DEVELOPMENT OF A DOUBLE FLYWHEEL WITH PENDULUM-BASED SPHERICAL ROBOT

by

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AUTHOR'S DECLARATION

I, Janith Sahanaka Jinadasa, declare that the research work carried out for this thesis was in accordance with the regulations of the Asian Institute of Technology. The work presented in it are my own and has been generated by me as the result of my own original research, and if external sources were used, such sources have been cited. It is original and has not been submitted to any other institution to obtain another degree or qualification. This is a true copy of the thesis, including final revisions.

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Signature:

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ABSTRACT

Robots have a very big role in human life such as in industry, medicine, households. They come in all sizes and shaped depending on the type of work they intend to do. Some are locomotive while some are fixed to a particular station. When it comes to locomotive robots there are several types of robots used. Such as robots on wheels, legs, belts. Depending on the surface the robot moves in its design would vary.

This study focuses on spherical robots to be used on rough terrains. The spherical robot is a novel mechanism design to move the robot in multi-conditioned surfaces. Unlike other kind of legged or wheeled robots, the main feature that make a spherical different from others is the ground contact point which is very small.

Traditionally spherical robots use a pendulum driven mechanism for locomotion, which is actuated by DC motors. But it has torque limitations. Hence, this study is related to increase the overall torque in the system using control moment gyroscopes. To reach the desired position, the GPS data is utilized as robot localization and robot's orientation is estimated by 9-degrees of freedom IMU while user can supply the target GPS location and robot will reach to target position.

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LIST OF ABBREVIATIONS

CMG = Control Moment Gyroscope
I = Inertia
PID = Proportional Integral Derivative

CHAPTER 1

INTRODUCTION

1.1 Background

Development of robots took a major turn with the development of science and technology in the past few years. Depending on the objectives and tasks required robots now come in various types and designs. It can be Locomotive or non-locomotive. This research focuses on locomotive robots.

Locomotive robots are commonly made up of wheels, belts, tracks. Some advanced robots use legs for advanced movements. Each of those types consist of unique advantages and disadvantages. When it comes to moving on rough terrains most of the common methods tends to get stuck as they have a small point of contact with the surface. Hence why spherical robots became the popular choice to move in some rough surfaces.

Spherical robots have been an important area of research in the past few years due to their robustness and agility compared to other legged or wheeled robots. Thus, it makes a good option when crossing various terrains since a sphere offers rigidity at all points on a surface. The enclosed surface of the robot also provides security to the internal mechanics and electronics. Furthermore, by sealing the outer shell a barrier can be formed to protect the robot by environmental conditions. It also allows the robot to be partially or fully submerged in water.

By nature, a spherical robot is non-invertible reducing the risk of becoming disabled. A spherical robot gives the ability to change direction at any point of its motion. Without reorientation it can recover from collisions discretely. Wheels, tracks or legs has the potential to be damaged affecting the robot’s locomotion. The larger diameter also allows the robot to move smoothly over certain terrains than small wheels.

By these advantages we can identify the various applications where Spherical Robot can be used. Surveillance, reconnaissance, search, and rescue are a few areas this robot will be useful in. Thus, encountering all sorts of terrain is something the spherical robots should be ready for.

1.2 Problem Statement

Center of mass movement or pendulum driven spherical robots are limited by its maximum drive torque. Its due to the fact that the center of mass of the system cannot be moved out of the walls of the sphere. Thus, the robots find it hard to overcome small inclinations and obstacles. This has taken a toll on the applications of spherical robots for rough terrains.

1.3 Objectives

To design and implement a spherical robot with enhanced torque capabilities compared to than that of a pendulum driven spherical robot. The robot should consist of an additional drive system apart from the pendulum drive.

1.4 Scope

The research will be done under the following scopes

- The robot will move autonomously to a given position.
- Should be able to move in rough terrains and inclined planes
- Manual control of the robot if required
- The robot should be portable and not heavy

1.5 Limitations

The research will have the following limitations due to the limited budget and capabilities of the required materials

- The extra torque is available only for a short time period
- Navigation capability is only restricted to outdoors
- Operating time of the robot is limited to its battery capacity

CHAPTER 2
LITERATURE REVIEW

Self-driven spheres have been developed for decades. Thus, in this chapter previous mechanisms and their mathematical models will be explained roughly. Most spheres made so far have a combination of sensors, actuators, and a control mechanism. What sets them apart is each having a unique driving mechanism. Some of the mechanisms discussed in this will be listed as follows:

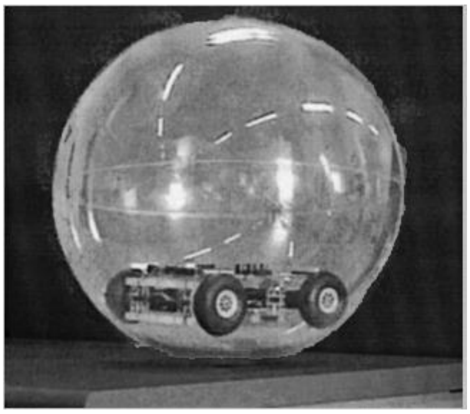
- Hamster Ball design
- Pendulum driven robot
- Multiple-Mass-Shifting robot

2.1 Hamster Ball Design

It is one of the earliest designs implemented. The working principal is like that of a hamster put inside of a toy ball. Normally a four-wheeled robot is placed inside the ball which is controlled via a remote control. This was implemented by J Alves and J Dias from Universidad de Coimbra, Portugal (2003). The weight of the toy car inside provides enough force to move the outer body of the spherical robot. A single wheel robot can also be used inside but a four-wheeled differential-driven provides more stability and smoother turnings. This is relatively easy to design, implement and control.

Figure 2.1

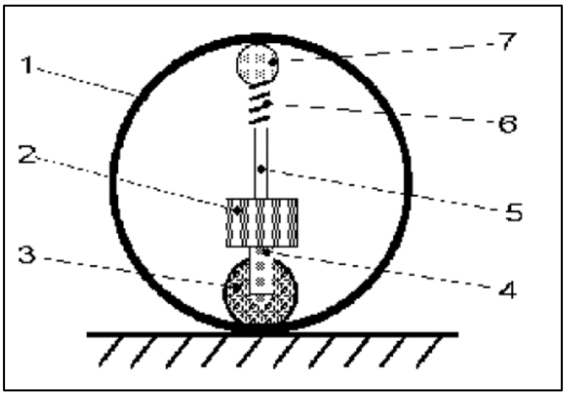
Hamster Ball Design (Alves & Dias, 2003)



There are quite a few drawbacks to this design such as slipping of the internal wheels can occur if the sphere is in a rough terrain. Apart from energy being lost, lack of friction will cause complications in the controlling of this sphere. In cases when the internal robot gets airborne due to sudden vibrations there will be a loss of traction and the ball will be uncontrollable. The internal surface of the hamster ball is very crucial to avoid slip. AIT's first spherical robot made by P. Htoo (2015) followed the same principal but with a three-legged omini-directional robot inside the sphere.

Figure 2.2

One Wheel-Based Robot

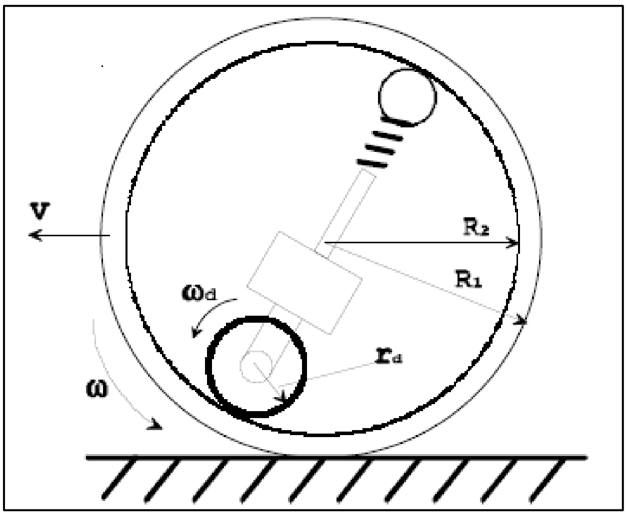


1. Structure
2. Control box
3. Driving wheel
4. Steering axis
5. Supporting axis
6. Spring
7. Balance wheel

The prior mentioned drawback of slipping can be avoided by using a spring-loaded system as shown above. Implemented by Aarne Halme, Torsten Schönberg and Yan Wang (2002).

Figure 2.3

Wheel-Based Design



R_1 is the external radius
r_d is the radius of the driving wheel.
v is the forward speed
ω is the angle speed of the ball.
ω_d is the angle speed of the driving wheel

The rolling speed of the sphere is given by,

$$\omega = \frac{d\phi}{dt}$$

Where ϕ is the rolling angle of the sphere around the center.

2.2 Pendulum Driven Robots

Pendulum driven spherical balls takes a prominent place in the industry. It is very popular and used heavily in various tasks. It is easy to implement, low power consuming and allows the shell to be sealed which places this design on top of other spherical robots.

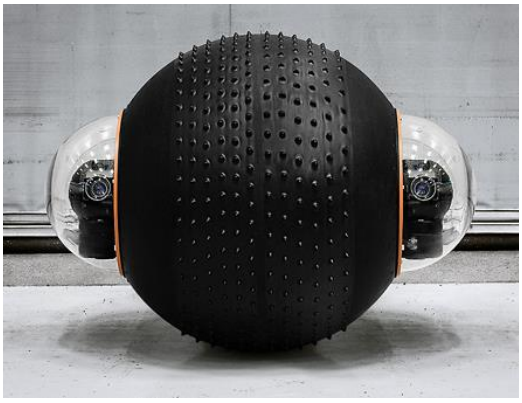
Over the past years' pendulum driven robots have advanced and become popular. Many researches can be found on this particular kind. Pendulum driven robots require less actuation systems thus weight can be reduced as well. Robots of this kind has become popular recently from fictional movies hence, pendulum driven spherical toys could be found as well.

2.2.1 Rotundus Groundbot

The robot, widely known as ‘Guardbot’ developed by Rotundus is an amphibious robot which is made to tackle all sorts of terrain such as snow, water, sand even. It used in various tasks such as surveillance, security, search and rescue and farming. The sheer size of this robot gives an advantage as it rolls over the terrain easily. The body which has a diameter of sixty centimeters does not easily get stuck on rough surfaces. The main intention of ‘guardbot’ was to explore other planets thus making it a very reliable spherical robot.

Figure 2.4

GuardBot



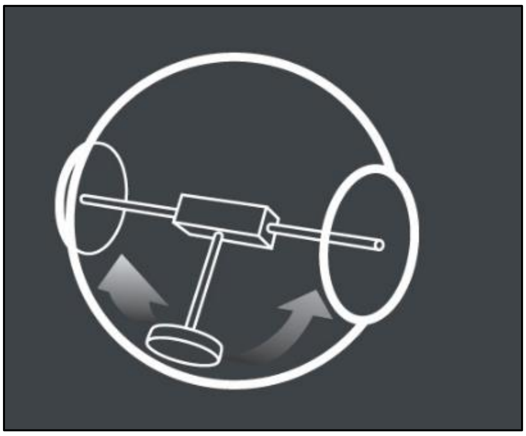
The main difference in this type from other spherical designs is on its turning behavior. A pendulum driven robot cannot do immediate turning but take curves instead which should be greater than its radius. Which makes it non-ideal for using in tight spaces.

2.2.2 Pendulum Mechanism

The internal forces are solely created by the bob as shown in the picture below. As the weight of the bob increases, higher the torque it can produce. By moving the direction of the bob in any angle the robot can be moved accordingly. This makes it very easy to control and maneuverer the robot. The control of this ball is straightforward. When implementing this robot making it dimensionally balanced can will be very helpful. In practice a well-designed pendulum driven ball would be able to travel an inclination of 30 degrees (see Figure 2.5).

Figure 2.5

Pendulum Mechanism



2.2.3 Prior Art in AIT

One such robot was developed by Satawat Prakancharoen from Asian Institute of Technology, Thailand (2017). This robot comprises of three motors. Two of them were utilized to drive the heavy pendulum forward and back while the third altered its heading. The final porotype is shown below.

Figure 2.6

A Pendulum Robot in AIT (Prakancharoen, 2017)

This ball consists of both manual and autonomous control. Manual control is done via a joystick while in autonomous control target positions are given in the form of Longitude and Latitude. System monitoring and targeting is given from a personal computer via a Xbee unit. This robot performed quite well in terms of reaching the target positions. The tests on this robot were done on flat surfaces thus its driving performances are not verified in cases of rough terrain and sloped surfaces.

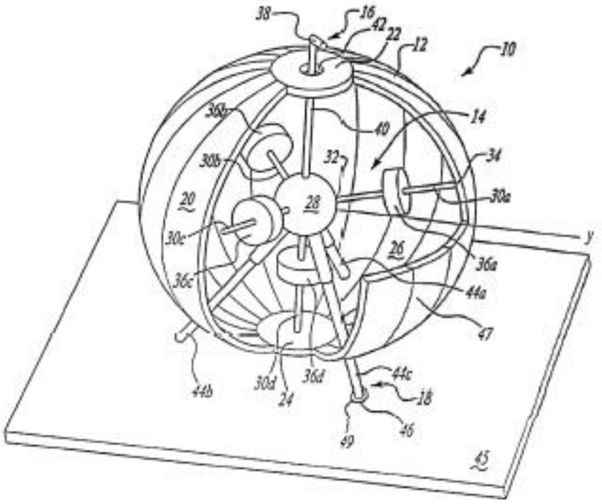
2.3 Multiple-Mass-Shifting Robot

This is another effective method used to drive a spherical robot. Inside the sphere consist of three to four masses that can be moved independently in a linear motion. By controlling the motion of the masses, the sphere can be controlled. Multiple mass shifting is of two types, radial design, and perpendicular design with rods not-intersecting each other.

The masses are moved radially as shown in the diagram below. Spokes are connected to the center and the masses are moved linearly along the rods. This is also good system mainly it being omnidirectional. This sphere can start moving in any direction from a zero speed. And the movement of the sphere are very precise too.

Figure 2.7

Internal Structure of a Mass Relocating Robot



Disadvantages of this design includes complexity of the mechanical design. The mechanical design should be made in a precise manner and smoothly. When moving fast the masses inside needs to reciprocate along the rods very fast as well which includes advanced controlling. Moving the masses in a high speed will make the sphere consume lot of power thus making it efficient. Sudden stresses of the heavy masses will also cause wear and tear on the actuators.

2.4 Summary of Traditional Driving Mechanisms

The hamster ball, the pendulum drive, mass shifting concepts uses different concept to drive a spherical robot. But they heavily rely on gravity to roll. All these mechanisms shift their center of gravity to make the sphere move in the desired direction. When the center of mass is displaced the force due to gravity creates a moment on the sphere which makes the sphere roll.

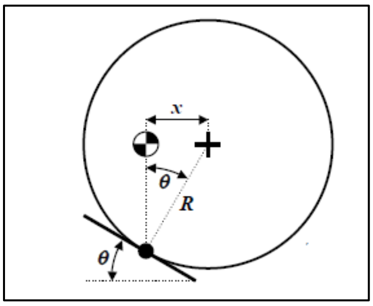
The drawback in these designs is their torque limitation. There is a certain limit as to how far the center of mass can be displaced within the system. The practical limit of displacement of the center of mass limits steep inclines and small heights. A study done by G. Schroll gives the maximum incline by,

$$\theta = \sin^{-1}\frac{x}{R}$$

where θ is the inclination angle, R is the radius of the sphere and x is the maximum displacement of the center of mass of the sphere. It can be seen clearly in the figure below.

Figure 2.8

Maximum Incline Angle



2.5 Proposed System

The systems that will be discussed in this section were derived to overcome the problems and shortcomings of the traditional ways. Angular momentum storage and dispensing is one such mechanism that will increase the torque limitation found in other traditional robots. This temporary boost would allow the robot to ascend steeper inclines and climb over obstacles. There are 3 main systems that store and utilize angular momentum.

They are:

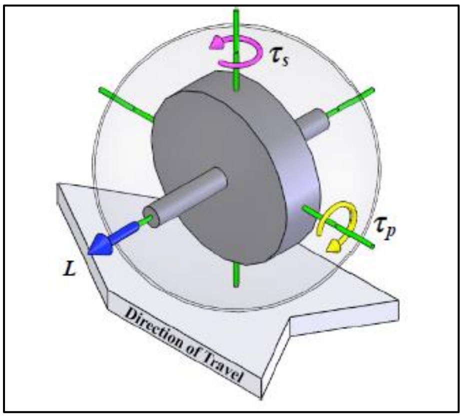
1. Reaction Wheel
2. Momentum Wheel
3. Control Moment Gyroscope

2.5.1 Reaction Wheel

This is a heavy wheel with a large inertia. According to G. Schroll (2010),when a torque is applied on the flywheel an equal and opposite torque is acted upon the sphere cause of the law of conservation of angular momentum. In the spherical robot the reaction wheel could be fixed parallel to the spin axis of the robot (Schroll, 2008). The sphere will move forward if a torque is applied to the reaction wheel in the opposite direction.

Figure 2.9

Reaction Wheel Configuration (Schroll, 2010)



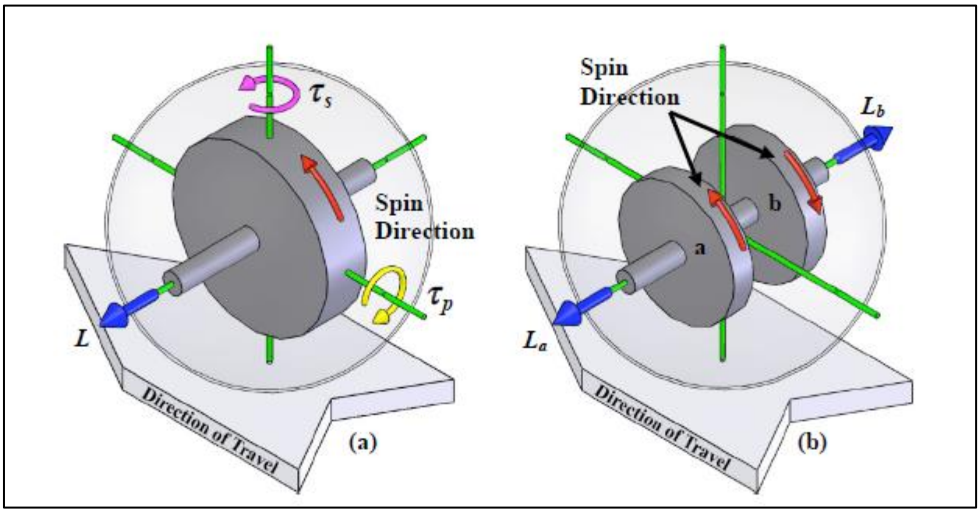
A reaction wheel can hold a large angular momentum and a large actuator would be required to control this wheel. In cases of stopping the robot or for sudden reversing a very high current will be required to bring the heavy reaction wheel to a halt which will cause inefficiency. One drawback of this system will be in maneuvering. If heading is changed while the sphere is moving fast it will cause the robot to be out of balance and to avoid this the reaction wheel must be slowly stopped after using for the sphere to change the direction.

2.5.2 Momentum Wheel

A momentum wheel is like the reaction wheel. The wheel is spun at a very high speed and a sudden brake is applied. The momentum which was gained by the wheel is then transferred to the sphere when it is stopped. The momentum wheel also encounters instability as the reaction wheel. To make the system more stable a dual momentum wheel configuration is used. The wheels are rotating opposite to each other thus the net angular momentum is zero. It acts as if there is no mass spinning. In this system τ_s is a torque created when the sphere is rolling due to tilts of the robot. And τ_p is the precession torque which occurs due to the tilting of the wheel. Two systems are put faced opposite to each other to cancel out the precession torques generated.

Figure 2.10

Single and Dual Momentum-Wheel Configuration



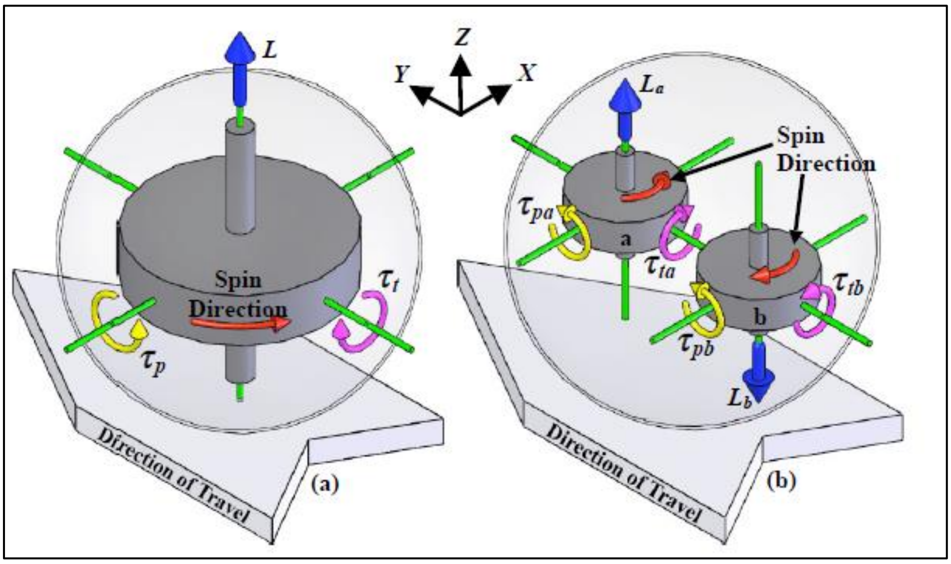
To make the sphere move forward and back only one momentum wheel is used. The other wheel is used to prevent the gyroscopic precessions and improve stability of the sphere. In this entire process the kinetic energy of the wheel is transferred to the sphere or lost. In this case also due to the weight and quick movements of the wheel a relatively large motor should be used. The overall robot would be fairly large.

2.5.3 Control Moment Gyroscope

In this method the kinetic energy of the wheels is not disturbed or lost. The gyroscopic precession which was unfavorable in other instances is to be used here. When the flywheels are used as in shown in the diagram below it is called a control moment gyroscope. This system is deemed more favorable as it requires less power to generate the required torque.

Figure 2.11

Single and Dual CMG Configuration



With a single CMG in Fig 2.10 (a) the sphere will move forward but due to the counter torques created by the wheel will make the system tilt and unbalanced. Thus, to cancel these torques a dual CMG configuration is used. The dual CMGs will rotate opposite to each other and cancel unnecessary torques. The torques τ_{pa} and τ_{pb} are the precession torques which will help to boost the driving of the sphere when the flywheels are forced tilted opposite to each other using equal torques τ_{ta} and τ_{tb}.

CHAPTER 3

METHODOLOGY

3.1 Design Overview

In this chapter the design and an overview of the mechanical, electrical and control will be discussed. The sub chapter system design will provide details of the electrical components and their layout and the control mechanism of the robot.

3.1.1 Pendulum and Flywheels

The main mode of providing torque is by shifting the center of gravity of the sphere. It is what causes the sphere to roll. The CMG's are incorporated to supplement the already existing torque of the pendulum. This way all the torques are applied on the main shaft of the system which is then connected to the main body. For gentle inclinations and on flat surfaces the pendulum action is adequate. But when it comes to slight steps or greater inclinations the flywheels are used.

The torque provided by the flywheels are for a short time, the amount of torque it provides is related to the speed of the tilting of them. For a greater inclination a fast tilt will be required. And when climbing small slopes, the flywheels are tilted slowly to provide the torque for a longer period of time.

3.1.2 Design Concept and Goals

In order to achieve the expectations in the theory several factors have to be considered. As discussed previously due to the pendulum action the center of gravity of the system needs to be lower as possible. Hence placing the heavy components such as batteries, motors, gears, pulleys in ideal positions is significant. The flywheels are quite heavy thus they increase the center of mass of the system and they take lot of space in the system as well.

In order to climb a step, the driving torque needs to be high compared to the torque needed to move on flat surfaces. Hence lot of details were considered when selecting items such as motors, gears and pulleys. The motors should be able to provide a torque greater than required to move the pendulum and flywheels. From theory it is necessary for the flywheels to be spun at high velocities to achieve enough momentum, but doing so affects the batteries. In overall the total weight of the system needs to be kept as low possible for optimal performance.

The whole system is designed to keep it simple and under the given budget. Number of parts were kept to a minimum as possible and most of the components are of similar type to reduce the number of tools used as well. Most of the parts were made using laser cut aluminum as its affordable and items such as steel shafts, screws, electronic components found in the lab were used as well.

3.2 Mechanical Design

The use and working of the components and mechanisms are explained in this section.

Figure 3.1

Mechanical Design

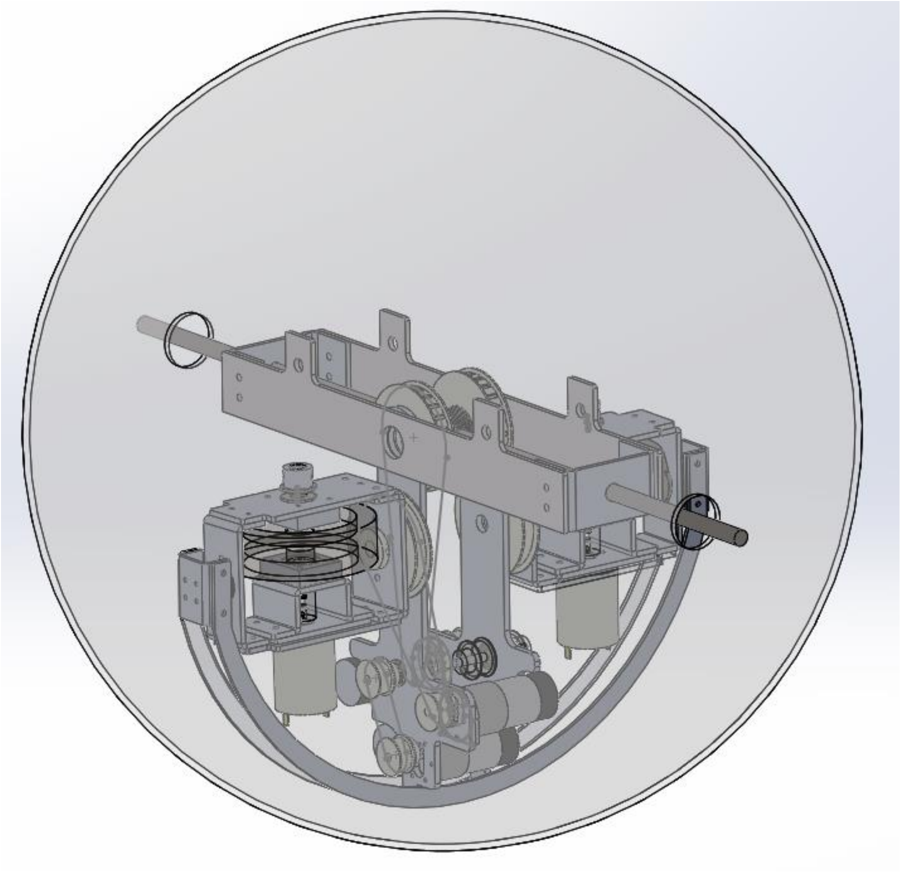


Figure 3.2

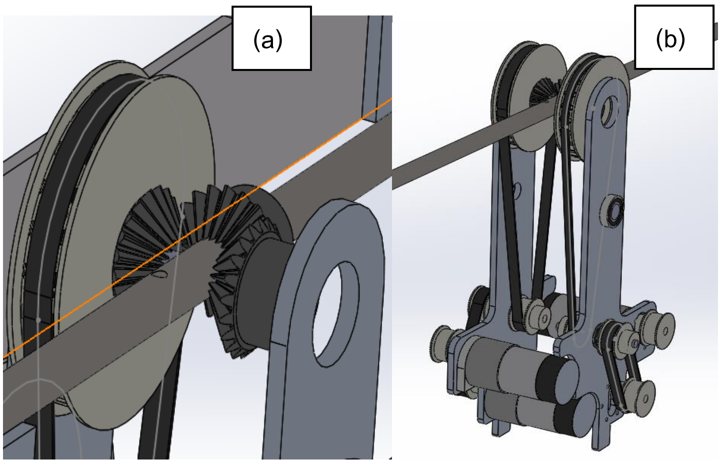
Final Prototype

3.2.1 Pendulum Drive Mechanism

The pendulum part should be able to go back and forth as well as to the sides in order to make the sphere move and steer. Since the motors have been brought to the bottom to optimize the center of mass the torque needs to be transferred to the center shaft. Pulleys and belts are used then. Three bevel gears are used for this process. One on the center shaft and two driven by the motors. It works similar to a differential drive. In this case when the two bevels are rotated in opposite directions the pendulum moves to the front. When one bevel is rotated faster than the other it causes the system to steer left or right.

Figure 3.3

Differential Drive System. (a)With One Pulley Hidden. (b)Full Pendulum Unit

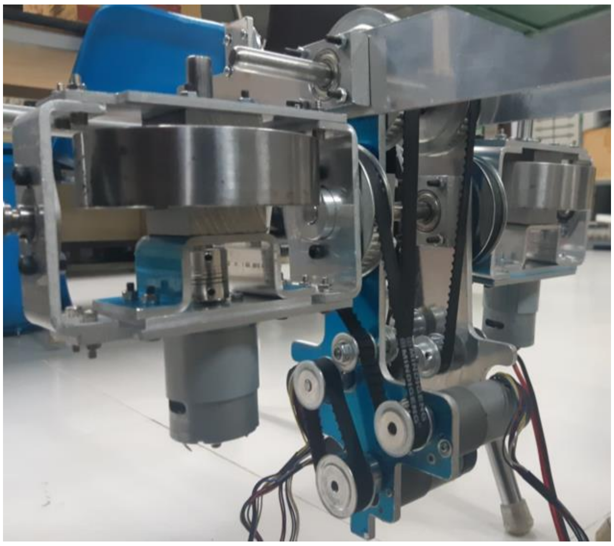


3.2.2 Motor, Gears, Pulleys and Belts

Since we want to keep the total weight down and get a decent torque, we used 37D motors from Pololu with built in encoders of 16 pulses per revolution. These small motors have a high rpm thus gearboxes of 100:1 was used to reduce rpm and increase torque. For all the pulleys and belts XL belts were used. For the flywheels to ensure high RPMs and torque, larger motors were used and coupled directly to the flywheels.

Figure 3.4

Pendulum and the Flywheels



3.2.3 Flywheel Design

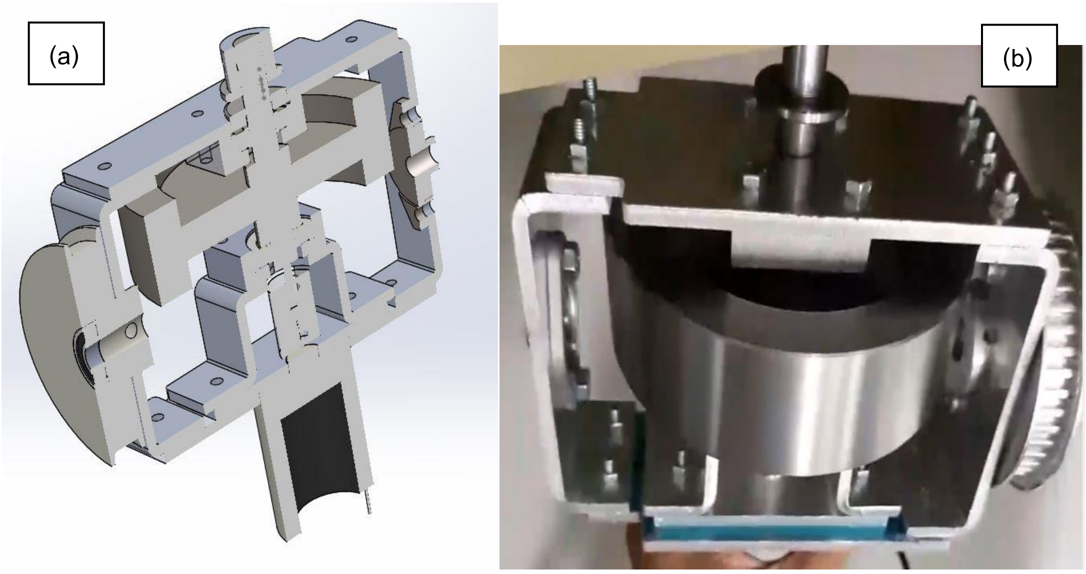
When designing the flywheel lot of focus was put to maximizing the angular momentum. From the equation below the angular momentum can be increased by distributing the mass in a thin ring.

$$I = \frac{1}{2}\pi\rho h(r_1^4 - r_1^4)$$

where ρ is the density, h is the thickness of the ring, r_1 is the inside radius and r_2 is the outside radius. Within the space of the sphere the flywheels need to be optimized and should have space to tilt as well. The flywheels were made from stainless steel as it is very dense and also cost efficient. The flywheels are high in strength and low cost compared to other materials. The flywheels had a weight of 2.2kg. and a moment of inertia of 10g*m^2 and the motors spin the wheels at around 5000rpms.

Figure 3.5

Flywheel (a) Solidworks Sectional Cut View (b)Final Flywheel Inside the Tilt Cage



3.3 Mathematical Model

The main addition to this pendulum driven system are the control moment gyroscopes. The gyroscopic precision which are put to use can be explained by the following equations,

$$\tau = \frac{dL}{dt} \tag{3.1}$$

$$L = I\Omega \tag{3.2}$$

$$E = \frac{1}{2} I\Omega^2 \tag{3.3}$$

Where,

τ is torque

L is angular momentum

I is moment of inertia

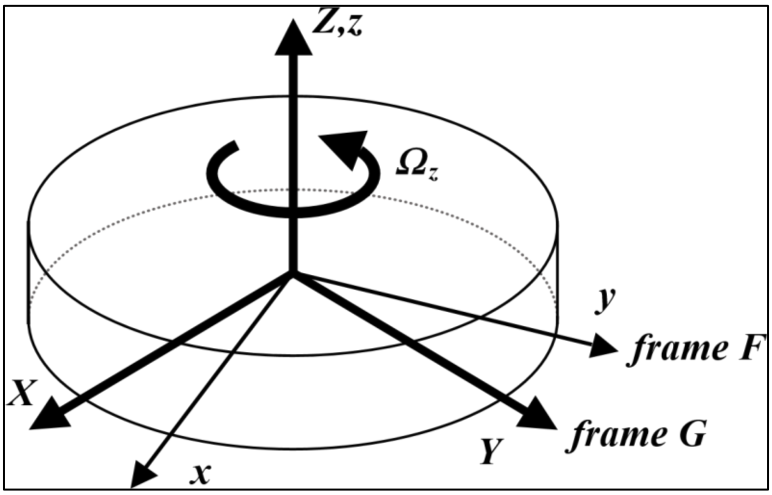
E is kinetic energy

Ω is angular velocity

The kinetic energy in the gyro wheel is a scaler. Hence when a torque is applied to change the direction of the angular momentum of the gyro wheel, the rotational kinetic energy of the wheel would be conserved.

Figure 3.6

Diagram of a Flywheel



In figure 3.6 the frame ***F*** is the reference. The origin of frame ***F*** is the center of mass of the flywheel. The axes ***x,y,z*** are aligned with the principal axes of the disk. The origin of frame **G** is also same as that of frame ***F***, and the axes ***Z*** and ***z*** coincide. The flywheel and ***F*** frame are rotated with angular velocity $\boldsymbol{\Omega_z}$ with respect to ***G*** frame around ***Z*** axis.

The 3D rotational equations of motion for the flywheel are,

$$M_X = I_{xx}\Omega_x + I_{zz}\Omega_z\omega_Y - I_{yy}\Omega_y\omega_Z \tag{3.4}$$

$$M_Y = I_{yy}\Omega_y + I_{xx}\Omega_x\omega_Z - I_{zz}\Omega_z\omega_X \tag{3.5}$$

$$M_Z = I_{zz}\Omega_z + I_{yy}\Omega_y\omega_X - I_{xx}\Omega_x\omega_Y \tag{3.6}$$

Where,

M_Y,M_X, M_Z are the net moments about the ***Y***, ***X***, ***Z*** axes respectively.

I_{yy}, I_{xx}, I_{zz} are the principal moments of inertia of the flywheel about ***y***, ***x***, ***z*** axes respectively.

Ω_x, Ω_y, Ω_z are the angular velocities of ***F*** frame with respect to ***G*** frame about ***x***, ***y***, ***z*** axes.

ω_X, ω_Y, ω_Z are the angular velocities of ***G*** frame with respect to a global frame about the ***X, Y, Z*** axes.

When frame G is at still and the flywheel spins with constant angular velocity Ω_z. Then equations above (3.4), (3.5), (3.6) becomes equal to zero as the angular velocity and acceleration terms goes to zero. When a torque τ_t is applied to tilt the flywheel around the ***Y*** axis, equation (3.5) become,

$$M_Y = \tau_t = -I_{zz}\Omega_z\omega_X \tag{3.7}$$

From equation (3.7),

$$\omega_X = -\frac{\tau_t}{I_{zz}\Omega_z} \tag{3.8}$$

The flywheel reacts to the torque τ_t by rotating with angular velocity ω_X around positive ***X*** axis. If the angular velocity of ω_X is resisted by an opposing external torque τ_p about negative ***X*** axis, then equation (3.4) will be,

$$M_X = -\tau_p = I_{zz}\Omega_z\omega_Y \tag{3.9}$$

Similarly, flywheel will react with angular velocity ω_Y about the ***Y*** axis.

$$\omega_Y = -\frac{\tau_p}{I_{zz}\Omega_z} \tag{3.10}$$

When an external torque τ_p is applied to the flywheel about the negative $\boldsymbol{X}$ axis, an equal and opposite reaction torque τ_p will be acted around the positive **X** axis. This is the gyroscopic precision torque which was mentioned before. This will be the output torque from the control moment gyroscope.

Rotational kinetic energy $\boldsymbol{E}$ and angular momentum $\boldsymbol{L}$ are unaffected as the angular velocity Ω_z remains not changed and the momentum M_Z is still zero. Because of that, we can say the power input, $\boldsymbol{P}_{\text{in}}$ to the control moment gyroscope from the tilting torque is equal to the output power, $\boldsymbol{P}_{\text{out}}$, from the control moment gyroscope through the precision torque.

$$P_{in} = \tau_t \omega_Y = -\frac{\tau_t \tau_p}{I_{zz}\Omega_z} = \tau_p \omega_X = P_{out} \tag{3.11}$$

The control moment gyroscope converts a torque from one direction to another torque which is in the perpendicular direction. With the tilting of the gyroscopes, the direction of the output torque also changes accordingly.

When two CMGs are incorporated as in our design, the equal and opposite torques applied to tilt and control the flywheels has no effect on the robot’s internal systems. It is due to the fact that the angular momentum of the wheels is in opposing directions. The tilting torques make the CMG, to output the precession torque in the same direction together.

The output precession torque around the global **X** axis can be related with the tilt angle of the flywheel through the below equation.

$$\tau_{px} = 2\tau_p cos\theta_{tilt} \tag{3.12}$$

Where τ_{px} is the component of precession torque about **X** axis and θ_{tilt} is the tilt angle of the wheel about the **Y** axis. Initially θ_{tilt} is at zero.

From this a relationship can be formed between the tilt rate and output torque of the CMGs. By substituting equation (3.9) in equation (3.12) we get,

$$\tau_{px} = 2I_{zz}\Omega_z\omega_Y cos\theta_{tilt} = 2L\omega_Y cos\theta_{tilt} \tag{3.13}$$

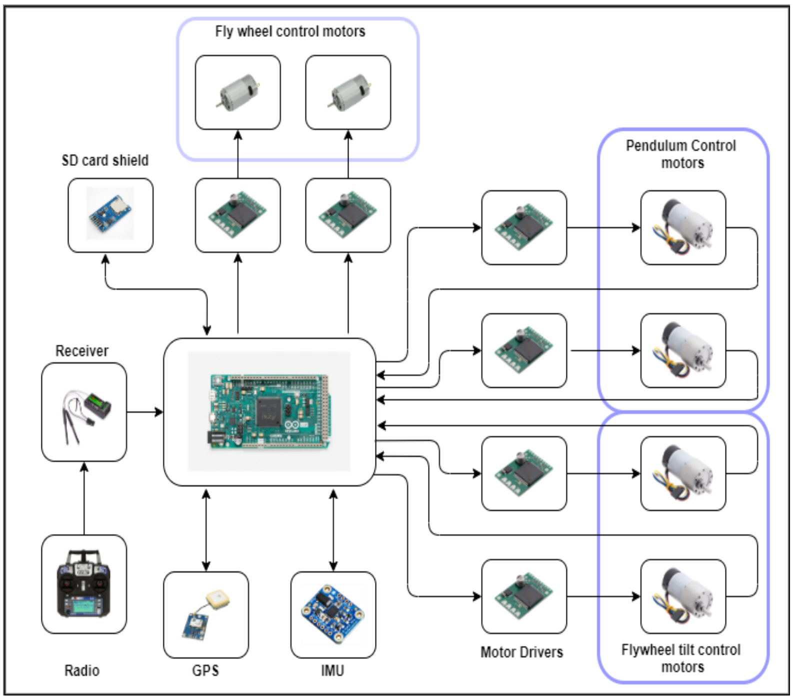
From the above equation it is evident that with a greater angular momentum, the flywheel will tilt slower for a given output torque. This will also help us to use the control moment gyroscopes for a longer period of time.

3.4 Electrical Design

Figure 3.7 shows the basic electrical components of the robot. Components such as batteries, limit switches, voltage regulators and meters are not show in the diagram. Two headed arrows are for the components which are communicating bidirectionally. Components such as the IMU, GPS, SD card communicates with the main control board all the time.

Figure 3.7

Electrical Components



3.4.1 Control Board

The spherical robot uses an Arduino Due as the main control board. Since this robot requires several inputs and outputs it was necessary to get a board with several digital pins. But compared to the Arduino mega this has many interrupt pins which was used for the radio and servo signals. Also, there was heavy computation required for the robot.

Table 3.1:

Specification of the Main Controller

Parameter	Description
Processor	AT91SAM3X8E/ARM
Operating voltage	3.3 V
Clock speed	84 MHz
Input voltage	7 - 12 V
Flash memory	512 kB
Digital I/O pins	54
Digital interrupt pins	54

3.4.2 Motors

One of the deciding factors for the system was choosing the correct motors. This was the main starting point of my design. After searching for compact geared motors with a decent torque I decided to select 12V 37D motors from Pololu. Four similar motors were purchased. Two of them were combined to provide torque for the pendulum action of the ball. The other two were used to control the tilt angle of the flywheels. One advantage was these motors comes with varies gear sizes and built-in encoders. A two-channel Hall effect encoder is used to sense the rotation of a magnetic disk on a rear protrusion of the motor shaft.

Table 3.2

Specification of Motors

Key Parameter	Description
Input Voltage	12V
Dimensions	Ø37 x 94mm
Gear Ratio	100:1
Output power	8W
Stall Current	5.5A
Stall torque	34kg.cm
Speed	100rpm
Encoder	64CPR

After considering the weight from the system it was necessary to machine flywheels that would provide necessary torque to the system. When it was decided to use flywheels weighing at over 2kg each it was necessary to find a motor that would be able to rotate the heavy wheels at a high rpm without the use of gears. Since we are not controlling the speed of the flywheels an assumption was taken that the motors would perform identical to the same voltage.

Table 3.3

Specification of Flywheel Motors

Key Parameter	Description
Input Voltage	12V
Dimensions	Ø37 x 75
Gear Ratio	1:1
Output power	60W
Stall Current	8A
Speed	8000rpm

3.4.3 Motor Driver

Since we were using several motors for the robot and placing them correctly to balance the weight was necessary. Since the entire system is made to be compact it was best to get a driver that could handle high currents but also small in size. Hence 6 VNH5019 motor drivers from Pololu was purchased. These drivers matched well with the motors as well.

Table 3.4

Specification of Motor Drivers

Key Parameter	Description
Supporting motor voltage	5.5 – 24V
Type	H-bridge
Maximum continuous motor current	12A
Peak motor current (10 seconds)	30A
Maximum PWM frequency 20 kHz	20 kHz
Dimension	38mm x 28mm

3.4.4 IMU

The IMU was used to balance the robot and also to make the movements to the system. The BNO005 module from Adafruit was used for this purpose. It is compatible with the Arduino and the sensor fusion technology was quite useful. For my robot I used the magnetometer and the gyroscopes. The gyroscope was to balance the robot and give steering commands to the robot and also to get the heading of the robot.

The compass unit in the system takes magnetic field readings from 3 axes. For my purpose since the compass is kept flat to the ground the magnetic 3D fields needs to be projected on a 2D plane. The magnetometer is prone to magnetic fields from the power systems and other electrical components; hence it needs to be mounted further away from the rest and also soft mounted.

Table 3.5

IMU Specifications

Key Parameter	Description
Operating voltage	3.3V - 5V
Communication method	I2C
Embedded modules	Gyroscope, Accelerometer, Magnetometer, Temperature sensor
Data updating frequency	100 Hz except for Magnetometer (20Hz)
Outputs	Eular and Quaterion angles, Angular Accelerations and Velocities, Magnetometer data and Temperature
Dimension	Dimension 20mm x 26mm

3.4.5 GPS

The GPS used is the Ublox NEO-6MV2. It is affordable and it has libraries for Arduino. Its compact and ideal for small projects. But in this case due to the small antenna there was a significant error on the readings. It does not work indoors. On clear days it gives decent readings with an accuracy up to 5 meters.

Figure 3.8

GPS Unit

The GPS uses serial communication at a baud rate of 9600. Since it sends data every second it makes the rest of the program slow. It sends data in NMEA format. The GPS+

library in the Arduino encodes this data and sends out the current Latitude and Longitude which is what we need for distance and heading calculation.

3.4.6 Radio and Receiver

The radio unit was the main communication setup for the robot. The remote is a 6-channel remote from FLYSKY, which is normally used for RC planes. It works in the 2.4Ghz range. The receiver also from the same brand is compatible with this remote and sends PWM signals ranging from 990 – 1900. This combo has a range of over 300meters.

Figure 3.9

Radio Unit

The signal coming in from the receiver is sent to the Arduino and decoded using interrupts and timers. The pulse time for each channel is calculated and then mapped accordingly. Channel 1 and 2 which is the right joystick is used for making pitch and roll commands. Channel 3 is not used. Channel 4 the vertical position of the right joystick. It is used to start the flywheel motors. Once PWM signal from channel 4 is greater 1500micro seconds the flywheel tilting action begins. Channel 5 is the arming switch for the robot. Only when the arming switch is ON the IMU will begin to work and be ready for manual commands or waypoint commands. Channel 6 is a 3-way switch. It is used to tell the robot to go to the programmed way points. Middle state of the switch is the waypoint 2.

Figure 3.10

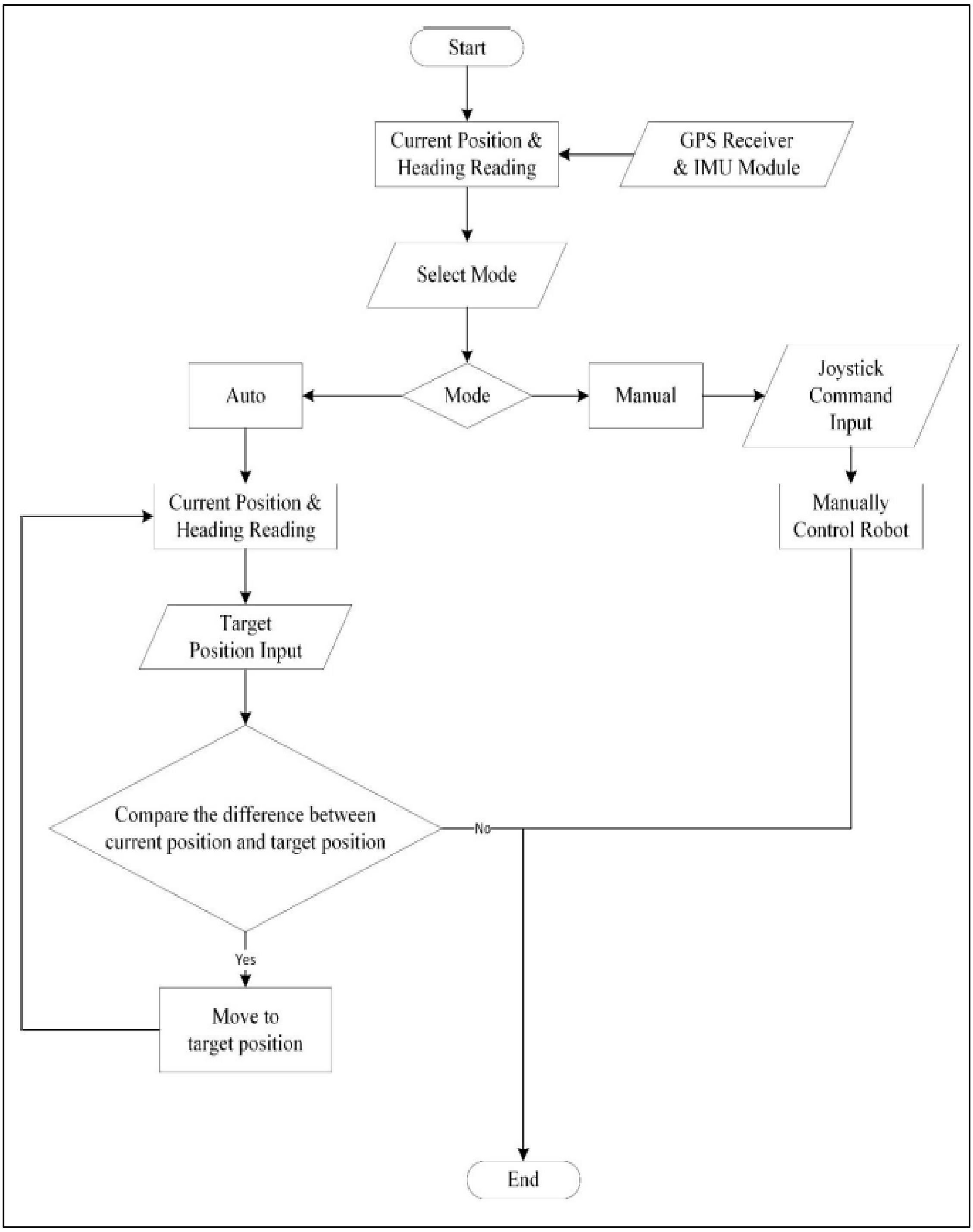
Radio Commands

3.5 Control System

Shown in figure 3.11 is the control flow chart of the robot. After powered is switched ON to the robot it will only function when the arming position of the radio is switched On. Once it is armed the IMU will activate and the robot will be in Manual Mode. If manual mode is preferred the user can move the robot using the joysticks. For GPS navigation the navigation switch has to be turned ON. Then it will start measuring the distance and heads to the given waypoints.

Figure 3.11

System Control Chart

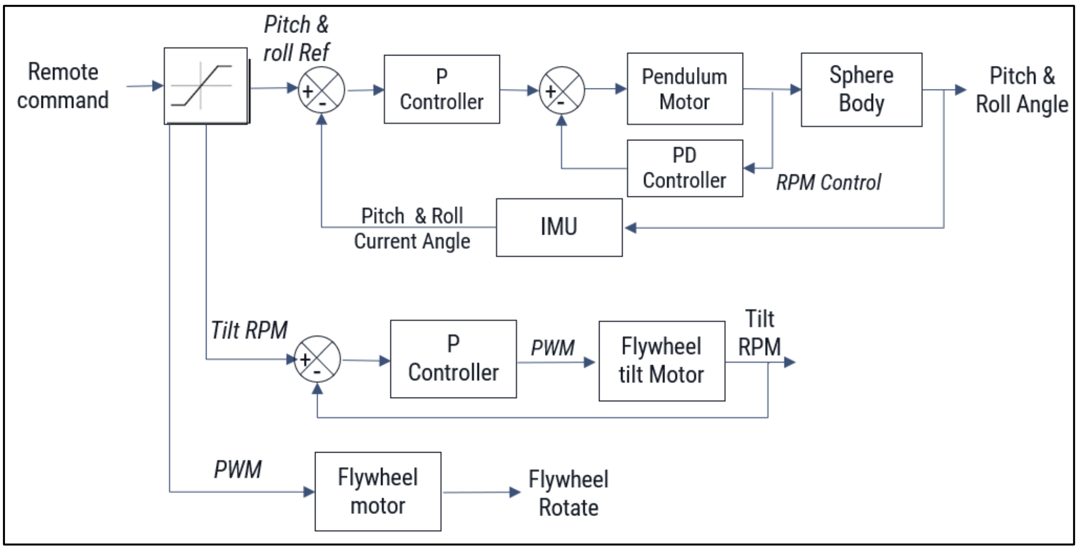


3.5.1 Manual Mode Control of Pendulum

The radio provides a reference pitch and roll angle to the gyro. The IMU uses a proportional controller to set its pitch and roll accurately. The Kp constant for both pitch and roll was 1.0. RPM of the pendulum motors are controlled accordingly as two motors are coupled for the differential drive in the pendulum. For this a PD controller was sufficient. With Kp constant being 8 and Kd constant 2. In case of turning to the sides the RPM of one motor is varied relative to the other. This would cause an unbalanced torque on the bevel gears and the entire pendulum unit would tilt.

Figure 3.12

Pitch and Roll Control of the Pendulum

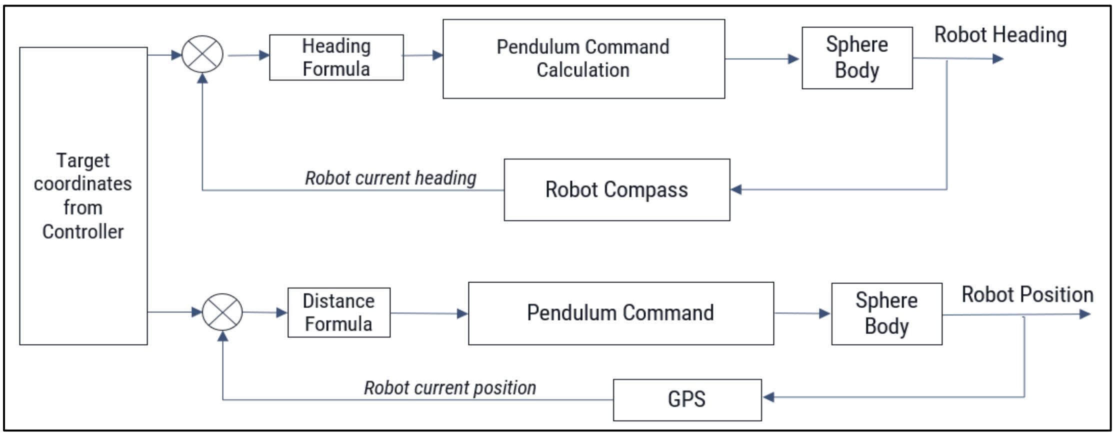


RPM of tilt angle are controlled using a proportional controller. Velocity of the flywheel tilting motors and mapped to the speed of the joystick command. The Kp constant for the motors were 0.7. A low gain was given as high-speed tilts caused severe damage to the system. Since there is no feedback from the motors fixed to flywheels an assumption had to be made that the rpm is same in both motors for a given PWM value.

3.5.2 *Robot in Autonomous Mode*

Figure 3.13

Autonomous Mode Control



In autonomous mode the reference points and target will be used to calculate the heading and distance. These functions will work when the autonomous switch is triggered in the system. The distance will be calculated first. The haversine distance formula is being implemented for this. Using the current position and target position the distance can be calculated.

$$haver\sin(\theta) = \sin^2\left(\frac{\theta}{2}\right) \tag{3.14}$$

$$d = 2R\sin^{-1}\sqrt{\sin^2\left(\frac{\phi_2-\phi_1}{2}\right) + \cos(\phi_1)\cos(\phi_2)\sin^2\left(\frac{\lambda_2-\lambda_1}{2}\right)} \tag{3.15}$$

Where:

d is the distance between two points

R is the radius of Earth (6371 km)

Ø1, Ø2 are the latitude of point 1 and point 2

λ1, λ1 are the longitude of point 1 and point 2

Once the distance is measured the heading will be calculated. Then the robot will know when to turn and where exactly the target location is. For this the compass is used. The heading formula shown below is used for this. The heading formula is computed in Radians and it is measured clockwise from the North.

$$h = atan2(\sin(\lambda_2 - \lambda_1)\cos(\phi_2)\sin(\phi_1) - \sin(\phi_1)\cos(\phi_2)\cos(\lambda_2 - \lambda_1)) \tag{3.16}$$

Where:

h is the heading angle

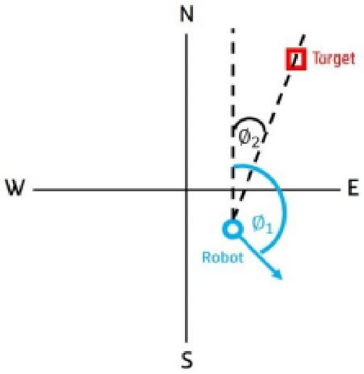
Ø1,Ø2 are the latitude of point 1 and point 2

λ1,λ1 are the longitude of point 1 and point 2

After calculation of the heading, it will be sent to the robot where it will be compared with the current heading and make adjustments. The new heading will be the difference between current heading and final heading.

Figure 3.14

Heading Direction of Robot



Where,

Ø1 is the heading of the robot from digital compass module

Ø2 is the heading angle from heading formula

CHAPTER 4

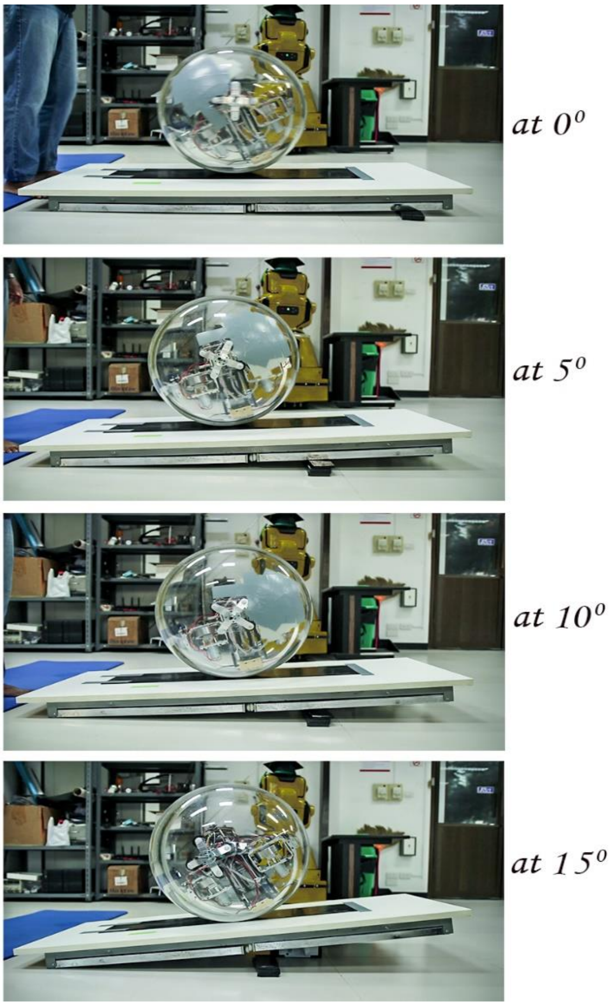
RESULTS AND DISCUSSIONS

4.1 Moving on an Inclination

In the figure 4.1 the performance of the robot was tested. The inclined plane was used to measure the maximum inclination angles the robot could move on. A rubber sheet was placed on the surface to minimize slipping. To get an exact measurement the inclination angle was increased on increments of 5 degrees beginning from zero degrees.

Figure 4.1:

Prototype Climbing an Inclination.

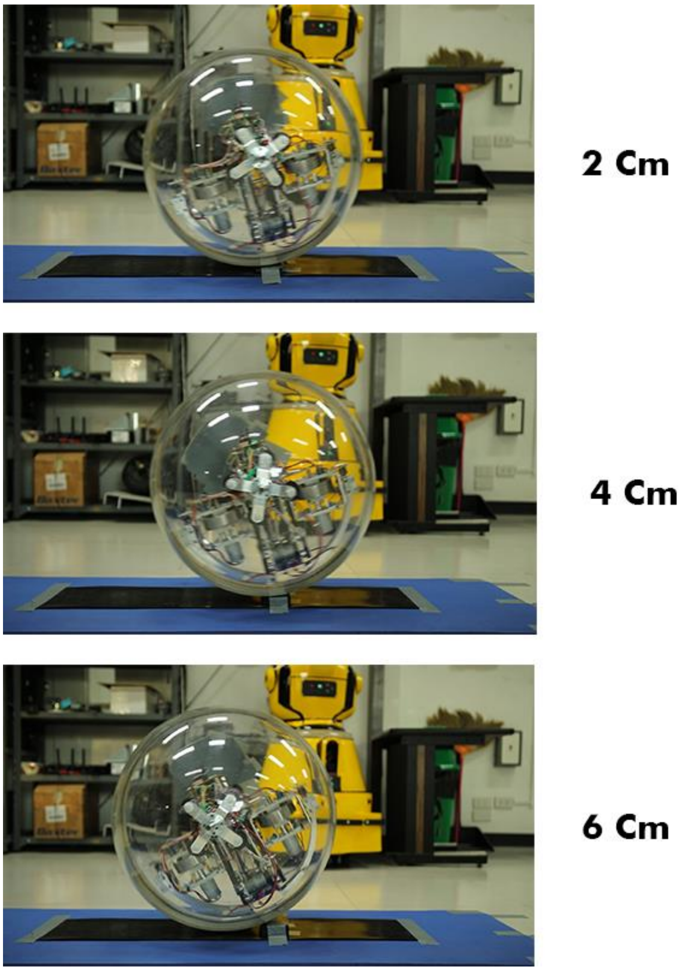


Using the pendulum alone the robot could climb up to 10 degrees of an inclination angle. For the 15 degrees inclined plane the CMGs were utilized to give a short boost. For a longer plane of 15 degrees the CMGs would be ineffective, but in this short ramp it was sufficient. Hence the maximum inclined angle the robot could overcome is 15 degrees given factors such as minimum slip and batteries are at full capacity.

4.2 Height Test

Figure 4.2:

*Maximum step Climb Tests Using the Pendulum with the CMGs***.**



In a controlled test ground 2cm thick steel plates were kept and gradually increased to see the maximum height the robot can achieve. The robot can easily achieve a height of 2 cm. The height of 4cm was a bit difficult to climb compared to the 2cm but with the use of the CMGs is achieved that height. The 6cm height was too high for the robot. From that I could say the robot can achieve heights up to 4cm.

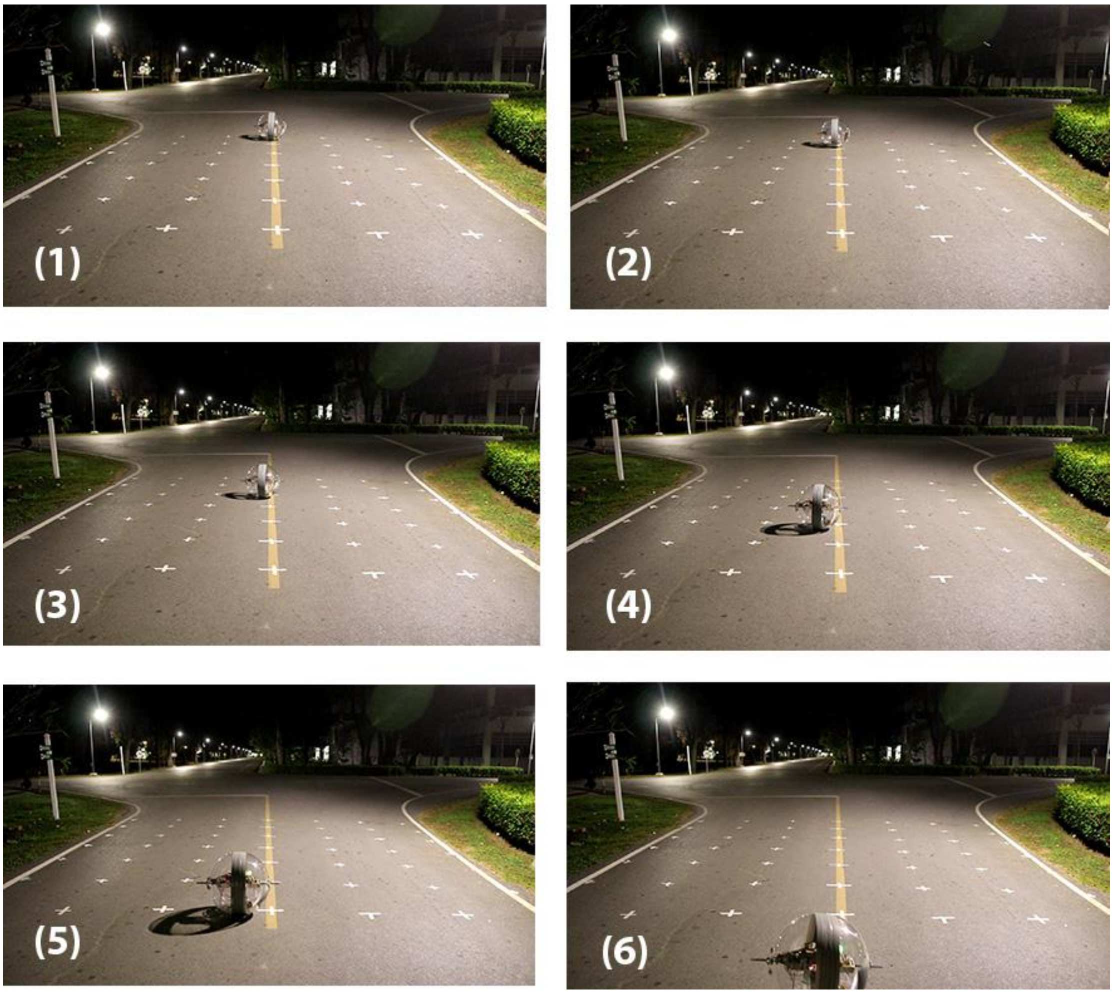
4.3 GPS tests

Testing the GPS module was a bit difficult as it gave readings only outdoors. The accuracy of the unit depended on the clearness of the skies and also on the weather. While performing tests the ball would get readings from a radius of five meters on a clear day.

4.3.1 Accuracy on a Straight Path

Figure 4.3

The Robot Moving on a Direct Path on Manual Mode

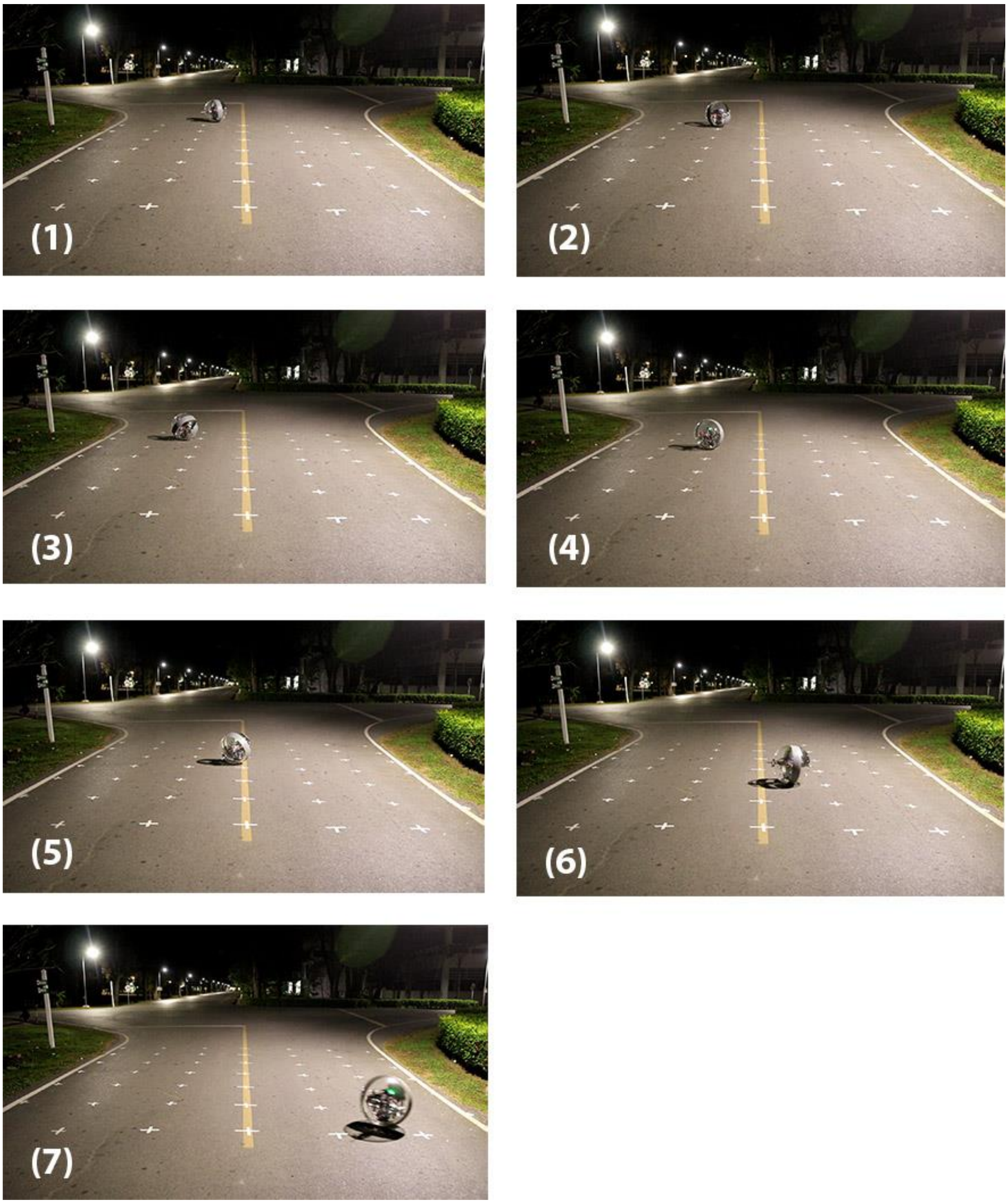


Here, (see Figure 4.3) the robot moves along the yellow line via the remote. The move forward command is given by the user. The robot moves forward using the pendulum drive while maintaining its stability. As you can see in remote mode the ball manages to move with greater accuracy

4.3.2 Accuracy while Moving in a Straight Path Using GPS

Figure 4.4

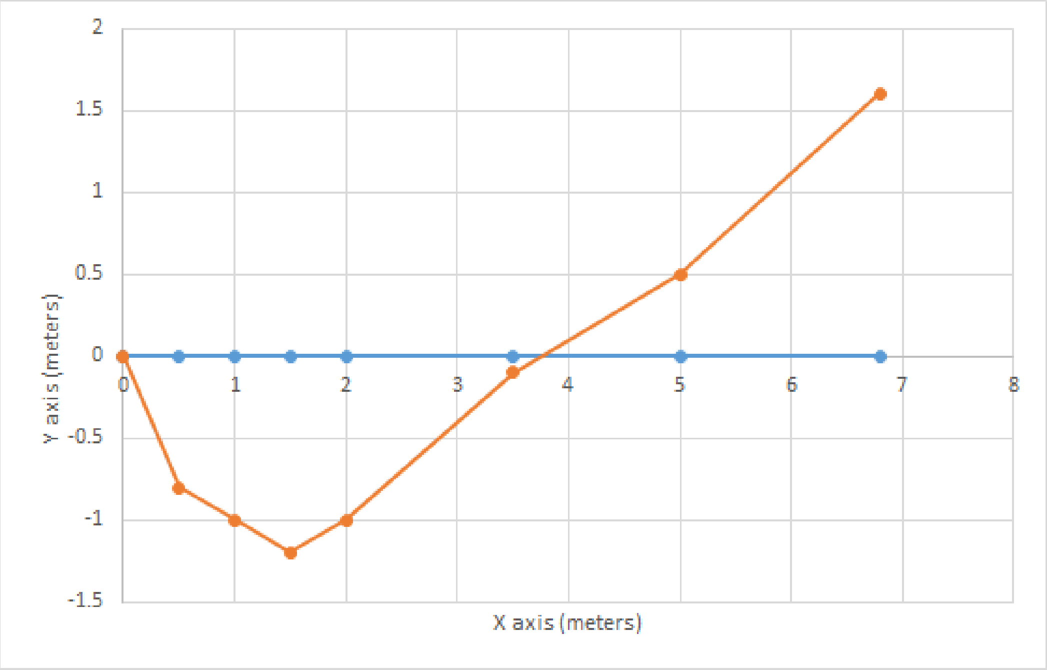
Robot Moving on a Straight Path in Auto Mode



The accuracy of the robot when moving in a straight line is very less in Auto mode. Due to the inaccuracies of the GPS the robot would encounter many readings within a 5-meter radius. We did several tests and each time there were slight variations in the accuracy. This particular test was the best of them all. The figure below would show a much-detailed explanation regarding the accuracy of the robot.

Figure 4.5

Distance Error on a Straight-Line in Auto Mode

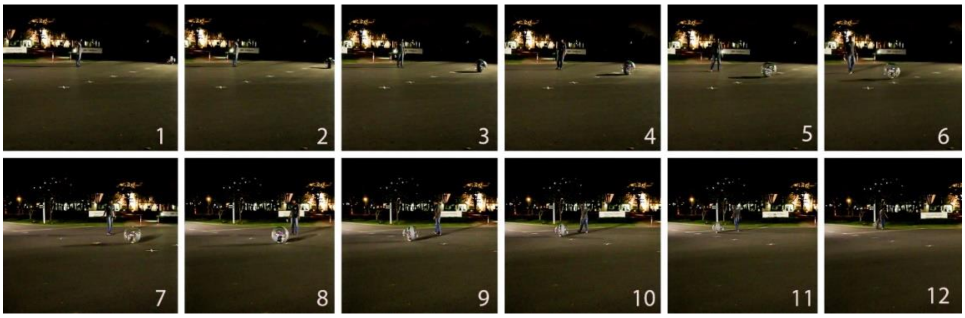


The Figure 4.5 shows how the robot moves on a straight line automatically using the GPS. The blue line is the command given by the user to the robot. The end coordinates. But the orange line is the path the robot took while moving to the given end coordinate. From the above graph you can see the robot has an error of -1.5m to +1.5m while travelling in a straight path with the help of the GPS. The mean square error in this graph is 6.635 in the Y axis.

4.3.3 Testing GPS Accuracy on a Given Path

Figure 4.6

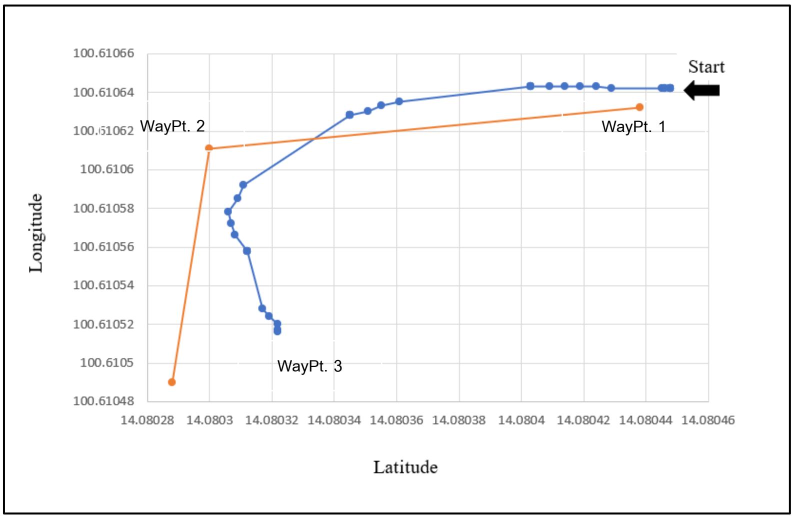
Robot Moving on a Path With 3 Given Way Points



This(see Figure 4.6) was one of the very few successful GPS tests of the robot. Due to clear skies the GPS signal strength was very good. 3-way points were programmed into the robot. The first way point was the current location of the robot. Second way point was the junction of the road in front of ISE. The 3rd way point was the center of the road between ISE and Main ground. Even though it did not correctly follow the path. But it managed to turn itself and move closer to the 3rd way point.

Figure 4.7

GPS Data from the Robot.



Note. Orange line is the shortest path from the 3 given way points

In figure 4.7 the data was recorded from the GPS module and saved onto the SD card. Every few seconds the GPS sends coordinates to the Arduino. The line in orange shows the 3 given waypoints. Coordinates of the waypoint 2 and 3 were obtained from google maps and programmed to the robot to be moved by a given command. Waypoint 1 is the current position of the robot. The mean square error in the Longitudinal direction was 6.29 while the mean square error in the latitudinal direction was 2.39. The GPS is unable to provide fast data to the system to make quick corrections. Slants and the rough terrain of the road also proved to be a factor in the errors.

4.4 Discussions

This is one of the most complex designs for a spherical robot, it requires great deal of time and machining processes. Due to the heavy flywheels the weight was significantly high than expected and portability was not easy. The spherical robot takes turns larger than its radius. Hence, it’s not ideal to move in limited spaces. Mostly due to lack of traction on the sphere surface the robot could not achieve its potential. While assembly slight misalignments have occurred in resulting some of the belts of the pendulum unit to slip at high torques. This reduced the performance of the robot.

While performing test one side of the shell cracked and needed to be fixed. Temporarily its solved using epoxy, from there onwards we stopped pushing the limits of the robot while testing. Although the batteries have a decent capacity and provided power for a longer time it was not sufficient for the CMG’s. When the CMG’s are spun at a high RPM the voltage would drop significantly making the tilting action slower.

One of the noted problems was the sphere tends to wobble during a sudden stop or when the IMU is getting some noise. Same happens if suddenly moved from rest. The primary axis would nutate when the sphere is moving at a certain speed and hits an uneven surface. When traveled slowly this nutation behavior is less. If moved too fast this would cause the sphere to go unstable and flip.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Pendulum robots are quite common now and are becoming popular due to their holonomic movements. And compared to vehicles with tires it can perform much better on rough surfaces. But due to torque limitations in some cases spherical robots have fallen out of favor.

By using enhancements such as flywheels this shortcoming of torque can be improved. But very few research has been done related to this part as design would be complex and also will require sophisticated control systems. The mechanism that we implemented to use two equal and opposite flywheels as torque enhancements provided us with much more insight to flywheel enhanced spherical robots. This is a first of its kind in AIT.

The pendulum design gave promising results as it overcame man surfaces from smooth to slightly rough terrain such as uneven paved roads and dirt roads. Using the pendulum alone it was possible to move through heights up to a certain extent. The PID controllers were crucial during this time and they gave good results. The only shortcoming was in the mechanical system. The flywheel mechanism did provide a certain enhancement to the system, but it was not enough to achieve the expected results. Its visible they were trying to provide a torque to the system but due to the robot's weight the impact was not much.

5.2 Recommendations

5.2.1 Mechanical Design

Laser cutting aluminum and sheet bending them is not ideal for this type of project. It's better to use CNC machined aluminum as it will reduce the align errors in the system. This affected specially when aligning the flywheels to the system. Flywheels' momentum must be increased as it did not generate enough torque to the system. Due to the compact size, it was difficult to use variable or free pulleys in the systems. Hence some of the belts were not properly tightened causing a slip situation in cases where high torque was required.

5.2.2 Spherical Body

The spherical body which was made from acrylic was not a perfect sphere. In order to achieve a perfect sphere a method such as injection molding should be used instead of acrylic sheet bending. To make it affordable the acrylic sheet used was of small thickness. While bending dimensional inaccuracies have occurred. The surface of the sphere was smooth acrylic, this cause problems during testing because the sphere was slipping is some surfaces. Greatly reducing the robot’s ability to overcome heights.

5.2.3 GPS Module

The GPS module needs to be improved. This gives in accurate data sometimes and satellite reception was quite low specially during the day time and none indoors. If a larger antenna were to be used might improve the signal strength. Also, it provided data for every one second. Hence, it took a toll on the program run time as computation of the distance and heading was slow. On a cloudy day the error increased up to 10 meters.

5.2.4 Working Areas

Better control systems need to be tried to improve the performance of the robot. A power source that is able to provide a high current draw should be used as rotating the flywheels affects the functioning of the other properties of the robot. The IMU also was prone to the vibrations of the system. A GUI should be implemented to enter the data into the system such as coordinates and also observe the performance data of the system.

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