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Mechatronics and Electrical Engineering

The Human Gyroscope
Motor driven simulator with a gyroscope design

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The Human Gyroscope

Bachelor Thesis in Electrical and Mechatronic Engineering

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Description of cover page picture: SolidWorks model of the human gyroscope with motors and slip rings
Abstract

This project surfaced through Hans-Erik Eldemark, business coach at Science Park Halmstad, who had been contacted by Boris Duran, Lecturer at the University Skövde and owner of the project.

The idea of the project is to take a first step in the making of a motor driven simulator with a gyroscope design. The simulator will be implemented as part of virtual reality systems, computer games, flight simulators, training platforms, etc. The motors in this platform will be controlled by the movements of the user’s joystick allowing him/her a continuous and unlimited rotation. A very simple way of understanding the potential of this platform can be seen in a practical application such as a flight simulator since flying needs continuous and unlimited yaw, pitch and roll types of motion. A motor driven gyroscope is a novel and practical solution for this kind of applications.
Acknowledgments

Thesis project, 15 credits, have been made with Boris Duran together with the School of Information Science, Computer and Electrical Engineering.

We would like to extend our deepest gratitude to Boris Duran and Hans-Erik Eldemark for getting in touch with and letting us work with this exciting project.

We would also like to thank our supervisor Nicholas Wickström for guidance and support throughout this difficult process.

Special thanks to the following people and companies for invaluable help in this project.

- Thomas Lithén at the electronical workshop for helping us with the hardware in the prototype making.
- Bertil Svensson and David Samvin at Science Park for helping us with Solid Works and FEM analysis.
- Håkan Petersson in the mechanical shop for helping us out in the making of the prototype.
- Gunnar Kronborg at Bevi AB for helping us out with choosing servo motors, motor drives and planetary gears.
- David Burge at Penlink AB for helping us out with the servo motors and slip rings.
- Plåtcenter for cutting out the rings to the prototype.

Without all of you this project would never have been done.

Alexander Kjellin & Mattias Runevad, Halmstad University december 2012
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1 Introduction

Today, the use of simulators in the gaming industry is widely spread. In arcades around the world we see moving flight, car and virtual reality simulators. These types of devices are being used purely for our entertainment. But there are other kinds of moving simulators that is being used to study reactions on the human body in preparation for space traveling or flight missions, where the human body will be subjected to high G-forces. The advantage of using moving simulators is clear, that in a safe controlled environment test the human body without risking the health of a person. Or as stated in the beginning, simulate driving or flying, just for fun.

1.1 Background

Boris Duran, lecturer at Skövde University College and a former student at the embedded systems master program at Halmstad University had an idea for a company. He approached Hans-Erik Eldemark with the concept and this thesis project is the first step in creating a motor driven human gyroscope.

1.2 Problem formulation

The motion gaming/testing simulators that exists today only moves with a certain degree of freedom (DOF). To design and construct a simulator that moves freely in all axes raises numerous of complicated technical challenges. The aim of the thesis project and the problems that comes with the idea is listed below. These initial problems in this first step of creating a full scale simulator are the problems that our project owner wanted to have suggested solutions to.

- Design and build a prototype with unlimited movement in one or more axis
- Show that the design concept is unique
- Design a full scale model with CAD
- Conduct FEM analysis on the CAD model
- Selecting the right type of motor and gearbox concerning moment of inertia
- Show how to control the motors
- Show how to supply the motors with power and signals
- Show how to implement unlimited rotation in all axes (x-y-z)
- Suggest software solutions and how to interface with the simulator

1.3 Purpose

Develop a motion simulator platform that rotates 360 degrees around the X, Y and Z axis. Among the most important target applications of the final project are: entertainment, training, testing and human studies.
1.4 Restrictions

- This thesis project will not build a full scale model
- Market analysis and product needs will not be conducted
- The project will only plan and design the full scale
- The solution will have to include the Oculus VR headset
2 Part one

2.1 Introduction

The thesis project is divided into two parts; this is due to the somewhat difficult nature of the project and to get a clear cut between the practical part of the project and the theoretical part. The first part will go through how and why we built a prototype for this project.

2.2 Prototype

To be able to understand the concepts of the project, and identify problems that must be solved, a smaller prototype that partially showed functionality was designed and built, CAD drawing showing the prototype in Figure 1. This smaller prototype differs from the full scale model in design but its main purpose is to show a proof of concept rather than full functionality.

2.2.1 Construction

The construction consists of three main rings each one representing one axis in the XYZ-plane. There are four shafts that were made to keep some distance from the outer and the second ring. This was to be able to fit a motor to the inner ring on the outside of it. In the first drawings that were made the motor in the inner ring sat on the outside. It was then moved to the inside for better stability and easier mounting. Each shaft rests on small ball bearings for better friction.

2.2.2 Hardware

For the prototype to move around the motors had to be controlled through a micro controller together with motor drivers. A bread board was initially set up that connected and made it easy to test all of the hardware separately before making a PCB (Printed Circuit Board). Later a PCB was designed in DesignSpark and then made in the electronical workshop. This was so that everything would fit nicely into an electronic closure to make it look better and not having a lot of wiring hanging out. To see the schematic and how the micro controller, the Arduino, and the motor drivers are connected, see (Appendix 2) and (Appendix 3) for schematic and PCB layout.
2.2.2.1 Motors and motor drivers

The motors used for this prototype is two SM-42BYG011-25 [23] bipolar stepper motors with 200 steps/revolution and step angle of 1.8 degrees. These two motors control the yaw and pitch of the prototype. The inner ring is controlled by a smaller unipolar stepper motor of type 28BYJ-48 [24]. The bipolar motors are driven by the EasyDriver v4 [25] that builds on the A3967SLB chip which is a complete micro stepping motor driver. This can drive the motor in full-, half-, quarter-, and eighth-step modes. That means that one full revolution on this motor with 200 steps per revolution actually is 1600 micro steps with this motor driver. The small unipolar motor is controlled by a K179 [21] chip. As stated in [3.3.2] a stepper motor ticks one step when receiving a pulse on the step pin in the direction that the direction pin is set to.

2.2.2.2 Slip rings

In order to supply the second motor with power you must be able to transfer it to a moving platform, this is done with a SRH0422 [14] slip ring from Penlink shown in Figure 4. This sits on top of the whole prototype, the initial idea was to place it in the bottom of the prototype and make the motor shaft go in through the bore hole of the slip ring and lead the wiring down instead of up. Due to the relatively big size of the connectors that was available, compared to the motor and thickness of the material, this could not be done, and therefore there is a frame on the outside of the whole structure supporting the connector and leading the wires. This is one of the big design deviations from the full scale model concerning power transmission; this can be seen in Figure 4 and Figure 3.
2.2.2.3 Micro controller

The micro controller used is an Arduino UNO [16] that uses the ATmega328 processor. The Arduino UNO has 14 input/output pins and six of them can be used as PWM (Pulse Width Modulation) or PDM (Pulse Delay Modulation) outputs. Six pins can be used for joysticks and other analog inputs. The Arduino is a relatively new platform for the school and has not been used in the normal education. However this micro controller differs from the normal development boards that the students normally use that builds on the PIC or ARM processors. One of the main advantages in using the Arduino is the built in boot loader that does not require an external programmer and you can upload new code to the processor directly from the PC via the built in USB interface on the board. This allowed for easy testing of different solutions and programming the prototype could take shape quite fast.

![Hardware flow chart](image)

**Figure 5 - Hardware flow chart.**

2.2.3 Programming

The Arduino is programmed in a C/C++-like language called Processing. We used Microsoft Visual Studio 2008 with Arduino support to program and debug. One of the advantages by using Visual Studio instead of the Arduino IDE (Integrated Development Environment) is that you can debug, step and set breakpoints in your program, something that is not possible when using the IDE.

When reading the joysticks it simply reads an analog value that comes from one of the two 10k Ohm potentiometers that each joystick has. The A/D (Analog to Digital) converter reads a value between 0 and 5 volts, resulting in a 10-bit A/D conversion value of 0 – 1023. This value is then interpreted by the program. If the value on one potentiometer is below 10 % of the neutral value, which is 512, it sends PWM pulses to the motor and sets the direction. The same goes for when the value is above 10 % of the neutral value then it sends PWM pulses and sets the motor to go in the other direction. A flow chart that shows how the control program is structured is shown below in Figure 6.
2.2.4 Conclusion

This prototype shows proof of functionality in two axes in a smaller scale. It also shows the overall concept of the design. The prototype has highlighted many of the future problems that could occur when designing and constructing a full scale model. It shows a solution to the power transmission between the rings. It also shows in a smaller scale how to interface with the motors and making the simulator move. It shows proof that the initial design idea holds and that the simulator can move in all three axes. By building this prototype and manage to get functionality in two axes the chance of succeeding in building a large scale simulator has increased significantly.

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Figure 6 - Software flow chart prototype.
3 Part two

This is the second part of the thesis and it describes the more theoretical work that has been put in to this project. In this part a pre study is conducted and a method chapter has been written to describe what the project needs and how it would achieve the end result. The hardware chapter will go through the different options this kind of project would have to consider before building a real simulator. The control system and software topic will cover how to communicate with all the different parts in the simulator.

3.1 Pre study

To be able to motivate that the project should be done in the first place, a pre study was made to get a deeper understanding of what the market had to offer today in the same technical field. That is in order to investigate that the project holds a unique solution compared to other gaming simulators.

The pre study in this project was made mainly through the internet and looking at the different companies websites and consulting with the project owner who had some insight into the gaming simulator market.

3.1.1 State of the art

The gaming simulators that are used today are often limited in some way. There can be limitations in movement or limitations for the user in the overall experience. The ideal case would be a simulator that mimics a real world application as close as possible. Gaming simulators often moves in two axes, they are implemented with only two of the three; pitch, yaw and roll motion. This topic will list the simulators that are out on the market today and in the same style and fashion as the idea of our project owner.

3.1.2 Gaming simulators

The gaming industry has grown tremendously for the past 20 years. To get better graphics and gaming experiences the envelope has to been pushed further every year. The whole concept is to create a feeling that you are actually moving in reality while playing a game. There are different techniques of achieving this and they are listed below. In the end there is a summary of the different gaming simulators.

Figure 7 – An early suggested model in the project with displays and joystick.
3.1.2.1 Racing simulator (Motion pro 2)

The Racing Simulator Motion Pro 2 [1] is a computer driven car simulator. The simulator is built with mechanical linear actuators, to simulate the acceleration and deceleration. The application is designed for a car simulator and the focus lies on mimicking car movements, i.e. pitch and roll motions. For display the simulator uses three 46” LCD screens.

3.1.2.2 VFlight

The VFlight2000 [2] is a flight simulator and it is designed for the flight gaming industry. It has a 185 degree roll motion and the display is a virtual reality headset or LCD projector.

3.1.2.3 The Viper

The Viper [3] is a flight simulator that has unlimited rotation in two axes, pitch and roll motion. The Viper was a school project for five college students in California, USA and is not a finished product on the market. It is made in a metal frame and it has a cockpit with three LCD displays.

3.1.2.4 Dream Flyer

The Dream Flyer [4] is flight simulator that works with a roll and pitch motion. It is focused on the gaming industry. The construction of the simulator is not based on engine or linear actuators but weight balance. The balance on the weight across the latitudinal axis of the chassis is what generates the motions when the user moves the joystick.

3.1.2.5 Red bird flight simulator

The Redbird FM [5] flying simulator is a full motion training device for real world flying. With features such as wrap-around visuals and fully enclosed cockpit. The cockpit is designed to be reconfigurable allowing the user to decide which airplane to simulate.

3.1.2.6 InMotion simulation

InMotion Simulation [6] is a large company in electric and hydraulic simulators for all type of applications such as military, human training, flight simulation and entertainment in the game industry. The construction is built with six mechanical linear actuators that move in six axes.
3.1.2.7 Summary

This summary shows the different simulators and their degree of freedom in each motion. It also lists the price for each one.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion Pro 2</td>
<td>✗</td>
<td>-</td>
<td>✗</td>
<td>-</td>
<td>✓</td>
<td></td>
<td>17 000</td>
</tr>
<tr>
<td>VFlight 2000</td>
<td>✓</td>
<td>185°</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td></td>
<td>10 000</td>
</tr>
<tr>
<td>The Viper</td>
<td>✓</td>
<td>360°</td>
<td>✓</td>
<td>360°</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dream Flyer</td>
<td>✓</td>
<td>±10°</td>
<td>✓</td>
<td>±10°</td>
<td></td>
<td></td>
<td>10 000</td>
</tr>
<tr>
<td>Redbird</td>
<td>✓</td>
<td>±20°</td>
<td>✓</td>
<td>±25°</td>
<td>✓</td>
<td>±30°</td>
<td>28k-65k</td>
</tr>
<tr>
<td>InMotion</td>
<td>✓</td>
<td>±35°</td>
<td>✓</td>
<td>±30°</td>
<td>✓</td>
<td>±45°</td>
<td></td>
</tr>
</tbody>
</table>

3.1.3 Conclusion

The reason for investigating other simulators is to ensure that the solution is unique and make sure that it does not already exists on the market. To be able to create a truly unique solution it must also be applicable to different uses, instead of gaming simulators or training platforms that is made for one specific game or application. The investigation has also made us draw conclusions on what type of design solutions that will work. Our initial idea about the overall design was affirmed when looking more closely on the The Viper for example. It had some basic technical solutions that worked and our beliefs that the project could accomplish the initial goals was enhanced and confirmed when seeing practical proven result. However the design will differ from The Viper regarding movement in one more axis and it will not be just for flight simulation.
3.2 Method

The method chapter will describe the different choices one must consider when building a full scale simulator. The different materials and technical solutions are suggested and only proven in theory. However, based on the investigations and the planning together with solid mechanical calculations, this will serve as a good foundation for a final product.

3.2.1 Construction material

The material for the construction must be light weight, strong and be able to sustain mechanical stress. The moment of inertia is dependent on the mass and size, greater torque affects the motor shaft.

3.2.1.1 Stainless Steel

Steel is an alloy combined with iron and several other elements, the most common element is chromium and carbon. The most commonly used stainless steel is ASS. This is because the excellent properties [9]. Unlike the other alloys the stainless steel is better for rougher environment since the material not readily corrodes. The density of the material is $7.9 \cdot 10^3 \text{kg/m}^3$ and the material has very high mechanical strength.

3.2.1.2 Aluminium

Aluminium [10][11] is among the most common elements. It is extracted from the ground and produced with bauxite. A chemical process is created when heating the material and this process is very energy consuming. The usage area of the material is wide; the building industry uses it because of good corrosion properties and long lifespan. The density of aluminium is $2.7 \cdot 10^3 \text{kg/m}^3$ and it is the third of steel, so the construction can improve and effective the whole process. Aluminium has advantages in systems where the weight is important and yet still manages high mechanical strength. Aluminium has yield stress between $70 - 700 \text{ MP}$, depending on the alloy permits and the how the process is performed.
3.2.2 Summary material

Each material has been given a number from 1 – 5 (higher is better) depending on how well it suits our needs concerning strength and weight.

<table>
<thead>
<tr>
<th>Category</th>
<th>Aluminum</th>
<th>Stainless steel</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Yield strength</strong></td>
<td>The material has a good yield strength related to the weight (4)</td>
<td>Stainless steel has very good yield strength (5)</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Aluminum is a very light weight material, $2.7 \times 10^3$ kg/m$^3$ (5)</td>
<td>The material density is quite high, $7.9 \times 10^3$ kg/m$^3$ (2)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

3.2.3 Construction

When making a full scale model you will need to construct this with help of 3D CAD programs. There are a lot of programs on the market and the most common is SolidWorks, Catia, Pro Engineer, Auto CAD etc. Halmstad University is using SolidWorks and Catia in their CAD courses as development environments, and therefore the choice fell on these two. The prototype Figure 1 was constructed in Catia, and the full scale model (shown on the front page) is designed in SolidWorks.

The first step in the project was to create a sketch from the main idea, and with brainstorming find good solutions for this application. The design idea for this construction is a gyroscope, to create a rotation of 360 degrees of freedom in three dimensions. The final product will be a large construction and therefore the weight and size must be taken into consideration. The size is depending on the human and the slip rings [3.3.4], that determines the distance between the rings. So the next step is to simplify the construction and reduce the weight. The weight of the product is related to the motor size and the gearbox.

3.2.4 Ball bearing

An important part in the project is the ball bearings [18], to be able to rotate the rings. It is placed on the bottom plate and creates a rotation in the whole construction. The slew ring ball bearing is divided in two separate solid parts that slides with bearings between them too reduce friction, see Figure 9.

To be able to connect the first and the second ring a flat ball bearing is needed. The ball bearing creates a rotating connection between with two separate parts, see Figure 9. The connection between the second and the last ring is
made with a standing ball bearing, see Figure 10, which takes up the forces and allows the ring to rotate unlimited.

![Figure 10 - Standing ball bearing.](image1)

![Figure 11 - Flat ball bearing.](image2)

### 3.2.5 Mechanical calculations

The simulations have been made with a conclusion that the construction is symmetric and the human is sitting in the middle. To verify the construction before manufacturing, calculations made with Finite Element Method (FEM) have been done. FEM is a method dividing a very complicated problem into small elements that can be solved in relation to each other with help of partial differential equations. The method is used to visualize how the material bends, twists, stretches and compresses. In FEM one can also see the distributions of stress and displacement in the model. Yield stress indicates the highest allowed stress that the material can sustain without permanent deformation. The strain is related to the yield stress and when it is lower the steel deformed elastic.

### 3.3 Hardware

#### 3.3.1 Motor

One of the most important pieces of hardware components in this project is the motors that rotate the rings. When choosing motors you must consider a couple of things, you must think of the nature of motion simulators. You must think about how the simulator will move in sync with a game, often the movements in a flying game will be quite slow, but when you think of movements in a car simulator the motions that is being mimicked will be short, fast and quick. So when rotating the three rings that weigh 90, 200 and 300 kg, you must consider the relatively large moment of inertia when accelerating the rings in a rotating motion. Therefore choosing a motor with high torque on low speeds is one key factor.
Another key factor is that the motors will have to be controlled in a quick and responsive way. Signals generated by the game from the users input must be read out and transformed into input signals to the motors. Therefore, motors that can be controlled from a digital control system is needed.

The motors should also be as small and lightweight as possible. So that the complete simulator does not weigh so much that it affects the balance and structural integrity in a negative way when moving. Therefore choosing the right type of motors is crucial to the outcome. In this chapter we will go through different motor types that could fit the needs of the final product.

3.3.2 Asynchronous AC-motor

Asynchronous AC motor [7] is an electric motor with a rotor and the ends contain an electrical conductor in aluminium or copper Figure 12. The rotor is located in the rotating flow, where the circuit will include in parts in the rotor. Because the conductor is short circuit the power will lead in the closed circuit, and a force affects the conductor so it cause the directed to counteract with the own formation. The motor is determined by the frequency of the supply current, so the speed is both constant and variable depending on the application.

\[ n_s = \frac{60 \times f}{p} \]

\( n_s \) = revolution per minutes [RPM]
\( f = \) frequency [Hz]
\( p = \) pole per phase

The synchronous speed \( n_s \) is determined by the frequency and the amount of poles. The factor (60) is a time scale factor, which converts revolution per second to revolution per minute.
3.3.3 DC-motors

The DC motor [7] is a mechanically commuted electric motor and supplies with direct current. The commutator consists of two isolated copper segments. Through the commutator goes the electric current to the anchor line that creates a magnetic force, which turns the DC motor.

3.3.1 Servo motors

The servomotor [7] is basically the same as the DC, AC- motors but with a servo configuration. The motors have a very precise position feedback. The main function of the servo motors is the supplying on the winding contact is a fixed voltage and the other is a proportional voltage based on a control deviation.

3.3.2 Stepper motors

The stepper motor [8] is an electric motor, which converts electronic pulses to mechanical rotation. The shaft on the motor rotates in discrete steps when an electric pulse is sent to the motor, showed in Figure 13, where one whole step equals to one »tick« of one tooth. Therefore the resolution is directly related to the number of »teeth« on a stepper motor. And because a stepper motors moves in steps you always now the direction and speed. The sequence of the input is directly related to the direction on the motor shaft rotation. The speed on the shaft is directly related to the frequency of incoming pulses and the length of the rotation is related to the amount of pulses.

![Figure 13 - Inside of a stepper motor showing the »teeth«.](image-url)
3.3.1 Summary Motors

Here is a list of the different motor types described with information on the most important features. A rating of 1 – 5 is given to each one according to the needs stated in [3.3.1].

**Torque:** Low (<5 Nm) Medium (5 – 30 Nm) High (>30)
**Size and weight:** Small (<3 Kg) Medium (3 - 7 Kg) Large (>7 Kg)

<table>
<thead>
<tr>
<th>Category</th>
<th>Asynchronous AC-motors</th>
<th>DC-motors</th>
<th>Servo-motors</th>
<th>Stepper-motors</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated voltage</strong></td>
<td>Up to 400 V AC (5)</td>
<td>Up to 24 V DC (1)</td>
<td>Up to 400 V AC or 24 V DC (5)</td>
<td>Up to 120 V DC (1)</td>
</tr>
<tr>
<td><strong>Precision</strong></td>
<td>Can have servo characteristics and the resolution is encoder dependent. (5)</td>
<td>Can have servo characteristics and the resolution is encoder dependent. (5)</td>
<td>Depends on the encoder. Position feedback. (5)</td>
<td>The resolution is dependent on the number of steps the motor has. Can be controlled in micro steps. (2)</td>
</tr>
<tr>
<td><strong>Torque</strong></td>
<td>Low to High. (5)</td>
<td>Low to Medium. (3)</td>
<td>Low to High. (5)</td>
<td>Low to Medium. (3)</td>
</tr>
<tr>
<td><strong>Controlling</strong></td>
<td>PC and Motor drives digitally. (5)</td>
<td>PC and Motor drives digitally. (5)</td>
<td>PC and Motor drives digitally. (5)</td>
<td>PC and Motor drives digitally. (5)</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>Small to Large. (3)</td>
<td>Small to Medium. (4)</td>
<td>Small to Large. (3)</td>
<td>Small to Medium. (4)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>23</td>
<td>18</td>
<td>23</td>
<td>15</td>
</tr>
<tr>
<td><strong>Comment</strong></td>
<td>Effective, long lasting. Expensive control units when used as a servo.</td>
<td>Can only function with DC-voltage. Can be controlled like a servo with position feedback.</td>
<td>AC, DC, or Brushless DC. High torque on low rpm. Slim all-in-one solution.</td>
<td>Limited resolution, not suitable. Optional with position feedback. Cheap.</td>
</tr>
</tbody>
</table>

Looking at the different characteristics and rating given; the most suitable type would be an AC motor or a servo motor. And the fact is that the best motor for using in the project is an AC servo motor with 400 V voltage rating. However, an AC motor with a servo encoder is not exactly the same as an AC servo with built in encoder. The pure servo will also be much more compact in design and cheaper. For this type of automation systems with positioning control a pure servo system is the best choice.
3.3.2 Gearbox

Because of the weight of the prototype the size of the motors get big, and in order to reduce the size of the motors a gearbox will be implemented. When using a gearing the outcome is a higher momentum with reduced speed. The speed is proportional to the gearing and in our case it does not matter since the maximum speed is 30 RPM. For this prototype it is going to be three different size of gearing depending on which ring to rotate. Gearbox, see Table 4, is used to establish a higher revolution of gearing, and gearbox is mounted on top of the motor.

Figure 14 - Planetary gearbox.

Table 4 - Summary gearbox

<table>
<thead>
<tr>
<th>Category</th>
<th>Planetary gear</th>
<th>Worm gear</th>
<th>Helical gear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>The planetary gear is a compact and robust gearbox. (5)</td>
<td>The worm gear is a large gearbox. (3)</td>
<td>The helical gearing is large and creates a 90 degrees shifting, not for our purpose. (1)</td>
</tr>
<tr>
<td>Momentum</td>
<td>The momentum is large and it is sustainable. (5)</td>
<td>The worm gear is strong and manages high momentum. (4)</td>
<td>The momentum is small related to the size. (2)</td>
</tr>
<tr>
<td>Price</td>
<td>Because of the construction the price is high. (3)</td>
<td>Reasonable price (4), related to more expansive motors.</td>
<td>Reasonable price range. (4)</td>
</tr>
<tr>
<td>Total</td>
<td>(13)</td>
<td>(11)</td>
<td>(7)</td>
</tr>
</tbody>
</table>

There are three types of gearing, helical, worm and planetary gear. For our purpose, see Table 4, the planetary gearbox is the best choice, because of the robust design and the high momentum.
3.3.3 Control system and Interfacing

This chapter will describe how a control system is built up. In different models it will be described, and a suggested solution will be presented that fit with one of the control models, and the motors suggested in the motor topic [3.3.1].

In general this is how the different blocks will fit together, see Figure 15. The simulator consists of software that generates all the signals from the game and user. The signals is interpreted and then transferred to the hardware block which consists of motor drives and other electronics that will then tell the motors to turn accordingly. That is the general workflow of the simulator.

![General workflow of a gaming simulator.](image)

Figure 15 - General workflow of a gaming simulator.

This model describes a system where everything goes through a small industrial PC that is placed inside the simulator, close to the user. All the software needed for the game, motor drives and serial input is in the PC. This would require a high speed industrial PC with HDMI output and USB interface. The motor drives should not be subjected to fast rotating and vibrating movement and therefore stands outside the simulator.

![Flow chart control system.](image)

Figure 16 – Flow chart control system.
The component in the control system was chosen for its functions with servo motors mainly because servos offer good positioning abilities etc. as stated in the motor topic [3.3.1]. The motor drive will communicate through a fieldbus such as CANopen or via serial protocol like the RS232 or RS485.

3.3.4 Slip rings

One of the key components in this project is the transmission of power and small signals to the motors inside the rings. The whole concept of the final product is the unlimited rotation in all axes and therefore we need slip rings to transfer power and signals to the motors and other electronic devices inside the simulator.

Figure 17 - Slip ring

This slip ring will sit between the innermost ring and the second ring, and it will need at least four channels for power transmission and eight channels for small signals, this will allow for transmission of power and signals to the innermost motor. The wiring will then go out to the second slip ring that sits between the first and second ring. This slip ring will be of the same type as the first one, and lead the wiring out to the first ring. Both the wiring from the innermost motor and second motor is now joined together into one more slip ring in the bottom, which will have eight channels for power transmission and 16 channels for small signals. The bottom motor will be still and needs no slip ring to power it.
3.3.5 Virtual reality headset

Instead of having large displays to create the illusion of being inside the game, you will need some kind of virtual reality headset. The advantage of having a virtual headset instead of large displays is that the user eyes cannot focus on anything outside the simulator, thus creating the feeling of being »inside« the game. There are certain disadvantages with being too much »inside« the game. People can experience motion sickness, see article [26] by Akay, M. and Marsh, A. »Virtual Reality and the Vestibular System: A Brief Review« in the IEEE database that covers this topic. The project owner chose the Oculus VR [15] headset for display.

Figure 18 - Oculus VR Headset
4 Results

The project has resulted in a small prototype which shows the concept of the targeted design and partially shows proof of functionality. Furthermore, thorough calculations and planning of a full scale model has been conducted. In this chapter the results of the thesis project will be presented.

The problem formulation chapter addressed a number of issues that this project set out to solve.

4.1 Prototype

The first task in the problem formulation was to build a prototype. In chapter [2] this is gone through in detail together with a conclusion. The final result was a prototype with movement in two axes that is controlled with two analog joysticks from the user. This meets the initial demands for this project where it was stated that a small scale prototype should be designed and built with movement in one or more axis.

4.2 Unique solution

The project should also prove that the solution is unique. Other gaming and motion based platforms was investigated and compared to the project goals. And based on these investigations, presented in the state of the art chapter [3.1.1], the final result proved that there is no similar solution that meets the project goals i.e. the targeted design concept is considered unique.

<table>
<thead>
<tr>
<th>Simulator</th>
<th>Car</th>
<th>Aircraft</th>
<th>Helicopter</th>
<th>Motorcycle</th>
<th>360° yaw</th>
<th>360° pitch</th>
<th>360° roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motion Pro 2</td>
<td>✔</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
</tr>
<tr>
<td>VFlight 2000</td>
<td>✖️</td>
<td>✔️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
</tr>
<tr>
<td>The Viper</td>
<td>✖️</td>
<td>✔️</td>
<td>✔️</td>
<td>✖️</td>
<td>✔️</td>
<td>✔️</td>
<td>✖️</td>
</tr>
<tr>
<td>Dream Flyer</td>
<td>✖️</td>
<td>✔️</td>
<td>✔️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
</tr>
<tr>
<td>Redbird</td>
<td>✖️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
</tr>
<tr>
<td>InMotion</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✖️</td>
<td>✖️</td>
<td>✖️</td>
</tr>
<tr>
<td><strong>The Human Gyroscope</strong></td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
</tbody>
</table>
4.3 CAD Design

A large model was made in Solid Works to show the gyro design of the simulator and how the motors would be arranged together with the seat and joystick. The complete design is shown in the front page. The construction, see Figure 19, is basically made out of three rings where each rings represents an axis. The base plate (4) in the bottom serves as the foundation of the structure. A turn ring ball bearing (7) in the bottom of the first ring (3) will carry out the yaw motion when turning the simulator, a motor in the bottom will rotate the gear ball bearing. On top of the gear ball bearing is a half ring (3) made out of 100 mm tubing with two ball bearings on each side. This will support the second ring (2) and allow it to spin continuously. In one end of the half ring there is a mount for the motor. This motor will turn the second ring (2) and this will allow for the pitch motion to be carried out.

Inside the second ring is the third ring (1) that is going to do the roll motion. This ring is controlled by a third motor that sits inside the ring itself behind the user seat. To power the inner most motor through all the other rings there is a slip ring mounted on each ring by the motor. These slip rings will allow the rings to turn but still transfer power from one ring to another.

Figure 19 – Construction design full scale model.
4.4 Unlimited rotation

In Figure 19 there can be seen an implementation of three axis movement. The slew ring ball bearing (see Figure 9) and (7) in the base of the structure is the axis controlling the yaw movement. The ball bearing (6) controls pitch movements and the ball bearing (5) controls the roll movement of the simulator. The problem formulation regarding movement in 3 axes is considered solved.

4.5 FEM analysis

The calculation shows that the construction can sustain a weight of a human (100 kilo). The axes are most exposed in the construction. As showing in the FEM analysis (Appendix 1) there will not be a problem and it can manage the load. The displacement in the construction is considerably small and it will not affect the structure.

4.6 Motors and gearbox

The project involved choosing the right type of motors and gearboxes concerning moment of inertia. As stated in the motor topic [3.3.1] the choice fell on servo motors for driving the simulator. The suggested motor for the final product is listed in (Appendix 4). This shows that a solution to the motor issue in the problem formulation has been given.

4.7 Control system and interfacing

The thesis has described a model in how to control the simulator. It has drawn up a general work flow in how the communication between the user and simulator would work. It has also suggested in detail how to accomplish a functioning system that can handle user input/output and making it move. As stated in the problem formulation the investigation has shown how to build up a control system in general terms.

Suggested hardware is described in (Appendix 5).

4.8 Slip rings

The slip ring that is suggested to be used is from Penlink, a SRH60135 [14]. This slip ring has outputs/input for small signals and for power transmission up to 10 A per channel. This is fabricated in different setups and types with different through bore holes, with different amount of small signal channels and power channels.

The project has shown that there is a solution to power the motors and other electronic devices inside the simulator. In chapter [3.3.4] this is gone through and a suggested slip ring is presented. The slip ring topic in the problem formulation is considered solved.
5 Discussion

As stated in the beginning of the report this would serve as a first step in creating a motor driven simulator with a gyroscope design. The first step however proved to be very long and deep, so we plunged in. The initial learning curve had a very steep derivative and it continued to be steep throughout the whole project.

The project was divided into two parts; the first part was pretty straightforward; build a functioning prototype in one or more axes. The second part was more difficult; it involved doing a lot of research in this field, which covered basically all disciplines in mechatronic and electrical engineering. The difficult thing was not to dig too deep in every part of the simulator, because then precious time would be spent on things not relevant in this first step. The different aspects of this project has changed through the whole process concerning what to physically build and what seemed important to research and dig deeper into.

When looking in the rear view mirror at this project there are things that could have been done differently. The prototype was developed very rapidly, that process should have been investigated more in the beginning and then the prototype would have been implemented with movement in all three axes instead of just two. It would on the other hand been much more costly and we would have ended up with a very large prototype, but it would have shown not only proof of concept but also proof of functionality. However, the prototype made was a good eye opener and exposed many though questions to answer.

The motor topic was one of larger topics and has taken very much time from the project. That is due to how important the motors were to this project. The choosing of the motor is closely related to the calculations regarding the moment of inertia. The mechanical calculations were also a big part of the project and the choosing of motor was dependant on those calculations. The final result of that research, we are quite certain, will be implemented into the final product.

Something that is left for improvement and should be dug deeper into is the interfacing between game and hardware and building a full scale simulator in one or more axis. That is two topics we think could result into two whole new thesis projects.

This thesis project will now serve as a foundation for further development and in the end realizing a gaming simulator with unlimited movement in all three axes. If and when that is accomplished the final outcome will be a truly unique solution that is going to fill an empty shelf space in the international gaming industry market. The work that we have done has been truly inspiring when you see an idea actually come to life in the early stages. We hope to see the fruits of our labour in a near future.
6 Conclusion

In this thesis project a small prototype for showing a proof of concept has been developed. And suggested solutions in how to realize a live size simulator has been investigated. The project has given answers to the problems set up in the problem formulation, and the project owner is pleased with the results.
7 References


[26] http://ieeexplore.ieee.org/xpl/articleDetails.jsp?tp=&arnumber=5236972&contentType=Books+%26+eBooks&searchField%3DSearch+All%26queryText%3DVirtual+Reality+and+the+Vestibular+System%3A+A+Brief+Review
Appendix

Appendix 1

The Human Gyroscope

FEM-analysis

Alexander Kjellin & Mattias Runevad

Figure 20 - FEM analysis in SolidWorks.
Introduction

This thesis project is the first step in creating a motor driven human gyroscope. The idea of this motor driven gyroscope is to be implemented as part of virtual reality systems, computer games, flight simulators, training platforms, etc. It should sustain a weight of one normal person, not over 150 kg. The construction should manage unlimited rotations in three dimensions with fast changes in the acceleration and deceleration. In the FEM analysis it will measure how the material is affected with different forces on the body. The cover of the FEM analysis, seen in Figure 20, shows yield stress on the construction.

Specification

The simulation will be static (stationary)
Things to take in consideration:

- Steady construction
- Dynamics (Simulate the construction in motion, max speed 30 rpm)
- Moment of inertia for the rings, to be able to choose the motors

Assumption

The calculation is made of the assumption that the rings are calibrated and the human is sitting in middle, so there is symmetry in the construction.
# Model information

**Table 6 - CAD Model data.**

<table>
<thead>
<tr>
<th>Solid Bodies</th>
<th>Document Name and Reference</th>
<th>Treated As</th>
<th>Volumetric Properties</th>
<th>Node</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ring3</strong></td>
<td></td>
<td>Solid Body</td>
<td>Mass: 95.1 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Volume: 0.035 m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Density: 2700 kg/m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weight: 932 N</td>
<td></td>
</tr>
<tr>
<td><strong>Ring2</strong></td>
<td></td>
<td>Solid Body</td>
<td>Mass: 60.0 kg</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Volume: 0.022 m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Density: 2700 kg/m³</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weight: 589 N</td>
<td></td>
</tr>
</tbody>
</table>

Total Nodes: 44349  
Total Elements: 22498
<table>
<thead>
<tr>
<th>Bracket1</th>
<th>Mass: 1.9 kg</th>
<th>Volume: 0.0007 m³</th>
<th>Density: 2700 kg/m³</th>
<th>Weight: 18.4 N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bracket2</td>
<td>Mass: 1.9 kg</td>
<td>Volume: 0.0007 m³</td>
<td>Density: 2700 kg/m³</td>
<td>Weight: 18.4 N</td>
</tr>
<tr>
<td>Ring1</td>
<td>Mass: 79.5 kg</td>
<td>Volume: 0.029 m³</td>
<td>Density: 2700 kg/m³</td>
<td>Weight: 779.3 N</td>
</tr>
</tbody>
</table>
The construction designed with aluminum because the light weight and the high mechanical strength. Stress is a measure of internal forces that deformation a body. So the external traction \( \sigma \) represents the force per unit area given on the body surface. The material that has been chosen for the product has the yield strength of \( 2,76 \cdot 10^7 \) N/m\(^2\). The analysis indicates the maximum stress \( 7,1446 \cdot 10^4 \) N/m\(^2\), as seen in the picture, which are in reasonable limited for contain the construction without deformation.

![Figure 21 - Maximum stress in the construction.](image)

Safety factor is a designation between critical to allowed stress in the construction. The factor is depending on the construction and use of application. The calculation with a safety factor is to prevent mechanical failure and create a safe environment for the user. With a safety factor of 2 the yield strength is \( 13,8 \cdot 10^7 \) N/m\(^2\), still reasonable and there is no risk for deformation.

\[
\sigma_{to} = \frac{R_s}{n_s} \rightarrow \frac{2,76 \cdot 10^7}{2} = 3,8 \cdot 10^8 \text{ N/m}^2 [\text{MPa}]
\]

\( \sigma_{to} = \text{allowed stress} \)
\( R_s = \text{yield stress} \)
\( n_s = \text{safety factor} \)
Displacement is a definition of distance a body moved in a direction. The analysis shows the displacement in the material and where it occurs, the maximal displacement is 0.101 mm which will not be a problem in this context to the construction. Figure 21 shows the yield stress analysis in SolidWorks.
Moment of Inertia

The acceleration torque is the momentum required torque to accelerate a load. How large the torque is with acceleration depends on the moment of inertia. The moment of inertia is a measure of the ability on the body to resist change in the rotation speed, it match the mass of the transfer movement. One of the requirements is that it should manage a human and to get a value as close as possible to the reality the simulation is made with a full scale human, as seen in Figure 22. The moment of inertia for the rings with a human is $33 \text{[kgm}^2\text{]}, 80\text{[kg/m}^2\text{]}$ and $225\text{[kgm}^2\text{]}$ for the hole construction.

\[
M_a = J \cdot a
\]

$M_a =$ Torque acceleration $[Nm]$

$J =$ Moment of inertia $[Kgm^2]$

$a =$ acceleration $[rad/s^2]$

The equation describes the connection between momentum of inertia and the torque.

**Ring1 and human [100 kg] (roll motion):**

$Mass = 192 \text{ kg}$

$J = 33 \text{ kgm}^2$

$M_{a1} = J \cdot a = 33 \cdot 5 = 165 \text{ Nm}$

**Ring2 and ring1 (pitch motion):**

$Mass = 256 \text{ kg}$

$J_2 = 80 \text{ kgm}^2$

$M_{a2} = J_2 \cdot a = 80 \cdot 5 = 400 \text{ Nm}$

**Ring3, ring2 and ring1 (yaw motion):**

$Mass = 360 \text{ kg}$

$J_3 = 270 \text{ kgm}^2$

$M_{a3} = J_3 \cdot a = 270 \cdot 5 = 1350 \text{ Nm}$
Appendix 2 – Prototype PCB schematic
Appendix 3 – Prototype PCB layout
Appendix 4 – For the full scale model, motor, motor drives and gearing

Table 7 - Full scale model suggested hardware.

<table>
<thead>
<tr>
<th></th>
<th>Ring 1</th>
<th>Ring 2</th>
<th>Ring 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>192</td>
<td>260</td>
<td>360</td>
</tr>
<tr>
<td>Moment of inertia (kgm^2)</td>
<td>33</td>
<td>78</td>
<td>270</td>
</tr>
<tr>
<td>Servo motor</td>
<td>DELTA ECMA-K11315, 1,5 kW, 2000/3000 rpm, label torque 7,16 Nm</td>
<td>DELTA ECMA-K11320, 2 kW, 2000/3000 rpm, label torque 9,55 Nm</td>
<td>DELTA ECMA-L11845, 4,5 kW, 1500/3000 rpm, label torque 28,65 Nm</td>
</tr>
<tr>
<td>Servo Amplifier</td>
<td>DELTA ASDA-A2-1543M, 400 V</td>
<td>DELTA ASDA-A2-2043M, 400 V</td>
<td>DELTA ASDA-A2-4543M, 400 V</td>
</tr>
<tr>
<td>Planetary gear</td>
<td>Wittenstein SP100, gearing ratio 70:1</td>
<td>Wittenstein SP180, gearing ratio 70:1</td>
<td>Wittenstein SP210, gearing ratio 70:1</td>
</tr>
<tr>
<td>Comment</td>
<td>All the listed items can be supplied by Bevi AB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix 5

This appendix gives some detailed information regarding the control system and interfacing. And it specifies suggested hardware that will work together with the suggested servo systems for the full scale model in Appendix 4.

An industrial PC, a MIO-5290 [12] with an Intel Core i7 processor with support for HDMI will manage outputs to the Oculus VR, and input from user via USB. The PC will handle output signals generated by the game and carry them out to the servos.

The heart of the control system (MIO-5290), will also manage the interfacing through the industrial PC. It will send commands over the CANopen [13] bus to the servo amplifier listed in the motor chapter [3.3.1], the DELTA ASDA-A2-XX43M. The motor driver will then drive the servo motors.

The programming in this project will need to implement the CANopen protocol, to be able to send commands to the motor driver (ASDA-A2-M). Busmaster [17] is an open source PC software for designing, monitoring, analysing, and simulating CAN networks. This could serve as a hardware interface between the game and motor driver, as well as handling the input from the user and sending commands to the ASDA-A2-M over the CANopen bus. Programming Busmaster is preferable made in C code.