Title: The Controlled Human Gyroscope

by

Randy Claude Arjunsingh

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We the undersigned committee hereby approve the attached thesis, “The Controlled Human Gyroscope” by Randy Claude Arjunsingh.

Advisor: Dr. Matthew Jensen
Title: Assistant Professor
College: College of Engineering

Committee Member: Dr. Razvan Rusovici
Title: Associate Professor
College: College of Engineering

Committee Member: Dr. Ondrej Doule
Title: Assistant Professor
College: Human – Centered Design Institute

Department Head: Dr. Hamid Hefazi
Title: Professor
College: College of Engineering
Title: The Controlled Human Gyroscope

Author: Randy Claude Arjunsingh

Advisor: Matthew Jensen, Ph. D.

The objective of this thesis was to design an adaptive rotational motion simulator capable of replicating the attitudes of spacecrafts and aircrafts, while avoiding gimbal lock. Flight motion simulators are currently used for flight training and research, but there are many limitations to these existing systems.

This thesis presents a low-cost design for a rotational motion platform titled, ‘The Controlled Human Gyroscope’. It uses a 4-axis system instead of the conventional 3-axis system to avoid gimbal lock and prevent the unnecessary motion of the user. The Human Gyroscope features unlimited rotation about the roll, pitch and yaw axes regardless of the occupant’s orientation. It will therefore provide high fidelity motion simulation and if it is paired with a translational motion platform, it can provide up to 6 degrees of freedom. Equations of motion for this specific system are presented in this paper and can be used to develop a control algorithm. A structural analysis on the load bearing components of the simulator was performed in order to validate the operating performance while maintaining a reasonable Factor of Safety. All these components passed with the minimum factor of safety being 1.6 under the most extreme loading conditions with most factors of safety above 2.9.
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Chapter 1
Introduction

1.1 Background and Motivation

Prior to the existence of ground-based simulators, pilots learned to fly on actual powered aircrafts. They would start as passengers in a plane for observation purposes. Learning how to use the rudder was accomplished by taxiing a low powered aircraft. A higher-powered machine would then be used to make short, then long hops off the ground using the elevator control. The penguin system did exactly this, but using a plane with a short wingspan. In an attempt to create a device that would actually act like an aircraft, the Sanders Teacher (Figure 1) was invented, which responded to aerodynamic changes.
The Sanders Teacher simulator was made from aircraft components mounted on a universal joint and placed in a headwind. The headwind would cause the system to pivot about the universal joint when the ailerons, elevators or rudders were moved. Changing wind conditions obviously presented issues with this system and it was eventually rendered unreliable. Mechanical, human operated devices, such as the Antoinette simulator (Figure 2) was capable of reproducing roll and pitch (Page 2000). The Antoinette simulator used two halves of a barrel that were mounted and manually controlled.
With World War 1 increasing the demand for pilots, and as a result simulator training, humans were replaced with electrical and pneumatic actuators capable of changing the device’s attitude based on the control input by the user. Instructors had the capability of inputting disturbances in the system to replicate wind changes. Edwin Link developed the popular ground based flight simulator between the years 1927-1929 and patented it in 1930. The Link trainer included instruments so that the user can monitor the simulator’s attitude and heading. Major advances in computational technology during the World War II era propelled flight simulator training as equations of motion were more easily solved. Although years of simulator development continued, it was only in the 1960’s they became an integral part of commercial flight training (Page 2000). Sending astronauts to the moon would have been impossible without simulator training. The Lunar Landing Module led NASA to the development of widely used motion equations in the simulation world. The reason simulators exist is to familiarize humans with an unfamiliar environment or situations. Many space and aviation accidents occurred because the pilot or astronaut was in an unfamiliar situation whether he/she knew it or not.
Space flight mission debriefings, which are conducted post flight, have reported numerous operational errors due to spatial disorientation on the International Space Station (Clement and Bukley 1989). This phenomenon occurs when a person’s perception of their orientation differs from their actual orientation. Roll, pitch and yaw, which are rotational degrees of freedom associated with flight, are not familiar modes of motion for a human. The Federal Aviation Administration (FAA) reports that 90% of Spatial Disorientation accidents are fatal (Autunano 2003). Spacecraft maneuvers are technical because for each motion in the low gravity environment, thrusters are used for propulsion and turning. With this comes a significant delay, which is unusual for an aviation pilot, however, this can be modeled and duplicated in a motion simulator increasing pilot performance.

In the years 1991-2000, Loss of Control of aircrafts contributed to 30% of accidents worldwide and in 1990-2001, 29.8% in the United States (Rogers et al. 2007). According to Rogers et al, Uncontrolled Flight into Terrain accounted for 46% of Australia’s general aviation accidents between 1991-2000. Boeing Commercial Airplanes reported that Loss of Control and Uncontrolled Flight into Terrain, made up 33 of 72 (45.8%) fatal flight accidents between 2005 and 2014 (Boeing Commercial Airplanes 2010).

The United States Department of Defense reported that defense cuts between the years 2012 to 2021 could surpass one trillion dollars (Department of Defence 2015). In the 2015 budget estimate, the Department of the Air Force indicated a 77.1 million decrease in the flying hour program (Department of the Air Force 2014). The number of hours a military pilot spends in a plane is therefore reduced and the demand for realistic motion simulators increases. In a survey conducted by the Government Business Council (GBC 2014), 34% of the United States Department of Defense
employees stated that the current training levels will not meet the military readiness needs. With a reduction in the budget for the flying hour program, and an accumulating need for training, flight simulation is quite valuable to the Air Force and other national defense agencies. National Defense Industrial Association in a 2012 article reported that the Air Force estimates it could save about $1.7 billion over five years by reducing flying hours by 5% and shifting more of its pilot and crew training to simulators (Erwin 2012). For a Boeing 747, the cost of a level D simulator operation to that of an actual aircraft is about 1:40 (Strachan 2000).

Cost can also come in the form of human life, especially when the model and simulation affects the safety aspects of the simuland (Duncan 2007). Safety is a major concern when conducting training exercises. Military training usually involves testing the pilot or aircraft to their limits. Pilots in this situation are at a high risk and accidents, however small, are very expensive compared to the operational costs of a motion simulator.

It is currently not a requirement to have pilots experience inclement weather conditions. In fact, these conditions are usually avoided by grounding flights or using alternative paths. Pilots, however, can get caught in these situations and having prior experience would be useful in avoiding unwanted incidents. Thunderstorms and violent wind conditions are undoubtedly challenging situations for a pilot, especially if it has not been encountered before. Between the years 2003-2007, weather related accidents accounted for 1,740 cases or 20.1 % (Federal Aviation Administration 2010).

Discomforts such as lower back pain in middle to long range flights may cause pilots to lose concentration affecting the safety of the flight (Goossens et al). Ergonomics
became so important that biomechanics and anthropometrics are studied subfields used in the analysis of ergonomics in order for the creation of design guidelines. These subfields help to describe the interaction between humans and machines (Andrade 2013). Simulated environments and flight allow for valuable ergonomic research and data collection. Better human-vehicle interfaces can be designed by using prototypes in the motion simulator, before the part is mass-produced.

The National Aeronautics and Space Administration (NASA) conducts many research projects that study human interaction with machines. Seeing that simulation would be a crucial part of the flight industry, NASA developed their own flight simulator that has been in operation since the 1970’s. Minor changes have been made to the motion platform since then. Although their system works for simple flight simulation, it is not capable of 360 degrees of rotation about any axis. The Kennedy Space Center has a Human Gyroscope that rotates 360 degrees in three different axes, but none of them is a controlled rotation. Having a simulator that has controlled with unlimited roll, pitch and yaw motion, will undoubtedly broaden research and training capabilities. The aeronautic and aerospace industry needs a simulator that can properly replicate the rotational degrees of freedom that their aircrafts possess.

It is clear that human error is a significant factor in aeronautical and aerospace mishaps. Due to the limitations of current flight simulators, effective training especially close to, or at an aircraft’s limit, has not yet been possible. A cost effective training method capable of exposing pilots and astronauts to the mentioned situations is a high fidelity, rotational motion simulator. Literature indicates that there is a lack of flight simulators capable of the rotational motion envelope of a spacecraft or aircraft.
1.2 Purpose and Significance of Study

Motion simulation provides a cheap and safe alternative to field training. It submerges the operator into a virtual environment and synchronizes this virtual motion with actual movement of the operator. Mistakes in the field can therefore be avoided, situations can be accurately replicated and dangerous training situations no longer have consequences, as they are not in an actual aircraft. Overall training cost of pilots or astronauts is reduced significantly since operation and maintenance of a simulator is cheaper than that of an actual vehicle. Less risk is involved while operating a motion platform than a spacecraft or aircraft, so insurance and liability costs are significantly reduced.

The School of Human-Centered Design, Innovation and Art at Florida Institute of Technology proposed developing an adaptive spaceship cockpit motion simulator. Its purpose was to serve as a low fidelity rotational motion simulator to simulate human space flight. It needed to expose the human body to three-dimensional rotational motion like the NASA human gyroscope that was originally designed to train astronauts. Unlike NASA’s gyroscope, the vision of the project was to develop a device that would have independently controlled, unlimited rotation, about all axes. The Human Gyroscope needed to actively and independently control each axis of rotation in order to replicate roll, pitch and yaw in any given orientation. With a modular cockpit, different air or space crafts can be portrayed, therefore creating environments that are congruent to the actual vehicle. While this rotational motion platform was designed specifically to simulate spaceflight, there are many other uses.
Advanced and aggressive flight simulation can be conducted on this system. Most existing dynamic flight simulators have limited rotational motion making them inadequate in reproducing extreme flight situations. Even simple fixed wing Private Pilot training exercises such as steep turns and stalls are difficult to mimic on limited motion simulators. The angles that the system has to roll, pitch or yaw are simply too much for the simulator to replicate. Unusual attitude recovery is an important part of a pilot’s training. Situations arise in flight where visual flight rules are no longer applicable. Such situations include flying through clouds, at night or in inclement weather. Unusual attitudes occur in these situations because the pilot is unable to use visual cues to determine their orientation. The pilot may feel (based on other stimuli like balance and gravity) like the aircraft is in straight and level flight, but this is not always the case. The aircraft could be in a completely different orientation than assumed by the pilot and dangerous situations can arise. The human gyroscope can be used for training, while providing a safe, no consequence environment for the operator.

Spatial disorientation is a contributing factor in many aviation accidents (Nooij and Groen 2011). One of the main factors that contributed to the conceptualization of this project is space motion sickness and disorientation. Piloted tasks such as docking maneuvers and reentry or extravehicular tasks can be compromised due to motion sickness (Stroud et al 2003). Motion simulators can be used as preventative action for motion sickness and spatial disorientation. Stroud et al indicates that preflight training in virtual reality devices that can closely replicate spacecraft movement will reduce the incidence and/or severity of motion sickness and disorientation. A person’s spatial awareness is determined by his/ her position, orientation and external objects like buildings and other people. On earth, gravity and visual cues are the basis for determining orientation. In certain conditions, such as spaceflight, these stimuli
become unreliable or unavailable (Stroud et al 2003). When external factors and gravity are removed, vision becomes the primary method for perceiving orientation. This is not reliable as the subject would often be viewing things from an unfamiliar angle. A person can be trained to adapt to these unfamiliar situations by undergoing extensive motion simulator training.

The entertainment industry has an ever-growing need for motion simulators as rides get more advanced and realistic. The rotational motion of the Human Gyroscope is limitless and can therefore perform many duties for entertainment purposes. If the simulator is added to a motion platform that can translate, like a rollercoaster track, all 6 degrees of freedom will be unlocked.

Many motion simulators use the Stewart Platform as its source for motion. The Stewart Platform (or hexapod) is a parallel device that consists of a platform supported by six telescoping hydraulic or electronic struts (Van Silfhout 2001). The platform is moved by changing the length of the telescoping struts. Changing the length of one strut causes a realignment of all the struts which allows the platform to have six degrees of freedom (Van Silfhout 2001). While this does provide six degrees of freedom, its motion envelope is still very limited, typically to less than 45 degrees of roll, pitch and yaw.

Limited motion is one of the issues phasing simulators today. Many simulators have a limited range of motion and those that do offer unlimited rotation faces the issue of gimbal lock. Gimbal lock or kinematic singularity occurs when two of the three axis of a rotational system are driven into a collinear configuration. This results in the loss of one degree of freedom (Jie and Qinbei 2015). We therefore lose either pitch, roll or yaw. In order to achieve a high fidelity device, the system must be able to
avoid gimbal lock. While a 3-axis system can be controlled in such a way as to try to avoid these locking positions, the fidelity of the system is lost because the operator will undergo unnecessary movement while the system attempts to avoid locking positions. Figure 3 is a drawing of a 3 degree of freedom gimbaled system where the green ring controls pitch, the red ring controls yaw and the blue ring controls roll. If the simulator is oriented as shown in Figure 4, for example, a 90-degree roll in a spacecraft, one degree of freedom is lost. In this case, roll is duplicated and pitch is lost.

Figure 3: 3 DoF gimbal system
The only way to completely avoid gyroscope lock is to use a 4-axis device. In a 4-axis gimbal, one of the axes of rotation is redundant to another. In this system, since all four axes are controlled individually, they can be moved to always avoid gyroscope lock. It does this while maintaining the fidelity of the system by not moving the operator unnecessarily. Washout filters are used in limited motion simulators to return the simulator to a neutral position while moving at an acceleration lower than the level of human perception (Chen and Fu 2011). When fast pace, constantly changing maneuvers need to be simulated, a washout algorithm is unable to keep up.

There is certainly a need to develop new and better human vehicle interfaces, especially for unique gravity environments in space. A pilot or astronaut’s comfort can be studied from the basics such as their chair to specific control or button placement. Models of the cockpits can be used in the simulator and tested to approve control and button placement and effectiveness. Since modern aircrafts exhibit stick
fixed stability using hydraulic actuation devices, they are required to have force feedback systems. Operator interactions with the control and feedback system can also be studied using a motion simulator. Simply examining these cases in a static environment is only half of what needs to be done. Analyzing and surveying pilots in dynamic simulation devices can provide crucial information about the design of the cockpit, placement of controls and operator-machine interaction.
Chapter 2

Literature Review

The spinning mass gyroscope is one of the most common types of gyroscopes in existence today. A conventional spinning mass gyroscope contains a rotating disk or wheel that uses its inertial properties to resist any change in direction of its moment (Mario et al 2013). This device was first invented in 1852 by Leon Foucault, while investigating and demonstrating how the earth rotates (Biography.com 2015).

There are many uses for gyroscopes today, but they are primarily used in inertial navigation systems. The reason for this is because the principle of angular momentum follows closely to Newton’s first law, which says: a body at rest will remain at rest or a body in motion will stay in motion unless acted upon by an external force. The angular momentum of a system will remain unchanged (conserved) unless acted upon by an external torque. Since this holds true for gyroscopes, their inertial properties allow them to be effectively used in navigation systems.

Human gyroscopes, which are similar to spinning mass gyroscopes, were later developed for medical purposes and astronaut training. They have the ability to contain a human and rotate about two or three axes. These gyroscopes were also used to simulate the feeling of tumbling in space. Our design, which is discussed later in this paper, is a modified version of a human gyroscope that will act as a 3 degree of freedom, rotational motion simulator.

Aside from being a cheaper, safer alternative to field testing, motion simulators are capable of accurately and repeatedly replicating specific situations. Concentrated
testing and training of pilots and astronauts are conducted on existing flight simulators. As discussed previously, flight simulators have a long history and new developments still exist today. Motion simulators that are in use today usually possess advanced software and hardware integration, but none of them is capable of avoiding gimbal lock without unnecessary movement of the pilot.

2.1 Existing Air and Space Craft Motion Simulators

2.1.1 NASA Ames Vertical Motion Simulator

The NASA Ames Vertical Motion Simulator (VMS), shown in Figure 5, is the largest flight based motion simulator in existence today (Advani et al 2002). It has an interchangeable cabin (I- CAB) that allows the users to replicate the interior of different spacecrafts or aircrafts.
This simulator has a substantial 6 degree of freedom motion envelop, but is very limited in rotation. It has ±30 feet of heave, ±20 feet of lateral translation and ±4 feet of longitudinal translation. The current gimbal system limits the roll axis to ±18 degrees, the pitch axis to ±18 degrees and the yaw axis to ±24 degrees. Figure 6 is a drawing of the VMS and its motion systems. While this may be suitable for some applications, most high fidelity motion cues for the aerospace and aeronautical industry requires more rotational motion. The VMS was initially built to mimic the motion of rotorcrafts, which does not require unlimited rotation about any axis (Alponso et al. 2009). In order to produce accurate motion cues within the physical limitations of the VMS, washout filters are used in the motion cueing algorithms.
2.1.2 Desdemona Motion Simulator

The most advanced human gyroscope known to man today is the Desdemona motion simulator developed by TNO Human Factors and AMST in 2007. Figure 7 is a picture of the actual system located in the Netherlands. This system offers unique motion simulation not seen anywhere else in the world (Roza et al 2007).

Current motion simulators suffice for basic training, but they are not capable of exactly replicating complex motion due to their limited motion envelope. When situations become unpredictable or extreme, like in military aircrafts, ground vehicle accidents and rollovers, emergency maneuvers or spaceflight, standard motion simulators are not very useful.
Unlike other simulators, the Desdemona allows unlimited rotation about any axis because the cabin of the Desdemona is supported by a fully gimbaled system. This gimbal, consisting of right-angled concentric rings, is mounted on a mechanism capable of heaving it over 2 m. The heave mechanism and thus the entire system can move over 8m on a horizontal track. The track can rotate itself to generate up to a sustained 3 g load. The Desdemona therefore mimics 6 degrees of freedom within its motion envelop; however, the development of motion driving algorithms is complex. The degrees of freedom for the Desdemona motion simulator is depicted in Figure 8.
Standard motion cueing strategies used to control the six struts that move synergistically on a Stewart Platform (hexapod) cannot be used to control the Desdemona (Bles and Groen 2009). Using the simulator in extended hexapod mode or as a dynamic flight simulator where the cabin is rotated and the gimbal spun to a sustained g-loading does not take advantage of all the capabilities possessed by the Desdemona (Bles and Groen 2009).

New motion cueing algorithms are under development and some are already being implemented like the spherical washout algorithm (Wentink et al. 2005). Although originally designed for spatial disorientation training, it can be used in many other applications.

The interior of the simulator is modular and can therefore be easily rearranged to replicate an automobile interior, bridge of a small ship and the cockpits of many
aircrafts including helicopters and spacecraft. The Desdemona can be used by the aerospace, aviation, automotive and entertainment industry, among others.

2.1.3 Aerotrim

An Aerotrim is a gyroscope large enough to contain a human and they are used for cardiovascular workouts, entertainment and astronaut training. This device was initially developed for medical purposes specifically to relieve back pain. Since a human physically controls it, it was later used as an exercise machine. For stretching, aerobics, strength training, core workouts and improving coordination and balance, the rider shifts his/ her body weight to rotate different rings of the gyroscope.

There are many existing variations of Aerotrim, but none have full control about each axis of rotation. Some modern Human Gyroscopes today are powered either by an electric or hydraulic motor, but only one axis is controlled.

Figure 9: A 2 seater human gyroscope with a hydraulic motor
Figure 9 shows a picture of a two seater human gyroscope with a hydraulic motor. This particular gyroscope has only 2 degrees of freedom and the inner ring is left to tumble due to its dynamic center of gravity. The outer ring is spun with the hydraulic motor, which changes the position of the center of gravity shifting the system out of equilibrium. Figure 10 is a similar system that seats four riders and uses an electric motor instead of a hydraulic motor to control the external gimbal.

2.1.4 The Human Gyroscope Project

The Human Gyroscope project presented by Halmstad University is similar in concept to our design. It is a motor driven simulator that copies the design of a rotating mass gyroscope (Kjellin and Runevad 2012). Their device features three degrees of rotational freedom, but since there are only three gimbals, it is possible
that it would encounter gyroscope lock. Figure 11 is a three-dimensional rendering of the student’s design.

If this simulator has to replicate a vehicle pitching up 90 degrees, the roll axis is duplicated by the yaw axis and yaw motion is therefore lost. Even when the simulator approaches 90 degrees, true yaw motion is no longer attainable. The motion will be a mixture of roll and yaw. This lowers the fidelity of the simulation, as unnecessary or incorrect movement of the operator will happen in this orientation.

Figure 11: A 3 dimensional rendering of the students design (Kjellin and Runevad 2012)

Transferring power and signals to the internal motors of the simulator was a significant challenge but it was overcome by using electrical slip rings. The goal of their thesis was, to design and build a prototype of a motion simulator that is unique and has unlimited rotation about one or more axes. Figure 12 is a picture of the small-scaled prototype that was built at Halmstad University.
2.2 Flight Simulation Fidelity

Major airlines are currently conducting their recurrent, initial, transition and upgrade training entirely on flight simulators and they have practically eliminated training accidents at airlines that use high fidelity simulators (Burki-cohen, Go, and Longridge 2001). When pilots complete their simulator training, they are required to complete a supervised Initial Operating Experience. At this point, the trainees are entrusted with the safety of the passengers on the airplane. For a motion platform flight simulator to be effective, it is critical and absolutely necessary for the cues to transfer performance and behavior characteristics for the aircraft being simulated (Burki-Cohen and Go 2005). For a motion cue to even be considered valid, it should
never lead the visual cues. Synchronized roll and lateral motion cues are allowed to lag but it should not be more than 40ms (Chung and Johnson 1997).

Flight simulators are evaluated and classified by an FAA Simulator Evaluation Specialist. The ones that do not move are given numeric assignments: Level 1 to Level 7 with Level 7 being the most sophisticated (Marsh 2011). The ones that have a motion platform, are grouped into 4 classes: Level A (visual), Level B (Phase I), Level C (Phase II) and Level D (Phase III) (Federal Aviation Administration 1991). Simulator complexity increases from A to D. The high fidelity NASA AMES Vertical Motion Simulator, shown earlier in this study, is a Level D flight simulator.

In a study conducted on the Desdemona Motion Simulator, participants indicated that having the motion and forces made the simulation more realistic and helped them conduct their tasks better versus having no motion and forces.

All FAA qualified full flight simulators are required to have a motion base and their effectiveness for new pilot and recurrent training is well recognized (Longridge et al. 2001). Subject matter experts from industry, academia and FAA indicated that the absence of a motion platform on flight simulators is likely to have a detrimental effect on pilot control performance especially in maneuvers that require sudden motion with limited visual references. It is clearly important from literature that flight simulators should have a high fidelity motion platform that is capable of closely synchronizing physical motion with the users input into the virtual system.
2.3 Component Selection

Part of the requirement for this thesis project was to have a complete functional design for the motion simulator. In doing this, design choices had to be made on components of the entire assembly. Materials, motors and bearings were some of the main items of concern, among others.

For our motion simulator, hydraulic motors were selected over electric motors for a number of different reasons. Hydraulic motors are small, compact mechanical devices that generate steady, continuous torque (rotary motion), directly from the hydraulic system (Aeronautics Learning Laboratory 2004). These were all attractive features for our design. Since each axis had to be independently controlled, power needed to be transferred through the rotating components to the inner axes. This proved to be one of the more challenging parts of the design. To resolve this issue, rotary hydraulic unions with internal slip rings were selected to transfer hydraulic fluid and electrical power. These are similar to the rotary manifolds used on excavators.

Chromium- molybdenum (Chromoly) is a high carbon steel that is primarily used to produce tubing for bicycles and race cars. Though it is not as light as aluminum alloys, it has a higher tensile strength and malleability (Woodcock 2013). To form the circular rings of the Human Gyroscope, tubes will have to be bent into shape so malleability is crucial. Chromoly is also durable and corrosion resistant making it a great choice for our motion simulator. Chapter 3 goes into much more detail on why these design choices were made.
Chapter 3
Design and Methodology

3.1 System Requirements

The major tasks of the Controlled Human Gyroscope were to mimic a spacecraft’s launch, landing, reentry, atmospheric flight and microgravity flight. The operator should have unlimited rotation about the roll, pitch and yaw axes at any given time and hence avoid gimbal lock. The vector sum of the tangential accelerations at the user’s head should be at least 0.2 G’s, but up to 2 G’s. The system needed to accommodate an analog space suit and a Primary Life Support System (PLSS) backpack. The armrests, leg and head support should be adjustable in length and position since the system should accommodate 95 US percentile male/female. One of the most challenging requirements was to make the simulator as compact and as light as possible. In order to have a diverse motion simulator, the cockpit had to be modular where equipment could be switched out to represent different vehicles. The internal seat structure should be completely removable in the event that it needs to be updated. The cockpit must be powered either by battery or by AC power. The entire structure needs to comply with ISO26262 which is a functional safety standard. The internal mass to be supported, not including the rotational rings or motors, should be 250kg (including the max operator weight of 120kg). For the cockpit to contain all the necessary equipment for simulation, the internal ring (cockpit area) must have a minimum diameter of 1980mm.
3.2 Overview of the Human Gyroscope’s Design

The most basic form of our design is that of a spinning disc gyroscope. While our design looks similar to an Aerotrim, the functionality is very different. Instead of being physically powered by a human, every axis is individually controlled by hydraulic motors. The controlled human gyroscope has four gimbals, and therefore four degrees of rotational freedom, where one is redundant to avoid gimbal lock. The inner ring has a diameter of 2032mm, which meets the requested design requirements. Figure 13 is a 3D drawing of our Human Gyroscope without its internal components. The operator will be seated in the inner ring (blue) and each ring will control an axis of rotation.

Figure 13: 3D drawing showing the Human Gyroscope’s Design
3.3 Design Details of the Human Gyroscope

3.2.1 Avoiding Gimbal Lock

Most motion simulators have a limited range in replicating roll, pitch and yaw. Those that are capable of continuous rotation about every axis are likely to encounter gimbal lock. As mentioned before, gimbal lock occurs when two axes of rotation become collinear. When this happens, rotating any one of those axes will produce the same motion (either roll, pitch or yaw). One degree of freedom is therefore forfeited or in other words, the operator has lost one of his/her rotation axes. Depending on which two axes line up, the operator will no longer be able to either roll, pitch or yaw them. It is important for gimbal lock to be avoided to maintain a high fidelity simulation. Figure 14 is a drawing of a four degree of freedom system in a gimbal lock configuration. In this instance, the simulator is replicating a 90-degree roll as seen above in Figure 4. Similarly to the three DoF gimbals, pitch is lost here as well.
The only way to combat gimbal lock with the three DoF system is to use special motion cueing algorithms with washout filters. These filters help the system return to a neutral position or in other words, return to an orientation where roll, pitch and yaw can be simulated. As discussed before, this results in unnecessary movement of the operator and the algorithm may not be able to follow along with aggressive simulation. The four DoF gimbals possess the exact same properties as the design used in this project. Software on the system will detect when a potential gimbal lock situation is approaching and instead of moving to a neutral location, the fourth axis will move to avert this problem. Figure 15 shows how the motion simulator will move to maintain control of roll, pitch and yaw. The green ring now controls pitch,
the red ring controls yaw, the blue ring controls roll and yaw is duplicated with the yellow axis.

Figure 15: 4 DoF gimbal lock solution

3.2.2 Motor Selection

Hydraulic and electric motors are both used in the simulation industry. Each have their own pros and cons. Electric motors are capable of instantaneously generating torque while hydraulic motors have a delay. Hydraulic motors are often selected because of packaging constraints and torque requirements. In the case of this project, a motor that is capable of generating sufficient torque while fitting tight packaging constraints was needed. To keep the system compact, hydraulic motors were selected. Figure 16 shows the size comparison between the motors from a top view.
These motors were chosen to generate the required torque as they were all capable of the same RPM and were all seven horsepower motors.

There are five main types of hydraulic motors, each designed for different applications. The human gyroscope required high torque, high speed, compact, relatively low cost and reversible hydraulic motors. Gerotor motors (Figure 17) perfectly fit this description and was selected over the other types shown in Table 1 (Hahn 2013). The flow path of these motors control its direction of motion. The hydraulic pump used to pump fluid can reverse the flow path and hence the motor’s direction.
Figure 17: Drawing showing the internals and general design of a Gerotor Hydraulic Motor (Hahn 2013)

Table 1: Table comparing the different types of hydraulic motors (Hahn 2013)

<table>
<thead>
<tr>
<th>Motor Type</th>
<th>Compact</th>
<th>Reversible</th>
<th>Cost</th>
<th>Efficiency</th>
<th>Speed</th>
<th>Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Piston</td>
<td>No</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Gear</td>
<td>Yes</td>
<td>Yes</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Gerotor</td>
<td>Yes</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Radial Piston</td>
<td>No</td>
<td>Yes</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Vane</td>
<td>No</td>
<td>Yes</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
3.2.3 Transferring Power/ Fluid through Rotating Components

Controlling internal axes on the human gyroscope requires power or hydraulic fluid to be transferred through rotating components. Since hydraulic motors were selected and electricity is required to power the equipment in the cabin, both fluid and electrons need to be passed through the rotating rings. An electromechanical device called a slip ring is used to transmit electric power from a stationary component to a rotating component. Conductive brushes are pushed against rotating rings that have electrical leads attached to them. This prevents the wires from getting tangled while passing electricity through a rotating joint.

For hydraulic fluid, a rotary union (or manifold) is used. Since each hydraulic motor is controlled individually and ever motor has two hydraulic passages, multi- passage rotary unions were required. Each ring of the gyroscope has two rotational joints and
a motor is placed on one of these joints for control. Electric power and hydraulic fluid needed to both be transmitted through the other rotating joint. Dynamic Sealing Technologies Inc. is a company that manufactures rotary unions that have the option for an integrated slip ring (Figure 19). Their unions contain multiple independent fluid passages allowing for the individual control of each motor. With this union, continuous rotation of either attached component is allowed.

![Dynamic Sealing Technologies Hydraulic 3 Passage Rotary Union with an Integrated Slip Ring (Dynamic Sealing Technologies INC 2008)](image)

**3.2.4 Bearing Selection**

Bearings are used in the design to allow for rotation and reduce friction. The two main types of mechanical bearings that are used in this design are radial and thrust bearings. The names explain the types of loads that the bearings are designed to endure. Radial loads are perpendicular to the axis of rotation and axial loads are parallel to the axis of rotation. Within these two categories of bearings, there exists spherical and roller bearings. Spherical or ball bearings are the most common type of bearing used in mechanical components (Hamrock and Anderson 1980).
Cylindrical roller bearings are used in higher capacity loading cases and can be either thrust or radial bearings. Table 2 shows a concise comparison between the different types of bearings and what they are best used for. The Controlled Human Gyroscope uses cylindrical roller thrust and radial bearings. The thrust bearings support the drive gear’s weight when the system is flipped on its side.

<table>
<thead>
<tr>
<th>Bearing Type</th>
<th>Sub Type</th>
<th>Radial</th>
<th>Thrust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball Bearing</td>
<td>Conrad Type</td>
<td>Good</td>
<td>Fair</td>
</tr>
<tr>
<td></td>
<td>Self-aligning</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Cylindrical Roller Bearing</td>
<td>Separable inner ring non-locating</td>
<td>Excellent</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Self-contained 2 direction locating</td>
<td>Good</td>
<td>Poor</td>
</tr>
<tr>
<td>Tapered Roller Bearing</td>
<td>Self-aligning</td>
<td>Excellent</td>
<td>Poor</td>
</tr>
<tr>
<td>Spherical Roller Bearing</td>
<td>Self-aligning</td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>Thrust Bearings</td>
<td>Single direction ball, grooved race</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td></td>
<td>Single direction eye roller</td>
<td>0</td>
<td>Excellent</td>
</tr>
<tr>
<td>Needle Bearing</td>
<td>Complete</td>
<td>Good</td>
<td>0</td>
</tr>
</tbody>
</table>
3.2.5 Designing a Compact System

When a concentric ring is added to the system, the integration of motors and the rotary union must be taken into account. Every time a ring is added, approximately 1 foot (12 inches) of space must be left on each side to incorporate the mentioned components. Avoiding gimbal lock requires four axes of rotation, which relates to four concentric rings. In this scenario, only one motor is allowed per ring, which creates torque limitations making the system incapable of generating enough g-forces on the operator. In order to make the system compact while allowing for additional motors on external rings, a geared ring was used.

3.2.6 Material Selection

The Human Gyroscope Motion Simulator rotates a human about three axes of motion with a combined g-force of at least 0.2 G’s. Safety is a major concern, so the materials selected needed to be strong, rigid but at the same time lightweight. For the rings of the gyroscope, tubes were chosen instead of solid stock in order to save weight. Round tubing was then chosen over square tubing due to the strength to weight ratio. Chromoly 4130 was selected over plain carbon steel because of its higher Ultimate Tensile strength and Yield Strength. The round Chromoly tubes used in our design have a 2-inch outer diameter and a 0.25-inch wall thickness. This material is readily available in numerous size configurations and extremely manufacturable. Standard structural steel was selected for all the other components on the simulator. Steel is also easily obtained and relatively cheap.
3.2.7 Supporting the Geared Ring

When the motion simulator is turned on its side (Figure 20), the gears will have the potential to slip past each other due to gravity. In order to support these gears and the weight of the entire system, specialty bearings were used. The smaller drive gears are supported by cylindrical thrust bearings on each side. The bigger, driven gear proved to be more of a challenge to support. High capacity ball transfer units were used to hold the gear in place. These ball transfer units contain ball bearings that allow the top sphere to rotate. The gear can then slide freely over these units with minimum friction. Figure 21 is a picture of the Omnitrack ball transfer unit.

Figure 20: Picture showing the Controlled Human Gyroscope Turned on its side
A total of 20 ball transfer units were inserted into the side plates of the final axis and this is shown in Figure 22. This figure also shows the thrust bearing used to support the smaller drive gear.
3.3 Torque Generation

The selected hydraulic motors are compact but can generate a substantial amount of torque. Table 3 shows the specs of the motor selected for this project.

Table 3: Table showing the specs of the chosen hydraulic motor

<table>
<thead>
<tr>
<th>Hydraulic Motor Model- 6299K55</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horsepower</td>
</tr>
<tr>
<td>Torque</td>
</tr>
<tr>
<td>Max RPM</td>
</tr>
<tr>
<td>Max Flow</td>
</tr>
<tr>
<td>Fixed Displacement</td>
</tr>
<tr>
<td>Max Pressure</td>
</tr>
<tr>
<td>Overall Length</td>
</tr>
<tr>
<td>Shaft Length</td>
</tr>
<tr>
<td>Shaft Diameter</td>
</tr>
<tr>
<td>Keyway Width</td>
</tr>
<tr>
<td>Keyway Depth</td>
</tr>
</tbody>
</table>

Using some of these basic numbers, calculations were done to ensure that the torque specifications were met. The vector sum of the tangential accelerations at the user’s
head should be at least 0.2 G’s, but up to 2 G’s. Calculating tangential acceleration at the user’s head required us to calculate angular acceleration. Angular acceleration however, is a function of the object’s moment of inertia (tendency to resist angular acceleration). Inertia is calculated based on the objects size and shape so to simplify this process; moments of inertia were calculated and obtained using Solidworks. A 250kg spherical ball (2 times the weight limit) was added to the internal ring to simulate the components that would be later added to the simulator.

3.3.1 Inner Ring

The inner ring has a diameter of 2.03m and spins about the x-axis as shown in Figure 23. It was important to include the 250kg of mass that will be housed in this ring before obtaining the moment of inertia. When calculating the acceleration at the head, the dimensions for a 50th percentile male was used. An assumption was made that the person’s seat will be at the center of rotation.
The calculations were completed as follows:

\[ I_{xx} = 49.33 \text{ kg.m}^2 \]  

(3.1)  

\[ \tau = I_{xx} \cdot \alpha \]  

(3.2)  

\[ \tau_{\text{motor}} = 3141 \text{ in.lbs} = 354.9 \text{ N.m} \]  

(3.3)  

Using equations 3.1, 3.2 and 3.3:

\[ \alpha = \frac{\tau}{I_{xx}} = \frac{354.9}{49.33} = 7.19 \frac{\text{rad}}{s^2} \]  

(3.4)  

At the person’s head, 0.77m away from center of rotation, the tangential acceleration was calculated as follows:
\[ a = r \cdot \alpha \]  
(3.5)

\[ a = 0.77 \, m \times 7.19 \, \frac{rad}{s^2} = 5.54 \, \frac{m}{s^2} \]  
(3.6)

Acceleration at head in terms of G’s:

\[ a = \frac{5.54}{9.81} = 0.56 \, G's \]  
(3.7)

The first ring is therefore within the limits of the g-force requirements. The motor for the inner ring can be attached to a planetary gear to adjust the torque or max rpm of the system.

### 3.3.2 The Second Inner Ring

The second inner ring has a diameter of 2.7m and spins about the y-axis as shown in Figure 24. The internal mass (250kg) and the mass and size of the inner ring were taken into account when computing the moment of inertia for the second ring.
Figure 24: Drawing of the 2\textsuperscript{nd} inner ring of the Human Gyroscope

The calculations were completed as follows:

\[ I_{yy} = 113.8 \, kg \cdot m^2 \]  
\[ \tau = I_{yy} \cdot \alpha \]  
\[ \tau_{motor} = 3141 \, in.\,lbs = 354.9 \, N.m \]

From equations 3.8, 3.9 and 3.10:

\[ \alpha = \frac{\tau}{I_{yy}} = \frac{354.9}{113.8} = 3.12 \frac{rad}{s^2} \]
At the person’s head, 0.77m away from center of rotation, the tangential acceleration was calculated as follows:

\[ a = r \alpha \]  

\[ a = 0.77\ m \times 3.12 \ \frac{\text{rad}}{\text{s}^2} = 2.40 \ \frac{\text{m}}{\text{s}^2} \]  

Acceleration at head in terms of G’s:

\[ a = \frac{2.40}{9.81} = 0.24 \ \text{G’s} \]  

The second ring is therefore within the limits of the g-force requirements. The motor for the second inner ring can be attached to a planetary gear to change max torque and rpm.

### 3.3.3 Toothed Ring

The toothed ring has a diameter of 3.5m and spins about the z-axis as shown in Figure 25. The internal mass (250kg) and the mass and size of the two inner rings were taken into account when computing the moment of inertia for the toothed ring. The toothed ring can be controlled by up to four motors. For these calculations, two motors were used. It should also be noted that the gear ratio could be changed by altering the drive gear.
The calculations were completed as follows:

\[ \begin{align*}
I_{zz} &= 951 \text{ kg}\cdot m^2 \\
\tau &= I_{zz} \cdot \alpha \\
\tau_{motor} &= 3141 \text{ in.lbs} = 354.9 \text{ N.m} \\
\text{Torque using 2 motors} &= 354.9 \times 2 = 709.8 \text{ N.m} \\
\text{Gear ratio (driven:drive)} &= 11.7:1
\end{align*} \]

Using equations 3.18 and 3.19:

\[ \text{Torque applied to driven gear} = 11.7 \times 709.8 = 8304.7 \text{ N.m} \]
Rearranging equation 3.16 and substituting equations 3.20 and 3.15:

$$\alpha = \frac{\tau}{I_{yy}} = \frac{8304.7}{951} = 8.73 \frac{rad}{s^2} \tag{3.21}$$

At the person’s head, 0.77m away from center of rotation, the tangential acceleration was calculated as follows:

$$a = r \cdot \alpha \tag{3.22}$$

$$a = 0.77 \text{ m} \cdot 8.73 \frac{rad}{s^2} = 6.72 \frac{m}{s^2} \tag{3.22}$$

Acceleration at head in terms of G’s:

$$a = \frac{6.72}{9.81} = 0.69 \text{ G's} \tag{3.24}$$

The toothed ring is therefore within the limits of the g-force requirements.

### 3.3.4 Final (duplicate) axis

In order to follow the compact design requirement, the final axis is not an additional ring. The entire assembly of rings can further be rotated around the y-axis as shown in Figure 26. This duplicate axis can also be used to control the roll, pitch or yaw of the user depending on the orientation. This fourth axis of rotation will, however, primarily be used to avoid gimbal lock (depending on the control algorithm). Since this axis does not have tight space limitations like the internal axes, larger or additional motors can be used. Four motors identical to the ones used in the rest of
the system were used. The gears controlling this axis can be altered to change max torque or rpm.

![Drawing of the final axis and all internal axes](image)

**Figure 26: Drawing of the final axis and all internal axes**

The calculations were completed as follows:

\[ I_{yy} = 492.75 \, kg.m^2 \]  \hspace{1cm} (3.25)

\[ \tau = I_{yy} \times \alpha \]  \hspace{1cm} (3.26)

\[ \tau_{motor} = 3141 \, in.\, lbs = 354.9 \, N.m \]  \hspace{1cm} (3.27)

\[ Torque \, using \, 4 \, motors = 354.9 \times 4 = 1419.6 \]  \hspace{1cm} (3.28)
Rearranging equation 3.26 and substituting equations 3.28 and 3.25:

\[ \alpha = \frac{\tau}{I_{yy}} = \frac{1419.6}{492.75} = 2.88 \frac{rad}{s^2} \]  \hspace{1cm} (3.29)

At the person’s head, 0.77m away from center of rotation, the tangential acceleration was calculated as follows:

\[ a = r \cdot \alpha \]  \hspace{1cm} (3.30)

\[ a = 0.77 \text{ m} \times 2.88 \frac{rad}{s^2} = 2.22 \frac{m}{s^2} \]  \hspace{1cm} (3.31)

Acceleration at head in terms of G’s:

\[ a = \frac{2.22}{9.81} = 0.23 \text{ G’s} \]  \hspace{1cm} (3.32)

The final axis is also therefore within the limits of the g- force requirements even though this will primarily be used to avoid gimbal lock. This axis was set up this way for flexibility when the control algorithms are developed. The person developing these algorithms can use this axis to avoid gimbal lock or control the roll, pitch or yaw of the user depending on orientation.
Chapter 4
Analysis

4.1 Structural Analysis

ANSYS Workbench was the program chosen to run the Finite Element Analysis (FEA) on the components of the Human Gyroscope. Situations that could potentially cause the system to fail, such as applying maximum torque to the system from a stationary position, were analyzed. This caused the structural members to undergo the maximum amount of stress that can be applied by the system. The Static Structural function was used in ANSYS since its purpose was to determine stresses, displacements, etc. under static loading conditions. It is accurate to assume that the instant maximum torque is applied to the stationary system, a static loading condition exists.

The ideal Human Gyroscope, having four degrees of rotational freedom, should ideally have its center of mass and center of rotation aligned. The center of rotation (CoR) occurs where all four axes of rotation intersect. It was intentional that the CoR be exactly located in the center of the rings. The center of mass is still undetermined and variable as the internal components of the human gyroscope were not a part of the design requirements. The School of Human-Centered Design, Innovation and Art at Florida Institute of Technology will design the simulator’s cockpit. It was important however, to include the 250kg of mass in the internal ring for the simulation. The mass estimates for the components and user are shown in Table 4.
### Table 4: Mass Estimate for Cockpit Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seat Frame</td>
<td>35</td>
</tr>
<tr>
<td>Seating Supports, Padding, etc.</td>
<td>3</td>
</tr>
<tr>
<td>6 Point Seatbelt</td>
<td>2</td>
</tr>
<tr>
<td>Spacesuit</td>
<td>15</td>
</tr>
<tr>
<td>Computer</td>
<td>3</td>
</tr>
<tr>
<td>Projector, mirror, cameras</td>
<td>1.5</td>
</tr>
<tr>
<td>Projection display and sensors</td>
<td>1.5</td>
</tr>
<tr>
<td>Input devices including armrest</td>
<td>9</td>
</tr>
<tr>
<td>Spacesuit hardware</td>
<td>15</td>
</tr>
<tr>
<td>Speakers, Fans</td>
<td>2</td>
</tr>
<tr>
<td>Wiring</td>
<td>3</td>
</tr>
<tr>
<td>Research Subject</td>
<td>120</td>
</tr>
<tr>
<td>Upgraded Spacesuit (compressor, battery, tank, backup tank)</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>250</td>
</tr>
</tbody>
</table>
As mentioned before, a sphere with a mass of 250kg was used to represent the components in the cockpit. For the initial analysis, this sphere was placed at the center of the internal ring. This placed the center of mass of the system very close to the center of rotation. The sphere was then offset from the center to the lower left quadrant of the inner ring so that the centers of mass and rotation do not align. The new center of mass measured 0.2 meters from the CoR. This was an arbitrarily selected position used to study the effects of an offset center of mass. The selected position however was an overestimation of an offset center of mass because in reality, the cockpit will be designed to keep the centers of mass and rotation aligned. Operators of the Controlled Human Gyroscope will have unique weight distributions and the center of mass will change with every user. This change can be kept to a minimum by placing the user’s seat close to the CoR. The actual center of mass of the Gyroscope and user should never exceed the selected position (measured radially outward from the CoR). A second static structural analysis was done on this modified setup. The center of mass measured in Solidworks of the Gyroscope (without the stand and interior) was: X = -0.01m, Y = 0.02m and Z = 0.09m.

4.1.1 Inner Ring

The inner ring was analyzed first as this provided input information for the second inner ring. The standard earth gravitational force feature was used to simulate gravity acting in the positive x direction (down in this case). Since the rings were being analyzed individually, supports were added to simulate the mounting points for the rings. The maximum torque that the hydraulic motor can deliver was applied to the ring. Remote displacement supports were used on both ends of the ring with all degrees of freedom set to zero, except rotation about the axis where the moment was
being applied. This was done in order to replicate a ‘worst case’ situation. The default mesh was first used to generate ballpark solutions and then the mesh was refined around areas of concern. On this ring, the rotary union mount and motor attachment were the areas of concern. Force reaction and moment reaction probes were placed at the supports so that this data can be used in the next analysis.

Normalized Chromoly 4130 was used for the inner ring and the maximum equivalent (von-Mises) stress sustained is 90.3 MPa as shown in Figure 27. Upon closer examination of the area of concern (area with the maximum stress or lowest factor of safety), it was noted that the connection point between the flange and the ring undergoes the most stress. This is an area that would already be welded together by
design and thicker weld beads can strengthen this particular part. The lowest factor of safety was 4.8. The area of concern is shown in Figure 28.

![Figure 28: ANSYS picture showing the minimum factor of safety for the inner ring](image)

When the internal mass of the gyroscope was offset, changes were noted in deformation, equivalent stress, force reactions and moment reactions. Although the deformation and stress was higher, it was not significant enough to compromise the parts. Figure 29 shows how the mass was offset and the new equivalent stress on the member. Initially, the maximum equivalent stress was 90.3MPa; however, with the offset mass, it increased to 95MPa. Additionally, the factor of safety decreased from 4.8 to 4.6 with the minimum value in the same location for both instances.
Figure 29: ANSYS picture showing the Equivalent (von-Mises) Stress on the inner ring with an offset internal mass

The second inner ring supports the first ring at two connection points: the motor and rotary union connection. Forces and moments will then be transferred from the inner ring to the second inner ring through these two connection points. In ANSYS, reaction probes were placed at these supports so that the forces and moments transferred could be calculated. These values were then used in the analysis of the second inner ring so that the inner ring could be removed. For example, Figure 30 shows the reaction force at the bottom of the inner ring. Since gravity acts downward in this picture, the weight had to be supported against gravity. The reaction force pointed up and away from gravity to keep the body static. The second inner ring provided this reaction force. Table 5 displays the values obtained from the force and
moment reaction probes on the inner ring with the center of mass in the middle of the structure (where all rotation axes intersect). Table 6 shows the force and moment reactions with the offset center of mass.

Figure 30: ANSYS picture showing one of the force reactions on the inner ring

Table 5: Table showing the reaction moments and forces for the inner ring with the center of mass in the middle of the structure

<table>
<thead>
<tr>
<th>Location</th>
<th>Reaction x</th>
<th>Reaction y</th>
<th>Reaction z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Reaction 1 (N)</td>
<td>-1484.1</td>
<td>-0.14</td>
<td>710.3</td>
</tr>
<tr>
<td>Moment Reaction 1 (N.mm)</td>
<td>3.90E+05</td>
<td>65.3</td>
<td>316.5</td>
</tr>
<tr>
<td>Force Reaction 2 (N)</td>
<td>-1486.2</td>
<td>0.25</td>
<td>-0.13</td>
</tr>
<tr>
<td>Moment Reaction 2 (N.mm)</td>
<td>0</td>
<td>120.1</td>
<td>626.9</td>
</tr>
</tbody>
</table>
Table 6: Table showing the reaction moments and forces for the inner ring with the internal mass offset

<table>
<thead>
<tr>
<th>Location</th>
<th>Reaction x</th>
<th>Reaction y</th>
<th>Reaction z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Reaction 1 (N)</td>
<td>-1485.3</td>
<td>-172.68</td>
<td>0</td>
</tr>
<tr>
<td>Moment Reaction 1 (N.mm)</td>
<td>3.90E+05</td>
<td>31</td>
<td>-3.20E+04</td>
</tr>
<tr>
<td>Force Reaction 2 (N)</td>
<td>-1484.9</td>
<td>172.7</td>
<td>0</td>
</tr>
<tr>
<td>Moment Reaction 2 (N.mm)</td>
<td>0</td>
<td>25.13</td>
<td>-4.07E+04</td>
</tr>
</tbody>
</table>

4.1.2 Second Inner Ring

The second inner ring was also analyzed individually because using less computational resources allows ANSYS to display solutions quicker. Since this ring supports the inner ring, the reaction forces and moments from the previous analysis were used in place of the first ring. Similarly to the first analysis, ballpark solutions were generated with the standard mesh and the mesh was refined mainly around the areas of concern. Normalized Chromoly 4130 was also used for this ring and the maximum equivalent (von-Mises) stress was 147.1 MPa as shown in Figure 31.
Figure 31: ANSYS picture showing Equivalent Stress on the 2nd inner ring

The areas of concern for this ring were all the mounting points for this ring and the ring that goes inside it. Like the previous analysis, the lowest factor of safety occurs at a point that will be welded by design. It should also be noted that there are some stress concentrations as the highest stress areas are very small. This means that the lowest factor of safety may actually be higher. The lowest factor of safety obtained was 2.96 and the main area of concern can be seen in Figure 32.
Figure 32: ANSYS picture showing the minimum factor of safety for the second inner ring

Data was taken from Table 6 (offset center of mass) and input into another static structural analysis for the second inner ring. Again, changes were noted but none were significant enough to compromise the part. Figure 33 shows that the maximum equivalent stress did change, but only by 1.3MPa.
Figure 33: ANSYS picture showing the Equivalent (von-Mises) stress on the second inner ring with an offset center of mass

Since this ring is also supported by another ring, the gear in this case, reaction forces and moments were computed at the supports. Table 7 lists the force and moment reactions at the supports without an offset internal mass. Table 8 displays the same data but with an offset mass. The values from these tables were used as inputs in the analysis of the gear assembly.

Table 7: Table showing the force and moment reactions in the second inner ring with the center of mass in the middle of the simulator

<table>
<thead>
<tr>
<th>2nd Inner Ring Force and Moment Reactions (no offset)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Force Reaction 1 (N)</td>
</tr>
<tr>
<td>Moment Reaction 1 (N.mm)</td>
</tr>
<tr>
<td>Force Reaction 2 (N)</td>
</tr>
<tr>
<td>Moment Reaction 2 (N.mm)</td>
</tr>
</tbody>
</table>
Table 8: Table showing the force and moment reactions for the second inner ring with an offset mass

<table>
<thead>
<tr>
<th>Location</th>
<th>Reaction x</th>
<th>Reaction y</th>
<th>Reaction z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Reaction 1 (N)</td>
<td>1336.9</td>
<td>-3.2</td>
<td>153.5</td>
</tr>
<tr>
<td>Moment Reaction 1 (N.mm)</td>
<td>2.25E+04</td>
<td>0</td>
<td>2.76E+05</td>
</tr>
<tr>
<td>Force Reaction 2 (N)</td>
<td>1054.6</td>
<td>3.5</td>
<td>-153.5</td>
</tr>
<tr>
<td>Moment Reaction 2 (N.mm)</td>
<td>2.23E+04</td>
<td>3.60E+05</td>
<td>-1.50E+05</td>
</tr>
</tbody>
</table>

The force and moment reaction values here had a very small change from a centered mass to an offset mass. As the analysis moved from the inner ring outward, the change in force and moment values between an offset mass and a centered mass decreased. Using the offset mass values in the next analysis produced equal results so only one of them will be reported.

4.1.3 Gear Assembly

The material selected for this ring was structural steel as it is readily available and relatively cheap. The analysis for this ring was more challenging than the rest. The assembly of gears were imported into the analysis and the rest of the structure replaced with relevant supports. Figure 34 is a picture of the Total Deformation in millimeters experienced by the gears. Frictionless supports were used on the sides of the gear to allow them to slide but not move out of plane. Moments were applied to the smaller gears that would rotate the bigger gear in a clockwise motion. Remote displacements were used on the small drive gears and all the parameters set to zero except rotation around the axis where the torque is applied. Another remote displacement was used on the driven gear (bigger gear) completely fixing it in space.
This simulates the ‘worst case’ scenario as the driven gear is not allowed to rotate and the drive gears are trying to turn it.

Figure 34: ANSYS picture showing the Total Deformation of the geared ring

The maximum stress was 150.6 MPa and this occurred at the edge of the driven gear’s teeth. Figure 35 is a magnified picture of the equivalent (von-Mises) stress the gears experience. It should be noted that the max stress area was very small and it is likely to be a stress concentration.
Figure 35: ANSYS picture showing the maximum stress on the gear assembly

Figure 36 shows the mesh refinement on this gear assembly and the transition between bigger nodes to smaller nodes (top of picture to bottom of picture). The entire assembly was refined but the areas of concern required additional refinement (smaller nodes). Even though the mesh was refined around the area of concern, an analysis of the mesh quality indicated that the nodes that covered the drive gear’s fillet were of a lower quality. Since this is the same area of maximum stress, it is likely to be a stress concentration.
In order to clearly see what happened in the analysis of the gears, a scaled picture of the total deformation can be seen in Figure 37. In this figure, the deformation is scaled 63 times that of the original deformation. The driven gear, since it is fixed, is bending due to the torque applied to the driven gears. The maximum deformation however is only 2.72mm, which is insignificant and difficult to see on the true scale picture. The lowest factor of safety experienced was 1.66 at the edge of the drive gear’s teeth. All of the other areas on this assembly recorded a factor of safety of 5.0 or more. It is also important to note that during normal operation, the gear assembly will never experience such large forces. The other gears will always be allowed to
rotate. The low factor of safety will only be experienced if a component fails causing one or more of the gears to stop rotating instantly.

Figure 37: ANSYS picture showing a 63x scaled deformation plot of the gear assembly

Force and moment reaction probes were added to the frictionless support of the large gear. These supports were on either side of the gear and we expected these to have equal and opposite reaction forces.

Table 9: Table showing the force and moment reactions on the frictionless supports of the big gear

<table>
<thead>
<tr>
<th>Gear Force and Moment Reactions (no offset)</th>
<th>Location</th>
<th>Reaction x</th>
<th>Reaction y</th>
<th>Reaction z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force Reaction Big Gear (N)</td>
<td>0</td>
<td>0</td>
<td>7702.1</td>
<td></td>
</tr>
<tr>
<td>Force Reaction Big Gear 2 (N)</td>
<td>0</td>
<td>0</td>
<td>-7795.6</td>
<td></td>
</tr>
<tr>
<td>Moment Reaction Big Gear 1 (N.mm)</td>
<td>-6.22E+05</td>
<td>-2.23E+07</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Moment Reaction Big Gear 2 (N.mm)</td>
<td>-3.93E+05</td>
<td>2.19E+07</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Discrepancies in the values stemmed from the gear twisting under load. The total deformation was insignificant (2.72 mm) and the difference in the force values were also very small (93.5 N).

4.1.4 Final Axis

The final axis rotates the entire system of rings and it is responsible for supporting the weight of the simulator. The material chosen was standard structural steel as this is readily available and fairly cheap. To analyze these supports, the weight of the simulator (excluding these supports and the stand) was calculated using Solidworks. A force value was then computed from this weight (750kg) using gravity ($9.81 \text{m/s}^2$). This simulation is for the worst case, which is when the large gear is turned on its side. All of the forces due to gravity now act on these supports. Due to the symmetry of the motion simulator, only one side was analyzed. The force, approximately 7500N, then had to be divided by 2. A subassembly of these parts was created and imported into ANSYS. Figure 38 is a total deformation plot from ANSYS and it shows that these plates deformed at most 0.14mm under full load. This is an insignificant amount of movement.
Figure 38: Ansys picture showing the total deformation of the final axis

It was also important to look at the stress experienced by this part and the safety factor. The weakest point on this support was again, where it has to be welded. A factor of safety plot is shown in Figure 39. The highest stress experienced was 55MPa and the lowest factor of safety was 4.55.
In order to see exactly what happened in the analysis of the final axis, a scaled picture of the total deformation can be seen in Figure 40. In this figure, the deformation is scaled 530 times that of the original deformation. All of the forces due to gravity are acting on the lower plate and it is supported in a bearing by the cylindrical protrusion (blue in the diagram). In Figure 40, it is now easy to see that the weight of the system was trying to separate the two supporting plates.

Figure 39: Ansys picture showing factor of safety for the final axis

Figure 40: ANSYS picture showing a scaled plot of the total deformation of the final axis
4.1.5 **Supporting Structure**

A basic analysis was done on the supporting structure (stand). This may not necessarily be used as the motion simulator can be mounted on a translational motion platform. The stand was made out of Normalized 4130 Chromoly square tubing. The tube’s cross section measures 2 inches by 2 inches with a 0.25-inch wall thickness. The weight of the structure was computed and converted to a force value (using gravity) and applied to the stand. The resulting total deformation is shown in Figure 41. The maximum total deflection was 0.13mm and considered insignificant.

![Figure 41: ANSYS picture showing the total deformation of the stand](image)

The stand holds the bearings that allow the entire structure to rotate about the final axis. Supporting beams were added and triangulated to the block that holds these bearings. The highest equivalent stress (10.8 MPa) was observed at a lower joint. This supporting structure was intentionally overdesigned and it can be redesigned to
be more efficient. The area of concern and the highest stress value is shown in Figure 42. The highest stress value again occurred at an area that will be welded together.

Figure 42: ANSYS picture showing the area of concern of the stand analysis and the Equivalent (von- Mises) Stress

4.2 Kinematic Analysis

4.2.1 Mathematical Description of Gimbal Lock

As flight technology advances, spacecrafts and aircrafts become very maneuverable. Older aircrafts had gravity fed fuel systems that restricted the maneuverability of that plane significantly. If the plane banks excessively, fuel would be cut off to the engine
causing it to stall. Modern aircrafts have fuel pumps and baffled fuel tanks that remove rotational limitations of the aircraft. Once the plane is structurally capable, it will have unlimited rotation about its axes. Complicated out of plane maneuvers such as barrel rolls, lag rolls, displacement rolls and spirals, just to name a few, are part of aerobatics and military flight training and dates back to the early 1900’s. A three degree of freedom system will encounter kinematic singularities while trying to replicate this type of motion. An example of a three degree of freedom gimbal is shown in Figure 43.

![Figure 43: Drawing showing a 3DoF gimbal system](image)

In order to mathematically explain gimbal lock or kinematic singularity, Figure 43 will be referenced. An inertial frame has been set up where the positive y-axis points up, the positive x-axis points to the right and the positive z-axis points out of the paper. Each gimbal has its own frame of reference attached to it that rotates with that gimbal (body fixed reference frame). With the orientation in Figure 43, the outer gimbal rotates about the x-axis (pitch), the middle gimbal rotates about the y-axis...
(yaw) and the inner gimbal rotates about the z-axis (roll). In this orientation, the gimbal frames are all aligned with the inertial frame since this is the starting position. Rotation about any axis in this system can be converted from the inertial frame using a transformation matrix. The transformation matrices are given as:

\[
R_x(\delta_1) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\delta_1) & \sin(\delta_1) \\ 0 & -\sin(\delta_1) & \cos(\delta_1) \end{bmatrix} \quad (4.1)
\]

\[
R_y(\delta_2) = \begin{bmatrix} \cos(\delta_2) & 0 & -\sin(\delta_2) \\ 0 & 1 & 0 \\ \sin(\delta_2) & 0 & \cos(\delta_2) \end{bmatrix} \quad (4.2)
\]

\[
R_z(\delta_3) = \begin{bmatrix} \cos(\delta_3) & \sin(\delta_3) & 0 \\ -\sin(\delta_3) & \cos(\delta_3) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (4.3)
\]

Where \( \delta \) in these matrices are rotation angles and the subscripts describe which axis it is attached to.

The final transformation matrix from the inertial frame to the gimbal frame, used to convert velocity and acceleration vectors, is the product of the previous three matrices:

\[
T_{\text{inertial to body}} = R_z(\delta_3) \ast R_y(\delta_2) \ast R_x(\delta_1) \quad (4.4)
\]

Substituting the transformation matrices 4.1, 4.2 and 4.3:

\[
T_{\text{inertial to body}} = \begin{bmatrix} \cos(\delta_3) \ast \cos(\delta_2) \ast \sin(\delta_1) + \sin(\delta_3) \ast \sin(\delta_2) \ast \cos(\delta_1) - \sin(\delta_3) \ast \sin(\delta_2) \ast \sin(\delta_1) - \cos(\delta_3) \ast \sin(\delta_2) \ast \cos(\delta_1) \\ -\sin(\delta_3) \ast \cos(\delta_2) \ast \sin(\delta_1) + \cos(\delta_3) \ast \sin(\delta_2) \ast \cos(\delta_1) + \cos(\delta_3) \ast \sin(\delta_2) \ast \sin(\delta_1) + \sin(\delta_3) \ast \cos(\delta_2) \ast \cos(\delta_1) \\ \sin(\delta_3) \ast \sin(\delta_2) \ast \sin(\delta_1) - \cos(\delta_3) \ast \cos(\delta_2) \ast \cos(\delta_1) - \cos(\delta_3) \ast \cos(\delta_2) \ast \sin(\delta_1) - \sin(\delta_3) \ast \sin(\delta_2) \ast \sin(\delta_1) \end{bmatrix} \quad (4.5)
\]
The transpose of this matrix \( \left( T^\text{inertial to body} \right)^T \) can be used to convert kinematic motions from the body fixed frame to the inertial frame. Euler angles are used to describe the attitude of the body fixed frame with respect to the inertial frame. The kinematic motion for the gimbals are determined by computing the inverse of the mapping matrix from Euler angle rates to body rates (Carter et al. 2014). For the 3-axis gimbal shown in Figure 43, the Euler angle rates to body rates are given by:

\[
\omega^\text{body} = R_z(\delta_3) \cdot R_y(\delta_2) \cdot R_x(\delta_1) \cdot [\dot{\delta}_1, 0, 0]^T + R_z(\dot{\delta}_3) + R_y(\dot{\delta}_2) + [0, \dot{\delta}_2, 0]^T + R_z(\dot{\delta}_3) \cdot [0, 0, \dot{\delta}_3]^T
\]  

(4.6)

Substituting equations 4.1, 4.2 and 4.3 into 4.6:

\[
\omega^\text{body} = \begin{bmatrix}
\cos(\delta_2) \cdot \cos(\delta_3) & \sin(\delta_3) & 0 \\
-\cos(\delta_2) \cdot \sin(\delta_3) & \cos(\delta_3) & 0 \\
\sin(\delta_2) & 0 & 1
\end{bmatrix}
\begin{bmatrix}
\dot{\delta}_1 \\
\dot{\delta}_2 \\
\dot{\delta}_3
\end{bmatrix}
\]

(4.7)

Where \( \omega^\text{body} \) is the body angular rate with coordinates in the body fixed reference frame (Carter et al. 2014). We can then take the inverse of this matrix and use it to find the required gimbal rates. We will denote the rate vector by \( \dot{\gamma} \) and the matrix by \( A \):

\[
\omega^\text{body} = A \star \dot{\gamma}
\]

(4.8)

The rate vector:

\[
\dot{\gamma} = A^{-1} \star \omega^\text{body}
\]

(4.9)

The inverse of the matrix \( A \) \((A^{-1})\) is given by:

\[
A^{-1} = \frac{1}{\text{determinant}(A)} \star \text{adjoint}(A)
\]

(4.10)
The determinant of the matrix $A$ is:

$$\text{determinant } (A) = \cos(\delta_2) \cdot \cos(\delta_3) \cdot \cos(\delta_3) - \sin(\delta_3) \cdot (-\cos(\delta_2) \cdot \sin(\delta_3))$$

$$\text{determinant } (A) = \cos(\delta_2) \cdot (\cos^2 \delta_3 + \sin^2 \delta_3) = \cos(\delta_2)$$

$$\text{adjoint } (A) = \begin{bmatrix} \cos(\delta_3) & \cos(\delta_2) \cdot \sin(\delta_3) & -\cos(\delta_3) \cdot \sin(\delta_2) \\ -\sin(\delta_3) & \cos(\delta_2) \cdot \cos(\delta_3) & \sin(\delta_3) \cdot \sin(\delta_2) \\ 0 & 0 & \cos(\delta_2) \end{bmatrix}^T$$

$$\text{adjoint } (A) = \begin{bmatrix} \cos(\delta_3) & -\sin(\delta_3) & 0 \\ \cos(\delta_2) \cdot \sin(\delta_3) & \cos(\delta_2) \cdot \cos(\delta_3) & 0 \\ -\cos(\delta_3) \cdot \sin(\delta_2) & \sin(\delta_3) \cdot \sin(\delta_2) & \cos(\delta_2) \end{bmatrix}$$

$$A^{-1} = \frac{1}{\cos(\delta_2)} \begin{bmatrix} \cos(\delta_3) & -\sin(\delta_3) & 0 \\ \cos(\delta_2) \cdot \sin(\delta_3) & \cos(\delta_2) \cdot \cos(\delta_3) & 0 \\ -\cos(\delta_3) \cdot \sin(\delta_2) & \sin(\delta_3) \cdot \sin(\delta_2) & \cos(\delta_2) \end{bmatrix}$$

This inverse of $A$, like any other matrix, only exists if the determinant of $A$ is non-zero. The determinant of $A$ (stated above) is $\cos(\delta_2)$. The inverse of $A$ therefore does not exist where $\cos(\delta_2)$ is equal to zero. This occurs when $\delta_2 = \frac{n\pi}{2}$, where $n = \pm 1, \pm 3 \ldots$. At these values of $\delta_2$, the system encounters gimbal lock. Referring to Figure 43, if $\delta_2$ is $\frac{\pi}{2}$ or 90 degrees, the red ring rotates 90 degrees about the y-axis making the rings concentric and the system loses pitching motion.

### 4.2.2 Four Axis System

A flying machine travelling through space has 6 degrees of freedom, three of which are rotational. Simulating the attitude of these vehicles can be done with a 3-axis
gimbal, but certain attitudes will cause this to encounter gimbal lock. A 4-axis system was proposed that, if controlled correctly, would avoid kinematic singularity with its redundant gimbal. Creating an algorithm to control this system is a very complex process and not in the scope of this project, but equations of motion will be proposed. These equations can then be transferred to software that can solve the equations and incorporate these solutions in a control algorithm for the system.

Methods for solving these equations have been presented and one example of that is seen in the paper by Wang et al. Wang proposed that for a direct kinematic manipulator, a dual Euler method can be used to solve the expression of attitude angles. For inverse kinematics, a pseudo-inverse gradient projection method is used to obtain optimal velocity solution (Wang et al. 2010).

Referring to Figure 44, the axes of rotation have been labeled 1 to 4 from the outer to inner gimbal respectively. An inertial frame has been set up where the positive y-axis points up, the positive x-axis points to the right and the positive z out of the paper. Similarly to above, the subscripts of \( \partial \) describe which axis and gimbal it is attached to. Rotation about any axis in this system can be converted to the gimbal frame using a transformation matrix. The transformation matrices are given as:

\[
R_x(\partial_1) = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(\delta_1) & \sin(\delta_1) \\
0 & -\sin(\delta_1) & \cos(\delta_1)
\end{bmatrix}
\]

(4.16)

\[
R_z(\partial_2) = \begin{bmatrix}
\cos(\delta_2) & \sin(\delta_2) & 0 \\
-\sin(\delta_2) & \cos(\delta_2) & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

(4.17)
Like the 3-axis system, a final transformation matrix from the inertial frame to the gimbal frame can be computed. In this case, the rotation sequence is: $R_y(\delta_4), R_x(\delta_3), R_2(\delta_2), R_1(\delta_1)$. The complete transformation matrix is given by:

$$R_x(\delta_3) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\delta_3) & \sin(\delta_3) \\ 0 & -\sin(\delta_3) & \cos(\delta_3) \end{bmatrix}$$  \quad (4.18)

$$R_y(\delta_4) = \begin{bmatrix} \cos(\delta_4) & 0 & -\sin(\delta_4) \\ 0 & 1 & 0 \\ \sin(\delta_4) & 0 & \cos(\delta_4) \end{bmatrix}$$  \quad (4.19)
\[ T_{\text{inertial to body}} = R_y(\partial_4) * R_x(\partial_3) * R_z(\partial_2) * R_x(\partial_1) \quad (4.20) \]

Using equations 4.16 to 4.19 in equation 4.20:

\[ T_{\text{inertial to body}} = \left[ \begin{array}{ccc} C\partial_4 C\partial_2 - S\partial_4 S\partial_3 S\partial_2 & -S\partial_4 C\partial_3 & C\partial_4 \\ C\partial_3 S\partial_2 & S\partial_3 & 0 \\ S\partial_4 C\partial_2 + C\partial_4 S\partial_3 S\partial_2 & C\partial_4 C\partial_3 & S\partial_4 \end{array} \right] \left[ \begin{array}{c} \dot{\partial}_1 \\ \dot{\partial}_2 \\ \dot{\partial}_3 \\ \dot{\partial}_4 \end{array} \right] \quad (4.21) \]

For the 4-axis gimbal shown in Figure 44, the Euler angle rates to body rates are given by:

\[ \omega_{\text{body}} = R_y(\partial_4) * R_x(\partial_3) * R_z(\partial_2) * R_x(\partial_1) * \left[ \begin{array}{c} \dot{\partial}_1, 0, 0 \end{array} \right]^T + R_y(\partial_4) * R_x(\partial_3) * R_z(\partial_2) * \left[ \begin{array}{c} 0, 0, \dot{\partial}_2 \end{array} \right]^T + R_y(\partial_4) \]

\[ * R_x(\partial_3) * \left[ \begin{array}{c} \dot{\partial}_3, 0, 0 \end{array} \right]^T + R_y(\partial_4) * \left[ \begin{array}{c} 0, \dot{\partial}_4, 0 \end{array} \right]^T \quad (4.22) \]

Substituting the transformation matrices (4.16 to 4.19) in equation 4.22:

\[ \omega_{\text{body}} = \left[ \begin{array}{cccc} C\partial_4 C\partial_2 - S\partial_4 S\partial_3 S\partial_2 & -S\partial_4 C\partial_3 & C\partial_4 & 0 \\ C\partial_3 S\partial_2 & S\partial_3 & 0 & 1 \\ S\partial_4 C\partial_2 + C\partial_4 S\partial_3 S\partial_2 & C\partial_4 C\partial_3 & S\partial_4 & 0 \end{array} \right] \left[ \begin{array}{c} \ddot{\partial}_1 \\ \ddot{\partial}_2 \\ \ddot{\partial}_3 \\ \ddot{\partial}_4 \end{array} \right] \quad (4.23) \]
Chapter 5
Conclusion

Modern air and space crafts are capable of large roll, pitch and yaw angles. In some instances, they can rotate 360 degrees about these axes. Existing aircraft simulators that feature a motion platform have a limited range of rotational motion. Even some of the most advanced simulators that exist today can encounter gimbal lock, therefore making the system incapable of replicating certain maneuvers. The Controlled Human Gyroscope in this paper had unlimited rotation about all three axes. It used a redundant gimbal making it a 4-axis system that successfully avoided gimbal lock unlike the conventional 3-axis setup. Complex maneuvers like those performed by military and aerobatic pilots can be easily reproduced on this system.

Pilot training in general, and especially for the military, is very expensive because of the number of flying hours. A high fidelity motion simulator will reduce these hours therefore reducing the cost of training pilots. The 4-axis human gyroscope proposed in this paper allows for the simulation of all aircraft maneuvers. Dangerous training situations can then be presented to the pilots before they actually encounter them in an aircraft. Some flying situations are too dangerous to actually be practiced such as spatial disorientation and controlled flight into terrain. These can however be demonstrated and practiced on a motion simulator. Pilots are not trained in an aircraft in inclement weather. Introducing pilots to these conditions on a realistic flight motion simulator can prepare them for such situations as they are sometimes unavoidable during actual flights.
To replicate the rotational motion of a vehicle, each axis of the gyroscope needed to be independently controlled. Hydraulic motors were used to control the motion of each axis due to its high torque output and small footprint. The passage of hydraulic fluid and electricity from the outside of the motion simulator to the internal rings were one of the challenges faced in the design of this project. Hydraulic rotary unions with integrated electrical slip rings were selected to overcome this issue. This allowed the transfer of hydraulic fluid and electricity through freely rotating components.

The materials selected for the construction of this motion simulator are common, readily available metals and as a result, they are relatively cheap. These materials include standard structural steel and Normalized Chromoly 4130. Chromoly is available in the round tube size that was selected and it can be easily bent into the desired shape. With the Finite Element Analysis completed in ANSYS, structural predictions were made on the components of the Human Gyroscope. The situations where the structure was most likely to fail were replicated and analyzed. The components on the gyroscope had no less than a 1.6 factor of safety under the most extreme loading conditions with most factors of safety above 2.9.

The control systems aspect of the Human Gyroscope was not within the scope of this project, but sufficient information was provided to continue this study. This information can be used to develop a control algorithm for this system. The Controlled Human Gyroscope will provide high fidelity motion simulations of air, space or land vehicles. This system can be added to a translation motion base to provide up to six degrees of freedom for an even more realistic experience. For example, the cabin on the NASA AMES vertical motion simulator can be replaced with the Controlled Human Gyroscope. This will allow for a significant translational
and rotational motion envelope. A projector was initially suggested to provide the visual aspect of the motion simulator. Virtual reality systems are however becoming very popular and it will provide a more realistic setting. Virtual reality systems are very small compared to projectors and screens so this will help with packaging constraints.

Flight motion simulators, according to literature, has to provide high fidelity motion cues or the simulators can have a negative effect on the users when they transition to actual aircrafts. The Controlled Human Gyroscope with a suitable control algorithm will be able to accurately perform these motion cues without the unnecessary movement of the user since it is able to avoid gimbal lock. A high fidelity simulator such as this one will provide more accurate research and training capabilities.

5.1 Suggestions for Improvement

While the design of the Controlled Human Gyroscope is complete, improvements can always be made. Safety of the operator inside the gyroscope and individuals on the outside is a top priority. A surrounding structure can be built to encase the gyroscope while leaving enough room for the structure to freely rotate. This will keep external operators and observers safe.

Idler gears can also be added to the top and bottom of the driven gear to provide additional support (Figure 45). In the event that the hydraulic systems fail, or if there is an issue with the control algorithm, these idler gears will keep the driven gear in place. With the current design, the concentric rings were connected only through the hydraulic motors and the rotary unions. Forces that are transferred through these components will add to the frictional losses of the system. In order to minimize frictional losses, a different support structure can be used with low friction bearings.
Figure 45: Picture showing the idler gears that can be added to provide additional safety

The Controlled Human Gyroscope was capable of generating more than a combined 0.2 G’s of acceleration at the operator’s head. If more acceleration is required, planetary gears can be used between the concentric rings to gain more torque while staying within the packaging limitations.
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