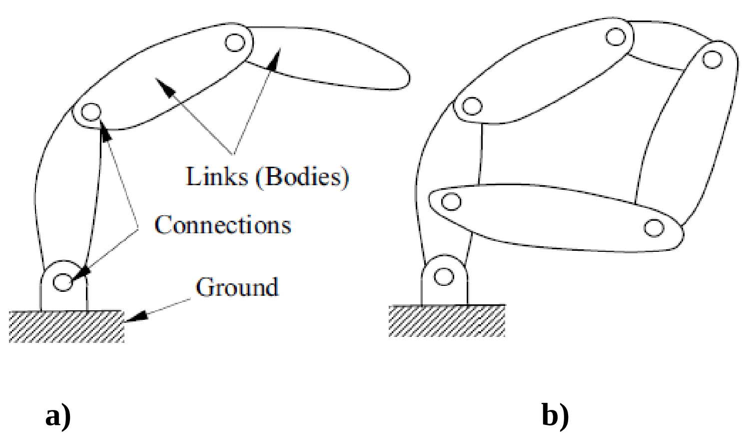


Figure 8 Schematic showing general mechanisms (a) Open loop and (b) Closed loop [10]

The mechanism is normally studied based on kinematic and dynamic motions. Kinematic study of motion does not consider any forces or loads acting on the system. In the case of dynamic study of motion, different external forces and loads acting on the system are taken into consideration. In addition, for the rigid body mass, gravity, moments of inertia are taken into account while performing analysis.

Different softwares are available to analyze the mechanisms. The mechanism plays an important role in the case of a prototype building. Prototype building is a small-scale model of the actual machine, and is tested under different conditions. Maximum emphasis is given to analysis of a mechanism based on dynamic study as it deals with actual forces acting on the system and helps in building a reliable model. Building prototypes with these, softwares can help in understanding and eliminating design related problems in its earlier stages. This saves considerable time, material, and money when it comes to manufacturing of a designed model.

1.5 OUTLINE

Following Introduction in Chapter 1, Chapter 2 deals with a brief review of literature on the gyroscope and the mechanism of its action. This section mainly focuses on the developments around these areas. Chapter 3 gives an overview of the historical development in the field of washing machines. This chapter focuses briefly on different kinds of washing machines that are developed so far, and an overview of the types of washing machines that are available in the market. The working principle of top loading washing machine is also given. In Chapter 4 the problem statement for the present investigation is given. In Chapter 5 the approach taken to address the problem is described. Chapter 6 presents different steps taken to analyze a dynamic mechanism using Pro-E Wildfire 5.0 CAD and Mechanism software. Chapter 7 deals with the details of the design and the selection process for various components and the magnetic field analysis for the gyro machine. Development of a fixture using parametric equations, fabrication, assembly, and installation of gyro machine is also covered in the same chapter. Discussion of results obtained from dynamic mechanism and high-speed photography are covered in Chapter 8. Further, it covers gyro machine's future potential industrial applications, such as washing machine based on the derived cycles, followed by the advantages of this machine. Conclusions of the present investigation and recommendation for future work are given in Chapter 9.

CHAPTER 2

LITERATURE REVIEW

2.1 Development in the Gyroscope

A number of gyroscopes were designed and developed for specialized applications. Most of them are used in the navigation of spacecraft, ships, and missiles. These gyroscopes are known as directional gyros. Nowadays, these systems are also used in advanced mobile phones, such as Apple's i-phone. However, mechanical gyroscopes are somewhat limited because of their size.

In 1817 Bohnenberger developed the first mechanical gyroscope [1], which he called gyro machine. The purpose in developing such a machine is for applications, such as surveying and navigation. In 1852, a French physicist, Leon Foucault, further developed the idea. He was the first to suggest the use of gyroscopes for indicators or special sensors to detect angular motion of rotating components. He noted that this type of application is possible by fixing one of the gimbals of the gyroscope. Many researchers started taking interest in the gyroscopic behavior and its applications. From 19^{th} century on, many researchers were involved in the application of gyroscopes. Many researchers came up with eye catching advanced applications of gyroscopes. From mid - 19^{th} century, based on these applications, modifications were carried out in gyroscopic instruments. A number of patents and articles were published in the literature.

This section gives a general overview of those findings and their industrial applications. The focus is on overview of different patents related to gyroscopic apparatus, mechanism design, and their applications. Design parameters, such as angular momentum, inertia, and damping coefficient are found to be important parameters that were taken into consideration while designing the gyroscopic instruments.

In 1951 Anderson developed a modified version of the gyroscope for spacecraft application [11]. He found that an error is involved in the vertical seeking gyro when carried out at high speed. Due to Coriolis acceleration, the gyroscope system aligns at false axis .

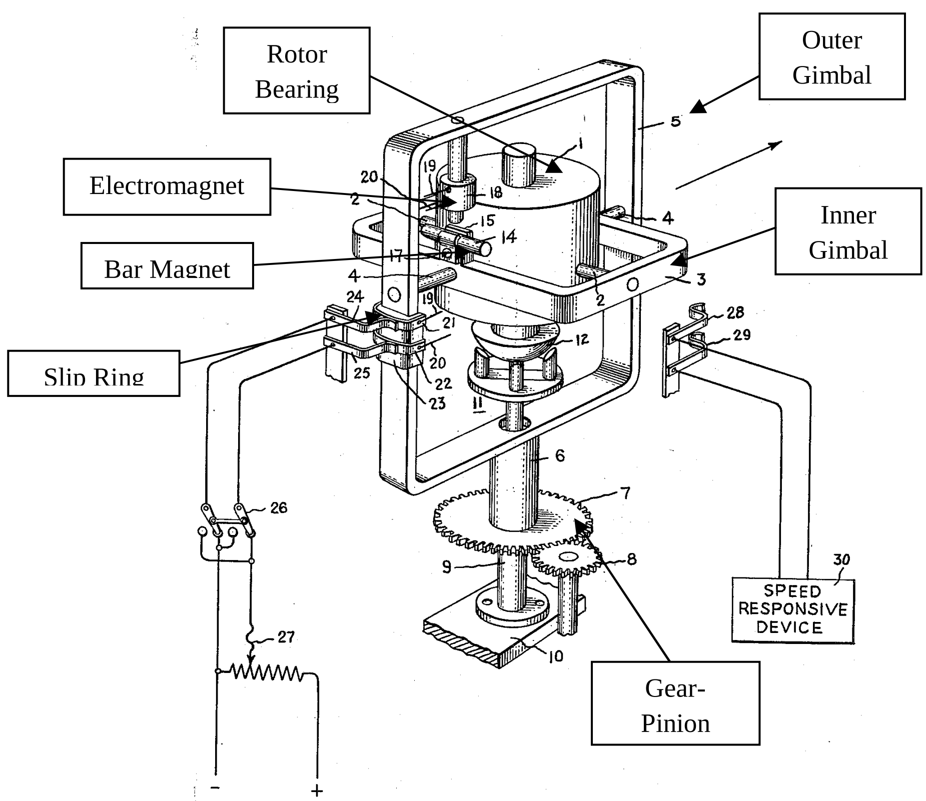
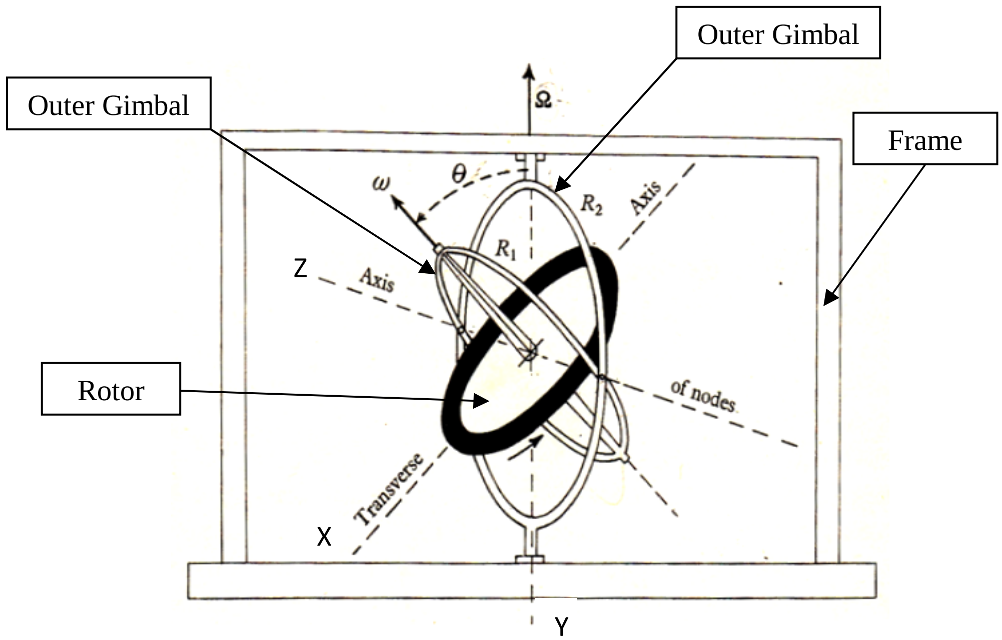


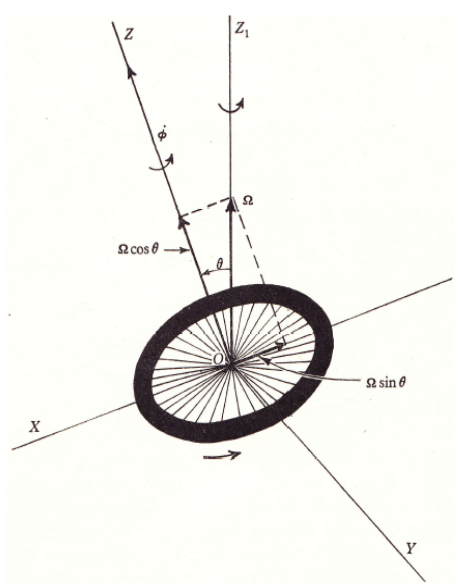
Figure 9 Gyroscopic instrument showing different elements of the system after Anderson [8]

When installed on a spacecraft and carried to high altitudes this error makes significant difference in the calculations. This error is overcome by providing equal and opposite impulsive torque on the inner gimbal. Figure 9 shows the modified version of the gyroscope. It consists of a rotor bearing mounted on the inner gimbal. The rotor is rotated by a conventional system (not shown in the figure). Inner gimbal was mounted on the outer gimbal. Gear pinion arrangement provided at the bottom rotates the outer gimbal. Precession of the gyroscope is achieved by providing a magnetic field with the help of electromagnets. Bar magnet is fixed on the inner gimbal and electromagnet on the outer gimbal as shown in Figure 9. Impulsive torque is applied by using attraction and repulsion between the electromagnet and the bar magnet. It is generated by reversing the current in the electromagnet. The timing to reverse the current is managed through a slip ring arrangement. So, in this invention, the errors due to Coriolis acceleration and vehicle speed in gyroscopic device with rotating gimbal systems is eliminated using impulsive torque application system on the inner gimbal.

In 1958, Scarborough developed gyroscopic equations based on steady and unsteady precession [12]. Figure 10 shows the general gyroscopic setup along with the schematic representation of the gyroscope at the steady state. In steady precession (Fig. 10 (b)), it was assumed that the gyroscope is spinning with constant velocity and torque acting on it is constant resulting in constant precession. In unsteady precession (Fig. 10 (c)), all factors are time dependent. Based on these assumptions, equations were developed to find the moments acting in the X, Y, and Z directions due to the effect of precession.



a)



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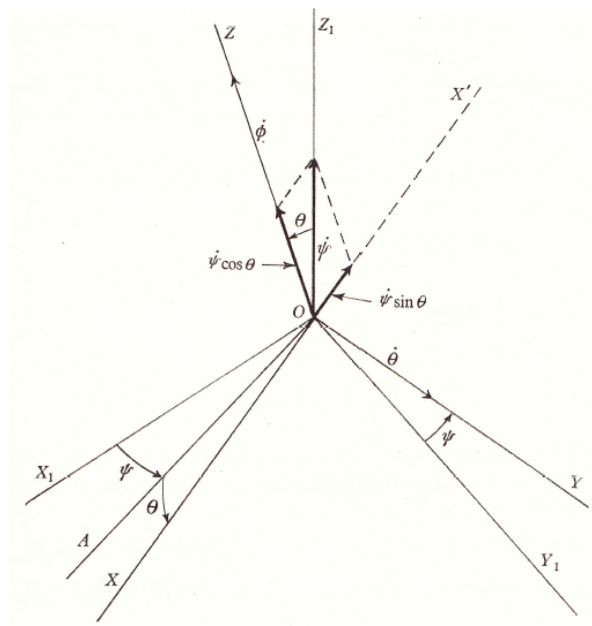


c)

Figure 10 (a) General gyroscopic setup (b) Gyroscope at steady precession

(c) Gyroscope at unsteady precession [12]

For steady precession, the following equations were developed:

$$M_x = 0$$

$$M_y = C\,\Omega\,\dot{\emptyset}\,\sin\theta \quad \text{or} \quad \Omega = \frac{M_y}{C\,\dot{\emptyset}\,\sin\theta}$$

$$M_z = 0 \qquad \text{….. (1)}$$

For unsteady precession, following were the established equations:

$$M_x = C\,\dot{\theta}\,\dot{\emptyset}$$

$$M_y = C\,\dot{\emptyset}\,\dot{\varphi}\,\sin\theta$$

$$M_z = C\,\ddot{\emptyset}$$

where,

$M_{x,}$ M_y , M_z : Moments acting in X, Y and Z direction respectively

C: The Moment of inertia of the disc,

Ω: The constant precessional velocity,

θ: The constant angle between inner gimbal and outer gimbal,

$\dot{\emptyset}$: Variable spin acceleration,

$\dot{\varphi}$: The Variable precessional velocity, and

$\ddot{\emptyset}$: The Variable Spin acceleration

Maintaining constant angular velocity of the rotor is the main challenge with gyroscope, especially when all three axes are rotating. In 1973, Mishler and Clakamas came up with an innovative gyroscopic device in which the speed of the rotor is controlled and can be increased manually [13]. Figure 11 shows a gyroscopic device. They concluded that the precession effect continues, unless and until there is spinning of the rotor. This spinning can be controlled by applying a torque manually in the reverse direction to that generated by the gyroscopic system. Normally, the ends of the spinning mass are rested on the bearings in fixed positions. In this device, the end shafts of the spinning rotor were guided in a groove made inside a ring. This way a rotor can rotate freely about its precession axis.

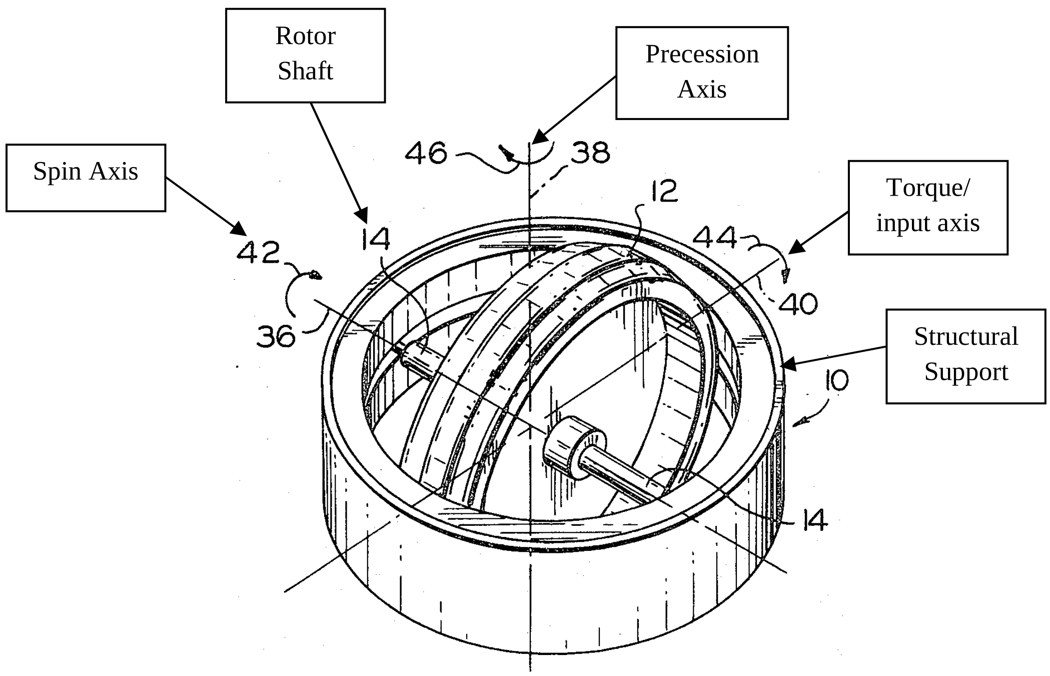


Figure 11 Gyroscopic device showing different elements after Mishler and Clakamas [13]

In 1975, Owens and Bishop [14] developed a modified version of directional gyroscopes. It is used in aeroplanes to help the pilot in finding the right directions. They developed a mechanism to reset the indicating dial without disturbing the axes of the gyro [14]. Their investigation included a special locking mechanism for the inner and outer gimbals to prevent misalignment with the axes of the gyro.

LaSarge in 1976 designed a gimbal control mechanism to dampen gimbal tumbling and to orient the axis of rotation of the gyro to the initial stage when it is not in operation [15]. It was found that the gimbal lock phenomenon is disadvantageous in the directional gyros, which are used to indicate angular rotations. When the spin axis is matched with the axis of the outer gimbal, gimbal lock occurs. To avoid violent and damaging rotation of the inner gimbal, cam follower mechanism was incorporated with a spring between the inner and outer gimbals. Figure 12 shows this mechanism which avoids gimbal lock. Cam follower mechanism with the circular bearing surface on top of it resists the inner gimbal in the opposite direction to that force generated by the system. It was noticed that implementation of the same mechanism between the outer gimbal and the frame makes the gyro system more stable and maintain the stability of the directional gyro system.

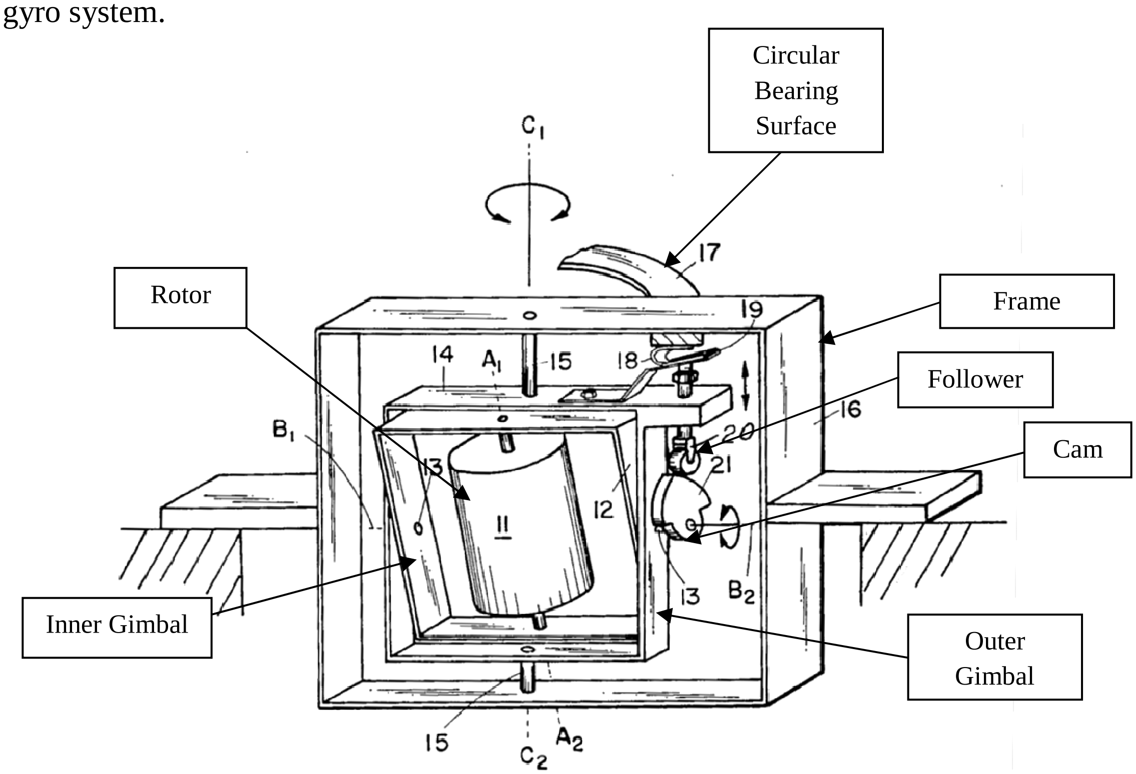


Figure 12 Gimbal control mechanism after LaSarge[15]

Virgil Hinds in 1979 introduced a gyroscopic system that can be applied for many applications. The system developed was mainly used to transfer constant torque in the power transmission system and hence was named Gyroscopic Power Transmission System. As per the gyroscopic principle, the oscillatory motion given to the spin axis will result in the precession oscillatory moment. The mechanism developed here works on the same principle. Figure 13 show different elements of this system. The rotor is rotated by an electric motor, and the motor and eccentric cam arrangement gives oscillatory motion to it. The output was taken from the precession axis. It was found that the system could generate constant average torque and can be used for different applications including machine tools, motor vehicle transmission systems, and for winches and elevators [16].

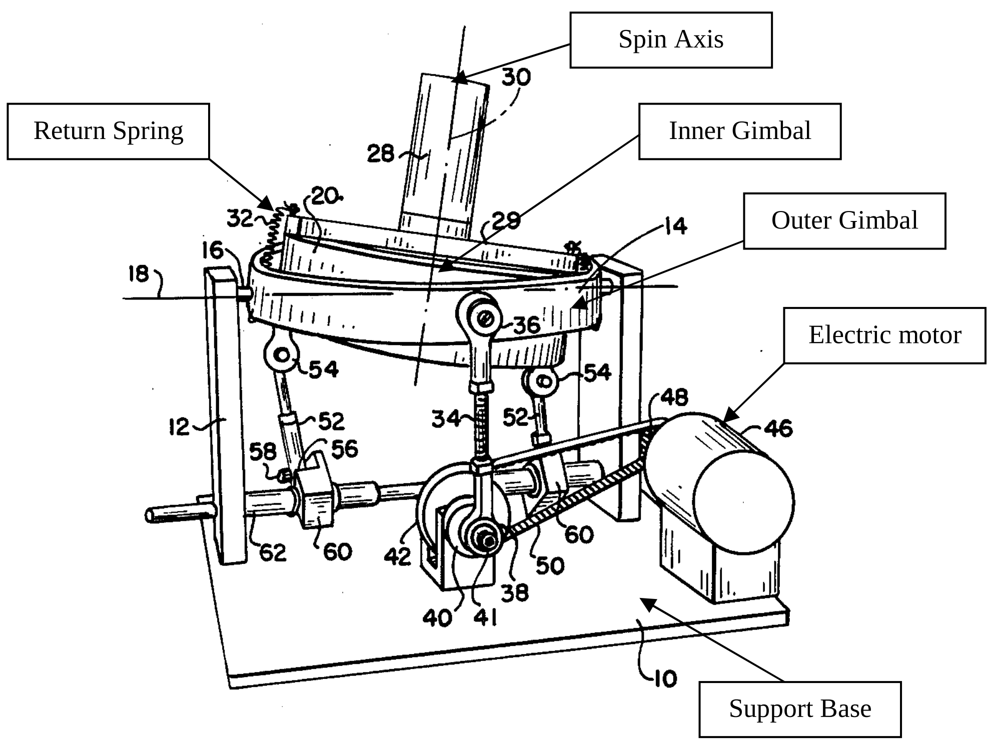


Figure 13 Gyroscopic power transmission system [16]

In 1980, Hoffman and Ferris [17] put forth efforts to reduce cost and weight of a gyroscope. They developed a three-axis gyro system for measuring angular rates of all three mutually perpendicular axes at the same time. They found the most promising application of this is in the guidance and navigating systems. They successfully replaced two gyros that were in use with just one reducing the cost and weight of the system.

In 1985 Werner came up with a simplified version of a directional gyro [18]. This apparatus was built with very few elements and yet the results obtained were accurate. The system consists of a rotor mounted on the inner gimbal. To add moment about the spin axis, a balanced mass was mounted below the inner gimbal. The result was precession of the outer gimbal. The pick off was mounted on the outer gimbal to measure the coarse angle. This instrument was found to be precise if used for coarse determination within short periods. Figure 14 shows a schematic of a directional gyro developed by Werner.

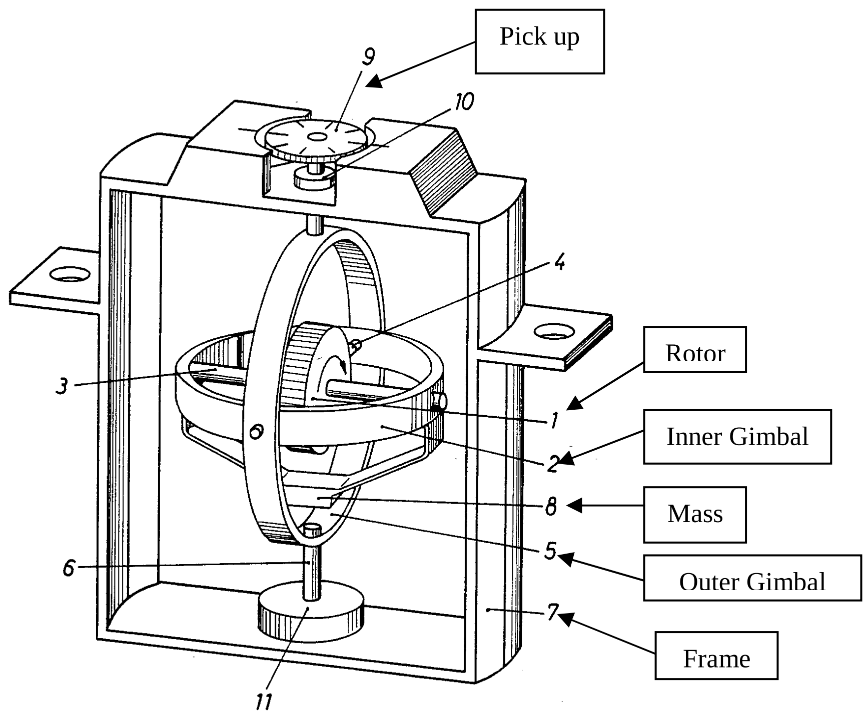


Figure 14 Directional gyroscope after Werner [18]

In 1985 Komanduri [19] came up with an idea to use a gyroscope for washing machines. He put forth an innovative idea to use a hollow sphere as the spinning mass that need to be mounted on the inner and outer gimbals. The clothes to be washed can be placed inside the hollow sphere. He stated that the use of hollow sphere with more than two degrees of freedom would mix the detergent with water more uniformly. In addition, there would be more effective cleaning of clothes because the sphere can rotate in all-possible directions. In 1995, he developed along with his students the first gyro system based on this idea at Oklahoma State University, Stillwater.

Cararelli and Sapuppo in 1999 designed an oscillatory gyroscope with a three gimbal structure [20]. They achieved close loop operation between the outer and the inner gimbals. They referred to it as a close loop gyroscope. They derived the output signal from the angular rotation of the inner gimbal.

Efforts were also made to use gyroscopes in automobiles. In 1930, Anderson found application of the gyroscope in the power transmission system but had a problem with the complexity of the system as it consisted of four different axes. In 1953, Taylor attempted to modify the system and ended up with having more flywheels. Consequently, not much research was carried out in this field since then because of complexity and manufacturing cost involved.

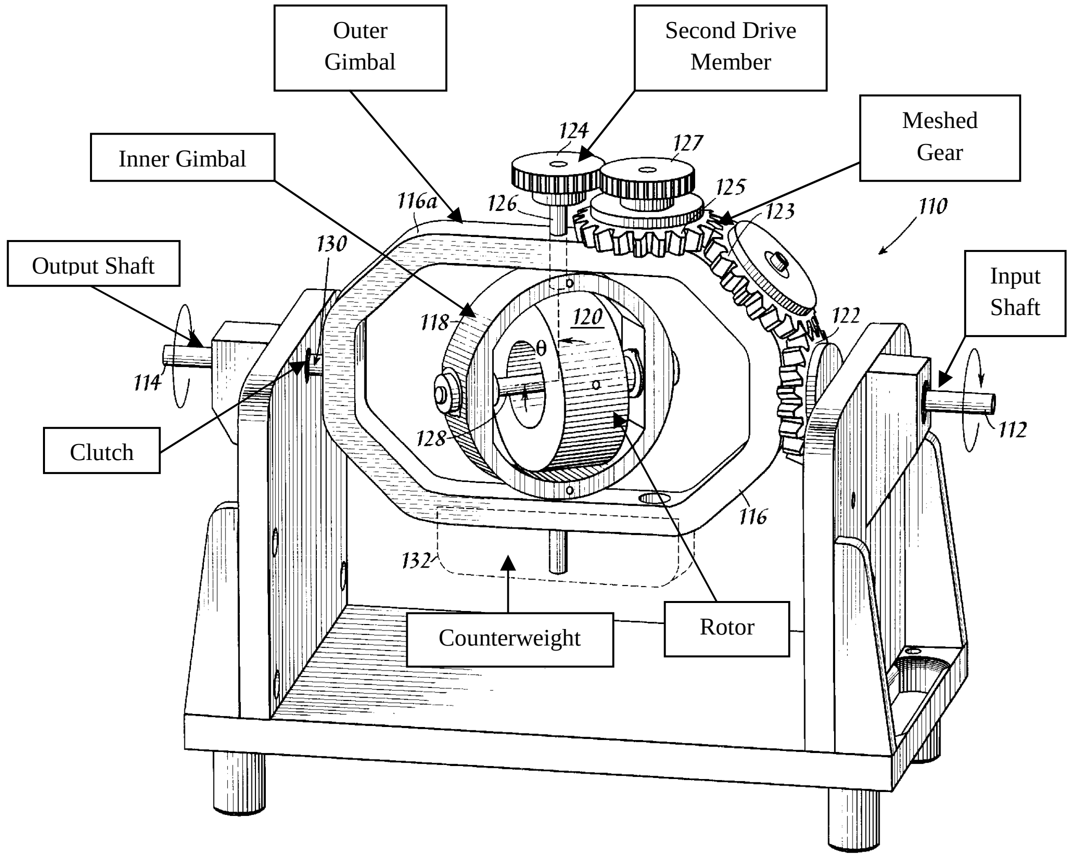


Figure 15 Gyroscopic torque converter showing different entities of the system after Adcock [21].

In 2003 Adcock came with an innovative idea to solve these problems [21]. He developed an efficient system with less complexity and low manufacturing costs. Figure 15 shows the gyro converter developed by Adcock. The system was built with the input shaft mounted on the outer gimbal. The motion was transferred from the input shaft to the inner gimbal with the help of meshed gear arrangement. The rotor was rotated by an electric motor. Precession takes place about the output axis, which was forced to rotate only in one direction due to a clutch arrangement. Likewise, power was able to transfer from the input shaft to the output shaft. They reported that a power of 180-horse power can be transferred via this arrangement.

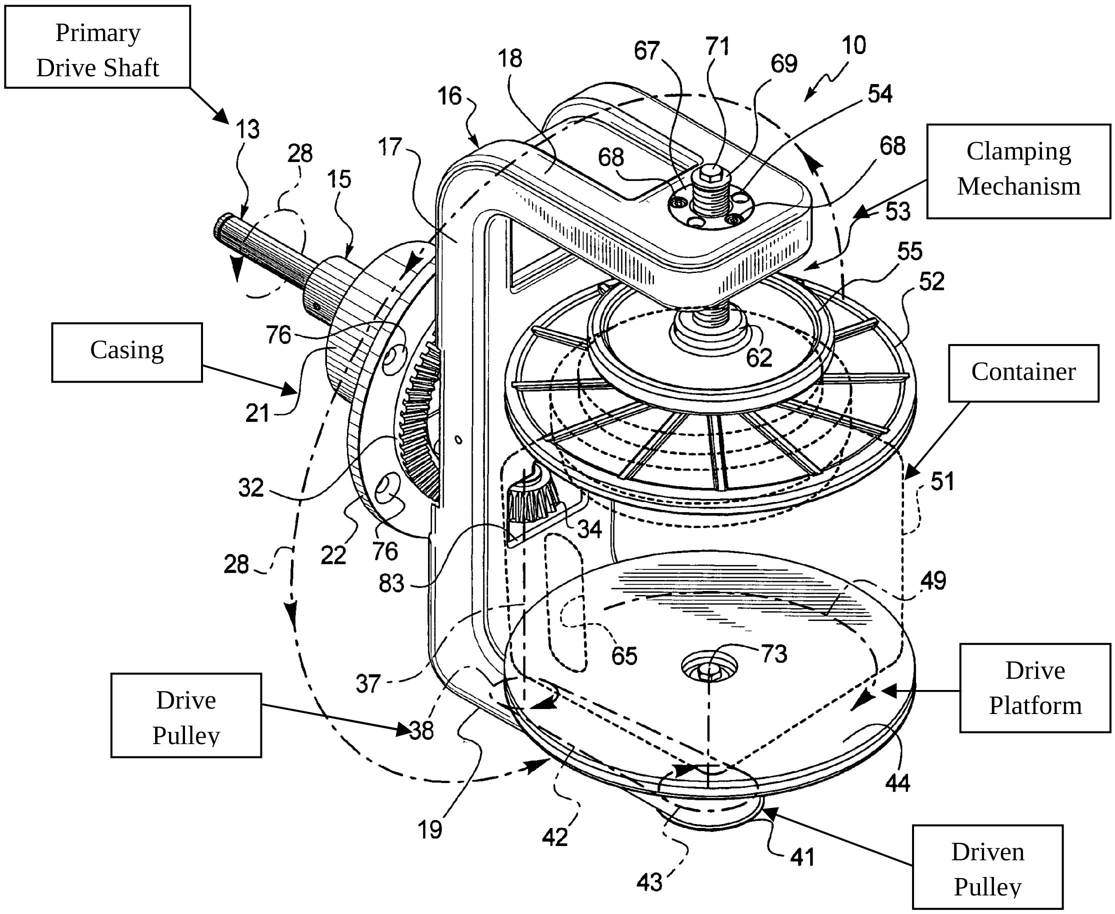


Figure 16 Various elements of the gyroscopic mixer after Sordelli and Miszenti [22]

In 2006 Sordelli and Miszenti developed a gyroscopic apparatus with two degrees of freedom [22]. They incorporate a unique feature of the gyroscope to mix different materials. They used this apparatus to mix the paints and are named it as the gyroscopic mixer. Figure 16 shows various elements of the gyroscopic mixer. They used only one input to provide the rotational motion to two mutually perpendicular axes. The bracket shown was designed to hold the container and is driven by a motor about its axis. A gear and pulley arrangement was used to transfer the motion from the first axis to the second.

A result spinning of the driven platform about a third axis takes place. They were able to provide gyroscopic rotation successfully with two degrees of freedom to the container. This machine was capable of incorporating a range of sizes of containers with different capacities as per the needs.

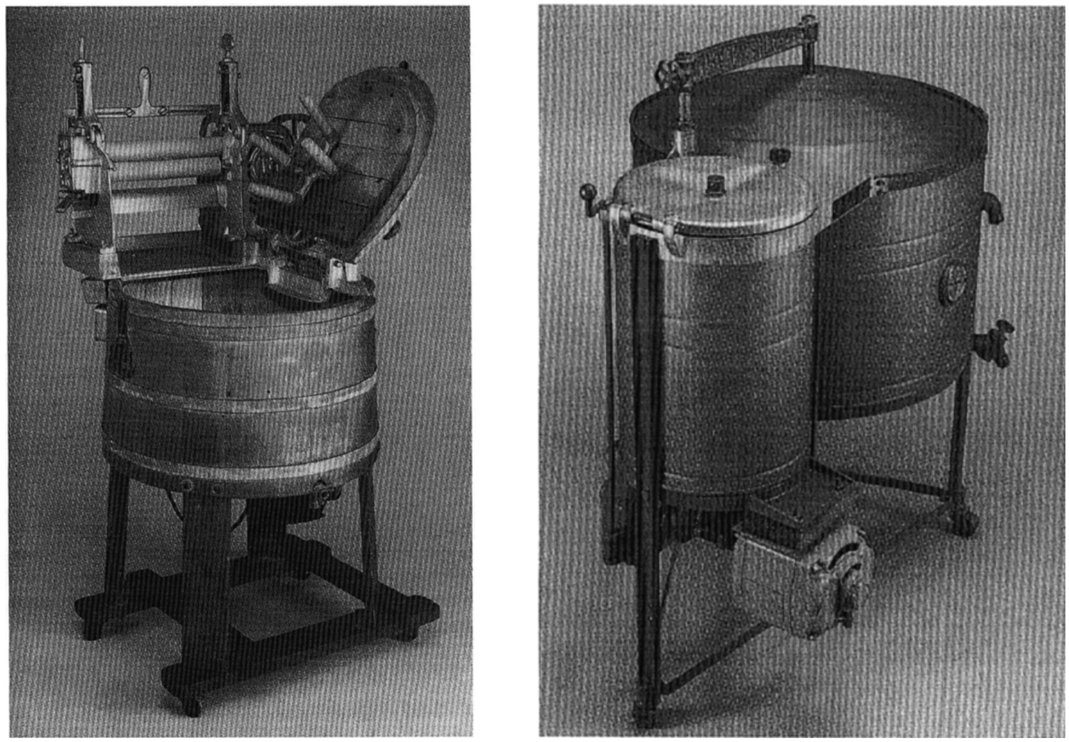
CHAPTER 3

DEVELOPMENT OF WASHING MACHINES

3.1 Introduction

Washing clothes manually involves high physical exertion. Before the invention of washing machine, clothes were cleaned by manual washing methods, such as scrubbing on hard surfaces (e.g. stones or scrubbing boards). In 1797, scrub boards were used for the first time to wash clothes. In 1851 James King came up with the first hand powered washing machine with a drum [23]. The drum was rotated manually with the help of levers. Between 1851 and 1871, many patents on washing machine were granted in Europe as well as in the United States. In 1874 William Blackstone [23] developed a manually driven wooden washing machine. In this, a lever was used to rub the clothes against the curved surface.

In 1900, in the United States, for the first time an electric motor was used to rotate the tub in the washing machine. The main problem with this machine is that motor was not protected from the dripping water from the tub. This caused short circuits and raised the questions on safety [24]. However, until 1920s manual washing machines were dominant. Figure 17 (a) shows a wooden domestic washing machine with a dolly-style agitator [25]. In 1932 due to the availability of electric power, the use of domestic washing machine as shown in Figure 17 (b) were common. Figure 17 (b) shows the Riby twin-tub washing machine with an electric motor attached at the bottom of the tub.



a) b)

Figure 17 a) Wooden Domestic washing machines with a dolly-style agitator 1920
b) Riby twin-tub washing machine, 1932 [25]

Inventors realized that washing clothes with hot water adds more cleansing effect in less time. Shipley [25] used for the first time gas burners to heat water. This type of provision was made in all washing machines until 1932. Inventors faced problems like tangling of clothes and heating of water by gas burners. The problem of tangling was solved by introducing oscillating motion. Between 1911 and 1951 different companies such as Maytag, Whirlpool, Bendix, GE, Miele, Bosch, LG, Samsung, Admiral, Amana developed different versions of washing machines. Bendix was the first to develop a machine that can perform different operations, such as washing, rinsing, and extracting water in a single operation [23]. In 1961, for the first time fully automatic computer controlled washing machines were introduced in Europe.

Initially, top loading models were popular in America and horizontal loading models in Europe. Figure 18 (a) shows a front loading washing machine and 18 (b) a vertical loading washing machine.

a) b)

Figure 18 a) Horizontal b) Vertical loading washing machine [25]

Most washing machines developed thereafter (1950 -2011) were based on the same principle of operation. Washing machine operation has been the same for many decades. Most of the advances deal with "bells" and "whistles" and some automation. These advancements in the past decades are either in terms of the changing the axis of rotation or in terms of the changing the speed and direction of rotation of the drums. In 2009, Kenmore came up with an innovative washing machine, which gives several motions to the clothes that are to be washed. They used fuzzy logic to control the motion of the drum. However, still the axis of rotation is the same and the difference was made by introducing the interruptions in the rotating drums.

3.2 General Working of Washing Machines

As pointed out earlier, two types of washing machines are currently available, namely, front loading and top loading. In both cases, the drum of the machine rotates on a single axis, either vertical or horizontal. The vertical axis rotating machines are vertical loading and the horizontal axis rotating machines are the front loading ones. There has not been a major advancement since the evolution of washing machines. It is primarily a single axis rotational movement provided for the washing as well as for drying of the clothes. The drums of these machines are essentially cylindrical in shape. In these washing machines, index drive motors are used. With the help of fuzzy logic, the rotation of the drum is controlled. Figure 19 shows different components in the washing machine. In the US, vertical loading washing machines are more popular.

As shown in Figure 19 vertical washing machine consists of an inner drum, an outer drum, and an agitator as the main parts. A motor is attached at the end of the cylindrical container. Agitator is the main part of the system as washing action including spinning and whirling experienced by the clothes is because of the rotating action produced by the agitator. In the case of horizontal washing machines, there is no agitator; the clothes are washed under gravitational effect. In both types of washing machines, different cycles are induced by controlling, indexing of the motor with the help of controllers.

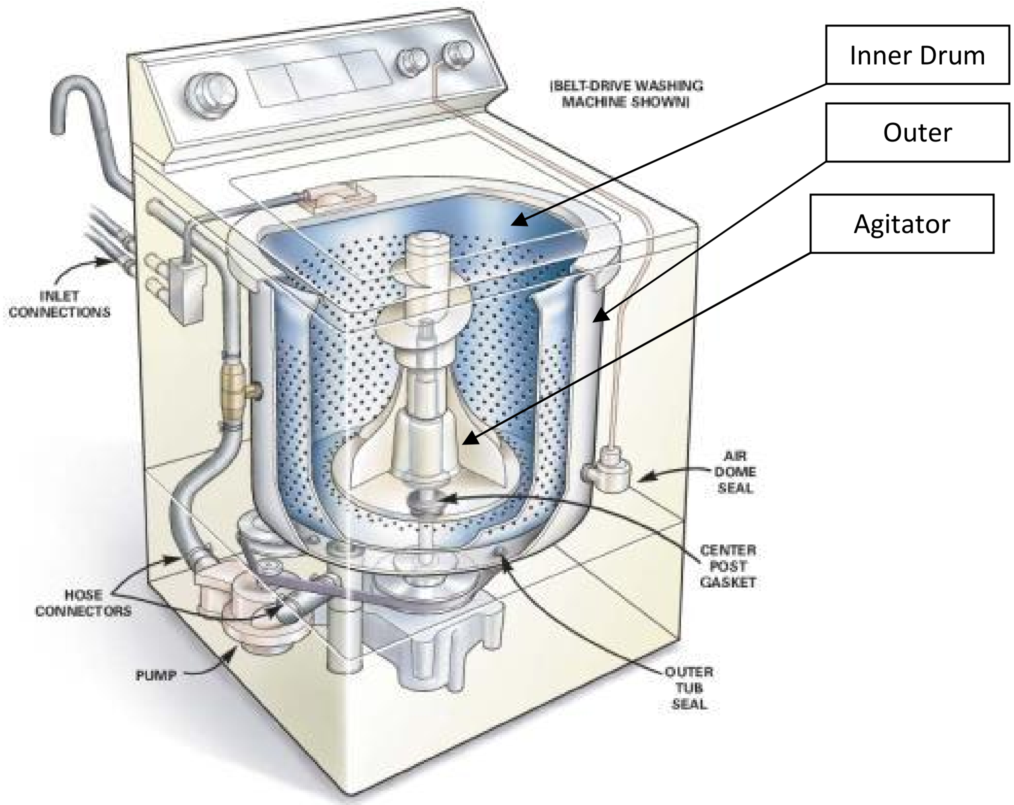


Figure 19 Inside view of a belt driven vertical loading washing machine [26]

CHAPTER 4

PROBLEM STATEMENT

From the literature review, it is clear that there has been considerable research and development work carried out in the field of gyroscopes. Research mainly focused on developing different gyroscopic equipment. That includes directional gyros for navigational and guidance systems, MEMS and laser ring gyros in the sensors for measuring angular velocities, mechanical gimbal gyros for automobiles for transferring power with a constant torque, and for mixing paints. The present study deals with mechanical gimbal gyroscopes. Gyroscopes have the ability to provide three degrees of freedom to the spinning mass to maintain its state of equilibrium. From the study made for the development of the washing machines, it is clear that there are no washing machines available in the market that have multiple degrees of freedom. Existing washing machines have one degree of freedom, either vertical or horizontal and is not interchangeable. So, it is clear that no efforts are made to provide more than one degrees of freedom to the container of the washing machine. Different cycles obtained within the machine are by either controlling the speed of the container or stopping and spinning it after regular intervals. Gyroscopic principle can be applied to wash clothes in a way that is more effective by providing three degrees of freedom.

Komanduri in 1985 [19] invented a gyro washing machine. It contains a hollow sphere as a spinning mass. Gyroscopic principles are applied to rotate and oscillate the sphere to wash clothes. To the knowledge of the author, no gyroscopic apparatus have ever been designed parametrically i.e. depending upon the size of the container, to determine the sizes of other components of the machine. This way the equipment can be easily scaled as per the size of the inner container of the gyro machine. So, all these factors would set a base for future studies to develop advance gyroscopic apparatus.

It is the primary aim of the present investigation to design and develop a gyroscopic apparatus that could rotate and oscillate a spherical container based on gyroscopic principle. An additional aim is to identify the capabilities of this machine that can be used for different industrial applications, such as washing machines. As pointed out in literature review Komanduri [19] had come up with such an innovative idea in 1985. A group of graduate students working under him at around 1995 started implementing this creative idea. The gyro machine started taking shape because of their efforts. They developed and fabricated various components of the machine including the frame, inner and outer gimbals, and aluminum sphere. They assembled various components of the gyro machine and were successful in achieving the required effect on the sphere by using the small battery operated motors having rubber wheels contacting the inner sphere, based on the gyroscopic principle. However, this is not practicable for commercial applications due to the limitations of generating small torques by battery operated motors and alignment issues related with them. Therefore, the task of obtaining more than two degrees of freedom at the sphere by rotating and oscillating based on the gyroscopic principle is the aim of the present study. The following tasks are proposed to accomplish the objectives set forth for this research.

1. Apply the principle of the gyroscope to design and build a gyro washing machine. Conduct literature review to investigate the work that has been done in the past and determine the efforts that are needed to make the apparatus unique. Develop a systematic approach by considering the working of the existing machine and based on that, modify the existing setup as needed to enable it to perform for the said application.

2. Use a mechanism based approach by considering the existing setup and the gyroscopic concept. Carry out dynamic mechanism analysis using Pro-Mechanism tool from Pro-Engineering Wildfire 5.0 software to save time and costs instead of conducting numerous tests in arriving at the optimum design.

3. To develop a mechanism-based gyroscopic concept and design if it is necessary to introduce additional components, or redesign the existing ones. Model all components with 2D drawings, select suitable material for each part, manufacture them if possible in-house or procure them if available off the shelf, assemble, and incorporate in the existing machine.

4. Conduct magnetic field analysis using COMSOL 3.2 Multiphysics FEM software to determine the magnetic field acting on the inner gimbal and its effect on the performance of the gyro machine.

5. Develop a computer controlled fully automated gyro machine using micro PLC based on the results obtained from the mechanism. Develop the logic for the controller from

the time profiles derived from mechanism to switch the polarities and to control the speed of the motor.

6. Study the motion of different components of the machine, especially the sphere and the inner gimbal using high-speed photographic technique. Compare them with the results obtained from the dynamic mechanism analysis.

7. Develop a systematic approach to design various components of the machine based on the size of the sphere using parametric relations.

8. Derive different washing cycles from gyro machine as a washing machine based on the variations obtained in the speed of the sphere for industrial applications.

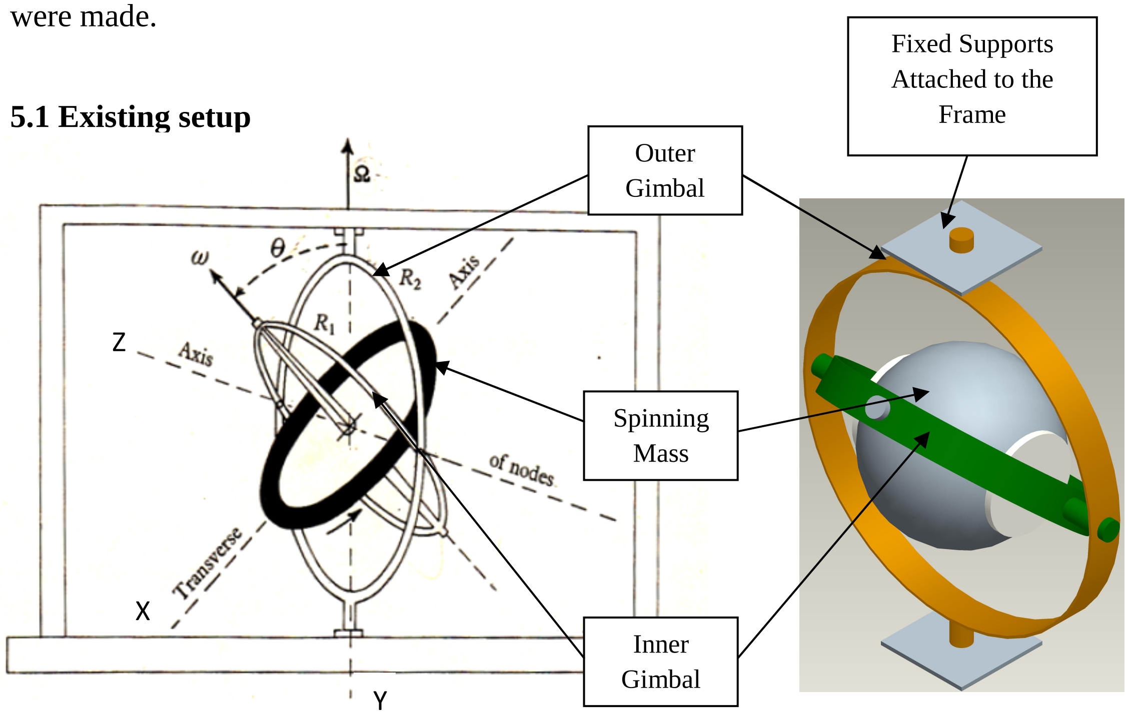
9. Point out the unique features in the performance of the gyro machine for washing clothes by comparing it with current commercial washing machines.

CHAPTER 5

STUDY OF EXISTING SETUP AT OSUAND METHODOLOGY USED

In this chapter, a systematic approach is developed using the basic working principles of the gyroscope to design, fabricate, and evaluate performance of the gyro machine. This chapter also considers the approach used by the previous group and problems associated with that setup. Different approaches were investigated to address these problems. The best approach was highlighted and based on that, further studies were made.

5.1 Existing setup



a) b)

Figure 20 (a) Principle of the gyro apparatus [12]
(b) Original concept by Komanduri [19]

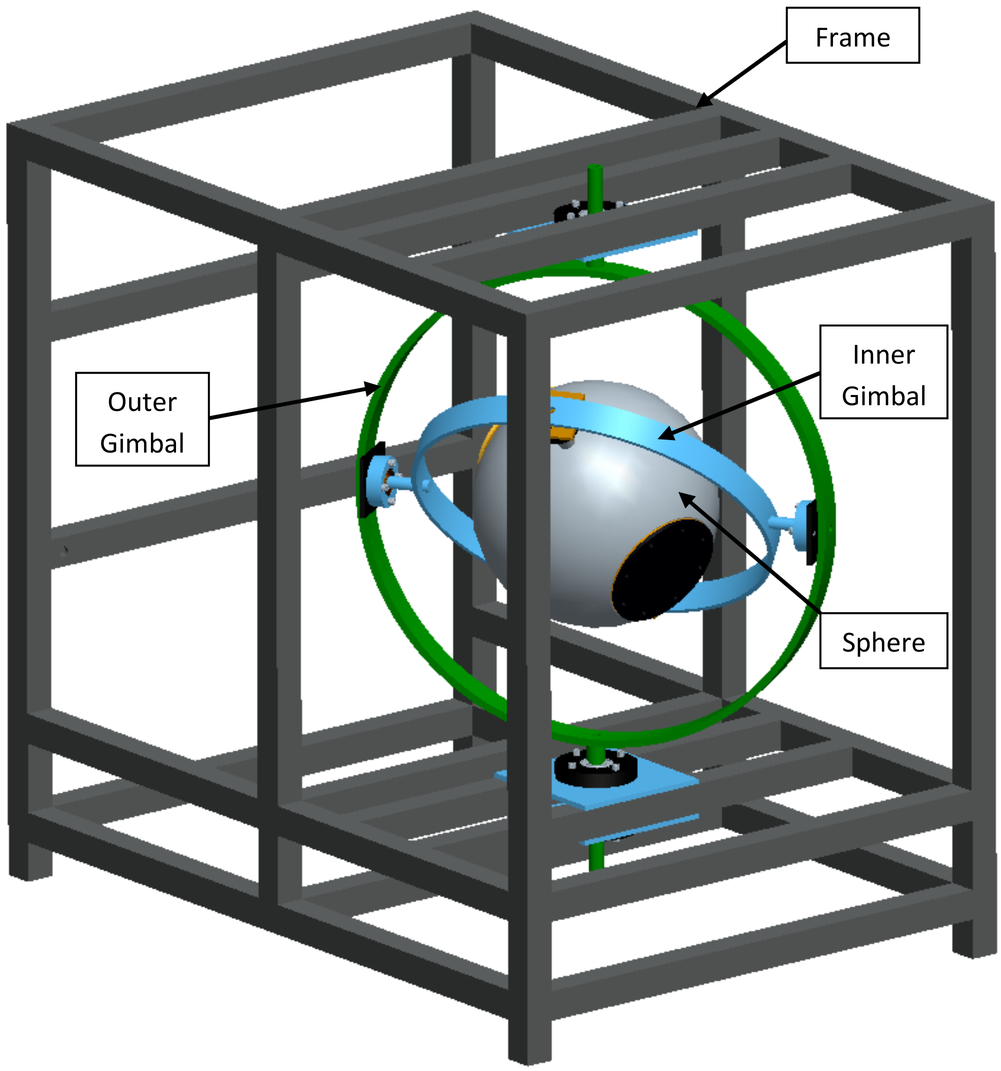


Figure 21 A 3D CAD Model of the existing gyro setup at OSU using Pro-E

The concept developed by Komanduri [19] is based on the schematic used by Scarborough to develop gyroscopic equation (1) [12]. Figure 20 (a) is a schematic developed by Scarborough and Figure 20 (b) is the original concept by Komanduri. It can be seen that the main difference between the two principles is that in the first case Figure [20 (a)] the spinning mass is a disc and in the case of Komanduri Figure [20 (b)] the spinning mass is a hollow sphere. Figure 21 shows a 3D CAD model of the current setup at OSU, (Refer to Appendix A for detailed part drawings). It can be seen, the original setup has a sphere mounted on the inner gimbal. The subassembly of sphere and inner gimbal was mounted on the outer gimbal. The frame supports all the components. The components were assembled in such a manner that a sphere can rotate about the three axes simultaneously. Battery operated, electric motors were used to drive the sphere and the outer gimbal, respectively (not shown in Figure 21).

Based on the gyroscopic principle presented in Chapter 1, the gyro apparatus has a spinning mass and input torque about the second axis. Under this, a spinning mass attempts to maintain its state of equilibrium by precessing about the third axis. Figure 22 shows the working principle in the vector format. It can be seen from Figure 22 that a torque is applied to unbalance the spin axis; precession takes place about the third axis. This is represented by the vector P, the cross product of the spin (S) and the torque vector (V).

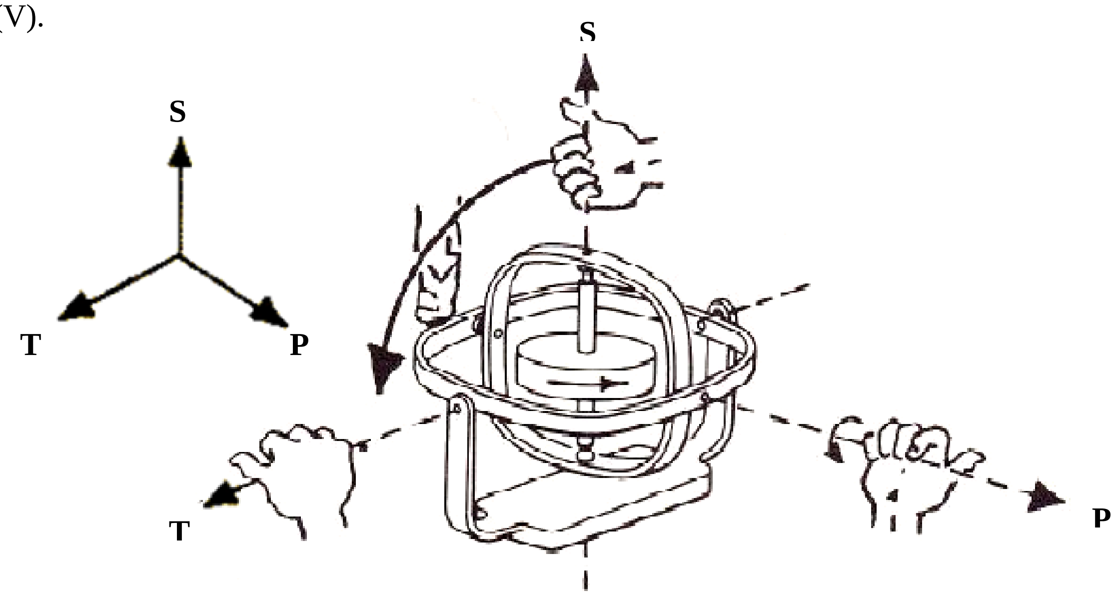


Figure 22 Vector representation of the gyro principle using the right hand rule [6]

In order to obtain the gyroscopic effect, there should be two different inputs to the gyro apparatus. The input to spin a mass about the first axis and another input to provide torque about a second axis perpendicular to spin axis. While building the setup at OSU (refer to Figure 21) the group used the same approach. The main target was to spin the spherical container (spinning mass) and provide the unbalanced force either on the inner gimbal or on the outer gimbal. They have used battery-operated motors to spin the spherical container (not shown in Figure 21) and provided torque by rotating outer gimbal about a second axis with the help of an electric motor (not shown in Figure 21). The main aim behind this was to obtain precession effect about the axis of the inner gimbal, which leads to three degrees of freedom to the sphere.

The main objective is to provide three degrees of freedom to the sphere, and it was achieved by rotating the three axes simultaneously. Here, they used a battery-operated motor to spin the sphere. They arranged two motors in diametrically opposite directions on the inner gimbal with the help of special designed fixtures. Rubber discs were mounted on the shafts of these motors with the main purpose of rotating the sphere by making tangential contact between the rubber discs and the spherical surface. Torque was applied on the axis of the outer gimbal with the help of a motor. Although it proved that, the concept this approach did not work out well because of several reasons. To rotate the sphere with a battery-operated motor using rubber discs which was not a practical method to spin the sphere. Continuous rotation to the sphere was not achieved due to slip between the rubber discs and the spherical surface. Maintaining alignment between the motor and the sphere was another challenge. Even though, if the concept worked out using battery operated motors, the spin of the sphere would be dependent on the life of the batteries. This sets a new base to search for an improved approach that could resolve the above problems.

5.2 Different Approaches

Based on the above discussion the main task is to find a way to spin the sphere and the outer gimbal to attain three degrees of freedom to the sphere based on the gyroscopic principle. As noted from the literature many researchers have spun gyro mass manually, or with an electric motor or with a special mechanism. With these ideas, they have ended up with building complex mechanisms. As pointed out earlier in almost all the cases a disc was used as the spinning mass. It was found that the outer gimbal can be rotated with the help of a motor but a way should be found to spin the sphere without modifying the existing setup. Therefore, every approach to rotate the sphere was considered and brainstormed. Different ways to spin the sphere are discussed in this subsection, and the best one was chosen for further study.

The first option is to spin the sphere manually. The difficulty with this approach is due to friction (resistance in the system) there would be a loss of speed of the sphere. To energize the sphere, one needs to stop the system and spin it physically every time. This would be an extra task. However, if this option is not chosen, then different ways to spin the sphere have to be considered, for example pneumatic or air driven.

The second way is to attach an electric motor to the sphere directly. This way a constant angular velocity can be provided to the sphere. This is one of the options that different researchers have considered in their mechanisms. However, this is not a good option as they ended up with complicated mechanisms with slip rings installed on them and other electrical components involved. In the present study, even if the motor is mounted to rotate the sphere on the inner gimbal, as all the axes are moving the motor would also rotate and that could lead to a complicated mechanism and prompt for a safer design.

The third option considered to drive the outer gimbal with a motor and by using the same input, drive either the sphere or the inner gimbal. Anderson [11], Willi [21], Sordelli and Miszenti [22] have implemented this idea by either providing a belt and a pulley arrangement or gear mesh arrangement. In the later, speed of the sphere would be dependent on the ratio of gears. In the present study, with the existing setup, this kind of gear mesh arrangement would be complicated because of the constraints imposed by the size of the frame already fabricated as part of the machine.

After brainstorming and different trial and error runs, it has found that flywheel approach was useful. Rotating the outer gimbal and sphere, with just one input by using a belt and a pulley arrangement can accomplish the set task without too many modifications to the existing setup.

5.3 Flywheel Approach

Flywheel works on the concept of storing energy in its initial stage and utilizing it over the entire period. The same concept can be implemented here, by treating the sphere as a flywheel. To energize the sphere, gimbal lock concept can be used. When the spin axis coincides with the axis that is perpendicular to it, then gimbal lock occurs. In this, the outer gimbal rotates due to the motor attached with a belt and pulley arrangement. With a gimbal lock, the spin axis coincides with the axis of the outer gimbal. When the outer gimbal starts rotating and as the axis of the sphere is aligned, sphere starts getting momentum slowly and after some time it starts spinning.

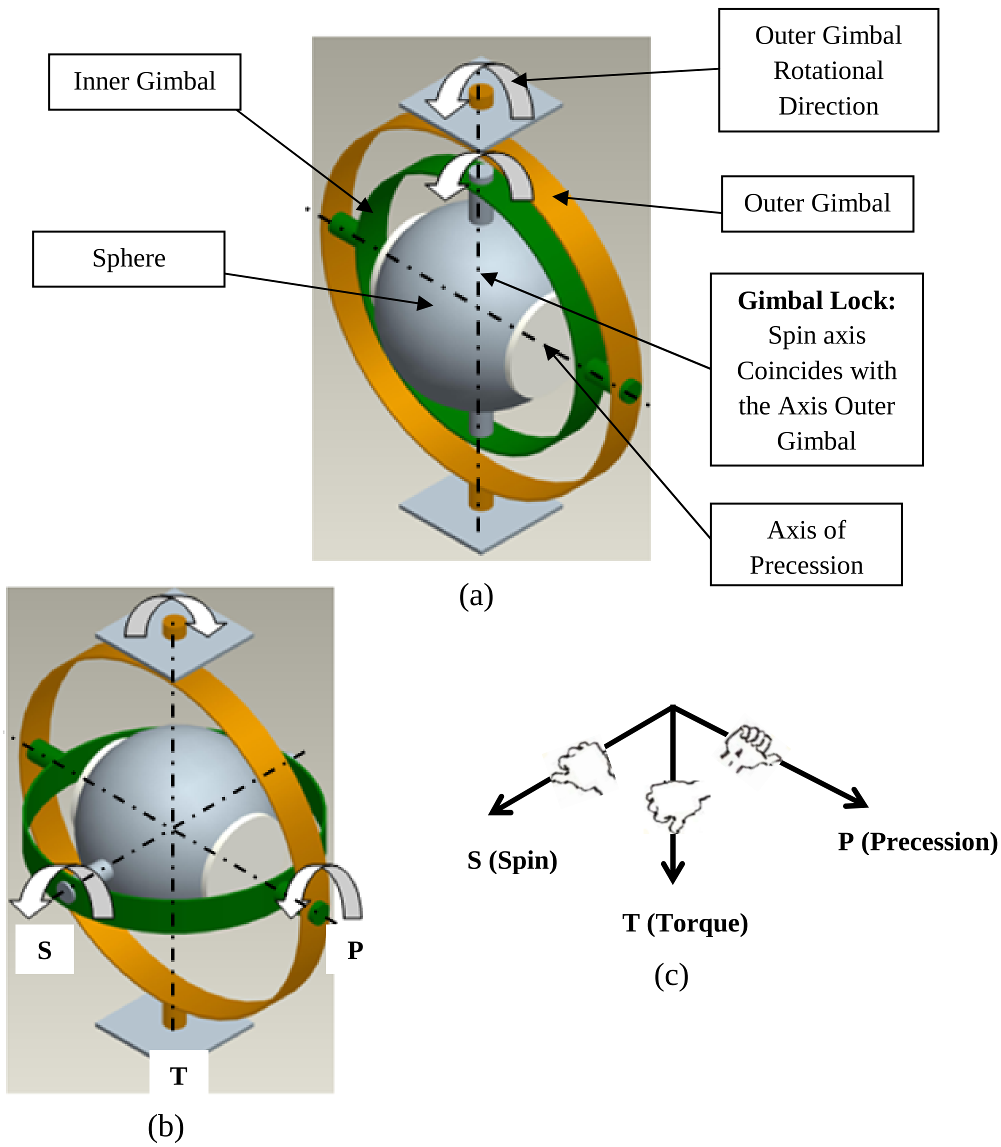


Figure 23 Flywheel concept (a) Energizing cycle (b) Gyroscopic effect (c) Vector representation using right hand rule

As shown in Figure 23, the flywheel concept can be implemented by providing gimbal lock at the start of the cycle. As Figure 23 (a) shows, the axis of the sphere is aligned with the axis of the outer gimbal. When the outer gimbal starts spinning it slowly transfers the momentum to the sphere and after some time the sphere starts spinning. Once the sphere acquires enough velocity, the outer gimbal is rotated in the opposite direction to that of the initial rotational direction. As soon as the direction is changed, the inner gimbal is free from gimbal lock due to gyroscopic torque acting on it. To maintain the state of equilibrium, the system starts precessing about the inner gimbal and the system acquires the position as shown in Figure 23 (b). The vector representation is shown in Figure 23 (c).

Further, it was found that flywheel concept could be applied successfully with minimal modifications to the existing setup. In this case, the sphere needs to be spun periodically. As the sphere is given angular velocity only when it is in a vertical position, over the period due to the resistance offered by the system it may lose its velocity. So, some provision should be made to set it back. It was found that a torsional spring could serve this purpose in setting back the system from the stage as shown in the Figure 23 (b) to the stage shown in Figure 23 (a). Before implementing this concept directly on the existing setup, the mechanism-based approach was taken. Chapter 5 deals with the building of a mechanism based on the flywheel concept.

CHAPTER 6

MECHANISM BUILDING & ANALYSIS

In 1995 a graduate research team working under Dr. Komanduri had started building the gyro washing machine along with the principle of gyroscope [19]. They fabricated the components of the apparatus: including the frame, the outer and inner steel rings, and a hollow aluminum sphere. The main objective of this section is to reverse engineer these components to build a 3D model using Pro-Engineering Wildfire 5.0 software, and to verify the approach of a flywheel using mechanism as discussed in Chapter 4. While building the mechanism, focus was to adapt the already-constructed apparatus, instead of building a new one from scratch, since it will result in considerable savings in time and cost.

In the present investigation Pro-E Wildfire 5.0, a 3D modeling software was used. In most industries, this software is used to create 3D and 2D drawings. It is capable of performing both mechanism and FEA analysis. Figure 24 shows the integrated mode of Pro-E software.

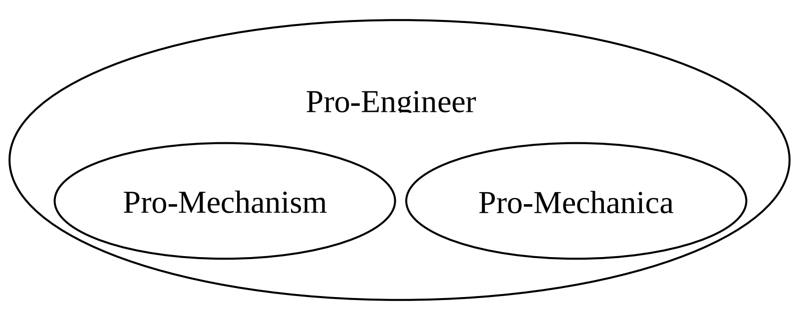


Figure 24 Integrated modes in Pro-Engineering

As shown in Figure 24, Pro-Mechanism is an integrated mode of Pro-E software. It can perform static (kinematic) as well as dynamic mechanism analyses. The forces generated from this analysis can be further analyzed using Pro-Mechanica software to perform FEA. In this investigation, this software is used to create a 3D model and 2D drawings, and to develop a dynamic mechanism. It is further used to validate whether the assembly and movement of components are as per the design intent or not, to check the effect of speed on different components, to select proper spring and damping coefficients, etc.

6.1 Mechanism Design Process

Mechanism building starts with constructing a mechanical design process. It consists of three major steps. The first step includes model building, followed by the second step, mechanism analysis, and finally the third step, obtaining the results. Mechanism building in the present study is based on such a mechanism design process. Figure 25 shows this process in the form of a flowchart. Based on the input, a 3D model is created using Pro-E software. Observations are made to check whether the motion obtained is as per the design intent to proceed to the further analysis part; or, if not, then the necessary changes are made and further analysis is carried out.

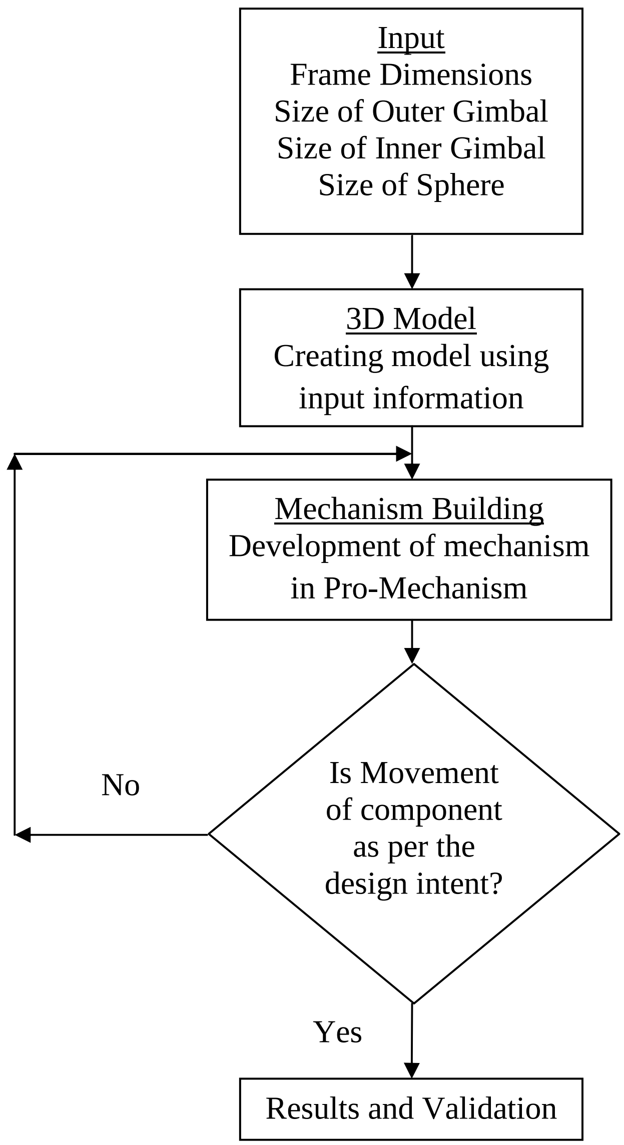


Figure 25 Flow chart for mechanism design process

6.2 Model Building

Before starting with building of a mechanism, it is necessary to have the 3D model of the existing setup. As mentioned earlier, major components of the Gyro machine were already fabricated and assembled. Building a 3D model based on this existing setup was the main objective before starting with the actual mechanism building. 3D modeling was done using the reverse engineering approach.

Reverse engineering technique is used where CAD models are unavailable and existing components need to be modified. The complex parts are normally reverse engineered using 3D position digitizers [27]. The data from these 3D digitizers is transferred to the CAD software where the 3D model is created from this provided input. These days advanced 3D digitizers directly create the 3D model of the part while generating data, which can be processed and modified further as per the requirement by using 3D CAD software's. However, the main disadvantage of using such software is cost.

In the present investigation, there is no need to use such costlier technology, as components fabricated are not complicated as far as the geometry is concerned. Furthermore, there are fewer chances to make errors while measuring the dimensions manually. Most of them, such as inner gimbal, outer gimbal, and sphere were readily available in the market. So, instead of using 3D digitizers, the measurements of gyro frame, inner gimbal, outer gimbal and sphere were taken manually. Based on the dimensions, rough sketches were generated. Using Pro-E Wildfire 5.0 software and from rough sketches, 3D models of different components along with their 2D detail drawings were generated. 3D model and 2D drawings of the gyro frame, outer gimbal, inner gimbal, sphere, bearing housings and supporting plates generated by reverse engineering technique are given in Appendix A.

6.3 Mechanism Development

Mechanism development consists of different steps such as deciding DOF, defining connections, loads and drivers. These steps are discussed in this subsection.

6.3.1 Degrees of Freedom (DOF)

The degree of freedom (DOF) is the first consideration in the development of the mechanism. Before starting with any mechanism building, DOF of any mechanism should be decided first and then controllers and motors are assigned [28]. In 1875, Reuleaux realized that the relative motion between rigid bodies depends on the connections between them and classified as mechanisms and kinematic chains [29]. Chebyshev, Sylvester, and Gruebler [28] developed a link-joint relationship to find the degrees of freedom of the planer system. As per this criterion, the system in plane has maximum three degrees of freedom. This relation is widely known as Gruebler's criterion. The equation to calculate the DOF of system in space is developed by Kutzbach [28]. As per this criterion the system in space has maximum six DOF and is stated as,

$$F = 6\,(N - 1 - J) + \sum_{i=1}^{J} f_i \qquad \text{............. (2)}$$

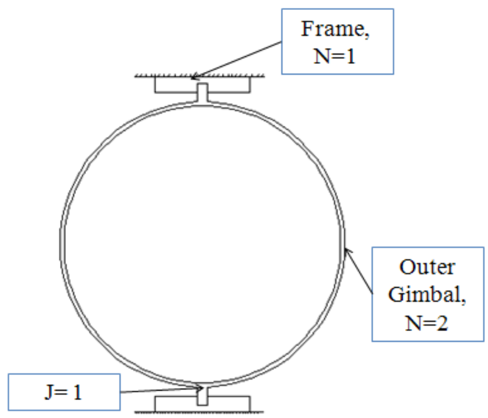
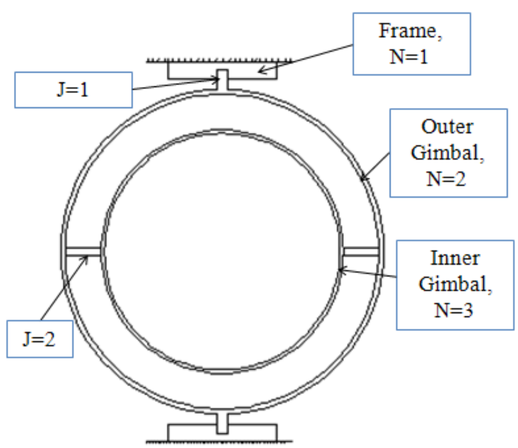
where,

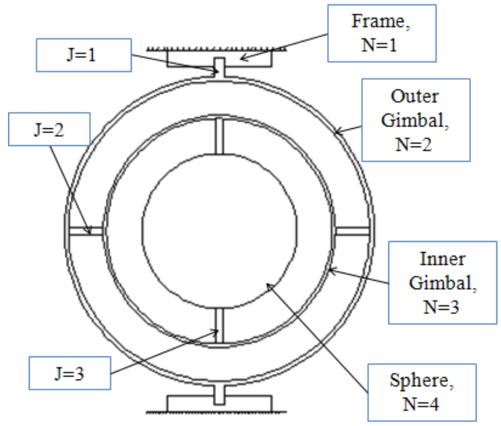
F = Degree of freedom, **N**= Number of links,

J = Simple joints in chain, **f** = degrees of freedom of i th joint

In any gimbal gyroscope, the rotating mass is connected in such a way as to get three DOF. In the present study, concerning the existing setup, DOF for each entity was decided. Once DOF was decided, connections were made to build the mechanism. Equation 2 was used to calculate DOF for different entities of the system namely, outer gimbal, inner gimbal, and sphere. The 2D sketches for each one of them are shown and the DOF calculated as follows depending upon the number of links and joints.

Table 1 Degrees of freedom calculations

Name of Entity	2D Sketch	DOF
Outer Gimbal		N = 2, J =1 $F = 6\ (2 - 1 - 1) + f_1$ $F = f_1 = 1$ DOF = 1
Inner Gimbal		N = 3, J =2 $F = 6*(3 - 1 - 2) + f_1 + f_2$ F = 1+1 = 2 DOF = 2

Name of Entity	2D Sketch	DOF
Sphere		$N = 3, J = 2$ $F = 6*(3 - 1 - 2) + f_1 + f_2 + f_3$ $F = 1+1+1 = 3$ DOF = 3

As shown in Table 1, degrees of freedom for different elements were determined. From the sketches, it is clear that outer gimbal is connected to the frame. So, overall it has two links: namely, the frame and the outer gimbal. In addition, there is only one joint between them. This joint has total five constraints, as it can only rotate about the vertical axis. So, when calculated with Kutzbach criterion, the outer gimbal has one degree of freedom.

Similarly, the inner gimbal has three links: namely, the inner gimbal, the outer gimbal, and the frame. Inner gimbal is connected to the outer gimbal, and the outer gimbal to the frame. So, overall there are two joints. As explained above, the joint between inner gimbal and outer gimbal also has five constraints. Thus, it has only one degree of freedom, and it can rotate about the horizontal axes. As it is connected to the outer gimbal, which has one degree of freedom, the inner gimbal has two degrees of freedom with respect to the frame, and only one with respect to the outer gimbal. As a result, it can rotate about itself and about the vertical axis of the outer gimbal. The sphere, connected inside the inner gimbal has four links: namely, the sphere, the inner gimbal, the outer gimbal, and the frame. In addition, the sphere is joined to the inner ring, the inner ring to the outer gimbal, and the outer gimbal to the frame, as discussed before. So, as per Kutzbach, it has three DOF with respect to frame, two with respect to outer gimbal and one with respect to inner gimbal. The sphere can rotate about itself, about the axis of the inner gimbals and about the vertical axis of the outer gimbal, and this results in the rotation in all possible ways.

6.3.2 Connections

Once DOF are determined, the mechanism can be built using Pro-Engineering Wildfire 5.0 software. Connections between different links or entities determine independent movements, which is nothing but the degrees of freedom. Every connected body has six DOF, includes translational and rotational motion in three axes. Figure 26 shows some of the basic joint symbols that are normally used to represent the connections between different bodies.

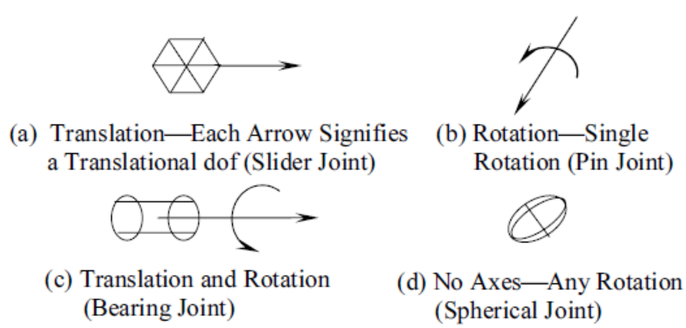
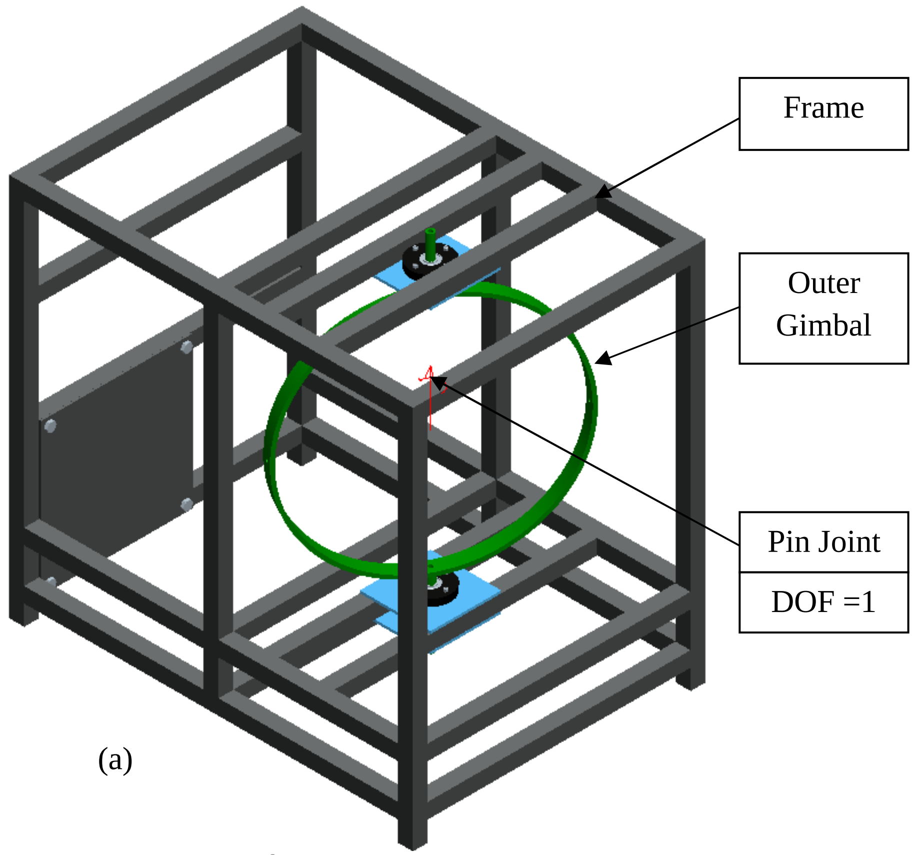
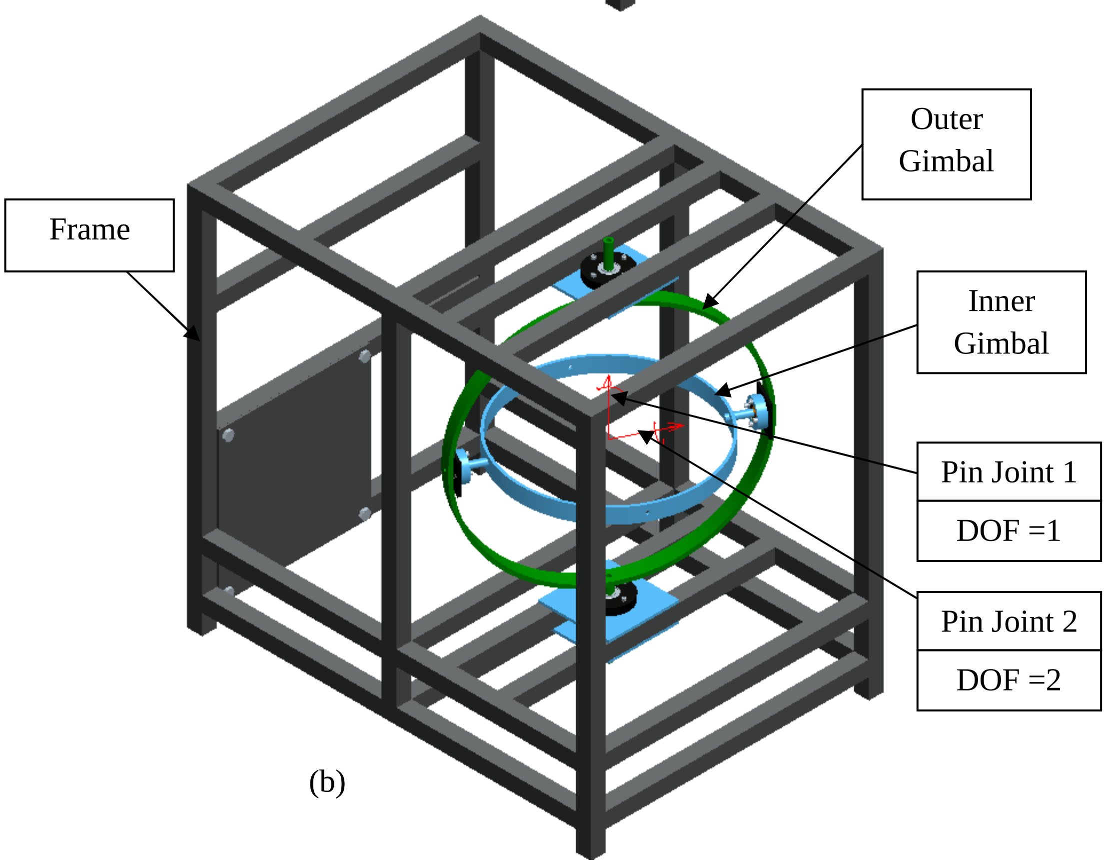


Figure 26 Basic joint symbols [10]

Based on calculated DOF the connections between the frame, the outer gimbal, the inner gimbal, and the sphere were made. In all these connections, pin joints were used. All these entities were connected in the pro-mechanism.


Frame
Outer Gimbal
Pin Joint
DOF =1
(a)


Frame
Outer Gimbal
Inner Gimbal
Pin Joint 1
DOF =1
Pin Joint 2
DOF =2
(b)

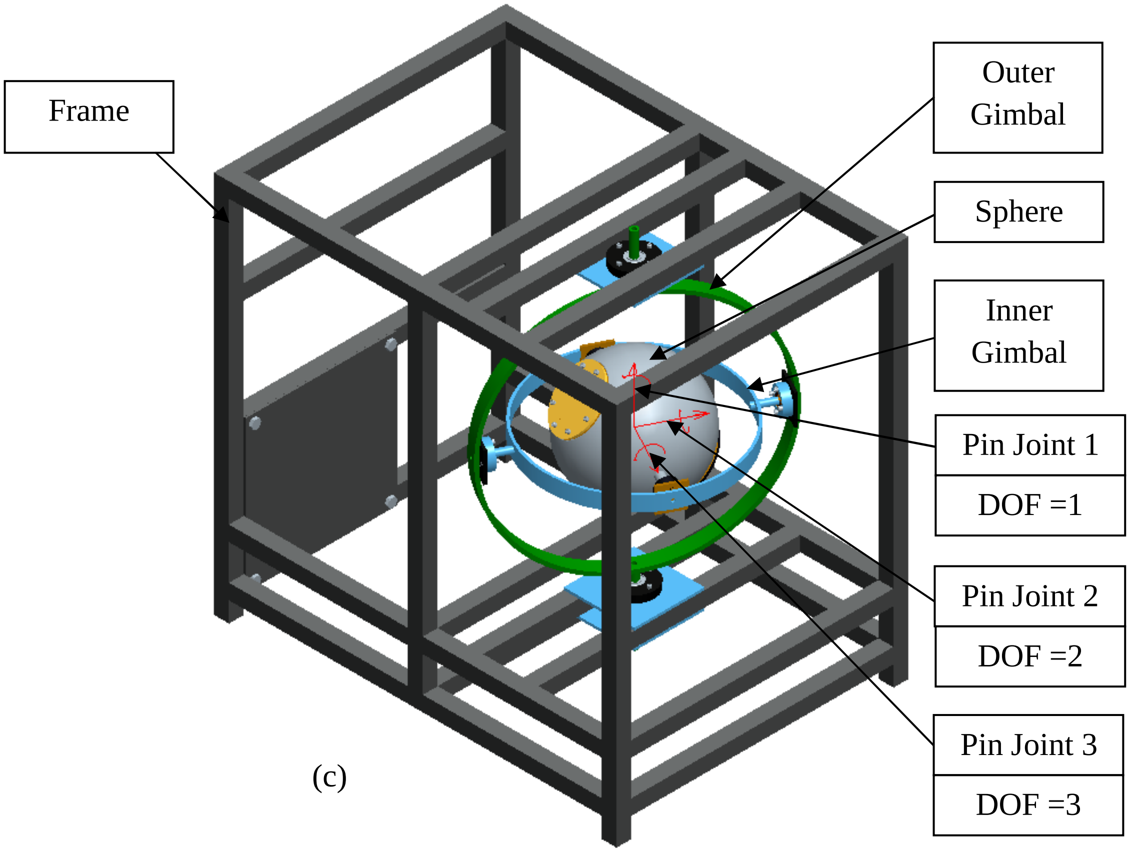


Figure 27 Connections in the gyro machine (a) Frame and outer gimbal (b) Frame, outer gimbal and inner gimbal (c) Frame, inner gimbal and the sphere

6.3.3 Selection of Torsion Spring

As discussed in Chapter 5, to implement a flywheel approach, torsion springs are used. The main objective of using the torsional spring is to provide gimbal lock in the initial phase of the system. Another task is to help the inner gimbal to achieve the original vertical position in a shorter time when it settles down to 90°. Selection of torsion spring was dependent on the weight of the system, as well as on the space available for its installation. It may be noted that there were some mounting restrictions in the selection criteria of the torsion springs due to fabricated setup and the set task to use the existing setup with a lesser number of modifications. The following steps were taken in order to select proper torsion spring.

6.3.3.1 Space Criterion

An inner gimbal was connected on the outer gimbal by shaft and bearings arrangement. Torsion spring would be more effective if installed on the shafts, not only on one side, but also on both sides of the inner gimbal.

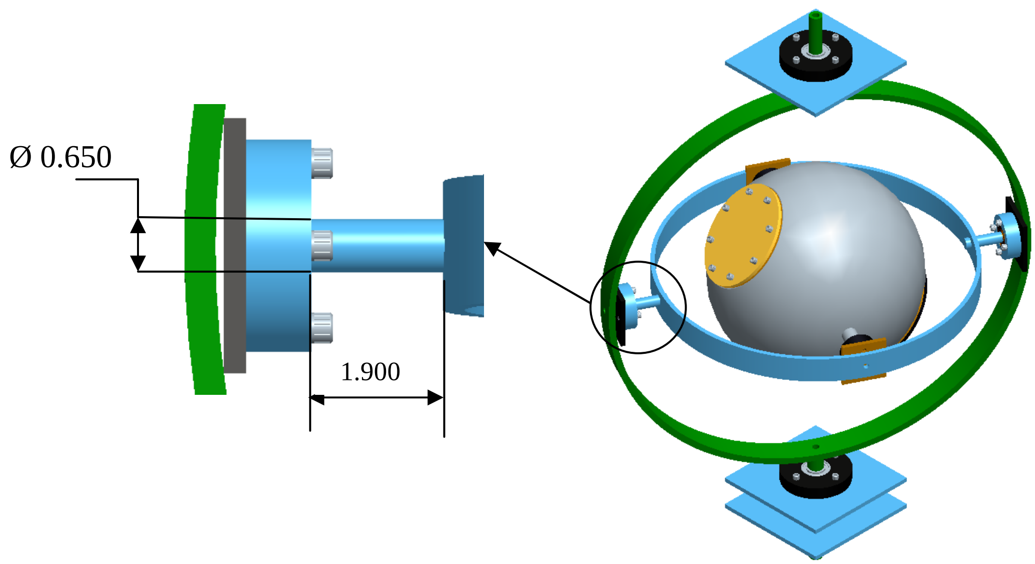


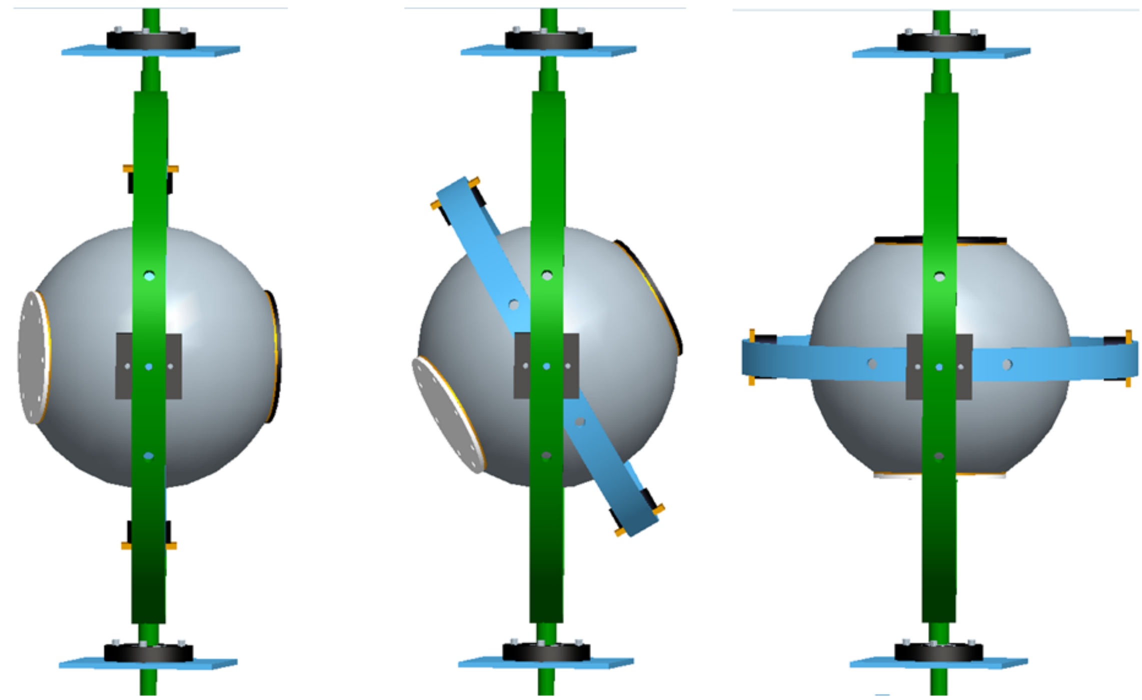
Figure 28 Selection of torsion spring on space criterion

It was observed that the gap (space) available between the bearing housing and the inner ring was 1.9 " and the shaft diameter was Ø 0.650 " as shown in Figure 28. Therefore, the selected torsion spring should have spring length at applied torque less than the specified spacing, and the diameter greater than the mentioned shaft diameter. A systematic approach was developed in Chapter 6, where a special fixture was designed to arrest the legs of the torsion spring. In the Pro-mechanism mode, torsion springs can be defined directly at the pin joint; so, there was no need to develop special fixture at this initial stage of a mechanism.

6.3.3.2 Load Carrying Capacity:

Load carrying capacity was the main criterion that should be taken into consideration while selecting a torsion spring. The selected spring should be able to take a sufficient load and return to its original stage when that load is removed. If this criterion were not taken into consideration, then there would be a failure of the torsion springs after a finite number of working cycles. It was noted from the gyroscopic equation developed by Scarborough (Equation 1) that the gyroscopic effect was more pronounced when all the three axes of the system are mutually perpendicular to each other. Figure 29 shows the position of an inner gimbal at different angles. It was observed that in the present study the torsion spring carries the maximum torque when the inner gimbal is horizontal. Once the inner gimbal is free from the gimbal lock due to gyroscopic torque, it attains the horizontal position under the effect of centrifugal force. At the higher speed of the outer gimbal, centrifugal force is more dominating than the gyroscopic couple acting on the inner gimbal.

Figure 30 shows the effect of centrifugal force acting on the inner gimbal. Magnitude of the centrifugal force acting upon the inner gimbal is more dominant than any other force acting on the system. Position of the torsion spring was fixed on both shafts of an inner gimbal. With this kind of arrangement, it was found that the maximum load acting on the torsion spring was the combined weight of the inner ring and sphere.



a) Inner gimbal at rest (Gimbal lock)

b) Inner gimbal at an angle θ

c) Inner gimbal θ=90°

Figure 29 Different inner gimbal positions

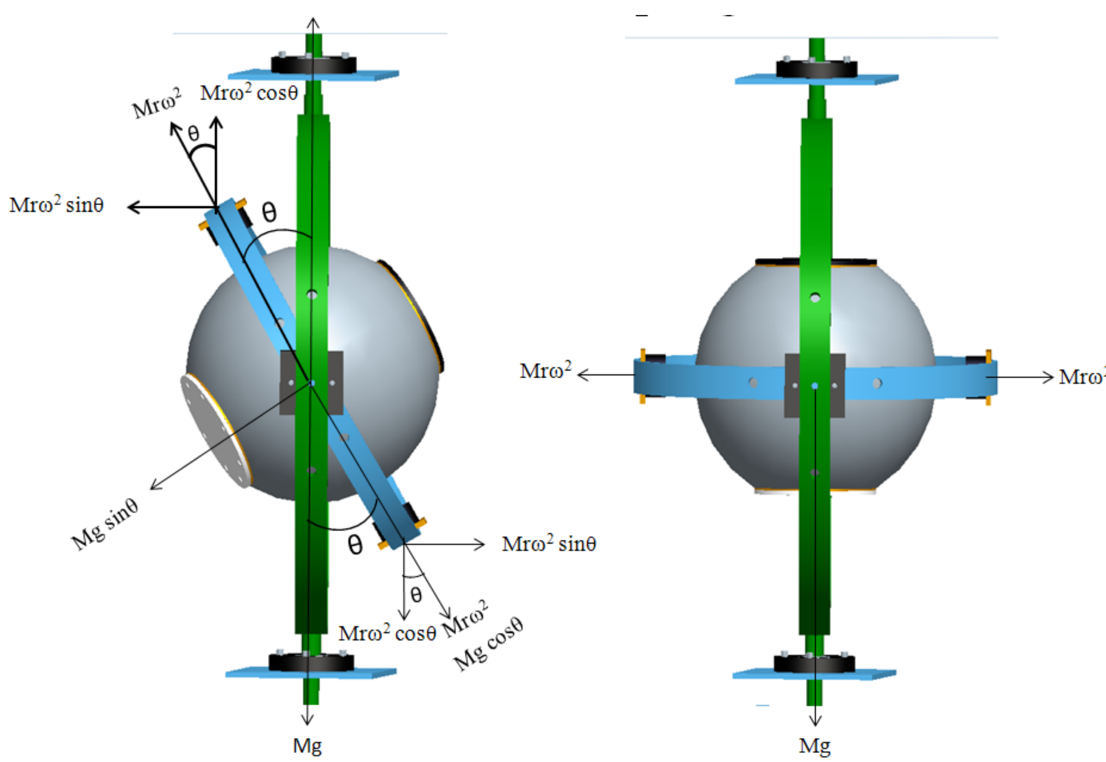


Figure 30 Effect of centrifugal force on inner gimbal

Meanings of different symbols used in Figure 30 are as listed,

M : Combined load of the inner gimbal and sphere,

ω : Angular velocity of an inner gimbal

θ : Angle between the axis of inner gimbal and outer gimbal

r : Radius of the inner gimbal

In all these considerations weights of the system play a very important role. Every-3D modeling software has a facility to assign a variety of materials to different components. In the present study, the mechanism developed was dynamic, and varieties of materials were assigned to the entities of the system. Therefore, once the material is assigned, there is no need to calculate properties, such as mass, center of gravity and moment of inertia. All these factors were calculated and taken into account by the software itself, which made the mechanism more realistic in nature. It was found that the total weight of the inner gimbal and sphere was 12 lbs. Figure 31 shows the design parameters that should be taken into consideration while designing the torsion spring. Leg length, load, and the moment arm are some of the design parameters.

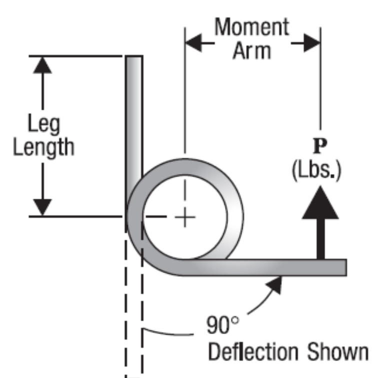


Figure 31 Design parameters of torsion spring

It was considered that the weight of 12 lbs was acting on the leg of the torsion spring at a distance of 3". So, the moment arm in this case was assumed to be 3" and P = 12 lbs. Torsion spring should be able to carry 3" x 12 lbs (Moment Arm x Load) = 36 in-lbs of torque. From the above assumptions and calculations, there were different design parameters that are listed as follows. Torsion spring that would satisfy these parameters was selected and used in the mechanism.

Table 2 Parameters for Selection of torsion spring

Parameters	**Values**
Deflection Angle	90°
Leg Length	4.000"
Spring Length at Torque	< 1.800"
Maximum Rod Outside Diameter	> 0.650 "
Torque	> 36.000 in-lbs

Table 3 Dimensions and properties of selected torsion spring

Parameters	**Values**
Deflection Angle	90°
Leg Length	4.000"
Spring Length at Torque	0.911"
Maximum Rod Outside Diameter	0.666"
Torque	42.860 in-lbs
Wire Diameter	0.135"
Material	Steel Music Wire
Wind Direction	Clockwise/Anticlockwise

Torsion spring from McMaster Carr was selected, which was the closest match for the above set criteria as shown in Table 2. Specifications of the selected spring are listed in Table 3. The value of 42.860 in-lbs torque was used while defining torsion spring at the joint axis of the inner gimbal. In mechanism, this torsion spring would act in both directions as it serves the purpose of clockwise as well as anticlockwise wounded torsion spring.

6.3.4 Damper

Damper is a type of a load that simulates real time forces on the mechanism. Damper removes the energy from the system and the moving mechanism. It exerts a force that is proportional to the velocity of the entity for which it is defined. More the velocity of the entity, more is the equal and opposite force. After a number of iterations the dampers were defined at the joint axis of the sphere and inner gimbal and the values were set to 0.05 lbm in^2/ (deg sec) and 50 lbm in^2/ (deg sec), respectively.

6.3.5 Drivers

As per the flywheels approach, initially the sphere needs to be energized and then once it achieves sufficient speed, polarities of the motor should be reversed. In Pro-Mechanism software, there is no need to attach separate motor and belt pulley arrangement to transfer motion from the motor to the outer gimbal. The motor can be attached directly to the joint axis. In reality, the change in the polarities of the motor can be achieved with the help of the controller, controlled either manually i.e. semi-automated, or fully automated with the help of micro PLCs. In Pro-Mechanism this was achieved by defining a proper sequence with the required motor speed. Based on this, a graph was generated automatically, in which the motor drives the outer gimbal as per the graph. Figure 32 shows the symbol of the driver, when the driver is defined at the joint axis.

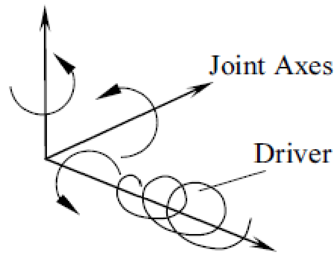


Figure 32 Driver symbols in mechanism [10]

In the present investigation, the outer gimbal is the main driving source. The motor was defined in Pro-Mechanism software at the pin joint 1 (refer Figure 27), the axis of the outer gimbal. The damper was defined at pin joint 3 (refer Figure 27) at the axis of the sphere and the torsion spring at the pin joint 2 (refer Figure 27) axis of the inner gimbal. Figure 33 shows a schematic of the developed mechanism.

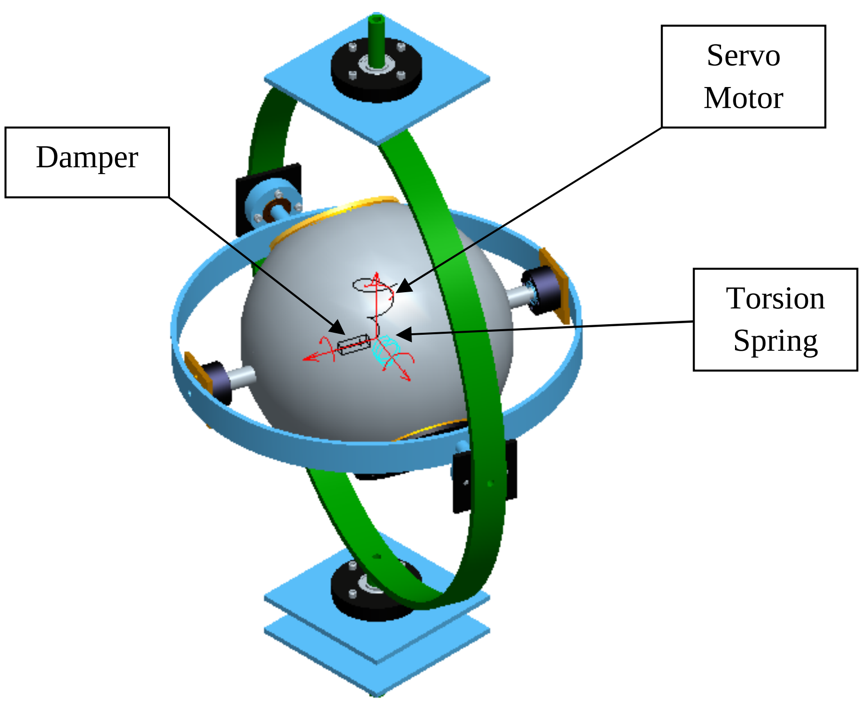


Figure 33 Mechanism development with different defined entities

6.4 Results and Observations

All parameters were entered into the system and the driver was programmed to work as per the plot shown in Figure 34. Initial position, which was assumed to be the gimbal lock, was achieved by setting up initial condition and enabling the regeneration value to be 0º. The mechanism was checked by running sample trial. The maximum speed of the motor was set at 400 rpm. The polarities of the motor were changed after an interval of 30 seconds. Figure 35 shows the position of the inner gimbal. The main purpose behind using torsional spring is to restrict the inner gimbal at 90°, as the gyroscopic effect is maximum when all the three axes are perpendicular to each other. It was observed that the change of polarity affects the position of an inner gimbal. It crosses the angle of 90° and oscillates to settle down at 90 °.

Installation of the torsion spring on the actual setup needs to be done very carefully. The gimbal lock was achieved with the help of the torsion spring. It is designed with a deflection angle of 90° and effective until that angle. If for some reason that deflection is exceeded repeatedly there would be failure of the torsion spring.

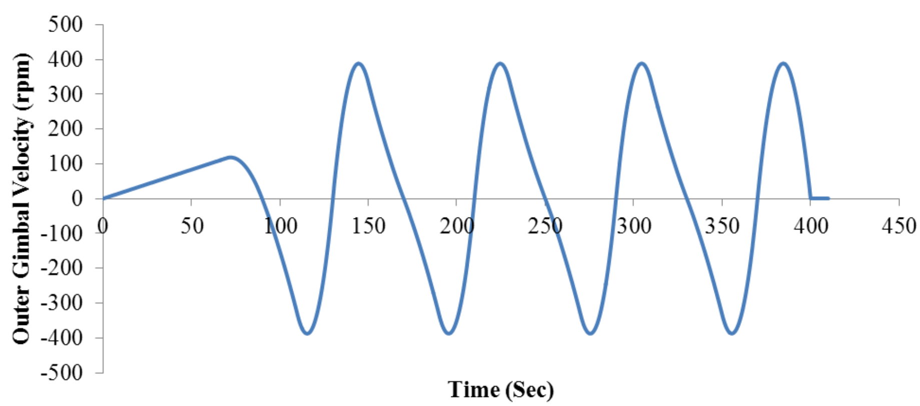


Figure 34 Speed of outer gimbal

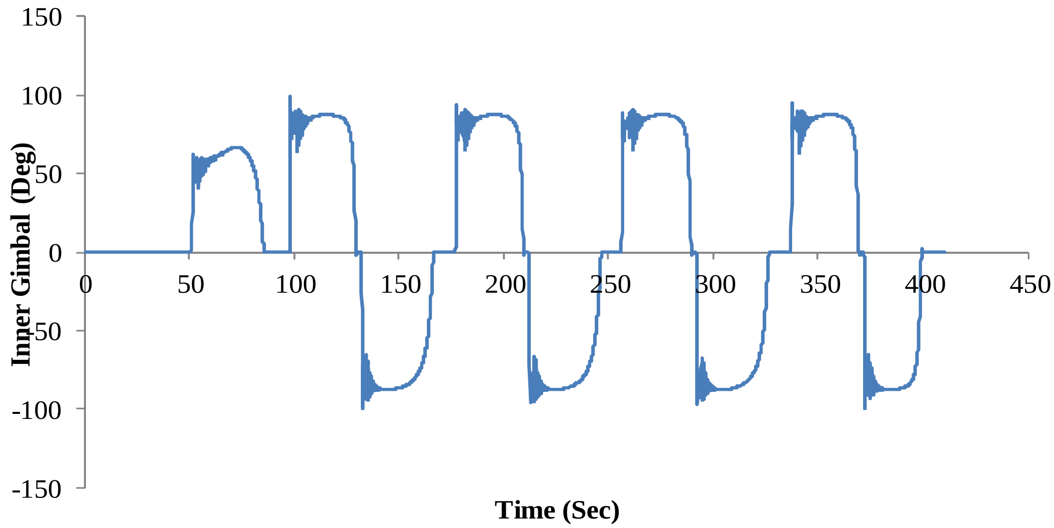


Figure 35 Position of the inner gimbal with a torsion spring

To solve the above problem and to make the system more efficient, extension springs were installed. The main purpose behind the use of extension springs was to avoid the 90° + travel of the inner gimbal. Selection of the extension spring was another challenge. It was assumed that the position of the inner gimbal is 90° and at this position, stretched length of extension spring was found out. Based on this, the suitable position to install the extension springs was identified.

After a number of iterations, position of the extension spring was determined. As shown in Table 4, at different positions of the inner gimbal the stretched length of an extension spring was found. From McMaster Carr extension springs were selected based on the overall length (2. 360 < 3") and stretched length (3.32 " > 3"). Overall length is the length of the spring when spring is not in tension. This length is decided based on the difference in the sizes of the gimbals. Here that difference is 3". The stretched length is calculated based on the load range given and stiffness coefficient of the spring. From Table 4 a maximum-stretched value is 3". Therefore, this spring was safe and hence was used in the present study. The extension springs were installed at 20°. To install the extension springs holes were drilled in the inner and outer gimbals. Mounting was done using zip ties. Trial runs were made with the same motor profile to check the performance of the inner gimbal. It was observed from Figure 36 that inner gimbal is not crossing the 90° angle and by this it can be said that torsion springs are safe. Table 5 gives the specifications of selected extension springs.

Table 4. Stretched lengths of extension springs

Angle (θ)	Stretched Spring Length
0°	0.00
10°	0.14
20°	0.37
30°	0.69
40°	1.05
50°	1.44
60°	1.84
70°	2.31
80°	2.63
90°	3.00

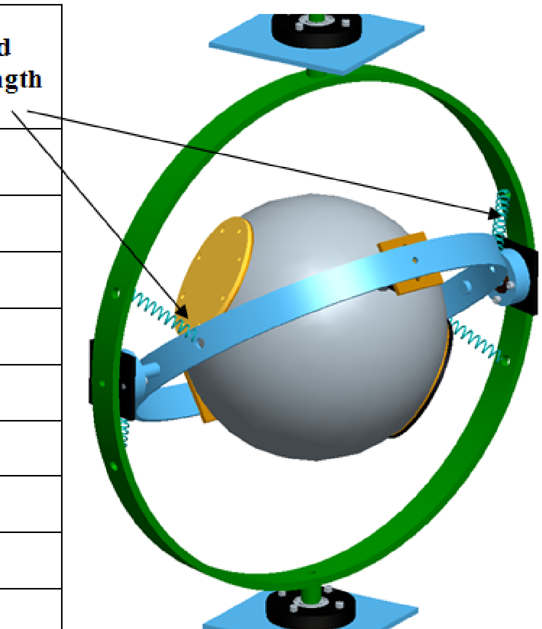


Table 5. Specifications of extension springs

Material	Stainless Steel 302
Overall Length	2.360 " (< 3.00 ")
Outside Diameter	0.500 "
Wire Diameter	0.055 "
Load	15.51 lbs
Rate	4.51 lbs/inch

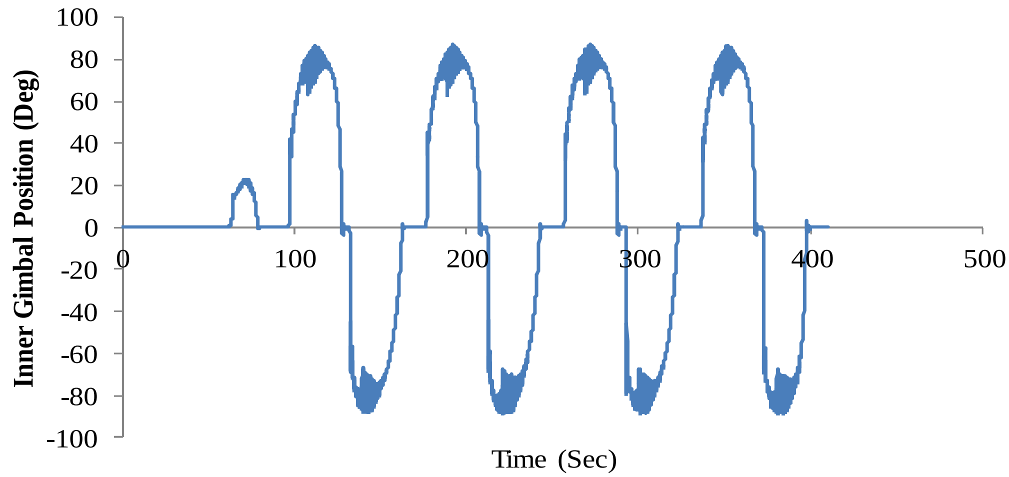


Figure 36 Position of inner gimbal with torsion and extension springs

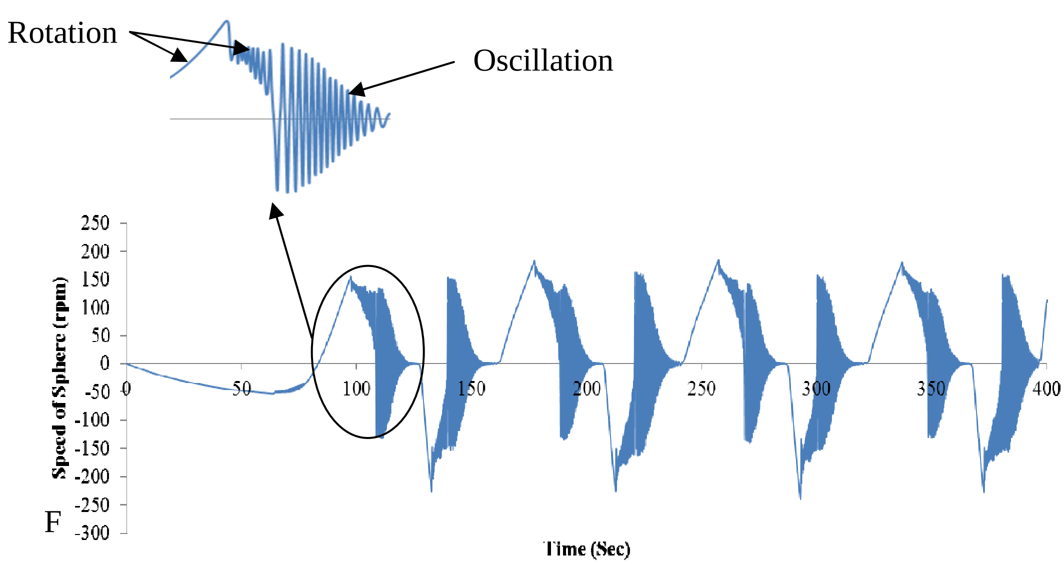


Figure 37 Speed of the sphere

From Figure 35 it was observed that the mechanism developed with the flywheel approach was able to provide the required combination of rotation and oscillation at the sphere. A number of iterations were carried out to determine the time gap between changes of rotational direction of the outer gimbal. A time gap of 20 to 30 seconds was found to be effective as after this the sphere loses its energy completely. Sphere was able to reach 200 rpm while the maximum speed of the outer gimbal was 400 rpm. Therefore, as per the developed mechanism sphere was able to achieve 50% speed compared to the speed of the outer gimbal, when each time the polarities of the motor is changed. So, a decision was made to implement this design on the actual setup. It was noticed that in the initial stage of energizing the sphere as shown in Figure 34, there was tilting of the inner gimbal. This indicates that gimbal lock provided by the springs was not sufficient, and this affected the speed of the sphere. It was concluded that there is a need to find alternate way to provide a firm gimbal lock at the initial stage of the cycle.

It may be noted that the inner gimbal was made of the steel. Therefore, use of magnets would be very effective. There was no provision in the pro-mechanism software to provide magnetic field. However, by providing point-to-point load on both sides of the inner gimbal it was found that holding force of 100 to 200 lbs was sufficient. So, bar magnets with size of 2 x 1 x 0.5 in^3 (from the K and J Magnetics) were selected and the concept was tested directly on the setup and found to be useful, as it provides sufficient holding force and required gimbal lock. Before implementing the idea any further, magnetic simulation was carried out in order to find the effect of this magnetic field on the inner gimbal.

6.5 Magnetic Field Analysis

Finite element analysis is an effective tool for the analysis of magnetic field in the system. The purpose behind choosing this size of magnets is that, these magnets were able to provide ~ 40 lbs of pulling force each. Handling of these magnets was found to be difficult as they are very powerful, and special types of fixtures need to be designed in order to fix these magnets. The magnets with larger size are able to provide more holding force; but, as mentioned before, handling was the main problem.

Commercially available COMSOL 3.2 Multiphysics FEM software was used in this investigation. COMSOL Multiphysics uses partial differential equations (PDEs) as a tool to solve engineering related problems. This software is user friendly and does not require any special training. Instead of defining any equations from FEA, the built-in physics allows the user to define the physical quantities, such as material properties, loads, constraints, and fluxes. Models created using different CAD softwares can be imported in the COMSOL software without any conflict. Normal method for FEA can be divided into four major steps [30].

1. Model Building
2. Specifying material properties
3. Obtaining Solution
4. Analyzing the solution

6.5.1 Model Building

As shown in Figure 38 the magnets were arranged radially. It is obvious that more magnetic field strength is achieved with more number of magnets. The distance between the magnets and the inner gimbal was finalized to be 0.2". The effect of magnetic field would be more interesting to analyze from the side view. As shown in Figure 37 the sectional 2D drawing of the magnet and its fixture were created using AutoCAD and was imported in the COMSOL software. Once the model is created, it was imported in the Electromagnetics => Magnetostatic's module. Around the model boundary was generated. This space around the model was considered as air ($\mu_r = 1$).

Figure 39 shows a schematic of the model generated in the COMSOL software. The next step was to assign the permeability values to the entities in the model depending upon different materials assigned to them.

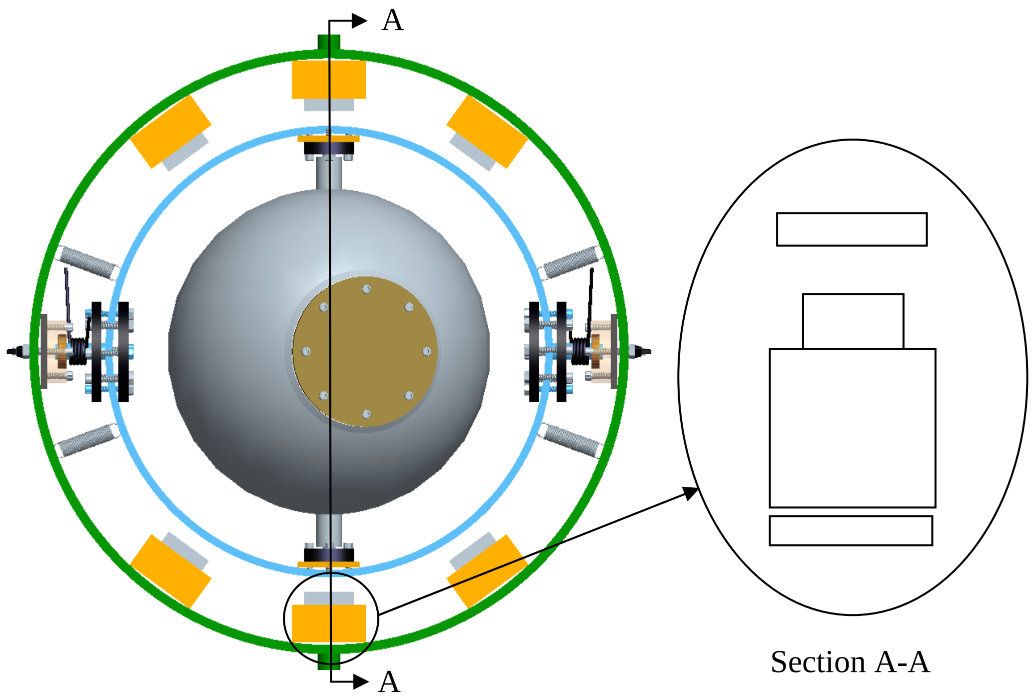


Figure 38 Sectional view of magnet and its mounting for magnetic analysis

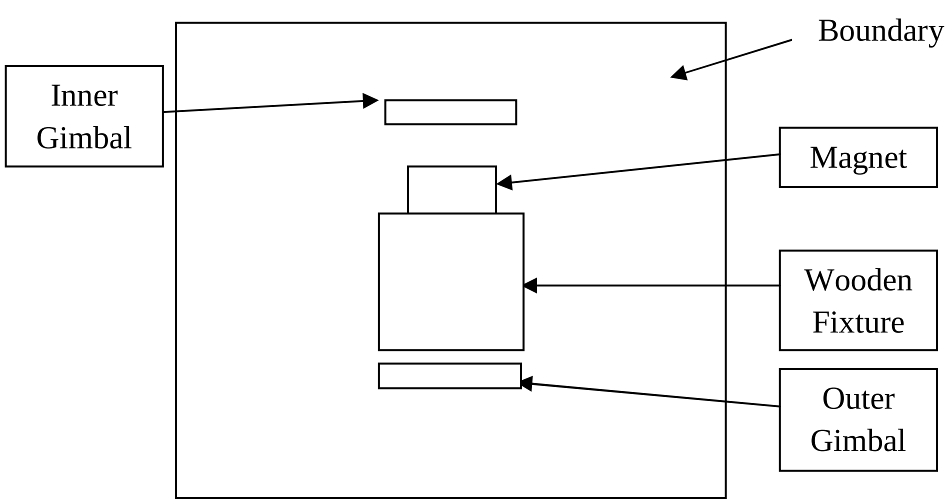


Figure 39 Schematic of the model generated by COMSOL

6.5.2 Specifying Material Properties

The model built consisted of the different regions

- Magnet
- Inner gimbal and outer gimbal made from steel
- Wood
- Air

Depending upon the material, different values of permeability constant were defined. For non-magnetic materials, such as air, wood this constant was taken as $\mu_r=1$. For steel, it was assumed as $\mu_r=100$. Property of the magnet depends upon its remanent flux density. This value was taken as B_r = 1.48 Tesla as per the manufacturer's rating.

6.5.3 Obtaining Solution

Once the model is built and different materials have been assigned, the next step involved is the post-processing mode. Post-processing involves defining of mesh parameters, element types, and boundary, subdomain and solver settings, etc. In COMSOL 3.2, software takes care of all these parameters automatically. Default element type in the present study is Langrange–quadratic, and the analysis type is static.

Figure 40 shows the mesh generated by default. There is no need to define the mesh size; the software itself defines the mesh size. Figure 40 shows a finer mesh generated around the magnet while, a coarse one away from the magnet. Figure 41 shows the surface profile of the magnetic flux density distribution. The color scale on the side indicates the value of the magnetic flux density corresponding to that color. After a number of iterations, these values have been set at 0.5×10^{-8} to 0.5 Tesla.

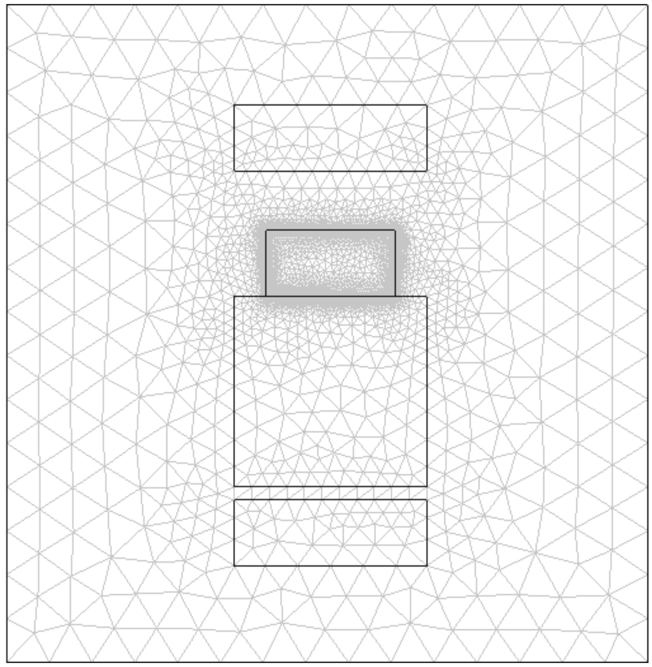


Figure 40 Schematic showing the mesh distribution within the model

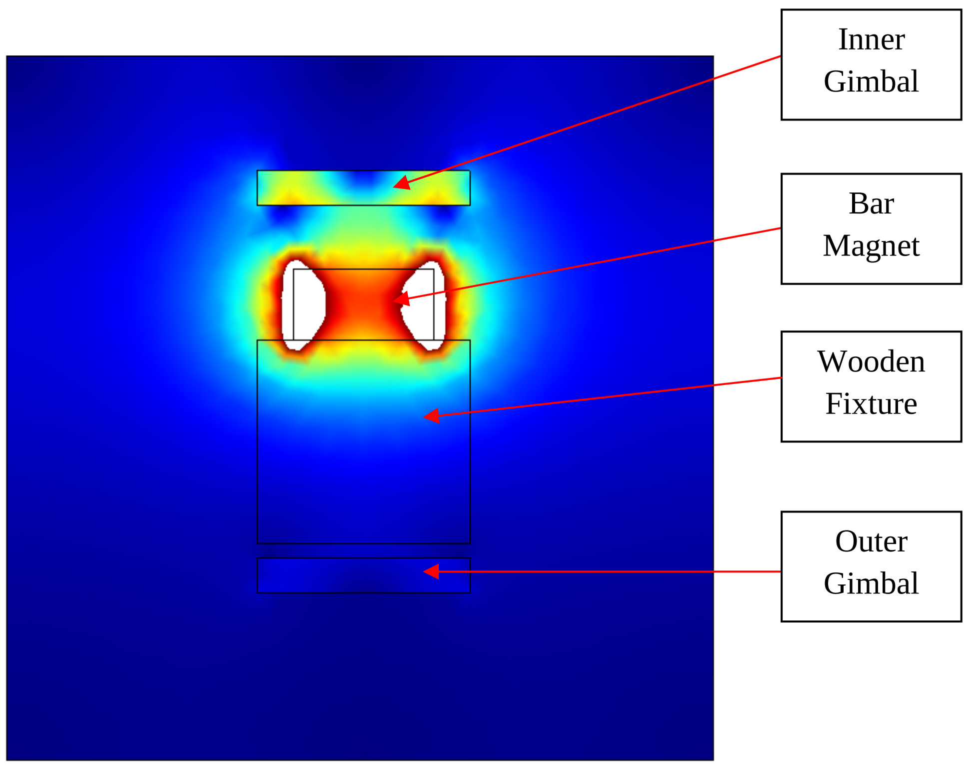


Figure 41 Magnetic flux density distributions at the gimbal lock

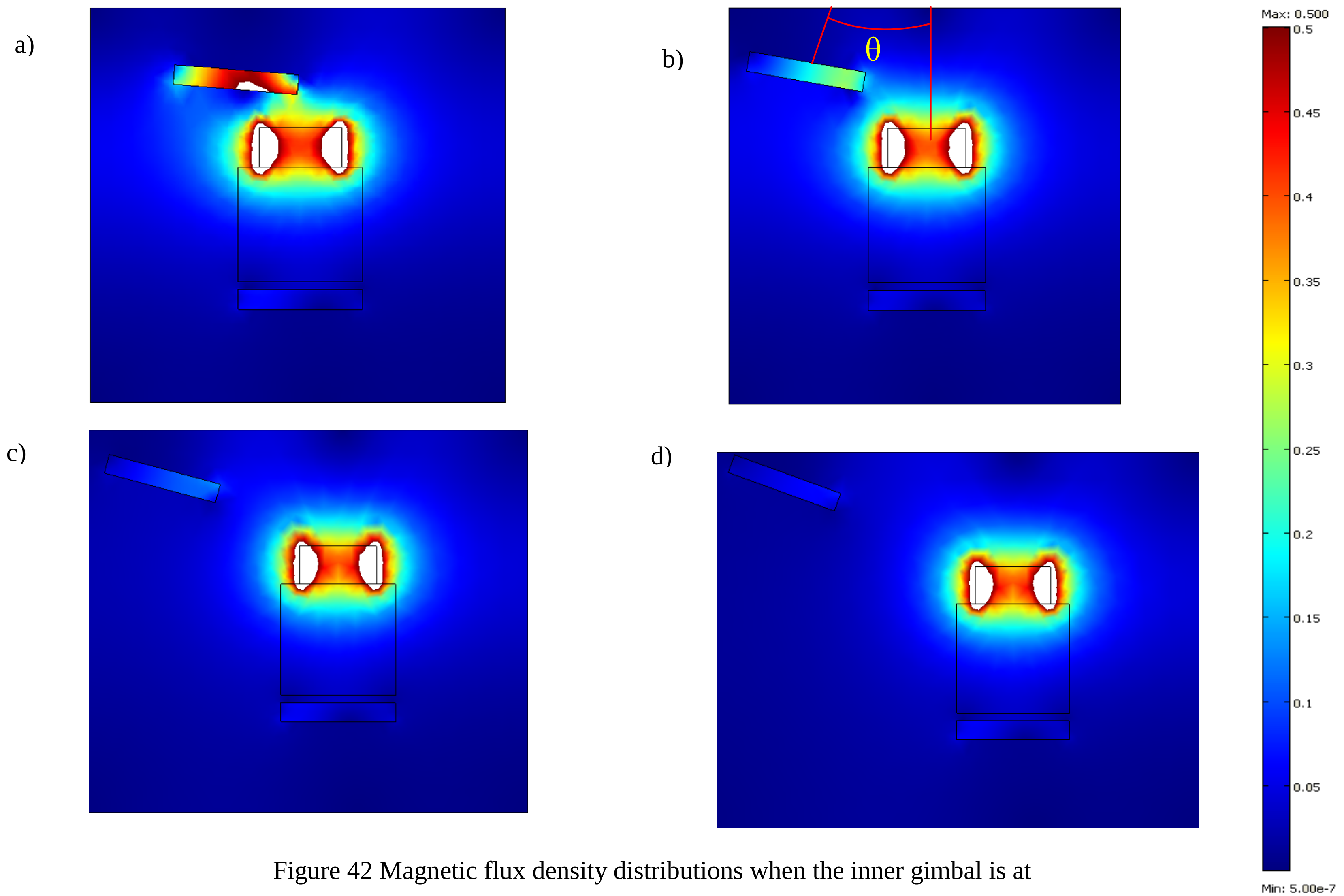


Figure 42 Magnetic flux density distributions when the inner gimbal is at

a) θ = 5° b) θ = 10° c) θ = 15° d) θ = 20°

The main aim behind this magnetic simulation was to find out the effect of magnetic field on the inner gimbal as it moves away from the magnet. To study this effect, the inner gimbal was rotated by 5° each time and the same steps were repeated. Figure 42 shows different positions of the inner gimbal with respect to the axis of outer gimbal. The color scale included gives the strength of the magnetic field distribution based on the values of different color in Tesla.

6.5.4 Analyzing the Solution

The objective of this subsection is to draw conclusions from the analysis that was carried out in the previous subsection. After analyzing Figure 42, it was concluded that at the initial stage, magnetic flux density of 0.25 to 0.30 Tesla was acting on the inner gimbal, which was able to provide sufficient holding force to arrest the inner gimbal in a vertical position. This way, gimbal lock was effective and the sphere can be energized by transferring moment from the outer gimbal. It should be noted that this was the magnetic force exerted by only one magnet. There are 4 to 6 magnets arranged radially, which produces 1.2 to 1.6 Tesla of magnetic flux density. In addition, it was observed that the magnetic flux density of 0.12 Tesla was still acting on the inner gimbal even if it is at an angle of 20°.

This observation was useful in the case of a momentum transfer phenomenon. Energizing the sphere after each cycle is based on the momentum transfer from the outer gimbal to the sphere. When the inner gimbal is at 90° and sphere loses its energy, the change in polarity of outer gimbal starts pulling inner gimbal in a vertical position. This pulling was in effect, due to the pulling forces exerted by the torsion springs, extension strings and the back torque generated because of change in the polarity. It was observed that lesser the time taken by the inner gimbal to achieve a vertical position more speed is achieved at the sphere. Now, with the help of magnets this could be more effective. As explained earlier, as soon as the inner gimbal comes in the zone of the magnetic field at 20°, magnetic force pulls the inner gimbal, which helps the sphere in achieving a vertical position in lesser time.

In the present study, the magnetic analysis was carried out and is restricted to the study of the magnets that were used in the setup. Although stronger magnets could be used, due to safety issues involved in handling them the scope of the present analysis was restricted to 2" x 1" x 0.5" bar magnet size.

Table 6 Specifications of the magnet

Style	Block
Dimensions	2 x 1 x 0.5 thk (in)
Material	NdFeB, Grade N52
Br max	14,800 Gauss
BH max	52 MGOe
Pull Force, Magnet to Steel Plate	96.2 lb

CHAPTER 7

GYRO MACHINE

This chapter provides details of all sub-components of the gyro machine, their assembly, and alignment. Based on the developed mechanism and analysis, different modifications were carried out on the existing setup. Whole assembly was created using Pro-E wildfire 5.0. Based on that, 2D drawings for different components were generated. Newly designed components were machined and assembled on the setup. Figures 43 (a) shows 3D CAD models of the existing (old) setup at OSU and (b) shows 3D CAD model of the modified one. Figure 44 shows the 3D model of the machine developed in the Pro-Engineering software showing different components of the machine. Figure 45 shows a photograph of the in-house built machine, and Figure 46 shows the 3D exploded view of the equipment. The Gyro machine is designed and manufactured in-the house in the present study. Major components of the Gyro Machine are listed as follows:

- Gyro frame
- Outer gimbal and inner gimbal
- Sphere
- Springs
- Magnets and fixtures
- Drive attachment

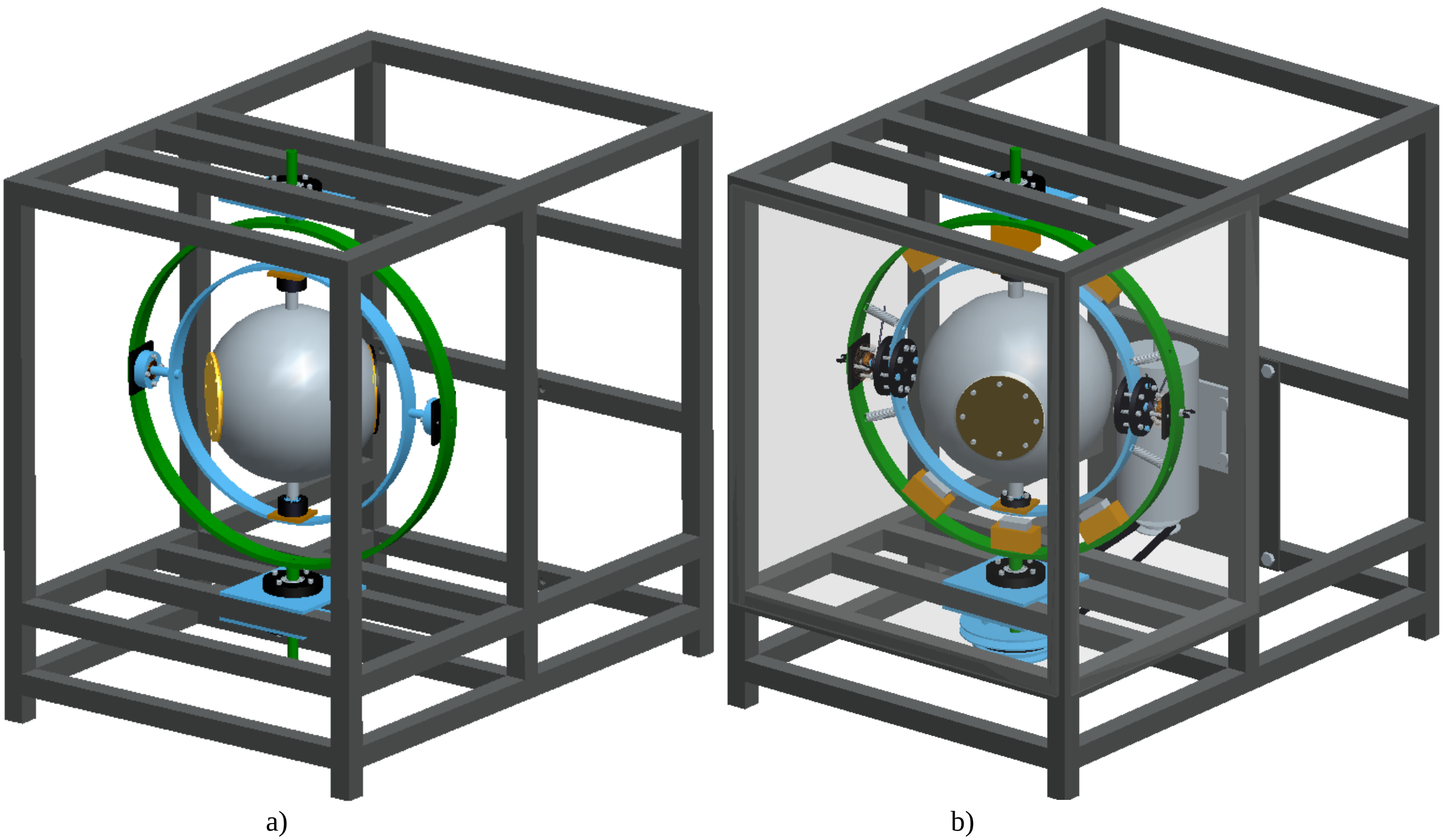


Figure 43 3D CAD Models of (a) Original setup at OSU and (b) Modified setup using Pro-E

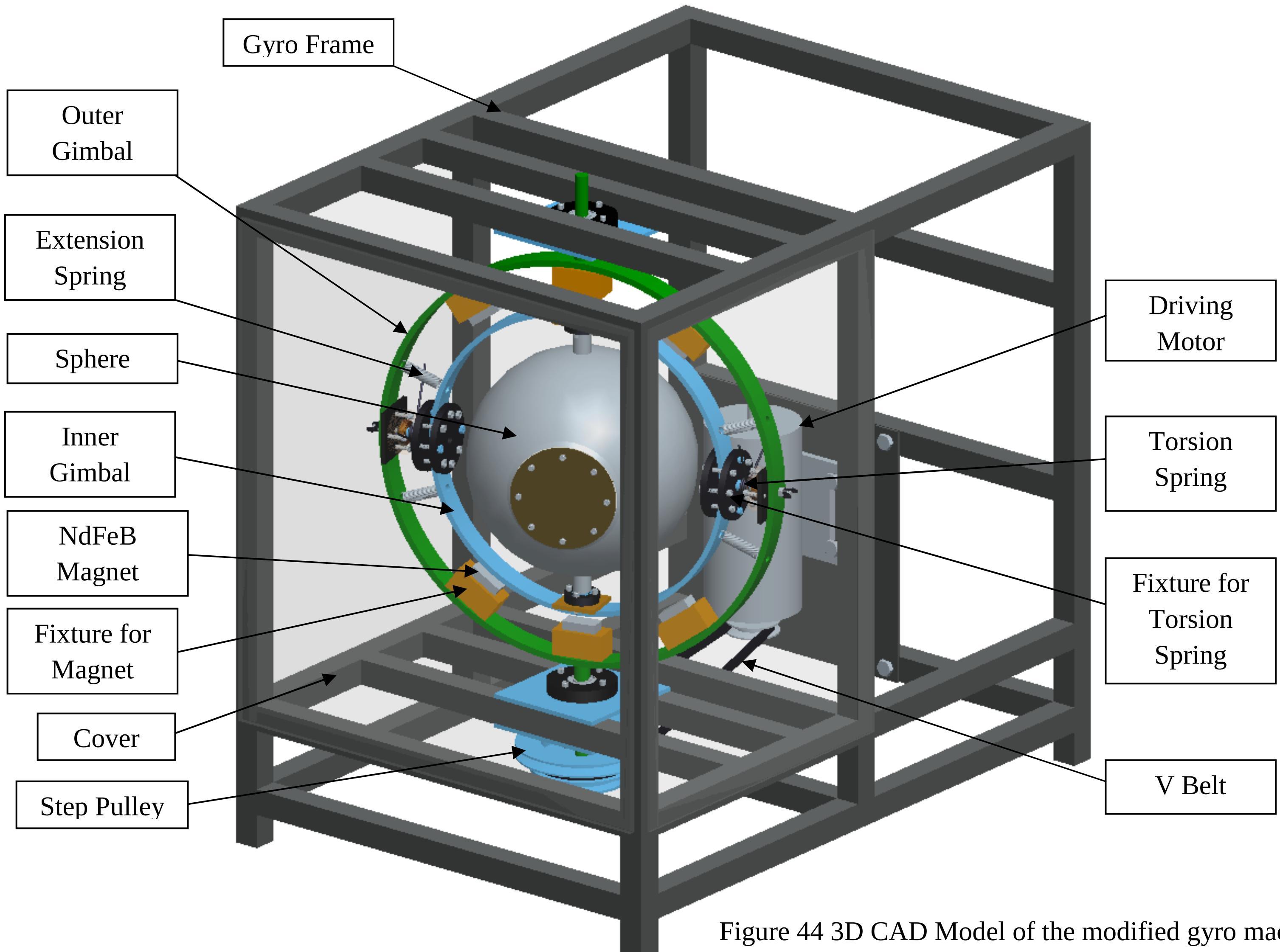


Figure 44 3D CAD Model of the modified gyro machine showing different components of the machine

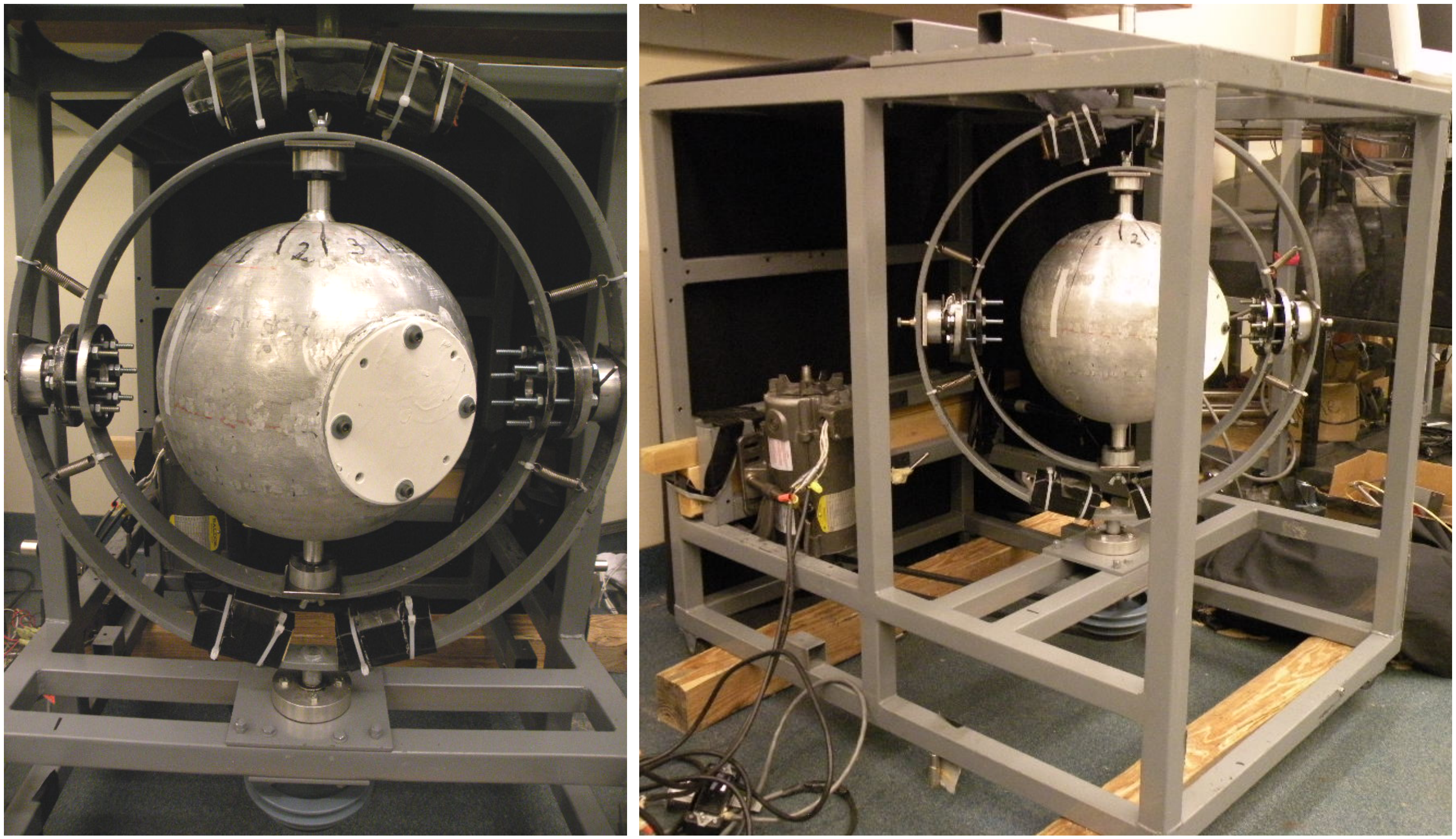


Figure 45 In –House fabricated gyro machine

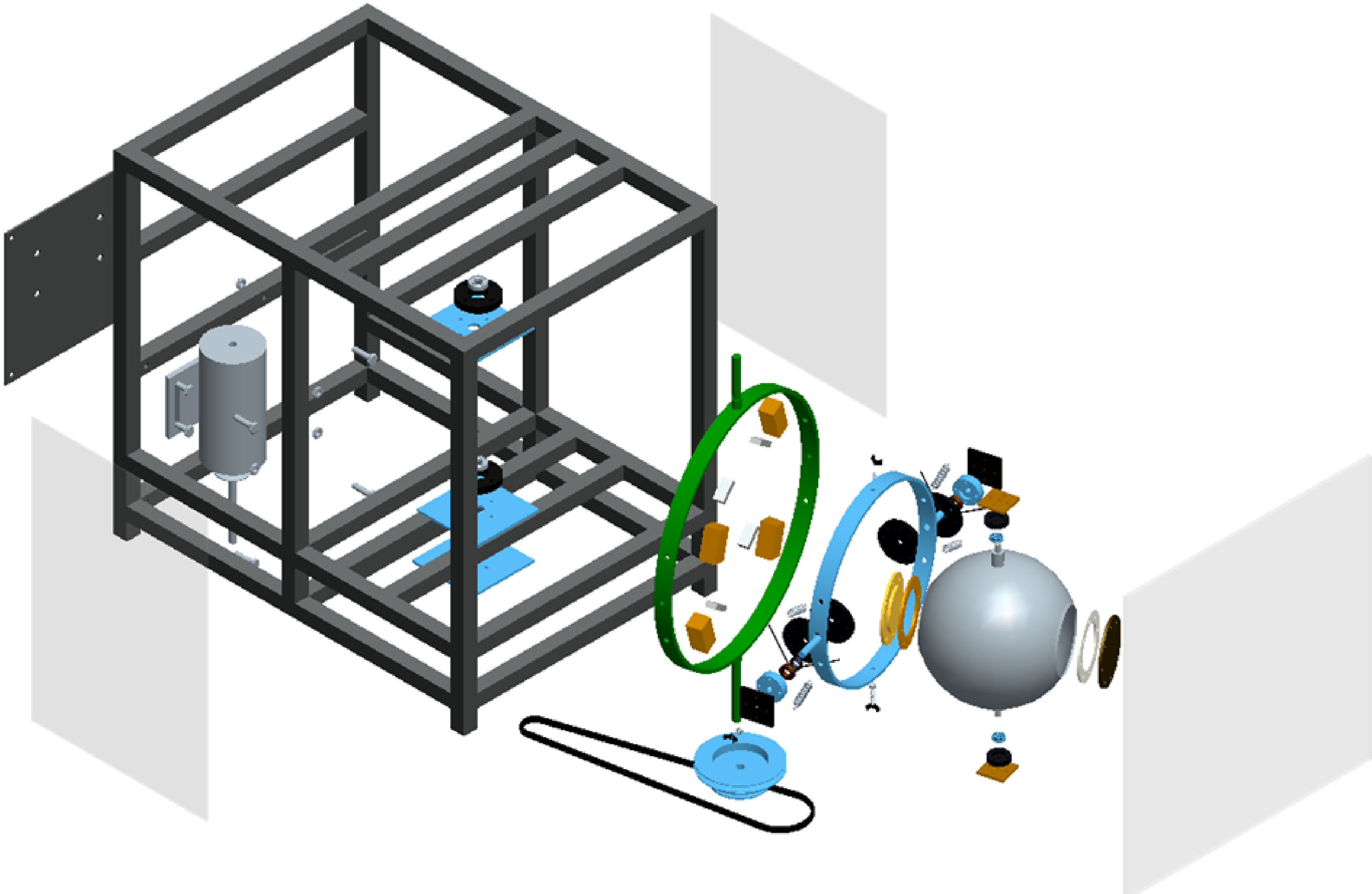


Figure 46 Exploded view of gyro machine

Based on the size of the sphere, efforts were made to develop a geometric dimensional relationship to determine the size of different components of the gyro machine. Along with the description, multi-view drawings were generated for all subcomponents with parametric relationship. Chapter 5 has already covered the multi-view drawings for gyro frame, sphere, inner gimbal, and outer gimbal along with their supports for the housings of the bearings.

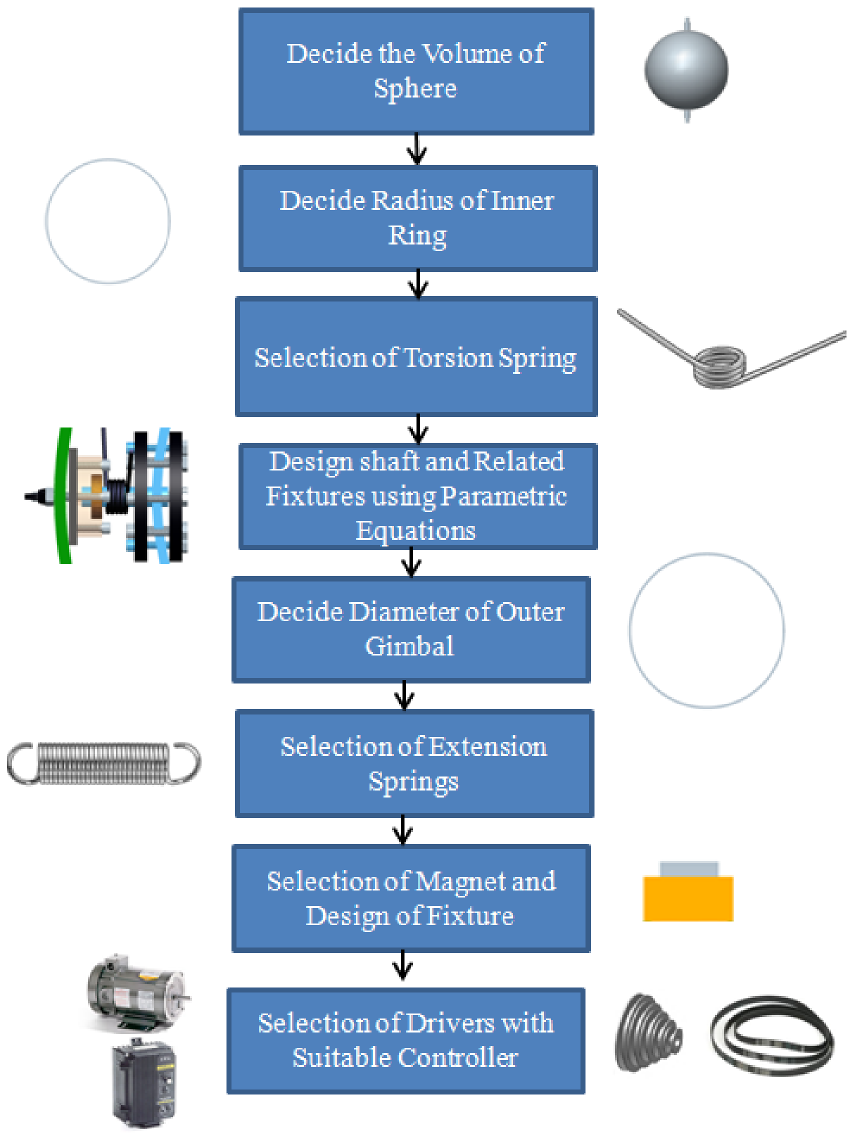
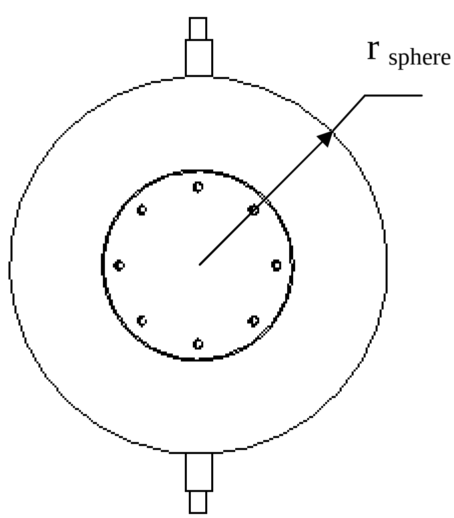


Figure 47 Approach used to design the gyro machine

Figure 47 shows the approach developed to design the gyro machine. This approach is very useful to scale up or scale down the gyro machine depending on the capacity of the sphere.

7.1 Sphere

The sphere is the heart of the gyro machine. The purpose for the use of sphere is to provide uniform shape without corners. One shaft is welded on either side of the sphere, so that it can be supported with the bearings on it. The bearings were fitted on aluminum housing and rested on the inner gimbal with a lock nut arrangement. The hollow sphere is made of aluminum. The sphere was cut diametrically for openings, and the detachable covers were also made from aluminum. Material (e.g. clothes) can be loaded by removing these covers. In the present study, a hollow sphere of 12" diameter was used. Depending upon the volume required, an appropriate sphere size can be selected (Refer Appendix A, Figure 80 for details of the sphere) Figure 48 shows the dependency of the size of the sphere based on the required volume.



$$V_{Sphere} = \frac{4}{3} \pi r^3_{Sphere} \qquad \text{............. (3)}$$

Figure 48 Size of sphere

7.2 Inner Gimbal

The sphere is attached to the inner gimbal. So, depending upon the size of the sphere, the size of the inner ring is determined. In the present study, this relation was developed based on the sizes available. The size used of the inner gimbal is 18" (Refer Appendix A, Figure 74 for details of the inner gimbal). The steel ring used is manufactured by the forging process. These forged rings can be ordered depending upon the requirements,. The inner gimbal was connected to the outer gimbal with bearing supports on both sides. Bearings were fitted in the bearing housing and mounted on the fixture and connected to the outer gimbal. The inner gimbal was mounted in such a way that it can rotate freely along the horizontal axis perpendicular to the axis of the sphere. Outer gimbal is one of the essential components of the gyro machine. The inner gimbal's position is restricted with the help of springs attached on it as explained earlier. This restriction leads to oscillations. Figure 49 shows holes drilled to mount extension springs on the inner ring. Relation between the radius of the inner gimbal and radius of the sphere was developed as showed in Figure 49.

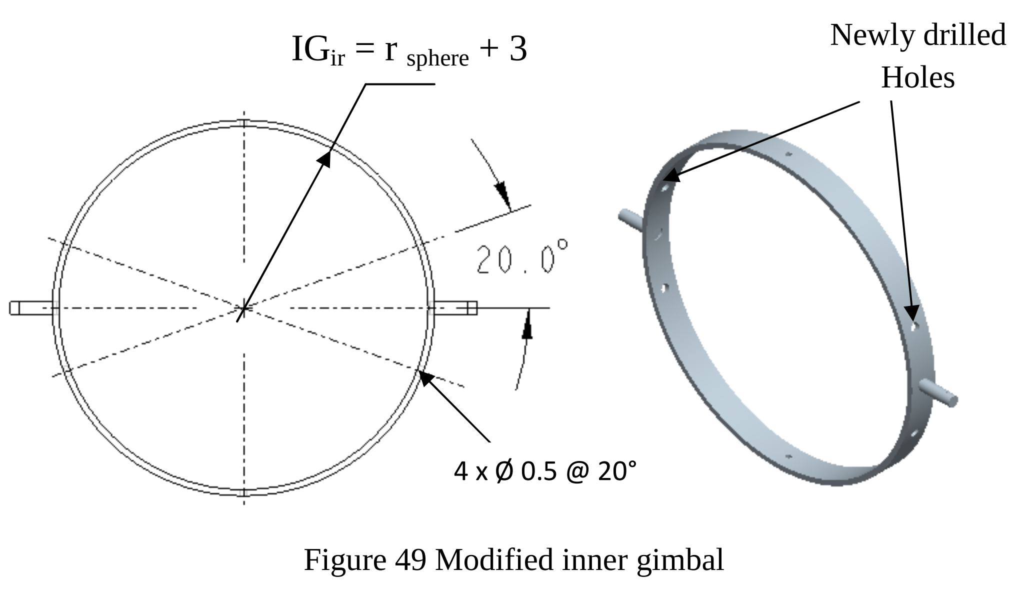


Figure 49 Modified inner gimbal

7.3. Torsion Spring and Fixture

The main purpose of the torsion spring is to reset the inner gimbal to the gimbal lock position in order to energize the sphere for the next cycle. Design and selection procedures are already discussed in Chapter 6.

On the setup, a special disc fixture was designed to mount the torsional springs. On aluminum discs, eight holes at 45° angle were drilled. On each side of the inner ring, two discs were clamped. Clamping was achieved simply with the help of a nut and a bolt arrangement. The purpose of using this arrangement is for easy adjustment to align the inner gimbal vertically. One leg of the torsional spring was arrested in the disc fixture while the other was in the bearing housing used to support shafts of the inner gimbals.

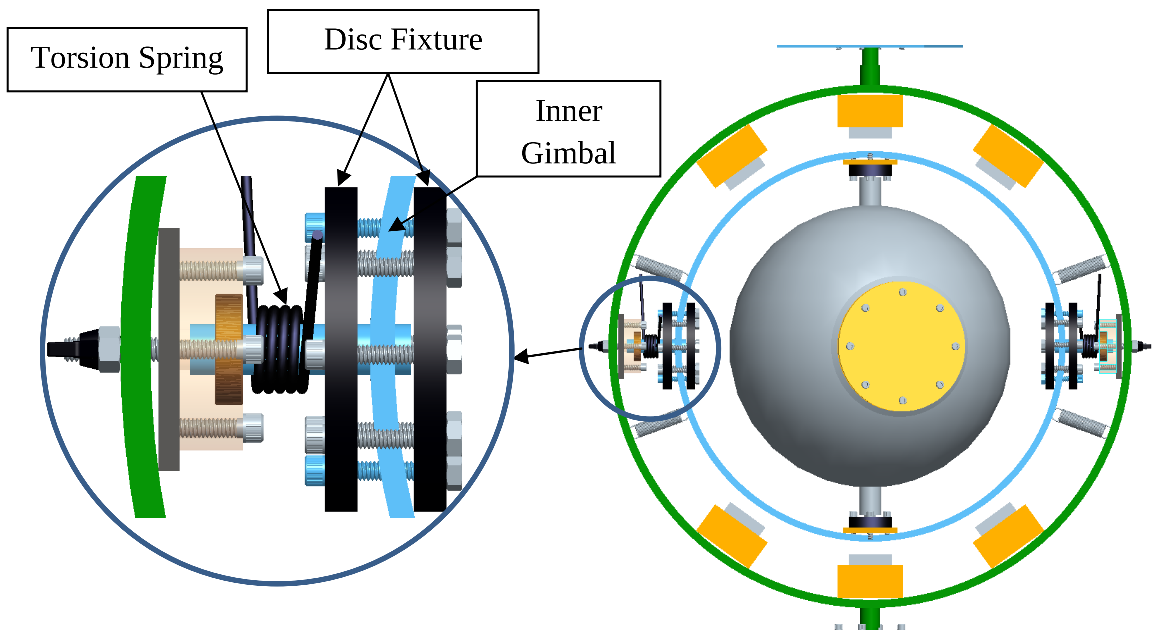


Figure 50 Fixtures for torsional spring

Figure 50 shows an enlarged view of the disc fixture. It was observed that the leg of the torsional spring should be clamped properly in order to prevent it from yielding. To do so, the leg that was arrested on the disc was sandwiched between two bolts. Figure 51 provides the drawing for this disc fixture while Figure 52 gives the parametric relationship developed and the explanation of the symbols used.

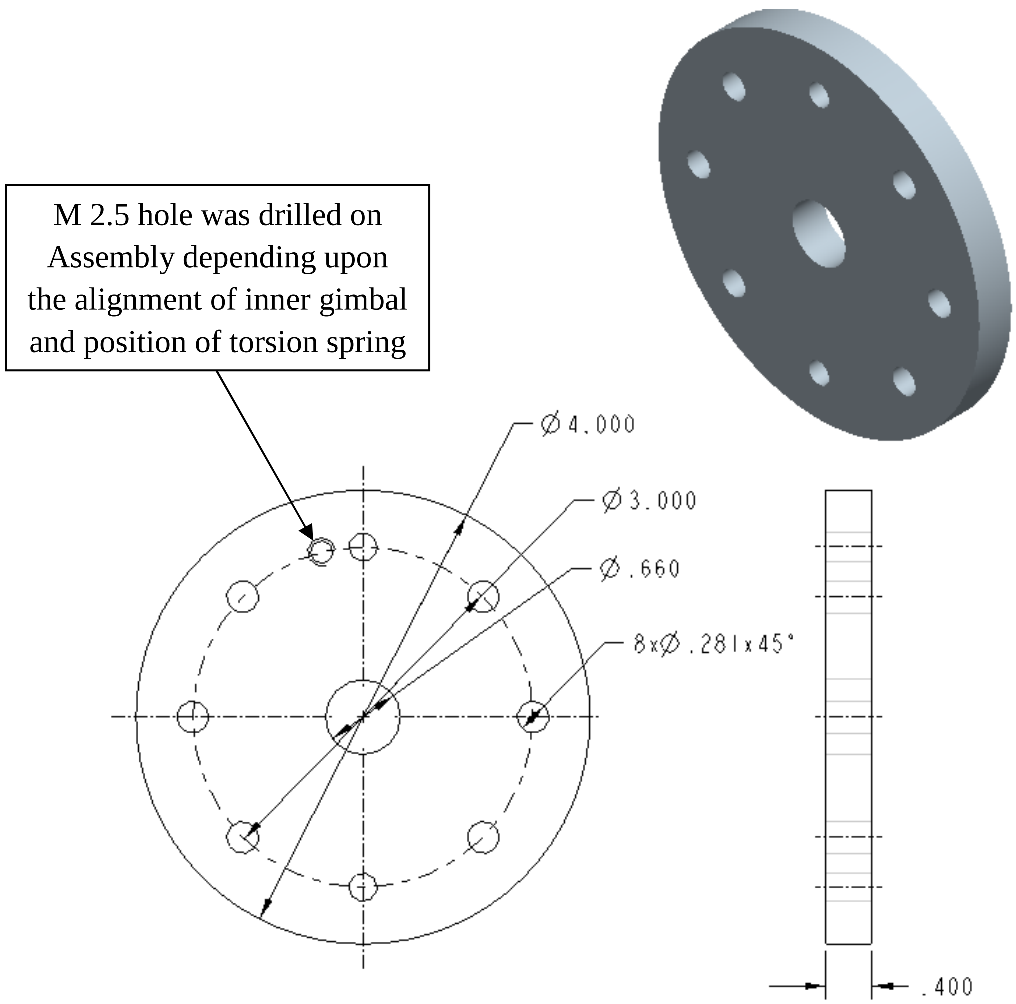


Figure 51 Disc fixture

Based on the fixture assembly and the positioning of the torsion spring from the current setup, geometric dimensional relationship was developed. The relations were based on the size of the sphere and the inner gimbal. This relationship is helpful in determining the inner diameter of the outer gimbal.

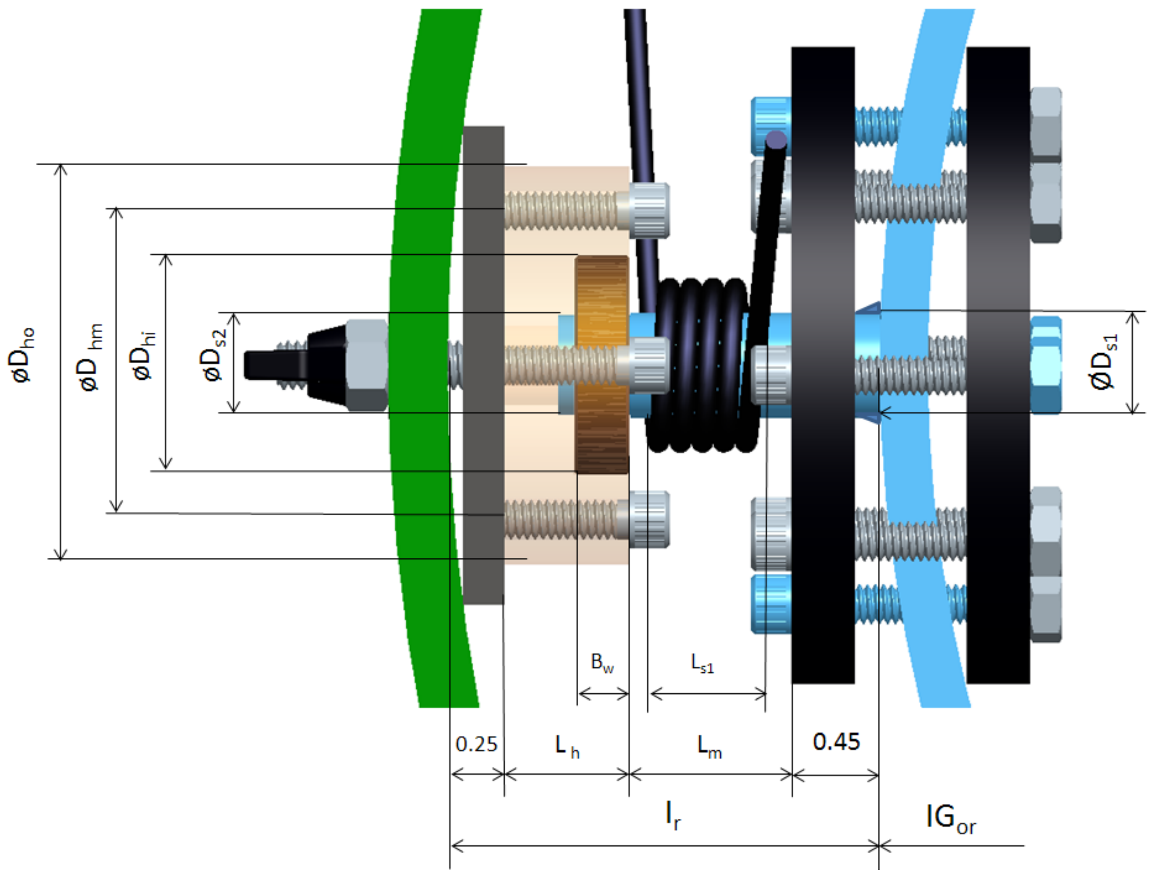


Figure 52 Parametric relationships for fixture design

- $\text{ø}D_{hi} = \text{ø}D_{Bo}$
- $\text{ø}D_{ho} = \text{ø}D_{Bo} + 1.125$
- $\text{ø}D_{hm} = \text{ø}D_{Bo} + 0.5625$
- $\text{ø}D_{s1} = \text{ø}D_{max}$
- $\text{ø}D_{s2} = \text{ø}D_{Bi}$
- $L_m = L_s + 0.1$
- $IG_{or} = r_{\text{inner ring}} + \text{thickness}$
- $L_h = 3 * B_w$
- $I_r = L_m + L_h + 0.45 + 0.25$
- $\square A = \text{ø}D_{ho} + 0.5$
- $L_s = L_m + B_w + 1$
- $OG_{ir} = IG_{or} + I_r$

…………. (4)

Where,

- $øD_{Bo}$: Outside diameter of bearing
- $øD_{Bi}$: Inside diameter of bearing
- $øD_{hi}$: Inside diameter of housing
- $øD_{ho}$: Outside diameter of housing
- $øD_{hm}$: Mean diameter of housing
- $øD_{s1}$: Maximum diameter of the shaft
- $øD_{s2}$: Minimum diameter of the shaft
- B_w :Width of bearing
- L_s : Length of maximum shaft diameter
- L_{s1} : Length of the spring at no load
- L_h : Width of the bearing housing
- IG_{or}: Outer radius of the inner gimbal
- I_r: Distance between the inner gimbal outer radius and inner radius of the outer gimbal
- OG_{ir}: Inner radius of the outer gimbal
- □A: Square dimension of the housing supporting plate.

7.4 Outer Gimbal

In the current setup, the outer gimbal with 24" in diameter was used. Depending on the dimension and the relations developed so far, the outer gimbal dimensions are related as $OG_{ir} = IG_{or} + I_r$. Similar to the inner gimbal, the outer gimbal is made from steel by a forging process (Refer Appendix A, Figure 75 to see the details of the outer gimbal) . It is the main sub component of the system as it transfers the power from the motor to the spherical container. It was mounted on the frame with bearing supports on both the extruded sides. To make assembly easier, a bush and cap arrangement was made on both sides of the outer gimbal. Due to bearings, the outer gimbal is free to rotate around a vertical axis. V shape step pulley and belt arrangement was provided in order to transfer power from the DC motor to the outer gimbal. As per the location of the extension springs, holes were drilled on the outer gimbal. Figure 53 shows the modified outer gimbal.

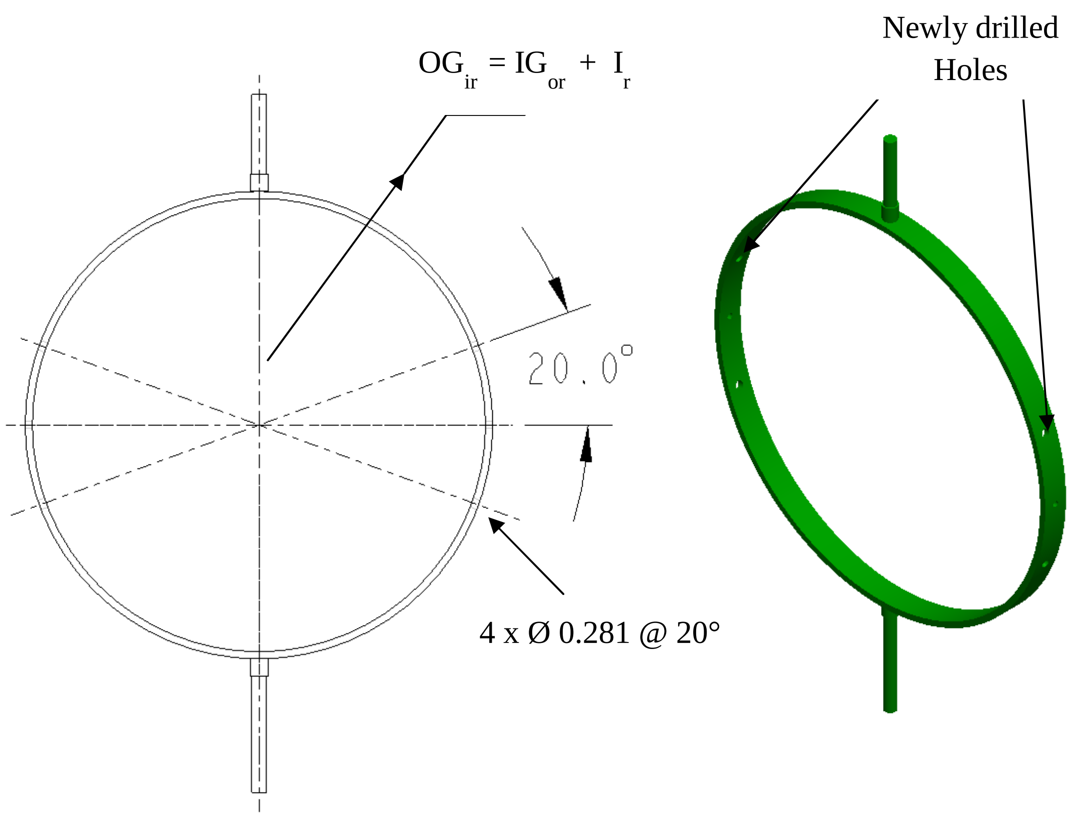


Figure 53 Modified outer gimbal

7.5 Extension Spring

The role and specifications of selected extension springs are given in the mechanism development section (Chapter 6) of the present study. The selection of the extension spring is dependent upon the size of the inner ring and outer ring.

$$\text{Overall length of extension spring} = OG_{ir} - IG_{or}$$

7.6 Magnet and Fixture

Gimbal lock was provided with the help of magnets arranged radially inside the outer gimbal. The role of the magnet and the magnetic analysis is discussed in Chapter 6, sub-section 6.6. Specifications of the magnet used are listed in Table 6. The magnets used in this study are very powerful so, mounting is the main issue. Mounting of the magnet was done on a wooden piece. (Refer Appendix A, Figure 81 for the details of the used fixture). Magnets were fixed on to the wooden fixture using superglue. The fixture with magnet was then fixed on the inner side of the outer gimbal using Gorilla tape and the zip ties.

7.7 Gyro Frame

The gyro frame provides the main support to the entities of the Gyro washing machine. Different extruded steel square pipes were joined by welding. The structure was mounted on wheels to facilitate transport. At ~ 450 rpm of the outer gimbal, the system starts vibrating. To damp these vibrations, the gyro frame was mounted on wooden supports and sand bags were used to hold the system in place. Alternately, the system can be fixed on the ground. The width (W) and height (H) of the frame are dependent on the size of the outer gimbal and indirectly on the size of the sphere. Figure 54 shows the relation to determine the width and height of the gyro frame. The relation is correlated with the size of the outer gimbal radius.

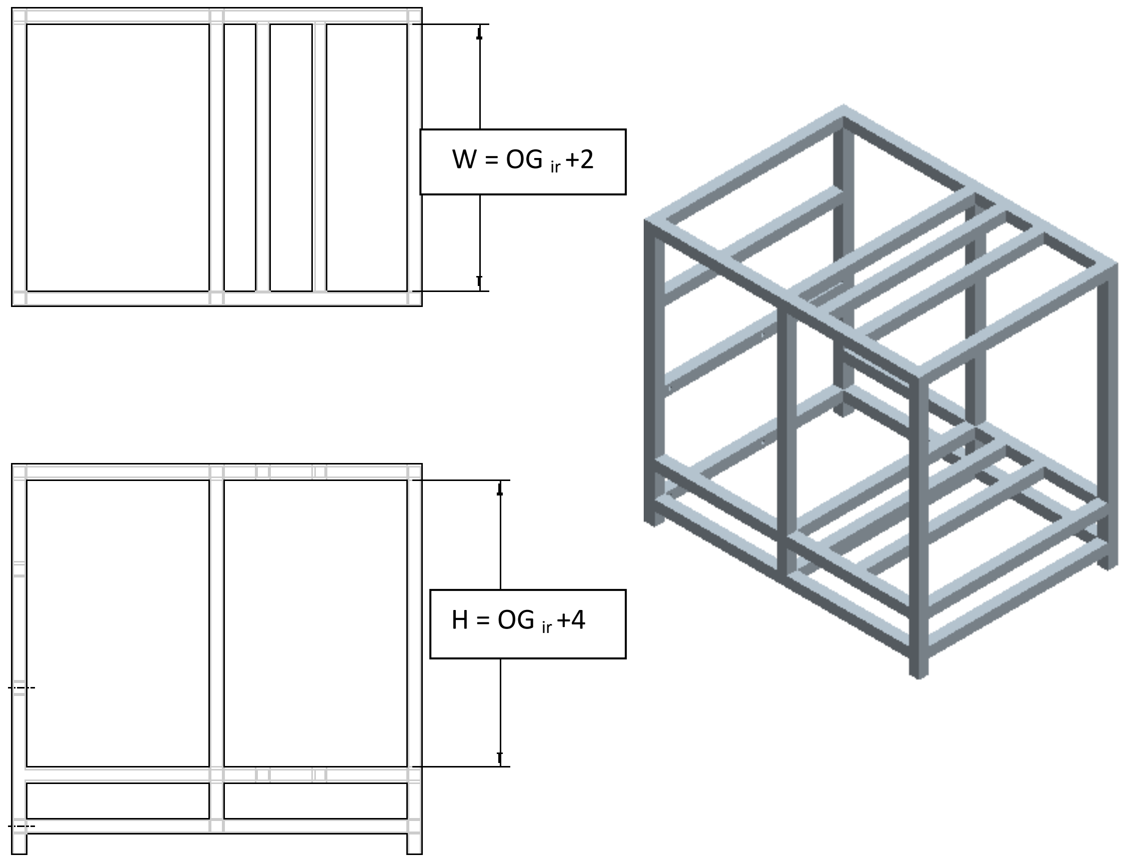


Figure 54 Gyro frame with size dependency on the outer gimbal

7.8 Outer Gimbals Drive Attachment

The prime function of outer gimbal drive attachment is to provide the necessary force to rotate the outer gimbal at a desired speed. Drive attachment consists of two main parts: 1) Micro controller and 2) Pulley and belt arrangement.

7.8.1 Micro Controller

A motor and micro-controller were used to transmit rotary motion to the outer gimbal via belt and pulley arrangement. The motor used in the investigation is a BALDOR D.C. motor with a maximum speed of ~ 1750 rpm. A semi-automatic speed driver, NEMA 4-X from BALDOR was used to control the speed from 0 to 100 % of the rated. It was also used to change the rotational direction, i.e. the motor can be rotated either in a clockwise or in a counter clockwise direction of motor. The microcontroller was developed under the guidance of Mr. V. Shanmugaraj (a Scientist from CMTI, India) to fully automate the machine. Figure 55 shows the block diagram of different electrical components that were used to build this microcontroller along with their photographs.

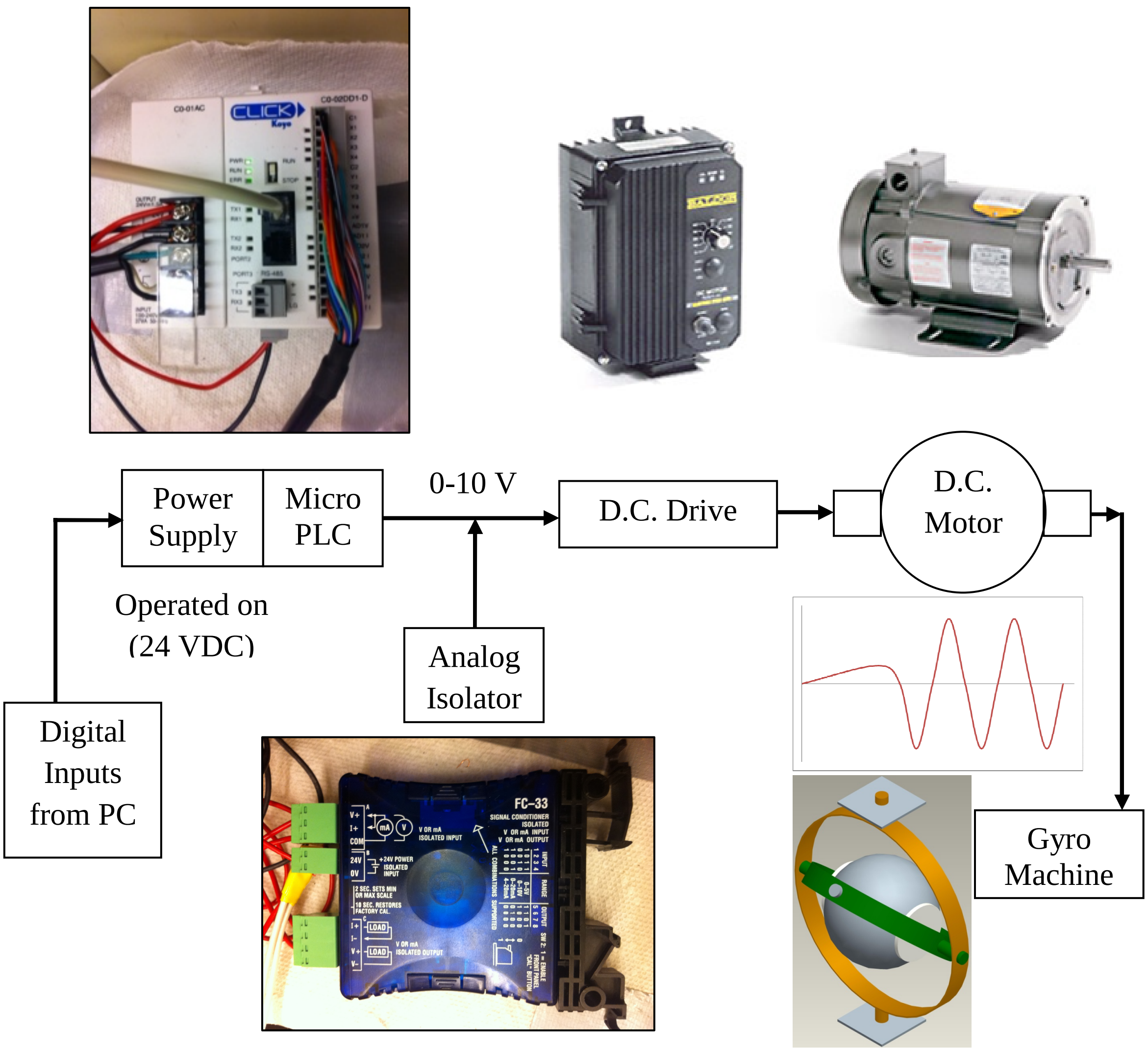


Figure 55 Block diagram of micro-controller used for the gyro machine

7.8.1.1 Micro PLC (Programmable Logic Controller)

Performance of the machine is dependent upon the speed at the outer gimbal and the sphere. As explained earlier there is a need to control the direction of rotation of the outer gimbal as well as the speed of rotation. A semi-automatic controller needs to be operated manually, and the operation may lead to manual errors. Here, the repeated profiles in terms of sinusoidal wave needs to be obtained by switching the polarities of motor periodically.

In this investigation, the microcontroller was used to control the rotation of the outer gimbal by controlling the speed of the DC motor. Micro PLC (Programmable Logic Controller) was used to control the motor as per the logic developed (Refer Appendix B for the Ladder Program developed to control the motor). This type of PLC takes analog inputs generated from the program built using ladder diagram logic from programming software. Micro PLC operates on a 24 VDC power supply. PLC controls the DC drive. Micro PLC controls the electronic switch from the DC drive to control the polarity switch time of the motor. In addition, PLC controls the speed of the motor by controlling the voltage of the DC drive (from 0 to 10 V). The connection between PLC and DC drive was made via an analog isolator.

7.8.1.2 Analog Isolator

As shown in Figure 55, the analog isolator is connected between the PLC and the DC drive of the motor. The main purpose is to isolate them from each other. This way, if there is some problem in either of them due to voltage or current, it protects them from having physical contact.

7.8.1.3 D.C. Drive

A semi-automatic DC drive, type NEMA 4-X from BALDOR was initially used to control the speed of the motor and to switch the polarities of the DC motor manually. For automation purpose, the limit switch and the potentiometer were replaced with an electronic switch. DC drive was connected to the DC motor and was fully controlled by the micro PLC to get the required control over the motor. The DC motor is further connected to the outer gimbal via a pulley and belt arrangement.

7.8.2 Pulley and Belt Arrangement

The force necessary to rotate the outer gimbal is transmitted from the motor to the outer gimbal via a pulley and belt arrangement. Two different sizes of pulleys were connected via a belt. One of the pulleys with a diameter of 2" is mounted on the motor shaft, while the step pulley is mounted on the shaft of the outer gimbal. Depending upon the required speed at the outer gimbal, different diameters from the step pulley can be selected. All the components are aligned co-axially with the spindle. Misalignment can lead to vibrations, unnecessary sound, bearing wear, etc. A step pulley used in this study has three different diameters 4", 5”, and 6". The bore of this pulley is 1". Care is to be taken to provide sufficient tension in the belt to increase the transmission efficiency. Tension in the belt is adjusted as per the selected diameter of the pulley by adjusting the position of the motor horizontally with reference to the frame. Figure 56 shows the belt pulley arrangement used in the present study.

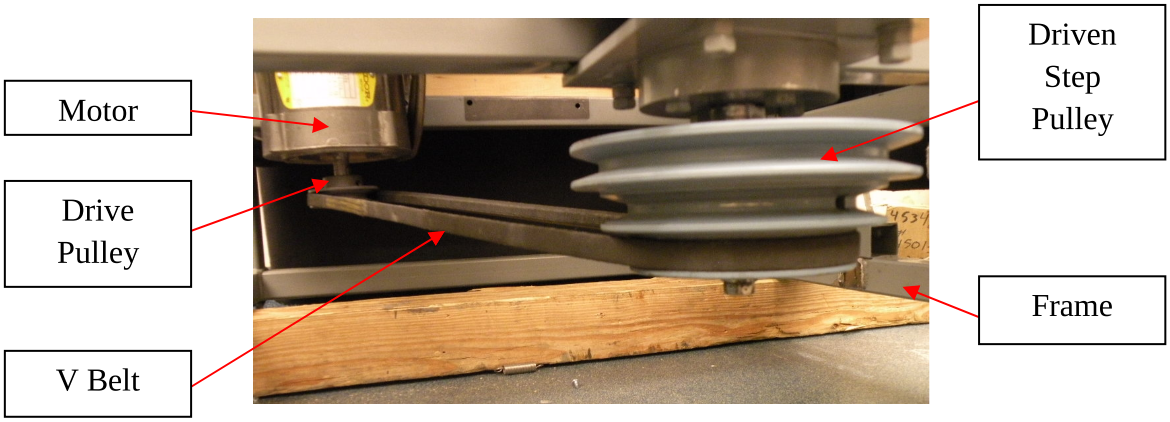


Figure 56 Pulley and belt arrangement

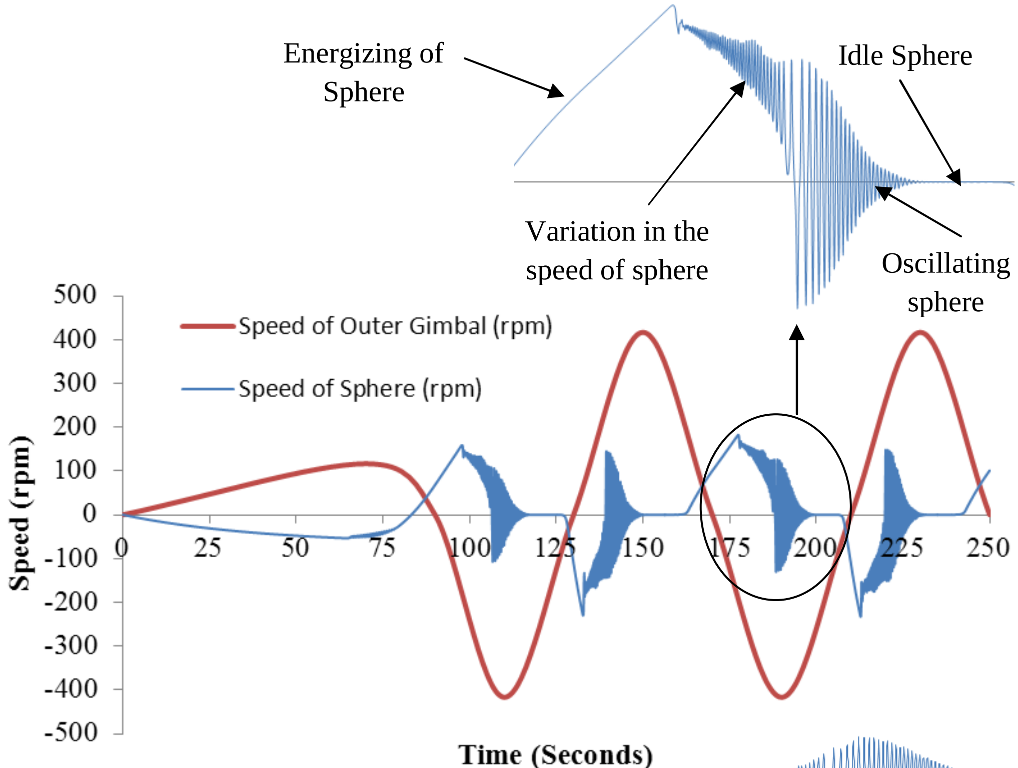
CHAPTER 8

RESULTS AND DISCUSSION

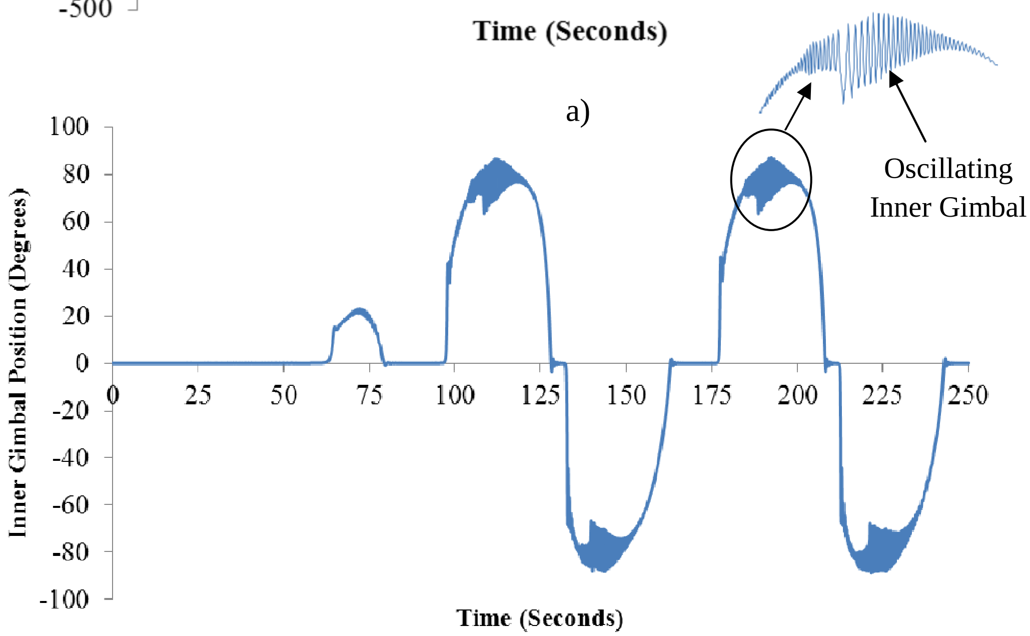
Results obtained from the mechanism and from the actual machine are presented in this chapter. Initially the results were obtained from the mechanism developed using Pro-Mechanism, which gives the performance of the machine in terms of speed of the sphere as a function of the time profile of the outer gimbal (motor). The suitable profile for the outer gimbal was obtained from these trials. The results showing performance of the fabricated machine are also presented. Depending on the performance, an industrial application, washing machine of the gyro machine is discussed.

8.1 Results from Mechanism

The mechanism developed was tested at a speed of ~ 400 rpm of the outer gimbal and at different time profiles (switching rotational direction) of the outer gimbal (motor). Based on these profiles, best profile is chosen for further studies. The machine was tested on this profile, and the results were obtained with the help of high-speed photography. Further, depending upon the performance of the machine, different cycles were identified along with their industrial applications. Figures from 57 to 60 show the speed of the outer gimbal, the speed of the sphere, and the position of the inner gimbal.



a)



b)

Figure 57 (a) Speed of outer gimbal and sphere and (b) Inner gimbal position at 40 sec of time gap in between changing the rotational direction of outer gimbal

The mechanism was first tested with rotating outer gimbal in one direction for 40 sec and then in the other direction for the same time. Figure 57 (a) shows the profiles of the outer gimbal and the sphere. Initially the sphere is energized for about 70 sec, and then once it achieves sufficient velocity ~ 150 to 200 rpm, the rotational direction of outer gimbal (polarities of motor) are switched. Switching of polarities is continued for the next 4 minutes to complete one cycle of total 6 minutes. As shown in Figure 57 (b), the inner gimbal is positioned in the vertical direction for a period of 0 to 100 sec except for 60 to 75 sec. In between 60 sec to 75 sec, the inner gimbal is tilted at an angle of 20 °, because in this timespan, the outer gimbal achieves a speed of ~ 100 rpm, and the holding force of the springs is not sufficient to keep the inner gimbal in the vertical position. After 70 sec, the rotational direction of the outer gimbal is changed by switching the polarities of the motor. As shown in Figure 57 (a), as soon as there is a change in the direction of the outer gimbal, inner gimbal returns to its original direction with rotating sphere and there is a gyroscopic torque acting on the inner gimbal because of spinning of the sphere and the outer gimbal. Figure 70 shows the vector representation of it. Force acting on the inner gimbal inclines it in either clockwise or in the anticlockwise direction as shown in Figure 55 (b). This direction is dependent on the direction of generated force.

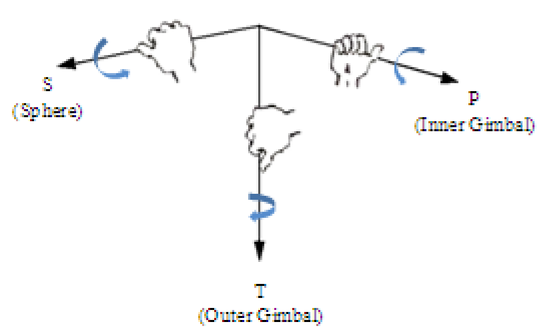
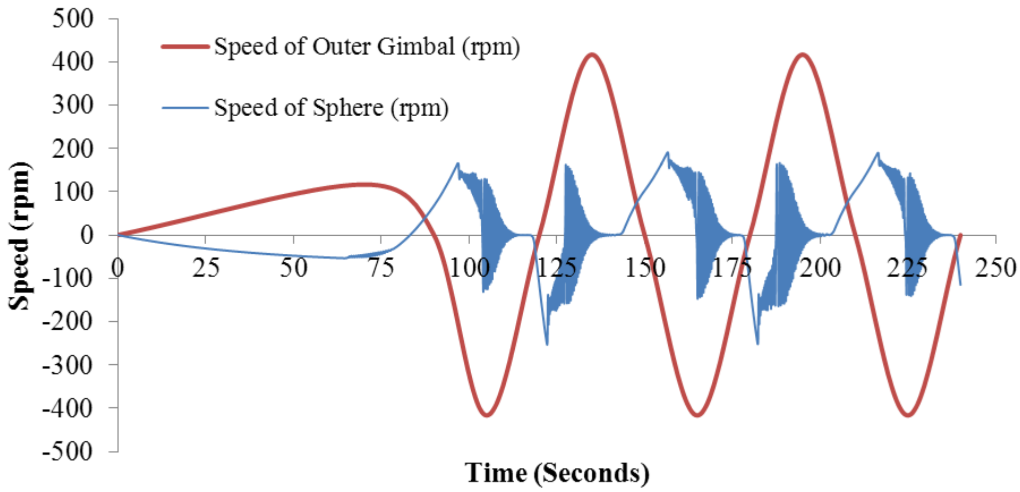


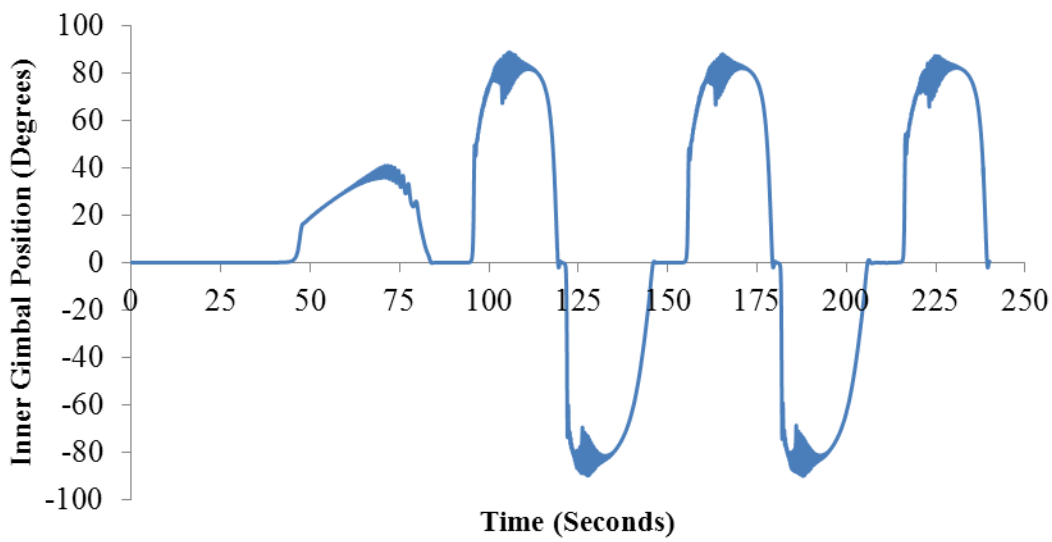
Figure 58 Vector representations
using right hand rule

Because of the gyroscopic torque acting on the inner gimbal, the sphere is freed from the gimbal lock. As the speed of the outer gimbal increases, the inner gimbal travels from 0º to 90 º. The resistance offered by the springs sets the inner gimbal to oscillate [Figure 57 (b)], and this introduces a variation in speed of the sphere as shown in Figure 57 (a). Over the period when all axes are mutually perpendicular, the sphere starts to oscillate. If the outer gimbal is rotated further, then the sphere loses its speed completely and stays idle. As shown in Figure 57 (a), the sphere has lost its speed in between 115 to 125 sec.

The main aim behind building the mechanism and testing it is to find a suitable time to change the rotational direction of outer gimbal to keep the sphere rotating. So, from the above it is clear that the gap of 40 sec for switching the direction of outer gimbal is not ideal. Therefore, the mechanism was run by reducing this gap. Figures 59 to 61 show different plots for speed of outer gimbal, sphere, and position of inner gimbal at the time gap of 30 sec, 20 sec, and 15 sec respectively to switch the rotational direction of outer gimbal.

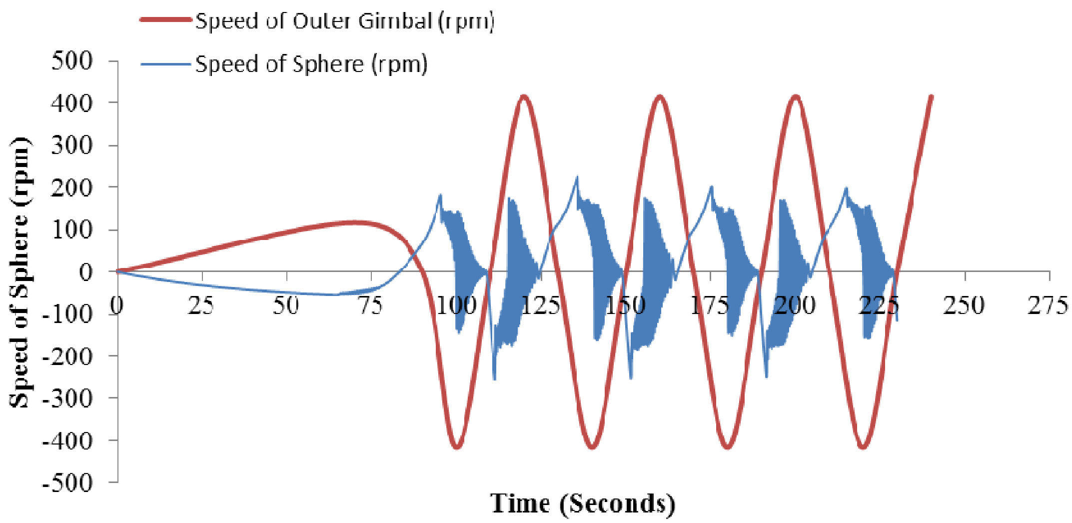


a)

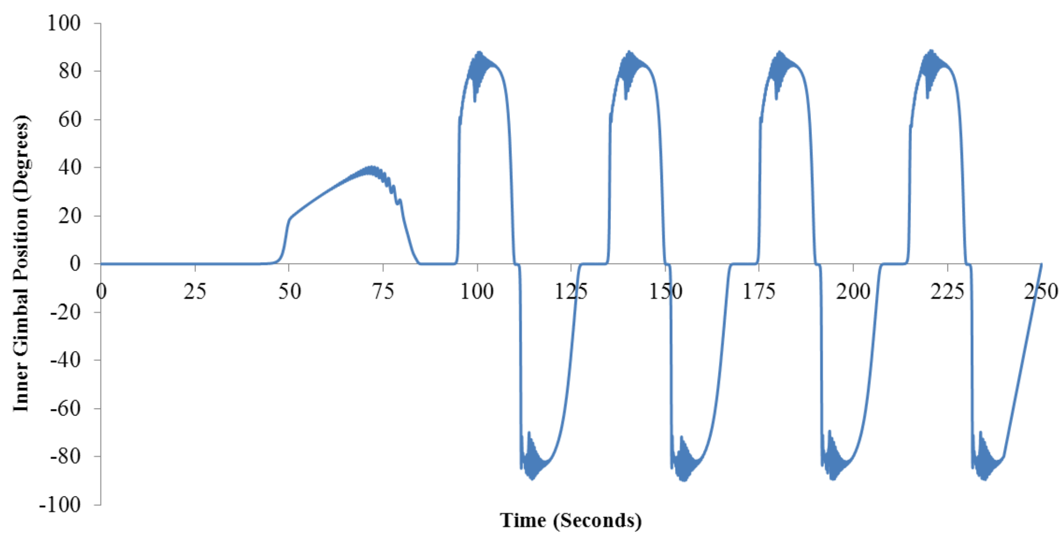


b)

Figure 59 (a) Speed of the outer gimbal and sphere (b) Inner gimbal position at 30 sec of time gap between changing the rotational direction of the outer gimbal

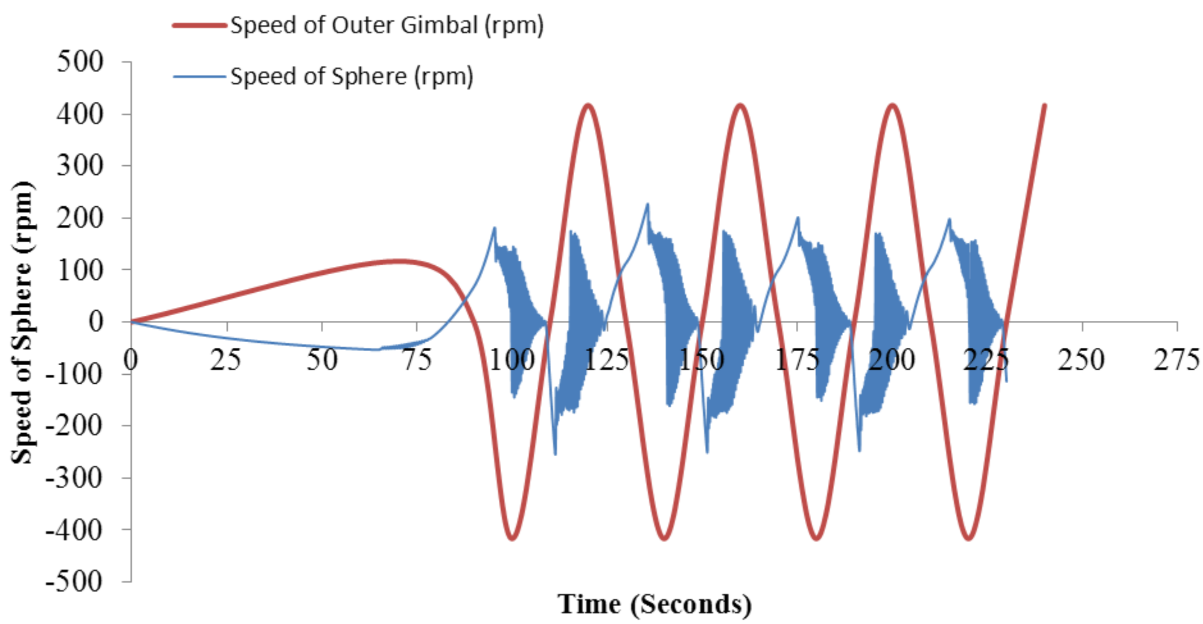


a)

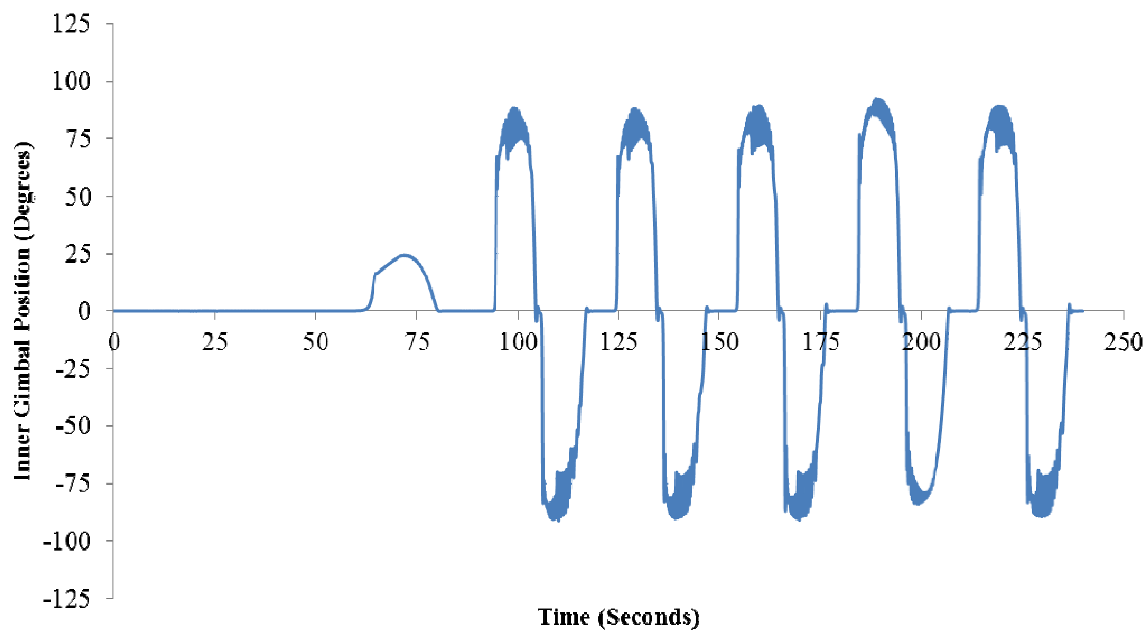


b)

Figure 60 (a) Speed of the outer gimbal and sphere (b) Inner gimbal position at 20 sec of time gap between changing the rotational direction of the outer gimbal



a)



b)

Figure 61 (a) Speed of the outer gimbal and sphere b) Inner gimbal position at 15 sec of time gap between changing the rotational direction of the outer gimbal

From Figures 59 to 61 it is observed that the profile of the outer gimbal developed to switch the rotational direction with 20 seconds or 15 seconds of gap gives a better combination of rotation and oscillation of the sphere. At one point, it achieves the highest speed when the outer gimbal changes its direction of rotation. Again the same cycle repeats, but in the opposite direction as per the right hand rule. It is observed that with a 15 sec profile, more polarity switching occurs. In this, polarities are changed for five times as compared to two times in the 40 seconds profile. This brings more variation in the speed of the sphere. The outer gimbals profile with a time gap of 15 seconds proved to be more effective than with a combination of four extension springs, two torsion springs, and four magnets. Therefore, this profile is used to operate the gyro machine. The logic is developed to obtain the desired profile of the outer gimbal and this was used in the microcontroller.

8.2 High-Speed Camera Photography

The time profile with 15 seconds was used while operating the gyro machine. Since all three axes are moving simultaneously, it is difficult to observe the motion of outer gimbal, sphere, and inner gimbal. Also, it is difficult to extract data, such as speed of the sphere and position of the inner gimbal from the system. Therefore, a high-speed camera technique was used to address these problems. The main purpose was to capture the images at different frame rates to analyze the data.

A high-speed camera from IDT (Model XS-4) was used to study the motion of different components of the gyro machine. Depending on the need, the image-capturing rate of the camera can be adjusted. With this camera, a maximum of 5100 images/sec can be captured. In the present analysis, 3000 images are captured at a rate of 50 frames per second. Figure 62 shows the setup used to analyze motion in the gyro machine components using the high-speed camera. Light arrangement is an important aspect of this technique. As shown in the Figure 62 sufficient light was provided with special arrangements. Figure 63 shows the high-speed camera images captured at 3000 frames per second. With this technique, it was difficult to get quantitative information as all the three axes moving together makes it difficult to analyze a single component at a time. However, qualitative information was extracted for specific intervals. Furthermore, from the captured images a video was created to visualize the mechanism in slow motion. From this visual validation was done. Rotation and oscillations at the sphere can be seen clearly in the slow motion video.

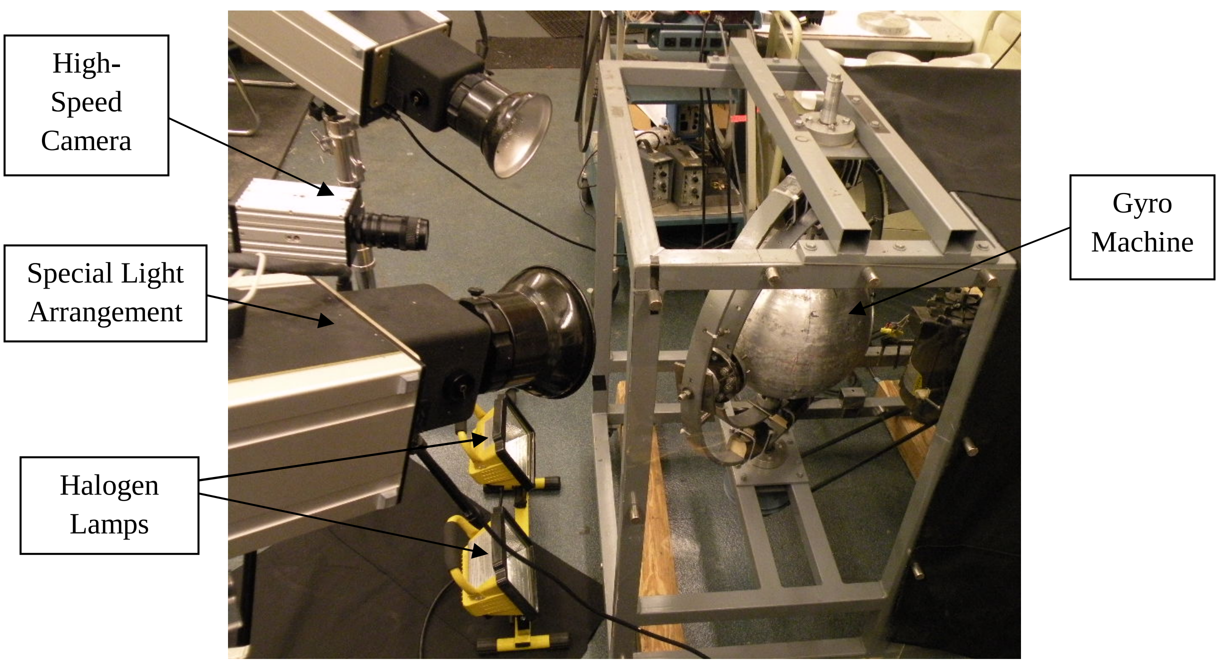
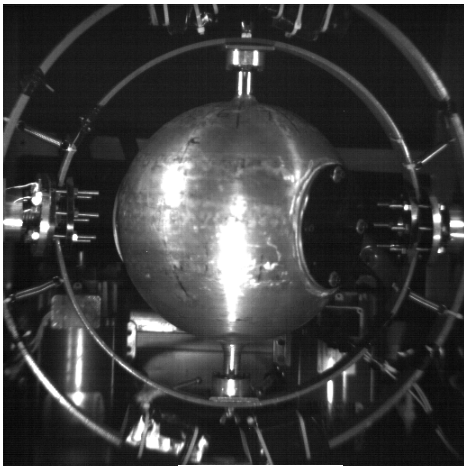
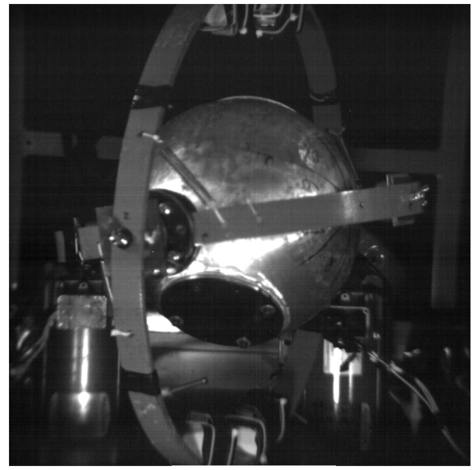


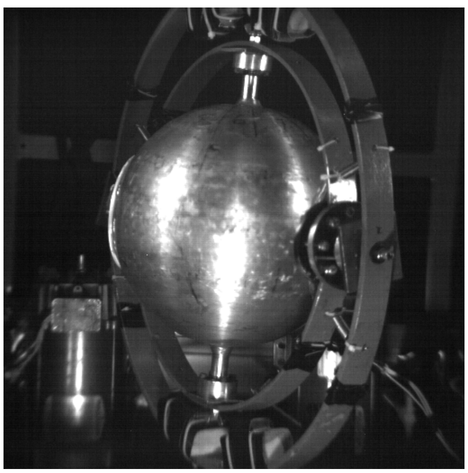
Figure 62 High-speed cameras setup



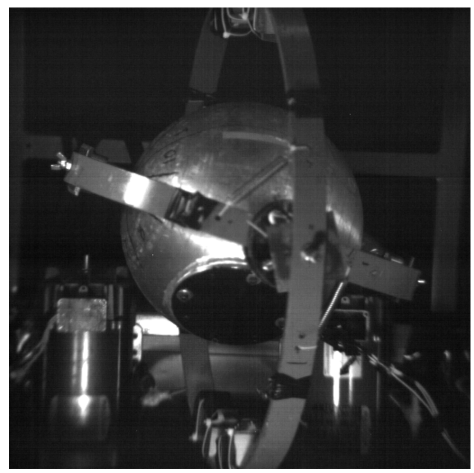
t = 0 s



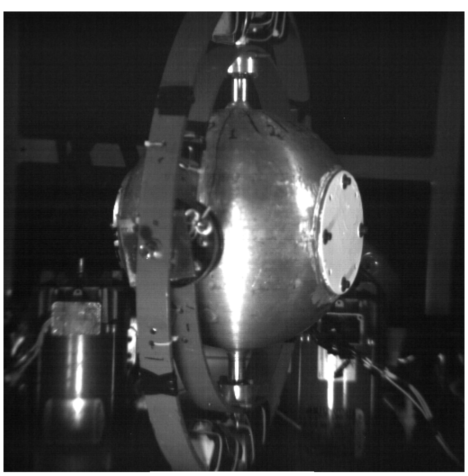
t = 5.9 s



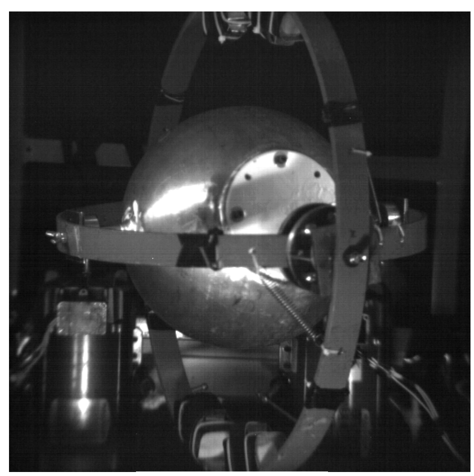
t = 15 s



t = 24.98 s



t = 30 s



t = 36.20 s

Figure 63 High-speed camera photographic images with 15 sec profile cycle of the outer gimbal

Figure 63 shows the high-speed camera images captured with IDT made, XS-4 camera. Fifty frames per seconds is the rate used to capture the images. The images were captured at different periods starting from t = 0 to 60 sec. So, overall 3000 images were captured for analysis purpose. Out of these, only selected images were shown in Figure 63. The reason behind presenting these images is to show a variety of positions different components of the machine can occupy as per the time steps. It may be noticed that there are in total four extension springs, two torsion springs and four bar magnets installed on the setup. With this setup, the profile of 15 seconds is more efficient. The image at t = 0 seconds shows the spin cycle when the sphere attains sufficient velocity. At t = 5.9 s the direction of rotation of the outer gimbal is changed and the torque acting on the inner gimbal makes it to incline by 90° as shown. This completes one cycle. At t = 15 s the change in polarities brings the inner gimbal at the vertical position and the sphere attains sufficient speed due to momentum transfer. At t = 24.98 s inner gimbal attains 90° position again. So, cycle repeat for t =30 s and t = 36.20 s but in the opposite directions.

From the images captured, positions of different components were determined. Figure 64 shows the plots obtained based on them. The video, by controlling the frame rate, was obtained from these images, and can be used to estimate the speed of different components. Trend of graph for the outer gimbal was obtained by micro-controller PLC. The graphs for the sphere and the inner gimbal were generated from the video. With the help of high-speed camera, the speed of the sphere was calculated and plotted as shown in Figure 64 (a).

a)

b)

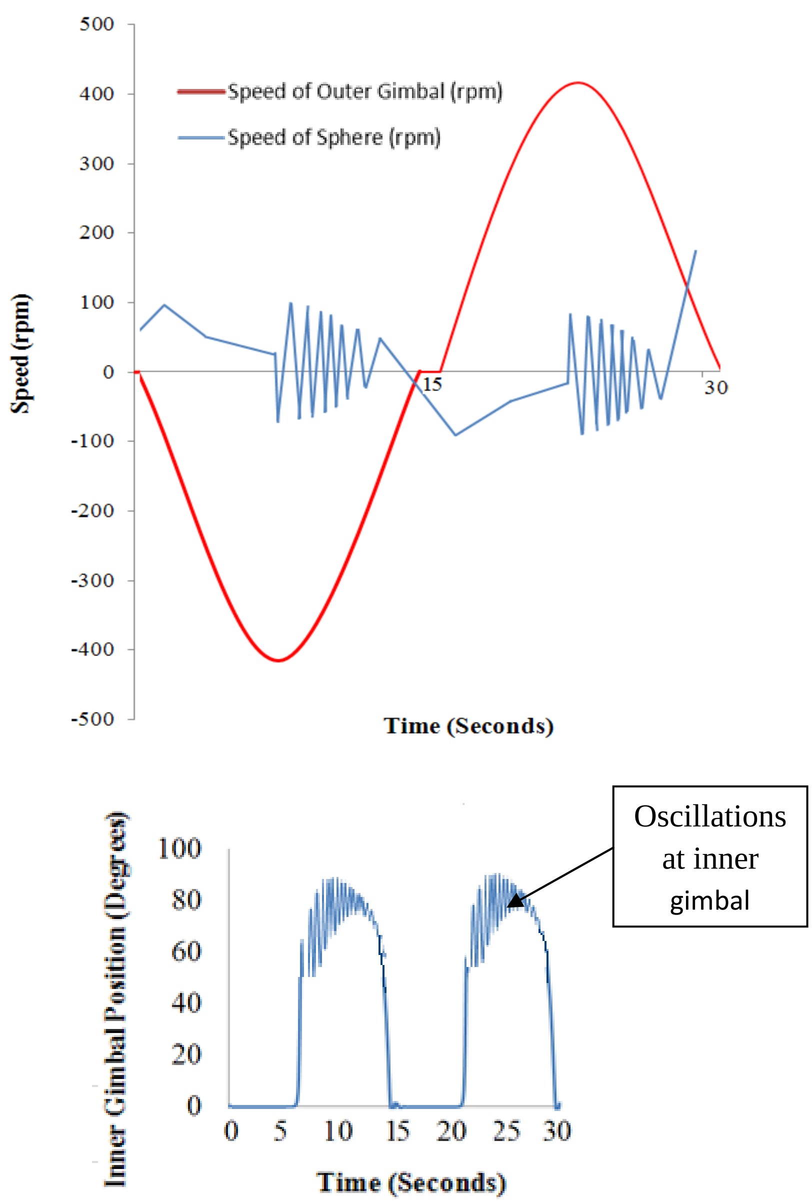


Figure 64 Experimental results of (a) Speed of the sphere and (b) Inner gimbal position at the outer gimbals profile of 15 Seconds

Figure 64 (a) shows the speed of the outer gimbal and the sphere at 15 seconds of a time profile (change in the rotational direction) of the outer gimbal obtained experimentally using the high-speed camera. There was an initial drop in the speed of the sphere once the polarities are changed. This loss of speed of the sphere was due to the magnetic force acting on the inner gimbal. When the rotational direction of the outer gimbal is changed, the torque is applied on the inner gimbal and the inner gimbal is supposed to release from the gimbal lock. Because of the magnetic field acting on the inner gimbal, the gimbal lock remains active for ~5 sec as shown in Figure 64 (b). Sufficient torque is required to pull the inner gimbal from this, and that is completely dependent on the speed of the outer gimbal. So, the magnetic force is the reason for the loss of speed of the sphere in the initial stages. It is observed that the sphere was able to gain ~100 rpm (20 to 25%) of the speed of that of outer gimbal due to momentum transfer after each cycle. The reason for obtaining such speeds is that the motor should operate the gyro machine. When the polarities of the motor are switched, the motor is supposed to stop instantaneously, and this provides the back torque on the inner gimbal to assure the sphere in gaining more spin velocity. However, in the present case the motor does not stop as soon as the polarities are switched because of the high momentum of the outer gimbal.

To overcome the above-mentioned motor driving problem some experiments were performed directly on the setup. From experimentation on the gyro machine setup, it was observed that an increase in the stiffness of the spring affects the speed of the sphere. A time profile of 20 sec is found to be more suitable. In the present investigation, there is a limit to increase the stiffness of the springs because of the space available for the installation of torsional as well as extension springs. As torsional springs and extension springs works in a series, a decision was taken to increase the stiffness of springs by increasing the number of extension springs. Instead of four, eight extension springs were used with two torsion springs and four bar magnets. The arrangement is shown in Figure 65. In this, all the eight springs were mounted at the angle of 20°. The four extra springs were mounted on the top of the existing setup of extension springs in such a way that they will not touch each other when stretched to the fullest. After this arrangement, polarity switch time for outer gimbal was set to 20 seconds with the help of microcontroller and the test was run. The high-speed camera was used, and Figure 65 shows the images that were captured at various time intervals.

It was observed from Figure 66 (b) that the inner gimbal was only able to reach up to 75º. This was because of the higher stiffness provided by extra springs. It was observed that the time required for the inner gimbal to attain the vertical position was reduced by a few seconds. The sphere was able to gain more speed. Because of higher speed of the sphere, cycle can be run for 20 seconds. As observed from Figure 65 (b) there was a gimbal lock, in effect, for ~ 5 sec, because of the magnetic field acting on the inner gimbal. As seen from Figure 66, the sphere was able to achieve ~150 to 170 rpm (~25 to 30%) when being energized after each cycle.

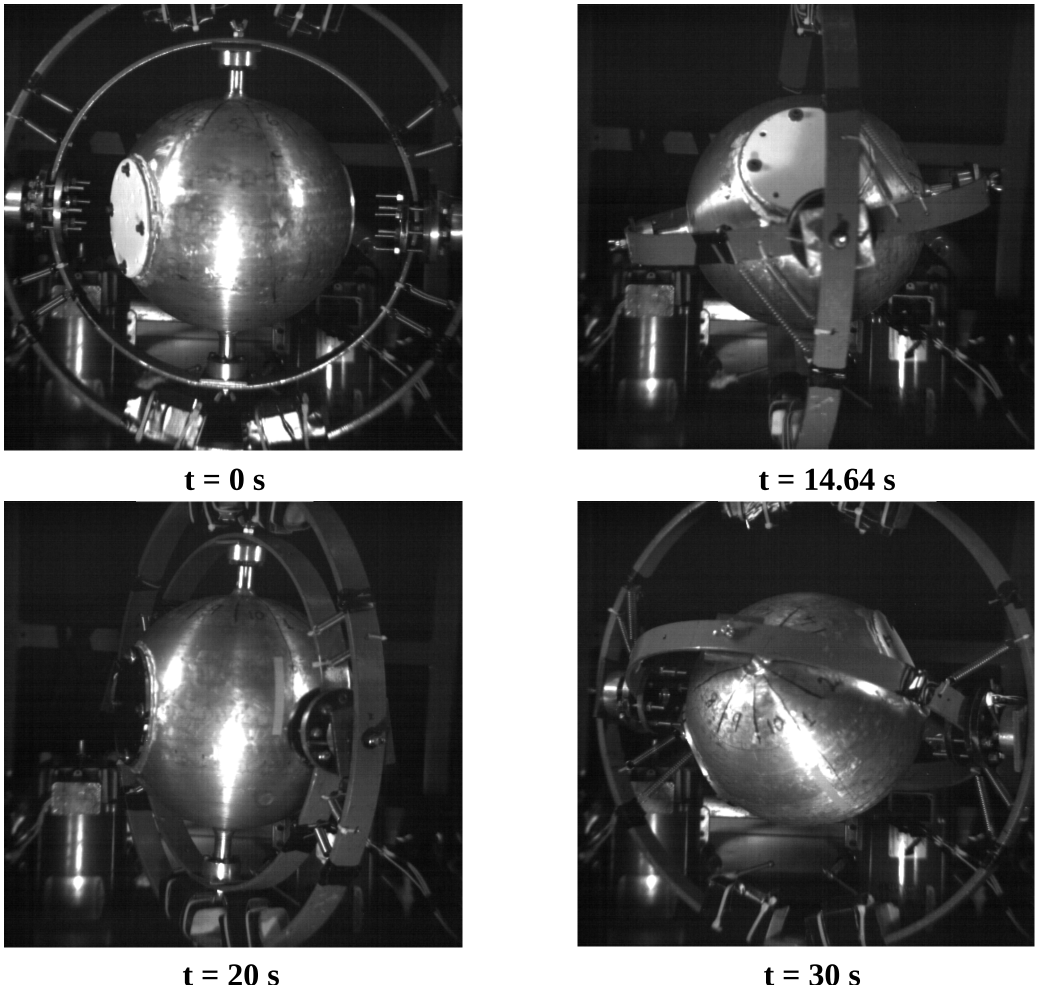
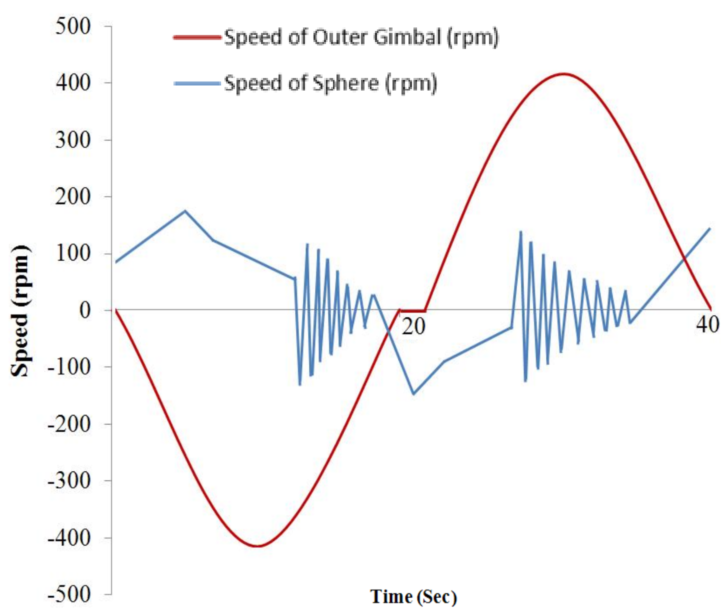


Figure 65 High-speed photographic images at 20 sec profile cycle of outer gimbal

a)



b)

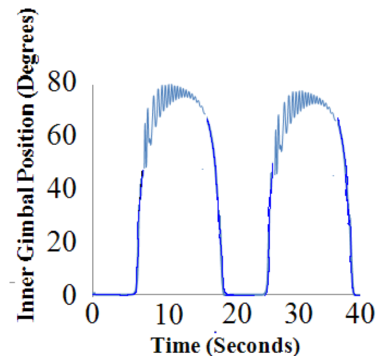


Figure 66 Experimental results of a) Speed of sphere b) Inner gimbal position at outer gimbal profile of 20 Sec

The positions of the inner gimbal should be changed along with the change in the direction of rotation of the sphere and the outer gimbal, as per the right hand rule as seen in the figure 58 to 61 (b) (Mechanism Analysis). In the case of gyro machine setup, this is not the case [refer to Figure 64 (b) and 66 (b)]. The inner gimbal was deflected in the same direction by 90^{o}, despite the direction of rotation of the sphere and the outer gimbal. This was mainly due to uneven mass distribution. It was observed that the inner gimbal is always inclined towards one side. This problem arises mainly because of improper assembly of the sphere with the inner gimbal, and can be solved by improving accuracy of the machining and assembly of the components.

8.3 Industrial Applications of Gyro Machine:

Based on the above the results, it was observed that the gyro machine is capable of producing a variety of combinational motions. The sphere, the main part of the system, can be used as a container to load different types of materials. The sphere is able to rotate and oscillate under the gyroscopic effect. While rotating oscillatory effect about the inner gimbals axis was also observed. All these effects were followed by the rotation of the outer gimbal. This machine is capable of rotating the spherical container in all possible directions by providing motion in three degrees of freedom. This unique property of the machine can be used for a variety of industrial applications. Figure 67 shows different cycles that are derived from the graph that was generated from the mechanism developed and analyzed using Pro-Mechanism software.

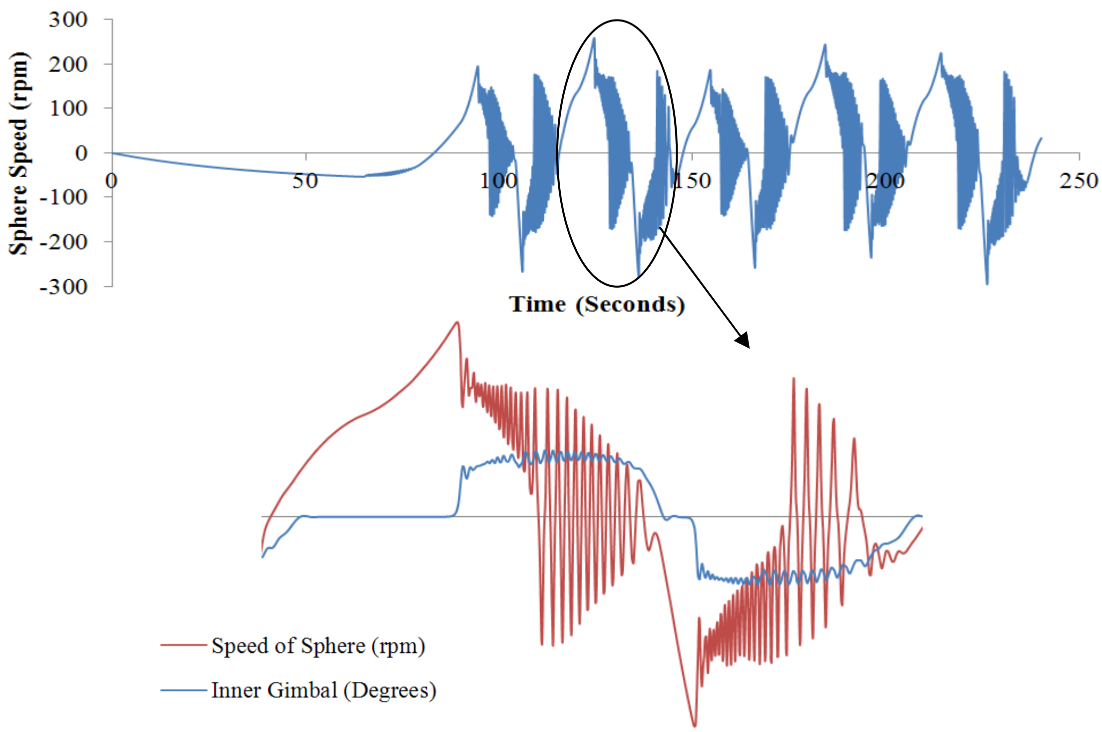


Figure 67 Study of different cycles due to variation in the speed of sphere

Figure 68 shows various cycles that can be achieved from the variation in the speed of the sphere. Spin, rolling and oscillatory cycles are different types of cycles. Figure 68 shows that initially, the sphere receives a part of energy from the outer gimbal and it starts spinning and attains a certain speed. This cycle is termed the spin cycle. In this cycle, inner gimbal remains vertical due to gimbal lock, and is shown by straight horizontal blue line in Figure 68.

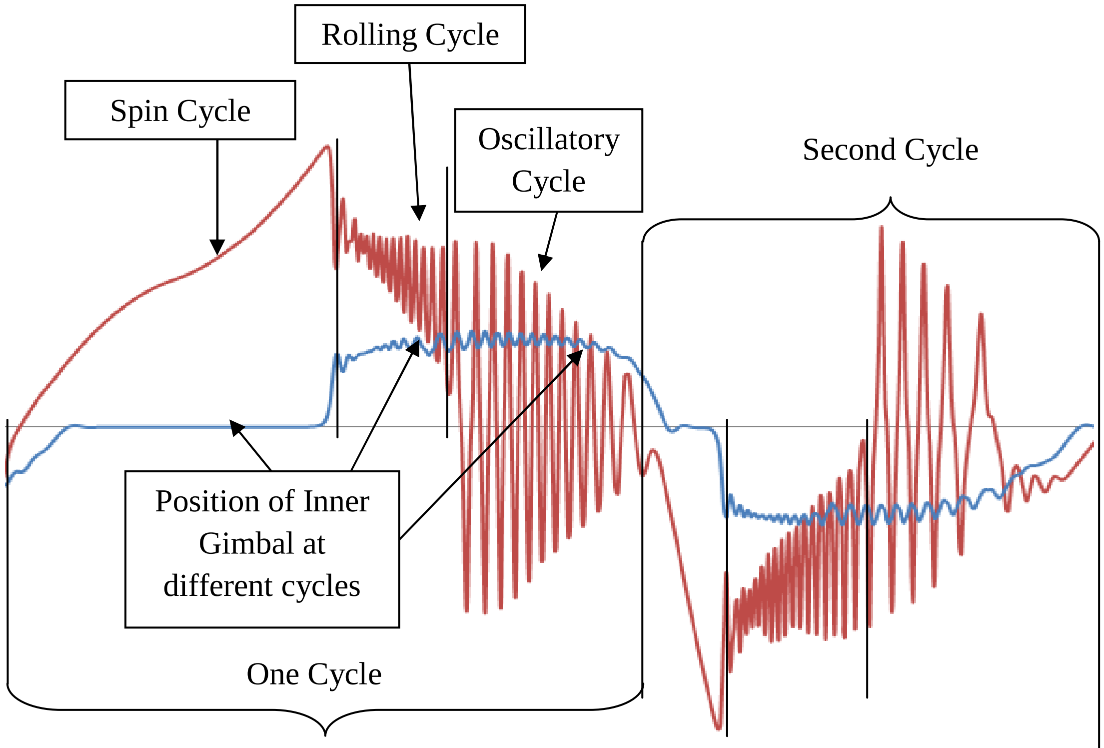


Figure 68 Different cycles identified for a washing machine from the graphs generated from Pro-Mechanism

Change in the direction of the outer gimbal tilts the rotating sphere, due to the inclination experienced by the inner gimbal, caused by the gyroscopic torque acting on it. This cycle is termed rolling cycle as the material inside the sphere experiences the rolling as well as tumbling action at the same time. As the inner gimbal reaches 90°, the sphere loses its speed and starts oscillatory motion because of the resistance offered by friction in the system. The material inside the sphere at this time experiences pure oscillations, so this cycle is named as the oscillatory cycle. When the direction of the outer gimbal is changed, these cycles are repeating but in the opposite directions.

The gyro machine developed can be used for a variety of industrial applications, such as: washing machine, mixing different granular or ceramic materials, paint mixing, chemical mixing, etc. The following discussion provides information about how the gyro machine can be used for cloth washing application, as this is one of the most promising applications of this innovative machine.

8.3.1 Gyro Washing Machine

The mechanical design of a cloth washing machine is not a new technology. This technology has been established for many decades. In recent washing machines – the basket/drum spins in one plane and in two directions: forward and reverse. Variety of programmable controllers developed so far rotates the cylindrical container in different ways, but only about a single axis. This axis is either horizontal or vertical depending upon the type of washing machine used, namely a vertical loading or a horizontal loading. The principle used behind a vertical loading and horizontal loading washing machines is to generate friction between water, detergent, machine body, and clothes.

8.3.1 Spin Cycle

Figure 69 describes the spinning cycle in detail. In this entire cycle inner gimbal remains at rest because of the gimbal lock provided. As profile showed, the velocity of the sphere increases slowly and reaches to the maximum. Vector representation showed is as per the right hand rule. The curled fingers are in the direction of spin and the stretched thumb indicates the spin vector denoted by S. The clothes inside the spherical container are rubbed against the surface of the sphere because of the centrifugal force, and are immersed in water for the whole time. The clothes inside the container will experience the profile as shown in Figure 69. Depending on the direction of spinning of the sphere, the clothes will experience either of the profiles shown in Figure 69.

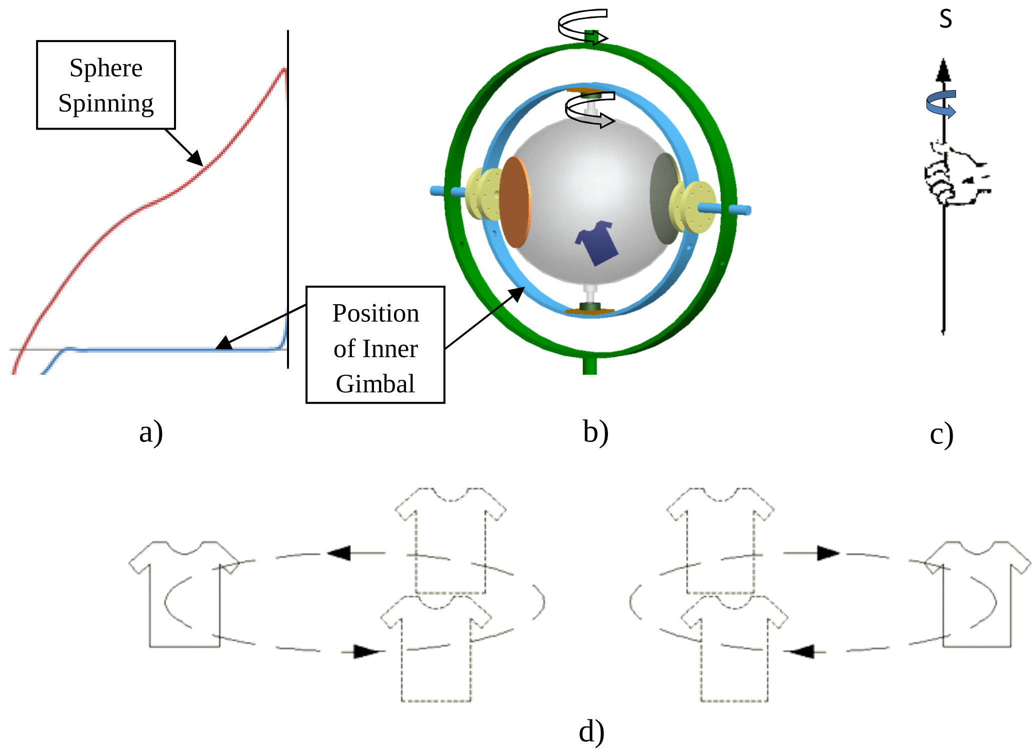


Figure 69 Spin Cycle a) Profile of spin cycle b) Positions of components c) Vector representation d) Spinning effect experienced by clothes

8.3.1.2 Rolling and Tumbling Cycle

The change in the direction of rotation of the outer gimbal gives rise to a new cycle. The torque acting on the inner gimbal takes the sphere out of the gimbal lock, and the rotating sphere starts experiencing the oscillatory effect due to oscillations at the inner gimbal, as shown in the profile in Figure 70. As a result, the clothes inside the sphere experiences simultaneous rolling (because of the rotating sphere) and tumbling-like motion due to oscillatory effect at the inner gimbal. Figure 70 shows the rolling and tumbling cycle. Vector representation is obtained as per the right hand rule. Precession vector at the inner gimbal is obtained by curling fingers from spin vector towards the torque vector (P = S x T). The rolling action gently moves or rolls the clothes in the sphere keeping it immersed in water. Depending upon the direction of rotation of the outer gimbal, the cloths experience either clockwise or anticlockwise rolling and tumbling action.

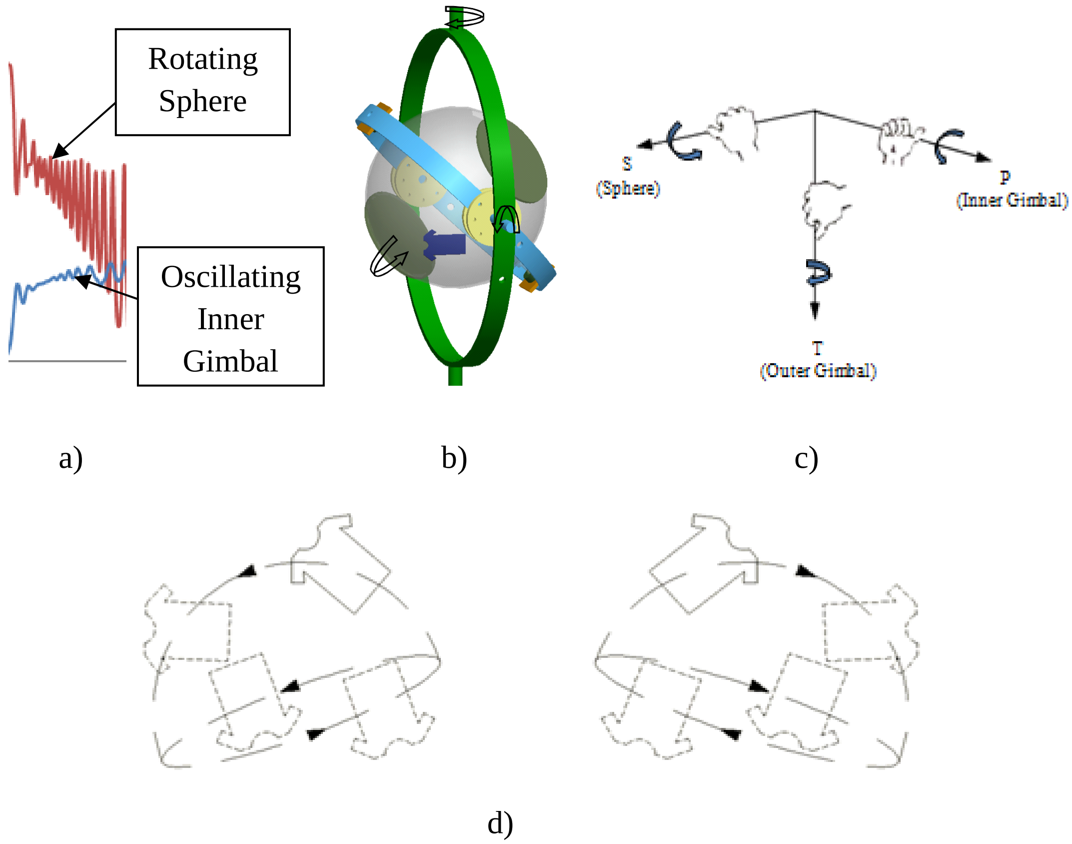


Figure 70 Rolling and Tumbling Cycle a) Profile of rolling cycle b) Positions of components c) Vector representations d) Rolling and tumbling effect experienced by clothes inside the sphere

8.3.1.3 Stepping or Oscillating Cycle

After the rolling and tumbling cycle, the inner gimbal gets dampen and act purely under the effect of centrifugal force. This force makes it horizontal, and all the three axes are mutually perpendicular. Over the period, rotating sphere loses its energy and starts oscillating. As shown in Figure 71 inner gimbal almost remains horizontal with the oscillating sphere. This provides step motion to the clothes. The clothes are raised to the maximum height and then are fall under gravity to get bumping effect against the surface of the sphere. This rising and falling action of clothes happens in both directions as shown in Figure 71 under the profile of stepping action. Therefore, clothes are taken from the bottom of the sphere to the top with high force resulting in powerful cleaning experience. Due to oscillatory effect, the clothes experience the stepping action in both clockwise and anticlockwise direction. This way more effective cleaning can be obtained.

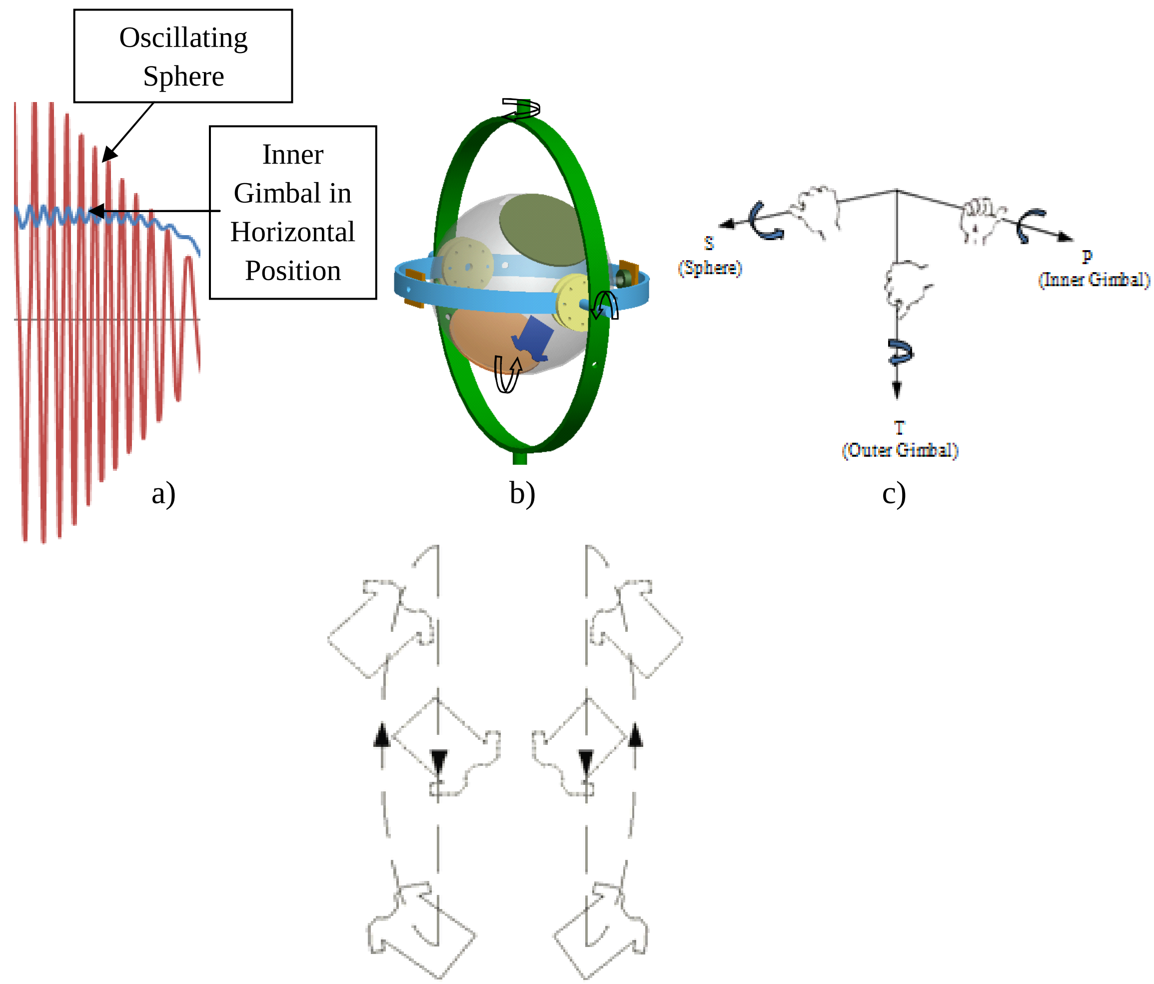
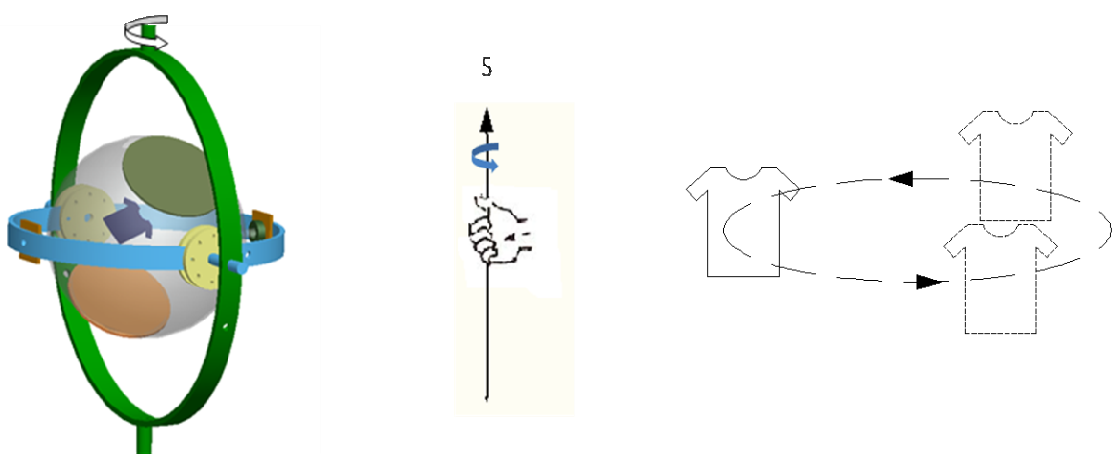


Figure 71 Stepping cycle showing a) Profile of stepping cycle, and (b) Positions of components (c) Vector representation, and (d) Stepping effect experienced by the clothes inside the sphere

8.3.1.4 Drying Cycle

This cycle comes last in the list. Once the set number of repetitions of cycles is done, then the set program takes machine into drying mode. In this mode, the outer gimbal is rotated at higher speed ~700 rpm. Because of the higher speed at the outer gimbal, centrifugal force acting on the inner gimbal orients the sphere horizontally by deflecting the inner gimbal by 90º. So, in this cycle the inner gimbal remains completely horizontal, and there is hardly any spinning of the sphere. The contents inside the sphere are rotated purely under the centrifugal force because of high rotational speed of the outer gimbal. This results in the removal of water from the clothes. The drying cycle ends after 5 minutes. Figure 72 shows the drying cycle.



a) b) c)

Figure 72 Drying Cycle representing a) Position of Components b) Vector Representation c) Position of Components

The cycles explained above are independent of the material loaded inside the sphere. Here, only one application, namely, the washing machine is described. With the help of this application, it is easier to understand a variety of profiles that this machine is capable of generating. This machine can also be used for mixing ceramic powders, different granular size materials, different paints, or chemicals. Spin, rolling and stepping cycles are capable of producing the same effect of rotating sphere in all possible ways to mix several materials, chemicals, or paints as in the case of washing machine.

8.4 Advantages of Gyro Machine

Gyro machine is designed based on a completely new technique. It adds up the advantages of both horizontal and vertical washing machines, as the axis of spherical container is initially vertical and over the period, it becomes horizontal. So, it gives combinational cleansing effect to the clothes. Apart from this the machine has advantages, such as time saving, improved performance under more load, elimination of the agitator, uniform mixing, reduction in vibrations, compact in size. These advantages are discussed in this subsection in more detail.

8.4.1 Time Saving

Most promising application of gyro machine is washing clothes. With this system, a significant reduction in time for the washing is anticipated. The washing cycle in the traditional washing machines is about 26 minutes; this time can be reduced with the gyro machine. This reduction in washing time is possible, as the machine is capable of producing different washing cycles. So, by changing the rotational direction of the outer gimbal in the interval of 15 seconds, the main three cycles can be repeated for around eight times in just 4 minutes. Therefore, effective mixing of water with the detergent is possible. So overall, if this whole cycle is repeated for four times, i.e. for 16 minutes, then there should be significant washing of the clothes with considerable saving in time.

8.4.2 Improved Performance with More Loading

The new, revolutionary washing system is built solely on the concept of the gyroscope. So, the mass of the sphere determines the efficiency of the system. Gyro machine works on Equation (1) [$M_y = C\,\Omega\,\dot{\varnothing}\,\sin\theta$] highlighted in the literature review section of this study. As per this equation more the load in the sphere, higher is the moment of inertia, which results in more gyroscopic effect resulting in a more efficient gyro-system. Based on this, as we load the sphere or the drum with more and more material, the system become more and more efficient.

8.4.3 Elimination of an Agitator

The most promising application of the gyro machine is the washing machine. The system operates without an agitator. In the current machines, one of the failures of the washing machine is the breakage of the agitator in the system. An Agitator is the heart of washing system, which takes care of different washing cycles. In the case of gyro machine, the spherical container itself acts as a dynamic agitator.

8.4.4 Uniform mixing

In the current washing machines, cylindrical baskets are mounted either in the vertical or horizontal axis. Sometimes while clothes are being washed, the detergent added inside gets stuck to the corners of the drum. So, not all the detergent poured in is used. In the gyro-washing machine as the sphere is used as a container this problem is eliminated due to the uniform surface of the sphere. There are no corners, and since we can add the shaking effect, there is proper mixing of the detergent with water. So, this uniform mixing can lead to better cleansing/washing effect.

8.4.5 Reduced Vibrations

A major problem with the current washing machines is the need for placing the clothes uniformly around the container. Non-uniform distribution of clothes in the container can lead to vibrations and noise in the washing machine. In the case of gyro machine, clothes are uniformly distributed due to the spherical shape of the container and motion of the sphere in all possible directions. So, with the use of this machine, these problems can be avoided.

8.4.6 Compact

Most machines, whether it is a washing machines or a paint-mixing machine, use a cylindrical container. In the present study, a sphere is used as the container. By comparing the volume of the sphere with the volume of the cylinder, it can be shown that the sphere requires less space to occupy. Following comparison between volumes shows that cylinder occupies more space lengthwise, as height of the cylinder occupies 1.3 times more space than that of a radius of the sphere. The relation between height of the cylinder and the radius of the sphere is shown on the next page.

$V_{cylinder}$: $\pi r^2 h$ V_{Sphere} : $\frac{4}{3} \pi r^3$

Where,

r = Radius of Cylinder = Radius of Sphere

h = Height of Cylinder

$$V_{Cylinder} = V_{Sphere}$$

$$\pi r^2 h = \frac{4}{3} \pi r^3$$

$$h = 1.33 r$$

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

9.1 Conclusions

1. In the present investigation, a new gyro machine capable of producing three degrees of freedom, based on the gyroscopic principles, was designed, built, and tested successfully.

2. The Gyro machine uses only one input in the form of a motor to drive a sphere, as well as a outer gimbal by using gimbal lock concept.

3. The Gyro machine development approach involves the applications of gyroscopic principles, reverse engineering, design, and construction of the apparatus, establishing optimum time profiles for motor and proposing proper industrial applications of the developed apparatus.

4. Basic apparatus design began by application of gyroscopic principle, geometric design of the components based on the existing setup and use of reverse engineering approach. The mechanism-based approach was used while developing and modifying the current, available setup. The mechanism was built using the Pro-Mechanism software. It was observed that the rotating sphere and the outer gimbal in the opposite directions produce the gyroscopic torque on the inner gimbal. This idea was further

extended and selection of springs and time profiles designing for motor were accomplished.

5. Use of a torsional spring was found to be very effective as it served the purpose of energizing the sphere by bringing the inner gimbal in a vertical position after specific intervals. Extension springs were used to prevent inner gimbal from crossing 90° and in preventing failure of the torsion springs. Furthermore, both types of springs worked in series and enabled the inner gimbal in attaining the vertical position in less time to get more spin at sphere.

6. Use of powerful NdFeB (2" x 1" x 0.5") magnets helped in improving the speed of the sphere. FEM analysis confirms that these magnets, when arranged radially, are capable of providing the gimbal lock, and are more efficient when kept at a distance of 0.2 " from the inner gimbal. It also confirms that magnet facilitates the inner gimbal to attain gimbal lock quickly because of the strength of magnetic field upto 15° to 20° of angle from the vertical axis of the outer gimbal. Handling and mounting of the magnet is an issue. In the investigation, the magnets were glued using superglue on a wooden fixture and attached firmly.

7. Parametric relations were developed to design components based on the size of the sphere. The gyro machine can be scaled up or down based on the size of the sphere.

8. Flemings right hand rule was obeyed by the mechanism built in the software, i.e. inner gimbal changes its position as per the right hand rule. The gyro machine setup when observed was not able to follow the right hand rule. It appears to be due to an uneven mass of the sphere or improper assembly of the sphere with the inner gimbal.

9. Analysis carried out with the help of high-speed photography has shown affirmative results. The gyro machine was able to produce rotation, oscillation of the sphere followed by pure rotation at the outer gimbal and oscillations at the inner gimbal. Combination of these motions has successfully obtained different cycles, such as spin, rolling and stepping or oscillations, etc.

10. Changing the rotational direction of outer gimbal after every 15 sec timespan was found to be the promising profile with a setup of 4 extension springs, 2 torsion springs, and 4 bar magnets. When tested this setup using Pro-Mechanism (without magnets) , it was found that sphere was able to achieve ~ 225 rpm compared to ~ 425-rpm speed of the outer gimbal and when tested on the gyro machine, the sphere was able to reach ~ 100 rpm. Increase in the stiffness coefficient by increasing the number of extension springs changes this profile from 15 sec to 20 sec and when tested on the gyro setup sphere was able to reach ~ 150 rpm after each interval. Difference in the speed of the sphere when obtained by comparing Pro- mechanism and actual experimental setup results was due to the delay in switching the polarities of the DC motor from the setup.

11. Gyro machine for washing clothes has found to be the most promising and impressive application with a variety of cycles that the machine is capable of producing. Different profiles that clothes can experience inside the sphere are derived and found to be more advantageous as compared with the existing washing machines.

12. The new gyro machines can be used not only as washing machine but also in mixing different ceramic powders, different granular materials, a variety of chemicals and paints.

13. Speed of the sphere is found to be dependent on the content inside the sphere. More the load inside the sphere more is the weight of the sphere and more is the gyroscopic effect.

14. Time saving, uniform distribution of material, compact in size are some of the salient features of this machine.

9.2 Future Work

1. Wireless sensors, accelerometers can be mounted on the gyro machine to gather information about the speed of the sphere, and the position of the inner gimbal more accurately. Also, vibro-meters can be used to study the vibrations in the machine.

2. In the present investigation, the rotational direction of outer gimbal is changed by switching polarities of the motor in order to keep the sphere spinning and to get gyroscopic effect in order to obtain unique motion at the sphere. The outer gimbal, as well as motor, should stop as soon as the polarities are changed, as it helps in developing a back torque at the inner gimbal, and reduces the time required for inner gimbal in achieving vertical position. This reduction in time increases the momentum transfer from the outer gimbal to the sphere, and helps in achieving higher angular velocity of the sphere. In the present study, motor takes some time before it changes its polarity. In the present study, the outer gimbal has no braking facility. Also, the controller of the DC motor has no dynamic braking system. Due to these two reasons, motor does not change its rotational direction quickly. Due to momentum of the outer gimbal, it continues to rotate and this makes it to drive further before it comes to stop. For safety reasons normally, the DC motors are developed with an inbuilt logic which

changes the direction of motor only when motor is stopped completely. So, in future this delay problem can be solved by providing braking either to the outer gimbal or to the motor via a controller. Thus, for future study, it is recommended to use a motor with dynamic braking; or, the braking can be provided at the outer gimbal by using solenoid valves to operate the baking system. The control of these valves can be done from the developed micro-controller via micro-PLC.

3. When gyroscopic torque start acting on the inner gimbal because of the permanent bar magnets inner gimbal stays in the gimbal lock position for sometimes and this decelerate the sphere. Therefore, these permanent bar magnets can be replaced with the electromagnets. A program can be developed to activate and deactivate the electromagnets depending upon the set time. The same micro-controller developed in the present study to control the motor can also be reprogrammed to control these electromagnets. The controller should operate these electromagnets depending upon the rotational direction of the outer gimbal and the inner gimbal position. Accordingly, as soon as the motor changes its polarity, there will be deactivation of the electro magnets, and the inner gimbal will be free from the magnetic field. This will help in maintaining the speed of the sphere. For the initial spin cycle and for the rest of the cycle, when the inner gimbal is approaching the vertical position, the electromagnets will be activated to pull inner gimbal and gimbal lock can be provided.

4. The machine can be developed further for its most promising application as a washing machine. Necessary modifications in point view as a washing machine need to be done by attaching different accessories such as a pump and timers to bring the machine to a commercial level.

5. The Machine can be developed and analyzed for applications other than washing machine such as mixing powders, chemicals, ceramics, or paints etc.

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APPENDIX A

Machine Drawings

The following are the drawings of different components of the gyro machine that were already fabricated by the previous team. The different entities of the gyro machine developed at OSU in 1995 were reverse engineered to generate this data. These drawings were used to build the CAD model and to develop the mechanism in the present investigation. These drawings can be referred to further modifications that are needed to be implied in the future.

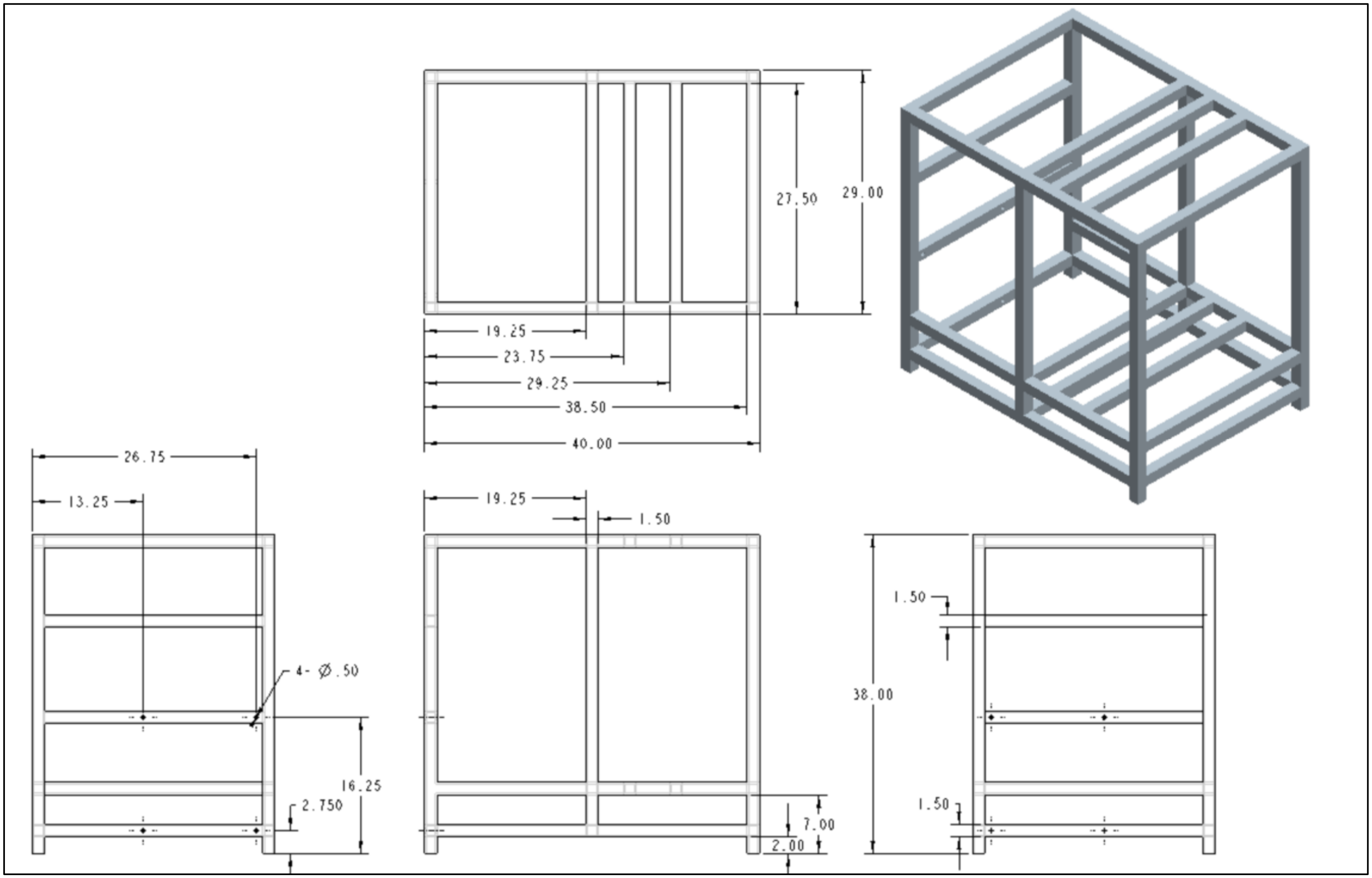


Figure 73 Multiview drawing of the gyro frame

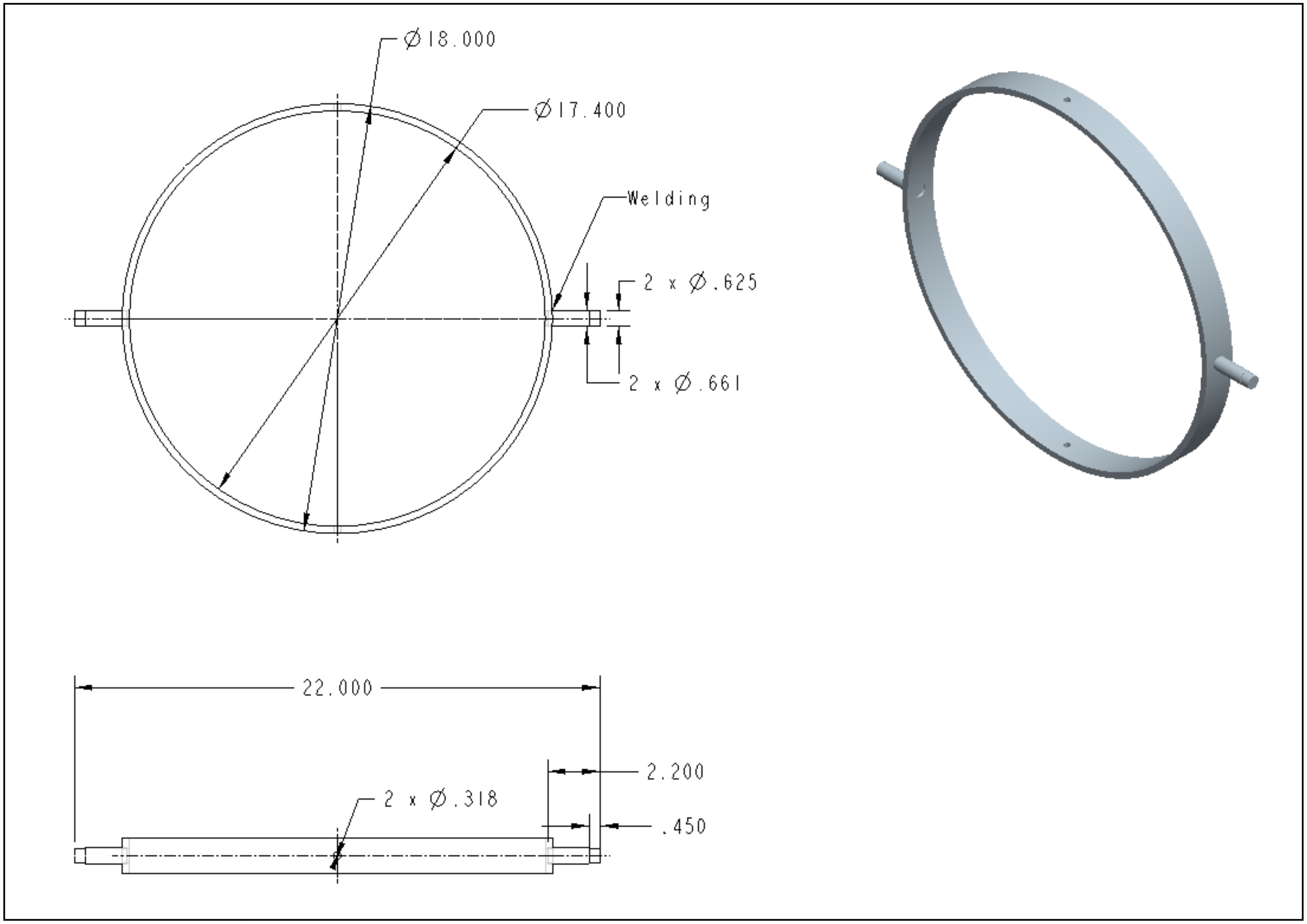


Figure 74 Multiview drawing of the inner gimbal

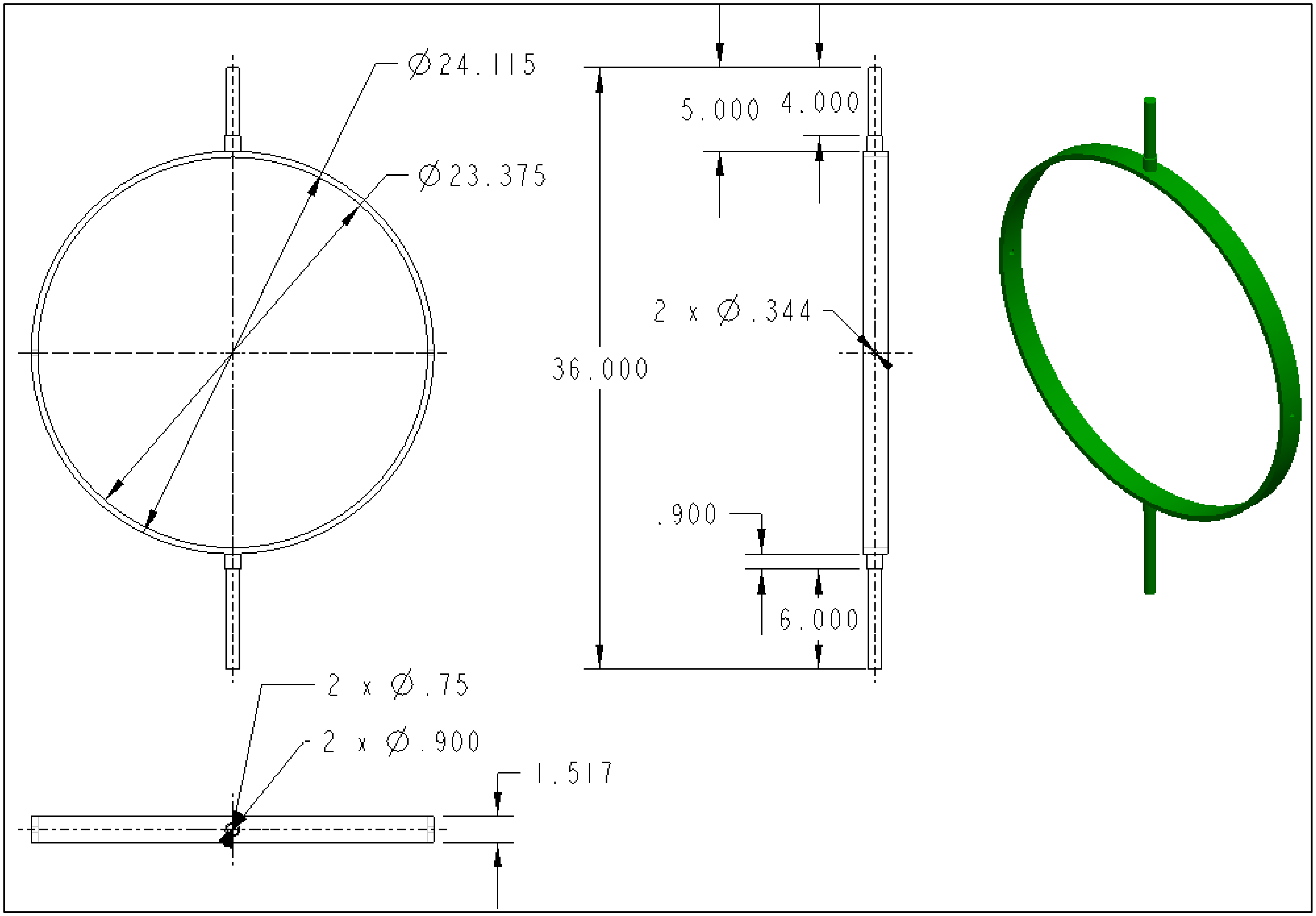


Figure 75 Multiview drawing of the outer gimbal

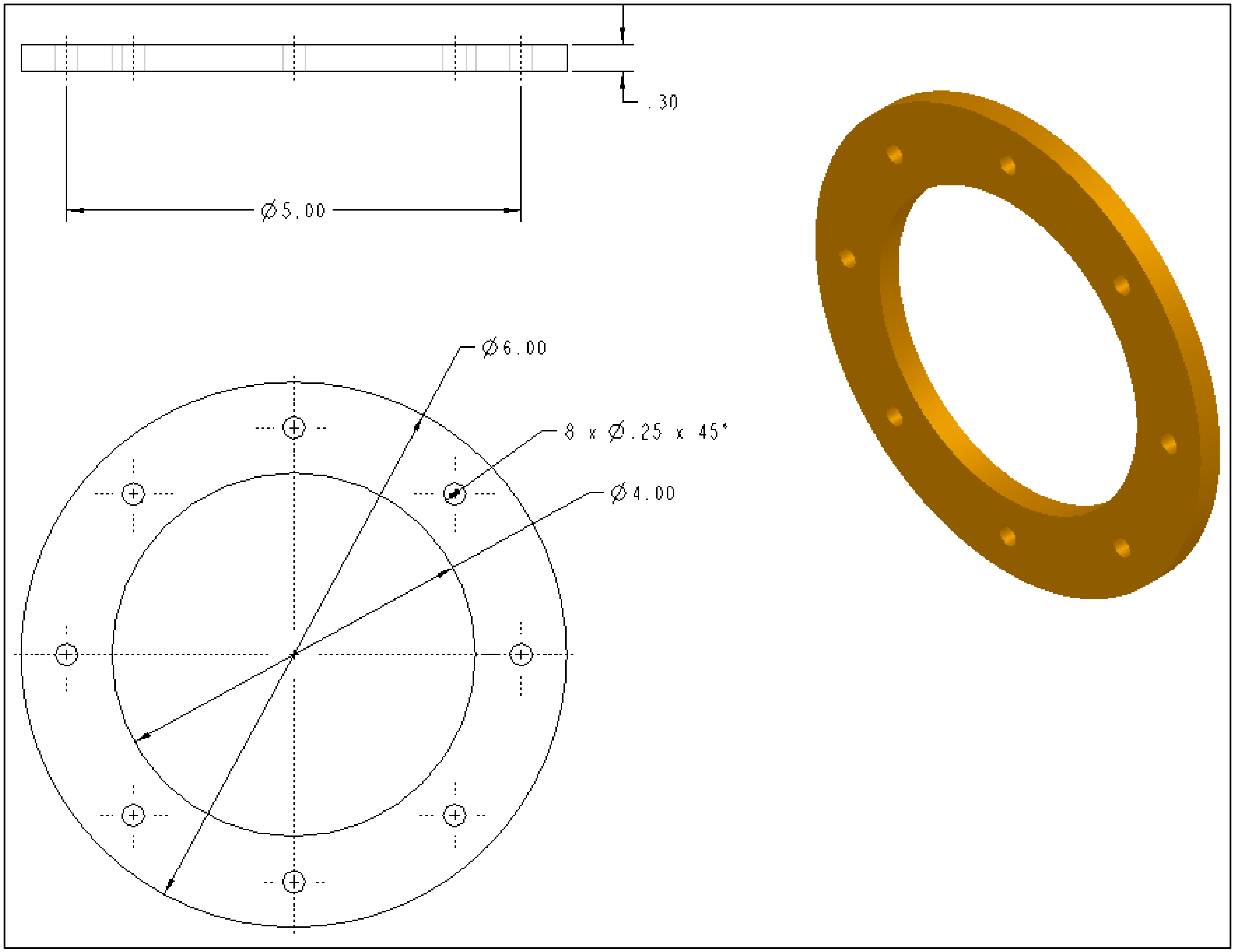


Figure 76 Multiview drawing of sphere base plates

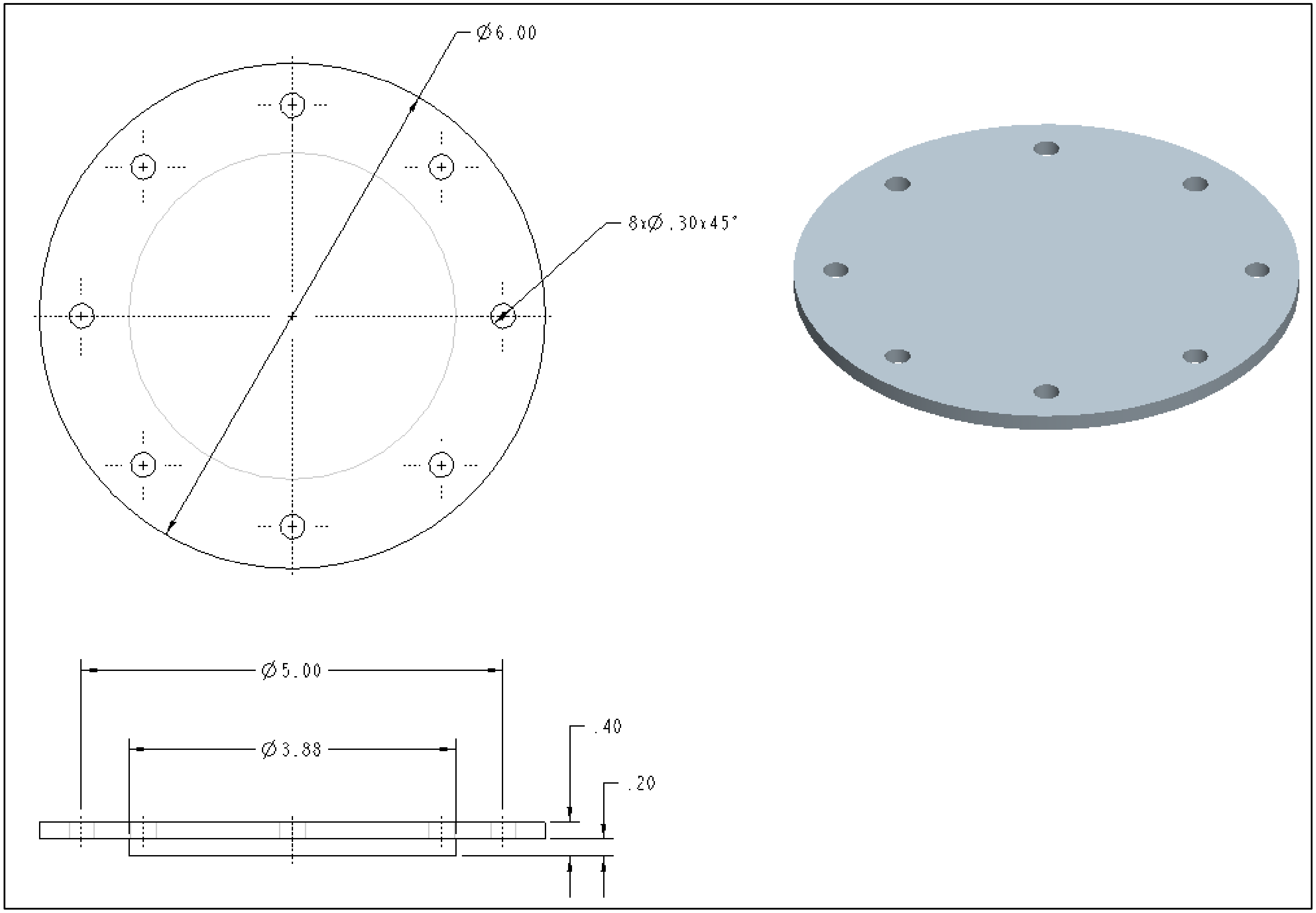


Figure 77 Multiview drawing of cover plates of sphere

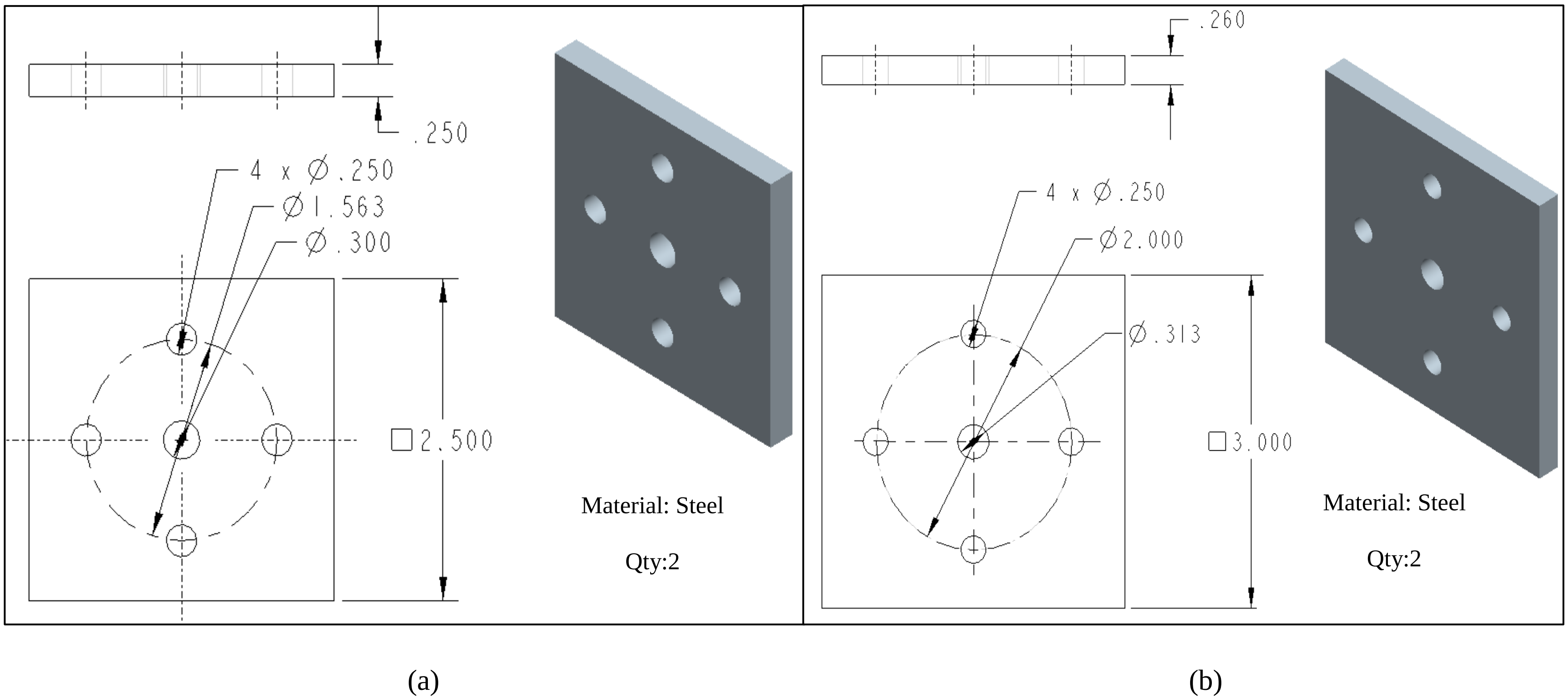
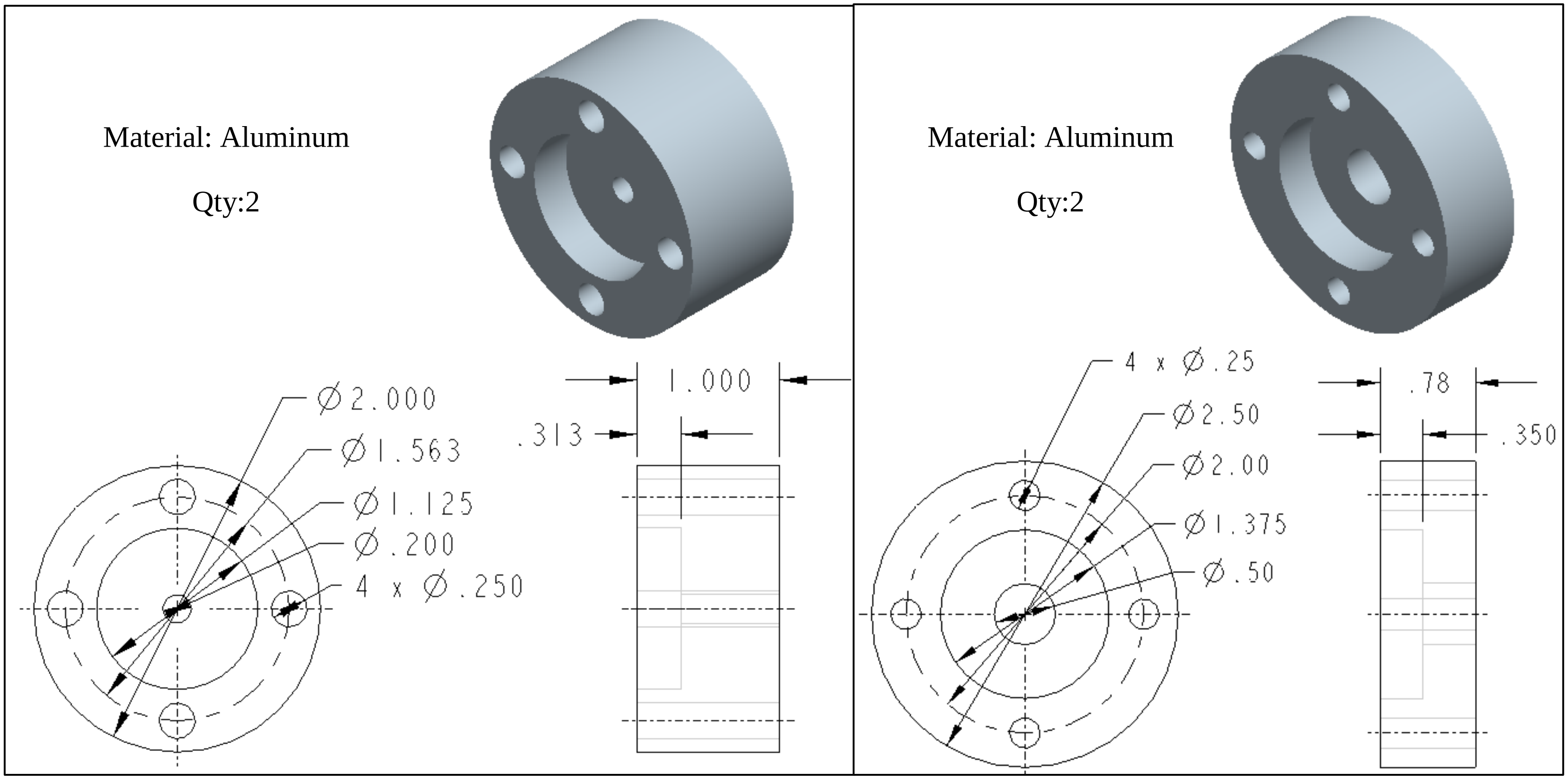
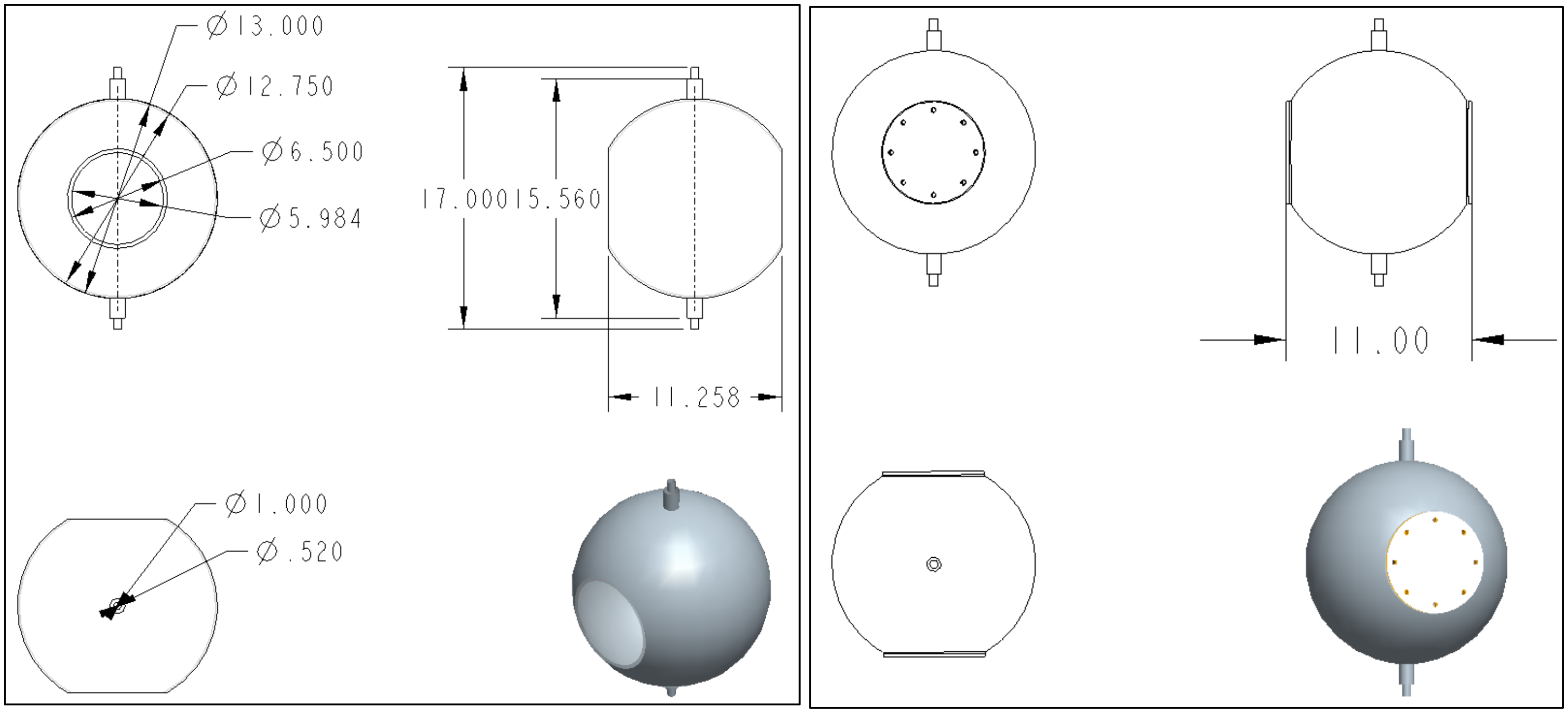


Figure 78 Multiview drawing of bearing housing supports for a) Sphere b) Inner gimbal



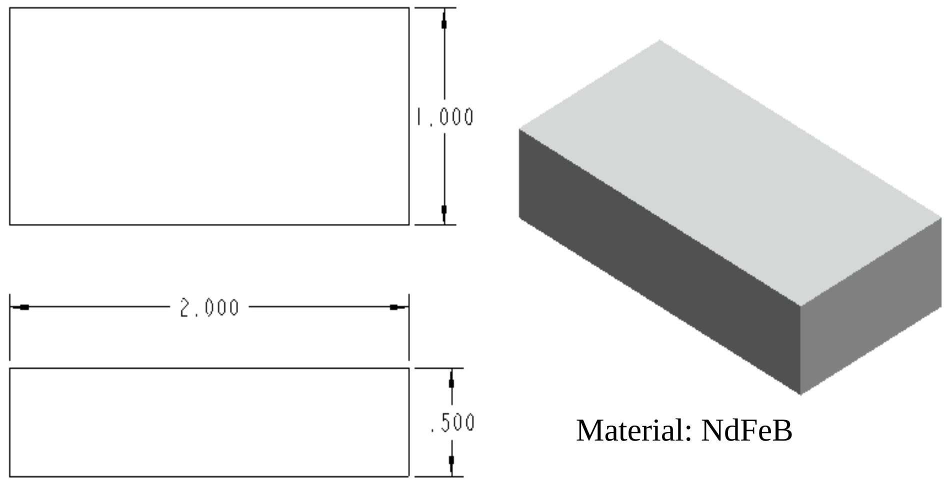
(a) (b)

Figure 79 Multiview drawing of bearing housings for a) Sphere b) Inner gimbal

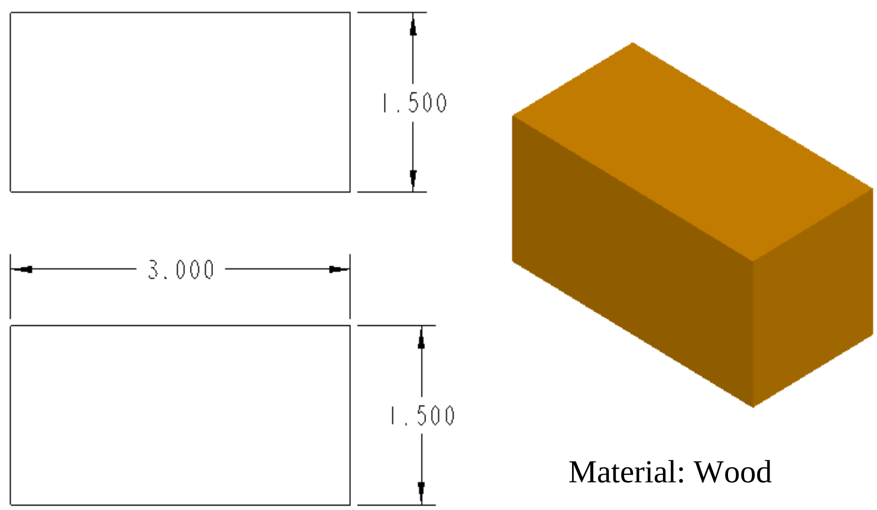


(a) (b)

Figure 80 Multiview drawing of a) Sphere b) Gyro sphere with cover plates



(a)

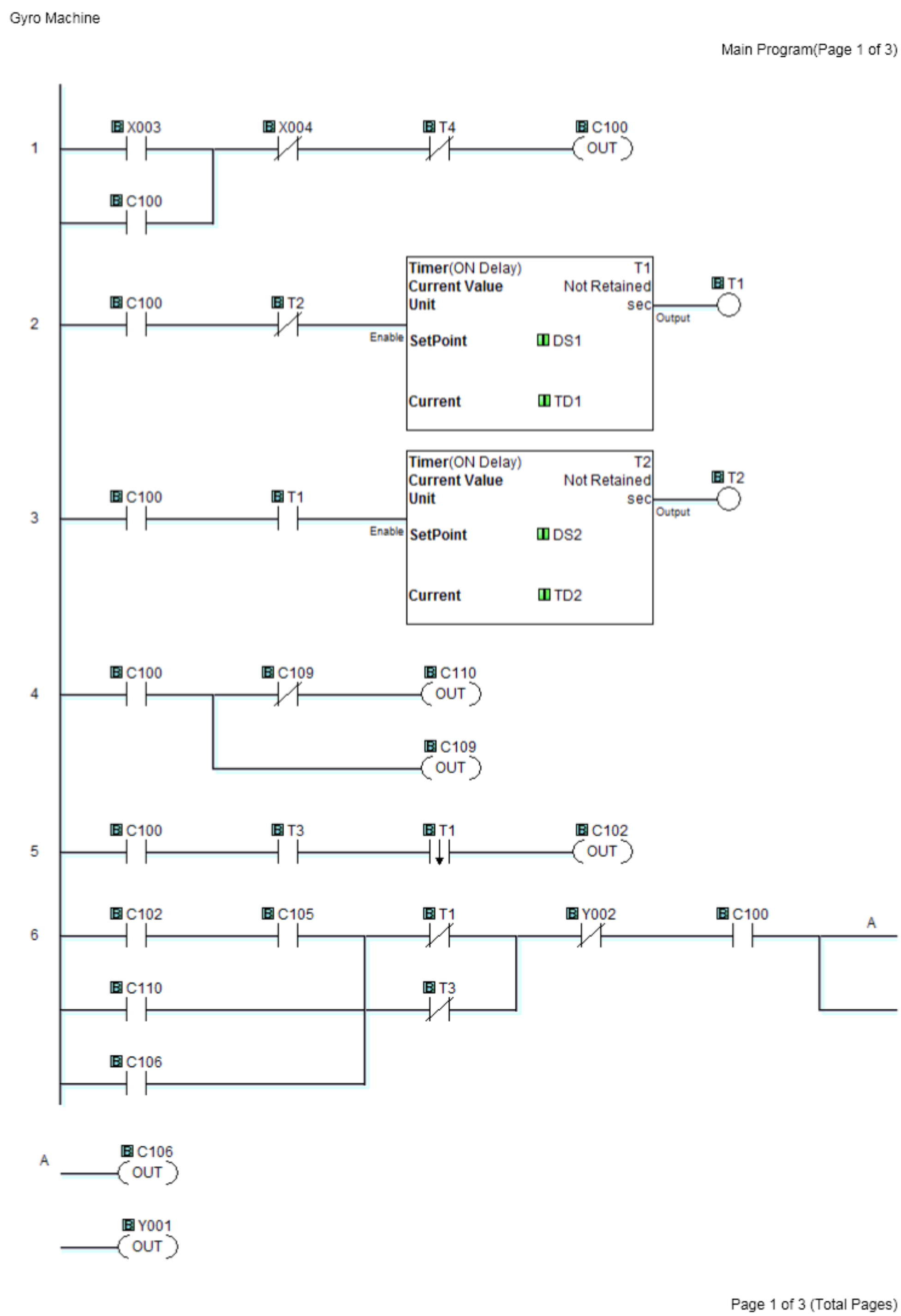


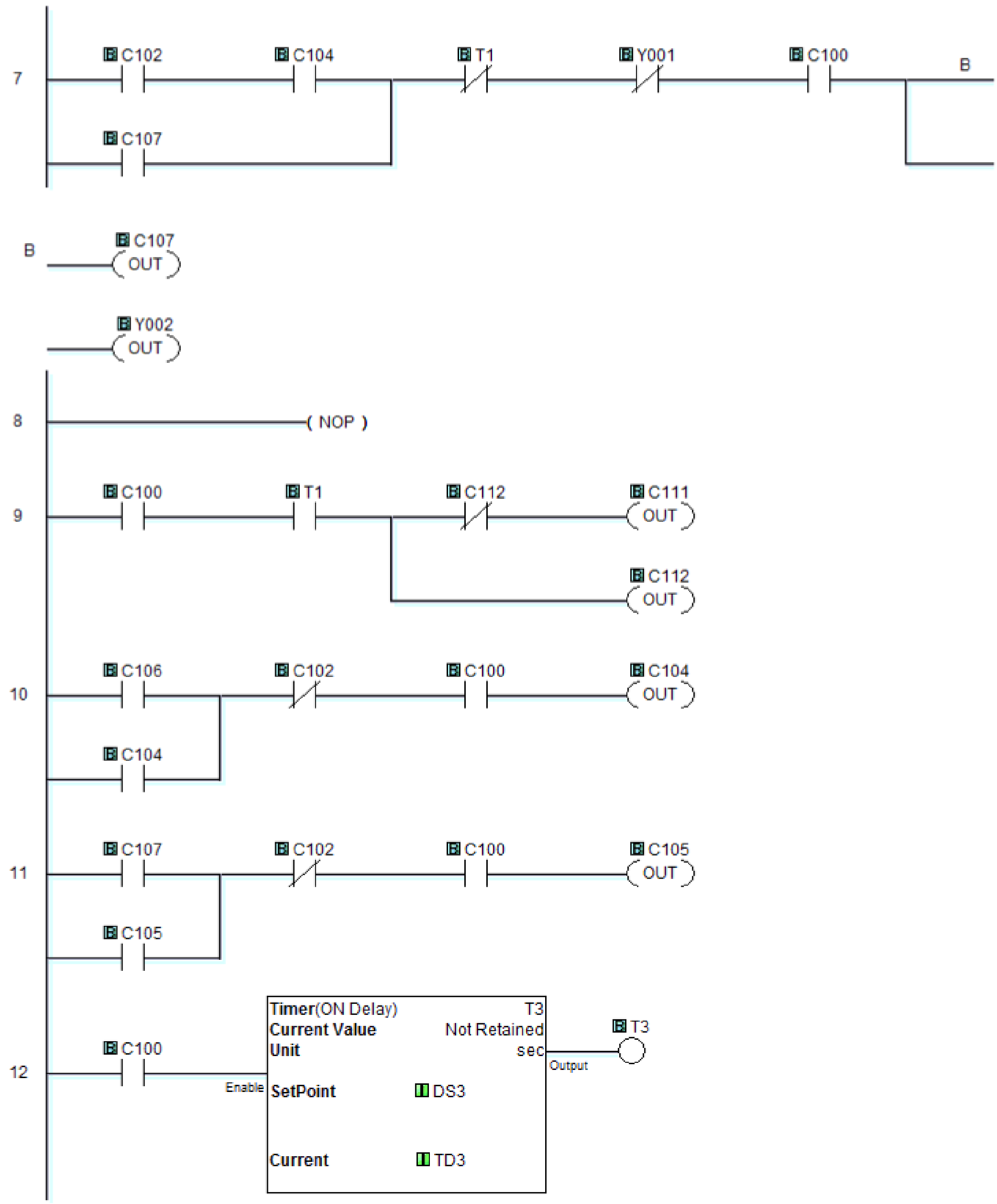
(b)

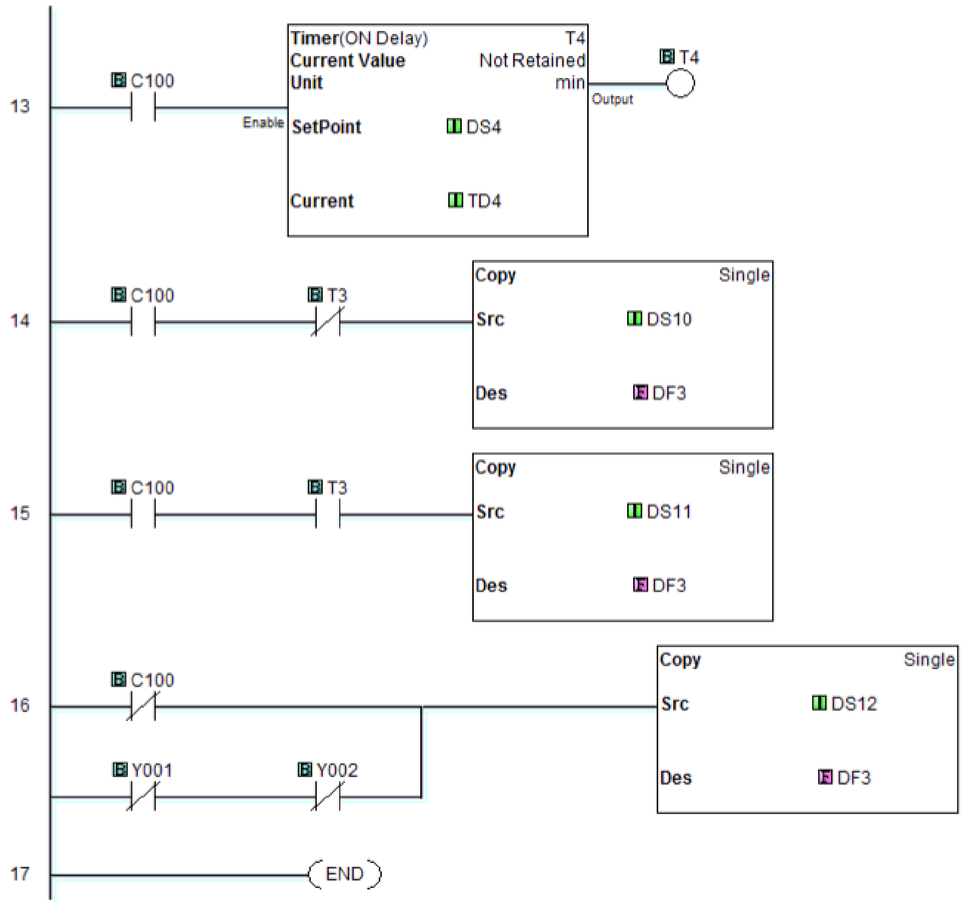
Figure 81 Multiview drawings of a) Magnet b) Fixture used to mount the Magnets

APPENDIX B

Program for Micro-PLC (Ladder Diagram)




7
C102
C104
T1
Y001
C100
B
C107
B
C107
OUT
Y002
OUT
8
(NOP)
9
C100
T1
C112
C111
OUT
C112
OUT
10
C106
C102
C100
C104
OUT
C104
11
C107
C102
C100
C105
OUT
C105
12
C100
Enable
Timer(ON Delay) T3
Current Value Not Retained
Unit sec
SetPoint DS3
Current TD3
Output
T3


13
C100
Enable
Timer(ON Delay)
T4
Current Value
Not Retained
Unit
min
SetPoint
DS4
Current
TD4
Output
T4
14
C100
T3
Copy
Single
Src
DS10
Des
DF3
15
C100
T3
Copy
Single
Src
DS11
Des
DF3
16
C100
Y001
Y002
Copy
Single
Src
DS12
Des
DF3
17
END

VITA

Chetan Kulkarni

Candidate for the Degree of

Master of Science

Thesis: THE DESIGN AND DEVELOPMENT OF A GYRO MACHINE FOR INDUSTRIAL APPLICATIONS

Major Field: Mechanical Engineering

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Mechanical Design Engineer at Pune Automation Technology, PVT. LTD Pune, Maharashtra, India, July 2006 – July 2008

Name: Chetan Kulkarni Date of Degree: July, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: THE DESIGN AND DEVELOPMENT OF A GYRO MACHINE FOR INDUSTRIAL APPLICATIONS

Pages in Study: 140 Candidate for the Degree of Master of Science

Major Field: Mechanical Engineering

Scope and Method of Study: A new Gyro machine with a hollow spherical container as the spinning mass was designed and built in-house, to obtain three degrees of freedom for various industrial applications. The revolutionary gyro machine is based on the underlying principles of the gyroscope motion following the right hand rule. A hollow sphere was mounted on the inner gimbal. This subassembly was remounted on an outer gimbal. Based on the degrees of freedom concept, the mechanism was developed using Pro-Engineering software. A magnetic field was induced in order to spin the spherical container and to rotate the outer gimbal with a single input based on gimbal lock concept. Springs were placed to energize the sphere after equal intervals. Different cycles were identified based on the data analyzed from the mechanism developed and from the fabricated machine using a high-speed photography technique. The sphere was able to rotate in all the possible directions due to relative motion between the sphere, outer gimbal, and gyroscopic effect on the inner gimbal. Based on the capacity of the sphere geometric dimensions of all other components are determined parametrically.

Findings and Conclusions: Gyroscope principle was applied to rotate and oscillate the spherical container. The sphere was able to reach 45 to 50% of speed as that of the outer gimbal in case of developed mechanism and 25 to 30 % in case of experimental setup followed by the number of oscillations. Changing the rotational direction of the outer gimbal in the time interval of 15 to 20 seconds found to be an effective way to obtain rotation and oscillations of sphere. Most promising application of gyro machine is proposed for industrial applications such as washing machine, mixing ceramic powders or different granular materials, in mixing variety of chemicals or paints.

Advisor's Approval: ___Dr. Ranga Komanduri__