MODELING A DRIVING MECHANISM FOR A SPHERICAL ROBOT

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May, 2015

ACKNOWLEDGEMENTS

This report presents details of our final year project, which is “Modeling a Driving Mechanism for a Spherical Robot”.

First of all we would like to express my deepest thanks to Dr. J. V. Wijayakulasooriya, Dr. H. A. Suraweera and Dr. M. P. B. Ekanayake Senior Lectures of Electrical and Electronic Engineering Department who were assigned as project supervisors. They guided us throughout the project by giving necessary suggestions and valuable information to successfully overcome difficulties.

Importantly we must thank Dr. D. H. S. Maithripala, Senior Lecture of Mechanical Engineering Department who helped us a lot to understand and derive dynamics of the system. We specially remind all the Lectures of Electrical and Electronic Engineering Department for their contribution.

Also we should thank instructors and technicians of Electrical and Electronic Engineering Department, who helped us in hardware configuration process.

And we would like to thank our parents and batch mates for their great help and cooperation and also for sharing their valuable experiences, being assistive each and every time we needed.

Finally we would like to thank everybody who has assisted us, even with a mere word, in the course of successful achievements of the project.

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ABBREVIATIONS

COAM	Conservation of Angular Momentum
COG	Centre of Gravity
CMG	Central Moment Gyroscope
DSP	Digital Signal Processor
IDU	Internal Driving Unit
PWM	Pulse with Modulation

Chapter 1: What is a Spherical Robot?

Spherical robot is a robot which moves by rolling on the ground. IDU of this robot is located inside the robot itself and completely covered. Unlike other robots there is no risk of flipping over and lose the ability to move. These kinds of robots are very much unlikely to suck at corners. Without getting much of an attention this robot can travel in different terrains, which makes this unlikely qualified for secretive applications.

Robot can travel along rough terrains. It can simply fall over a wall or staircase and then reorient itself and start moving. Not only that, but also this robot can travel through water ways without getting much trouble. Since the IDU can be completely sealed there is no risk of damaging the circuits.

Spherical robots can be used mainly in military applications, surveillance, hazardous environment assessment, search and rescue missions and planetary explorations. Performance of proposed method can be further improved according to the application.

Various kinds of techniques has proposed as driving mechanisms for spherical robots. Each one them has their own colorful features and drawbacks. Different novel ideas has developed to overcome that problems. Through this report we are trying to propose one such method.

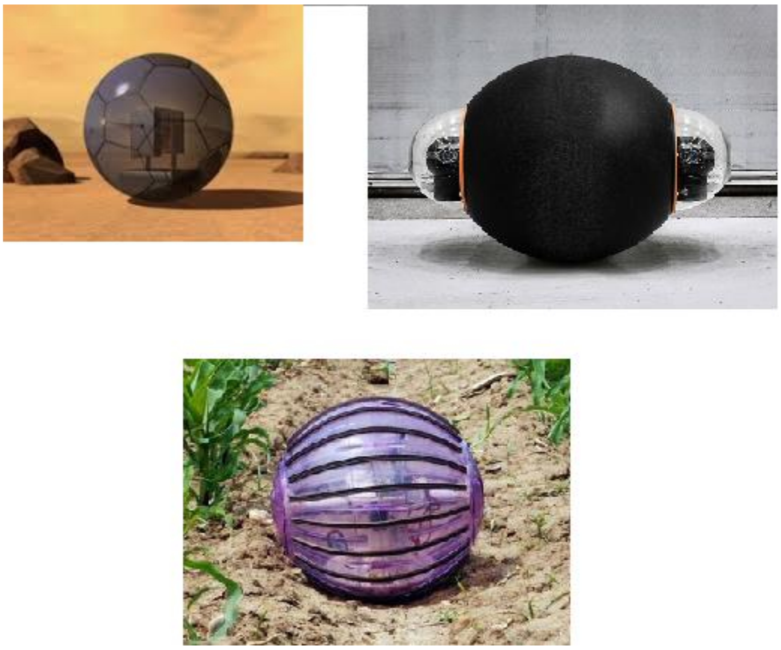


Figure 1.1 Different Types of Spherical Robots

Chapter 2: Prior Art

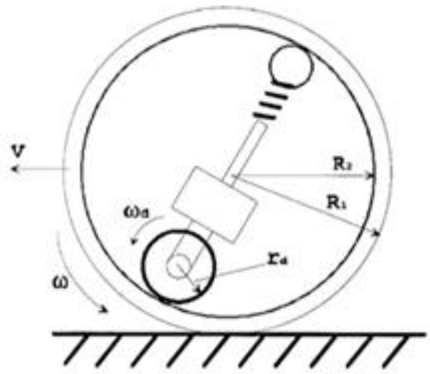
Spherical robotics is a field, which has captured the attraction of many researchers during last few decades. This has become an emerging research area due to various advantages over other mobile robots. Some of the advantages are rigidity, robustness, non-inevitability and ease of locomotion. Robot travels by rolling over ground and it consists of a spherical shell and an inner driving unit. Up to now various techniques are used as driving mechanism. They are,

1. Roller mechanism
2. Internal car based mechanism
3. Mass displacement mechanism
4. Self-deformation mechanism
5. Pendulum drive mechanism
6. Conservation of angular momentum mechanism.

Most popular methods are last two mechanisms.

2.1 Roller Mechanism

This is one of the methods which has used at very beginning of spherical robot era. In this mechanism IDU directly transfers power to inside surface of the hallow sphere. With this mechanism it is difficult travel along a desired path because when changing the direction IDU has rotate and reorient accordingly. During this rotating period sphere tends to move along undesirable directions. This prototype, named Rollo (1st version) has developed by Aalto University of Finland.



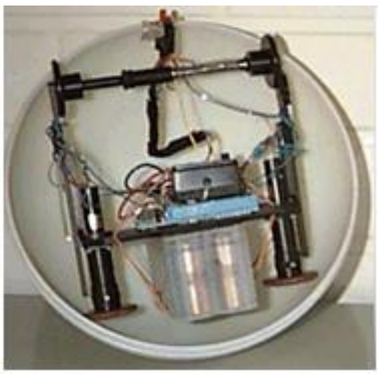


Figure 2.1 Sprung Central Member Driven Robot (Prototype Rollo 1st Version)

2.2 Internal Car Based Mechanism

In this mechanism also IDU directly transfers power to hallow spherical shell. Using an omni directional car it’s easy to change driving direction however there is a risk of flipping the car upside down. If that scenario occurs robot can’t reorient itself. Due to slipping between shell and car wheels also act as a negative point in this method. This prototype named SAR (Spherical Autonomic Robot) has also developed by Aalto University of Finland.

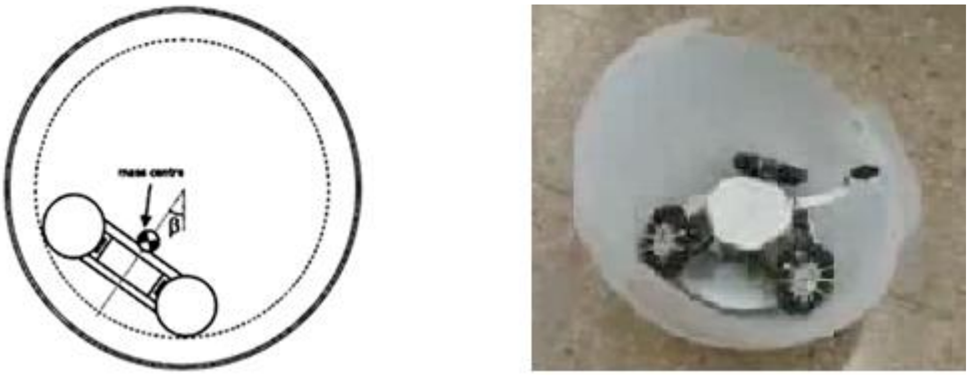


Figure 2.2 Internal Car Driven Robot (Prototype SAR)

2.3 Mass Displacement Mechanism

For the first time the concept of shifting the COG to rotate, is introduced with this concept. Structure of the robot is somewhat complicated, but mathematical this can be considered to be a simple model. Omni characteristics can be achieved very easily. Main drawback of this method is, the speed limitation. The torque which can be produced is limited. This prototype August has developed as a joint effort by Azard University of Quazvin and University of Tehran.

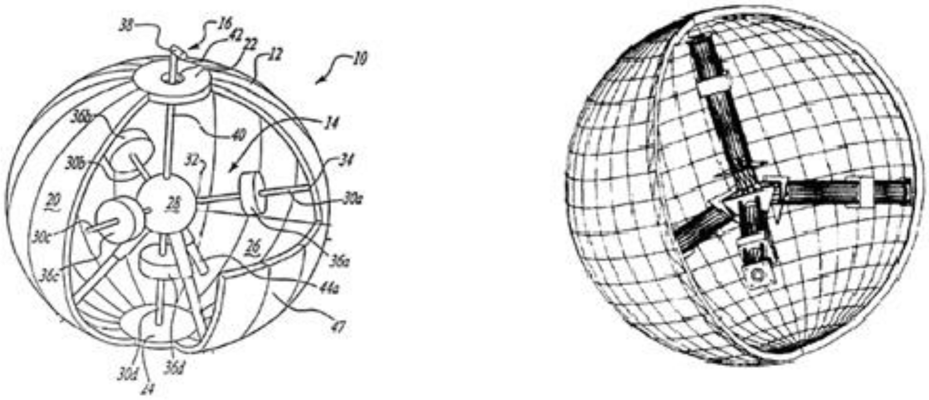


Figure 2.3 Multiple Mass Shifting Robot (Prototype August)

2.4 Self-deformation Mechanism

Another novel concept is using a self-deformation process to move in a desired direction. Effort need to develop this kind of spherical robot is, considerably higher. All other robots a solid outer structure is used and for this type a suitable flexible structure should be used. Though contracting and expanding the shell required deformation can be achieved, which causes robot to roll. Ritsumeikan University of Japan has developed one such prototype robot called Koharo.

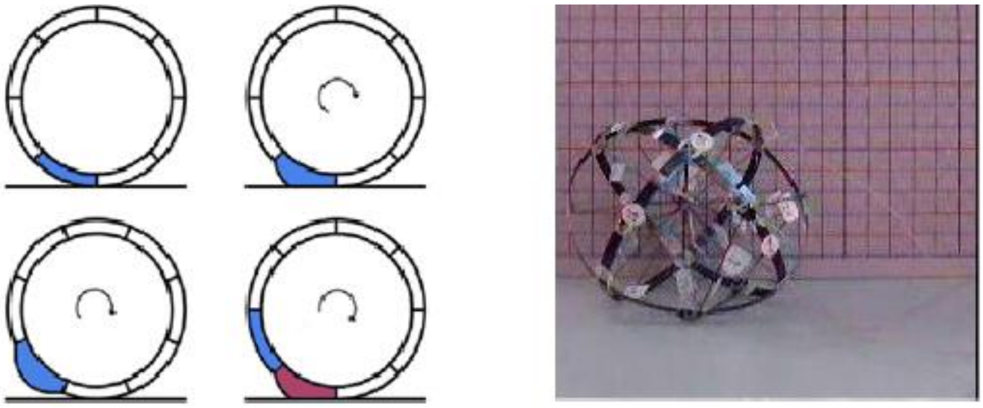


Figure 2.4 Self deformation Robot (Prototype Koharo)

2.5 Pendulum Drive Mechanism

Typically this robot has a main shaft, fixed to the shell and an offset mass, which can rotate freely. With the rotation of pendulum COG of robot changes and causes robot to roll. By changing rotation speed of the plenum speed of the sphere can be controlled. Robot loses its holomonic nature because pendulum can't be rotated parallel to the direction of main shaft. This provides less curvature to movement path

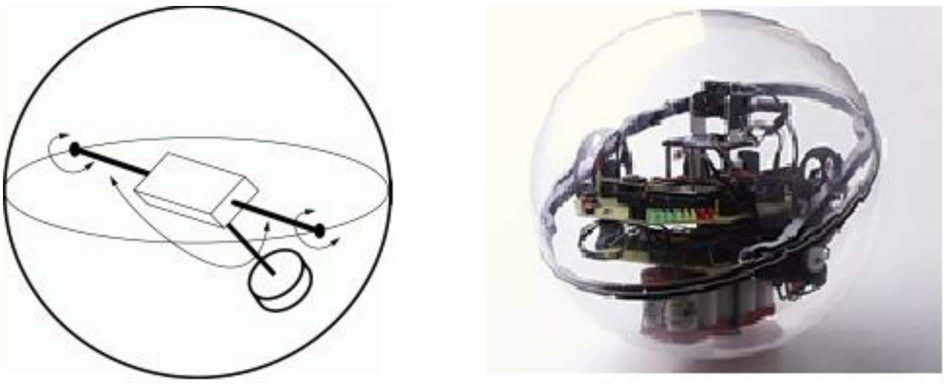


Figure 2.5 Pendulum Driven Robot (Prototype Rollo 3rd Version)

2.5.1 Two Pendulum Method

Different types of two pendulum mechanisms are proposed to overcome movement limitation of pendulum. One such method is, using two pendulums to generate different movement paths. Another merit of this method is, using two different speeds and angles, robot's moving direction can be controlled up to a far better level.

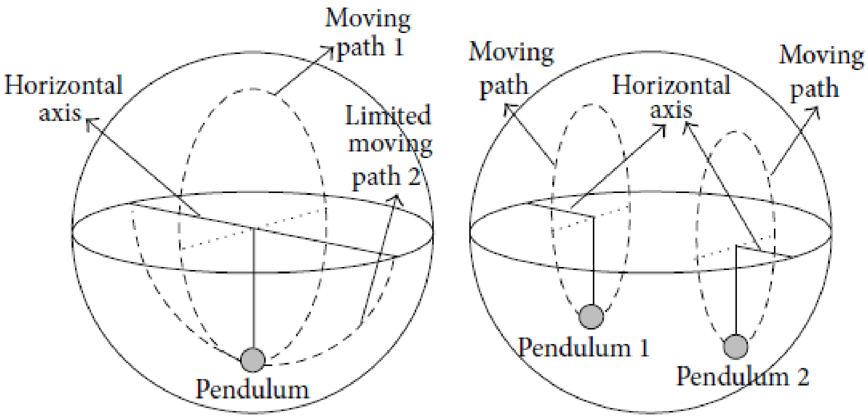


Figure 2.6 One Pendulum and Two Pendulum Drive Structures

2.5.2 Different Pendulum Configuration Methods

Using above method also robot can't move along direction parallel to the main shafts. To overcome that issue another method has proposed. KisBot II has developed, using this driving mechanism.

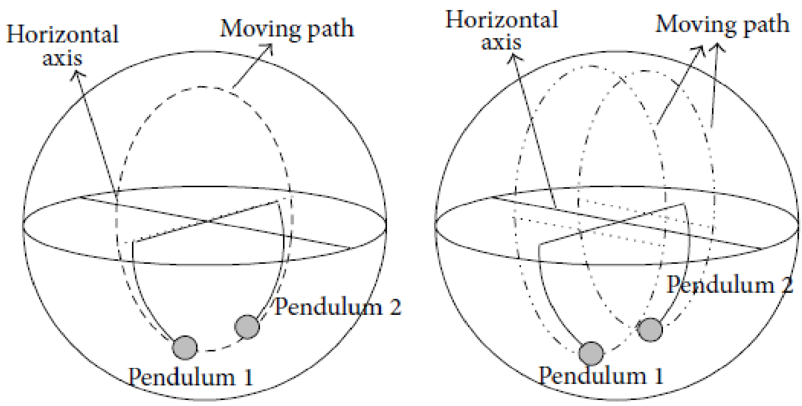


Figure 2.7 Two Pendulum Drive Structure

2.6 Conservation of Angular Momentum Mechanism

This is another different concept, which can generate high torque. In this method there are three kinds of configurations. They are,

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

In reaction wheel method, a torque is applied to a fly wheel and because of COAM opposite directional torque is generated on the sphere (the shell, which fly wheels are mounted to). Momentum wheel method is very much similar to this other that the used wheel is a high speed spinning wheel. In CMG method gyroscopes are used and the generated precision torque also used to move the sphere in a desired direction.

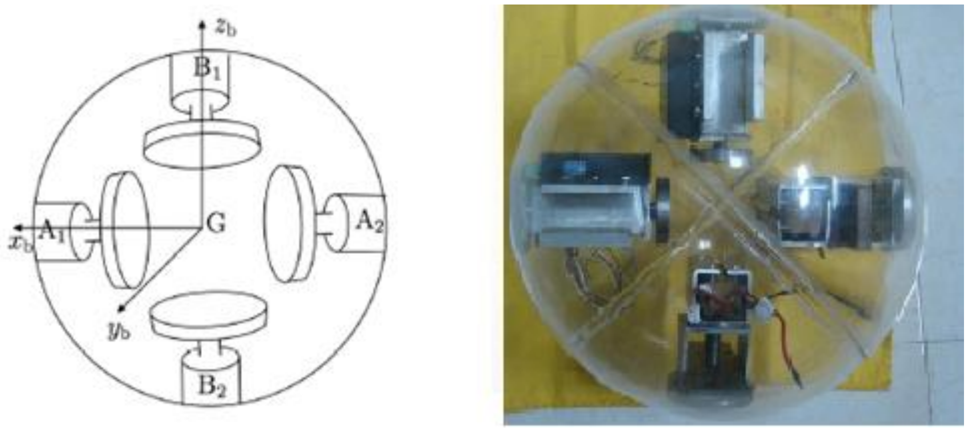


Figure 2.8 Rotor Pair Designed Robot (Joshi's Prototype)

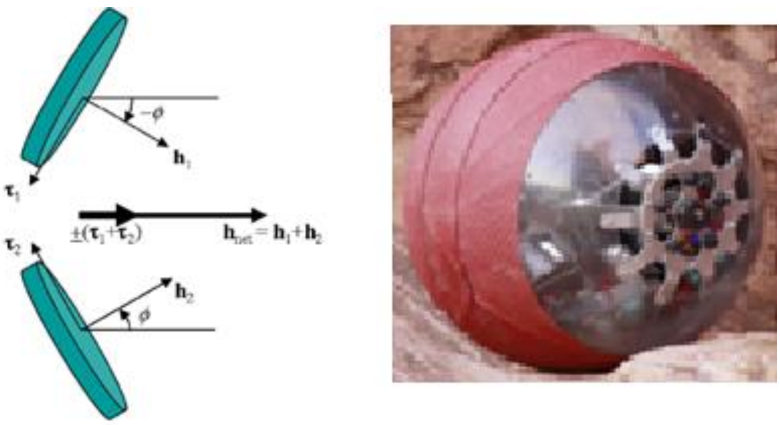


Figure 2.9 G. Schoroll's Spherical Robot

Chapter 3: Preliminary Work

During this semester two basic models were implemented using pendulum drive mechanism and COAM Mechanism. Further developments and controller designs were done only for pendulum drive mechanism prototype. For both cases hardware implementation were done for uni directional locomotion. This can be represented exactly in same way using a cylindrical robot. Therefore due to simplicity a cylinder was chosen instead of a sphere.

3.1 COAM Mechanism Robot

As the first attempt we developed a COAM mechanism based spherical robot model. Robot consisted of a simple cylindrical shell, DC motor and reaction wheel. V-rep software was used for simulations. When increasing or decreasing the acceleration of the reaction wheel, cylinder rolled in the opposite direction to preserve the conservation of angular momentum.

3.1.1 V-rep Simulation

Using this robotic simulation software, simulation model for the robot was developed and simulated for uni directional locomotion. Expected results were given from simulation

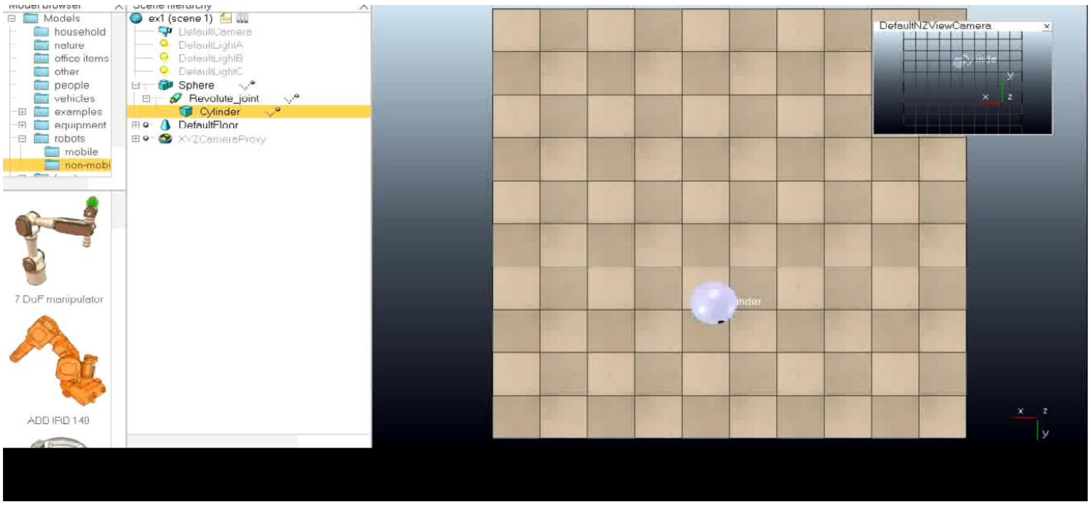


Figure 3.1 V-rep Simulation

3.1.2 Hardware Implementation

Simple hardware setup was implemented for basic modeling. Practically it's difficult to maintain a constant velocity for the cylinder due to implementation limitations. It's impossible to keep an acceleration for long time. Because of that, a wave form like a saw tooth or a pulse should be used. But in our prototype robot during the time applied voltage became zero robot started to rotate backwards. The main reason for this problem was, our robot was light weight and that caused robot to rotate back instead of rolling along the same direction with a reduced velocity. We couldn't increase the mass of robot because the motors we used were unable to provide sufficient for increased mass of cylinder. But robot gave expected performance when gradually decreasing and increasing the acceleration

There were few other problems associated with this robot also. Mathematical modeling was very complex for this robot. When moving from one dimensional case to two dimensional case precision torque also comes into the picture, making path planning and controlling more and more difficult. Our future plan is to develop and implement the robot for two dimensional path planning. Due to time limitations it's extremely difficult to derive complete model and implement to achieve acceptable results.

Figure 3.2 COAM Based Robot Prototype

However, this robot had few advantages over pendulum drive robot. Main advantage is that although the COG is not at the center it won't cause much of a trouble as it does with other method. Considering all those facts we decided to present a novel ideas to improve the mobility of a pendulum drive robot.

3.2 Pendulum Drive Robot

This was the 2nd method we used for the robot. Using other pendulum drive techniques holonomic nature can't be achieved. Our objective is to remedy that problem. Instead of using traditional pendulum in this project extra masses were attached to reaction wheels. Omni directional nature also can be achieved in this robot.

When using this method it's necessary to made sure that pendulum doesn't rotate more than 180^{o} with respect to the ground. If that scenario occurs robot become uncontrollable.

Figure 3.3 Proposed Pendulum Arrangement

The models were derived for uni directional locomotion.

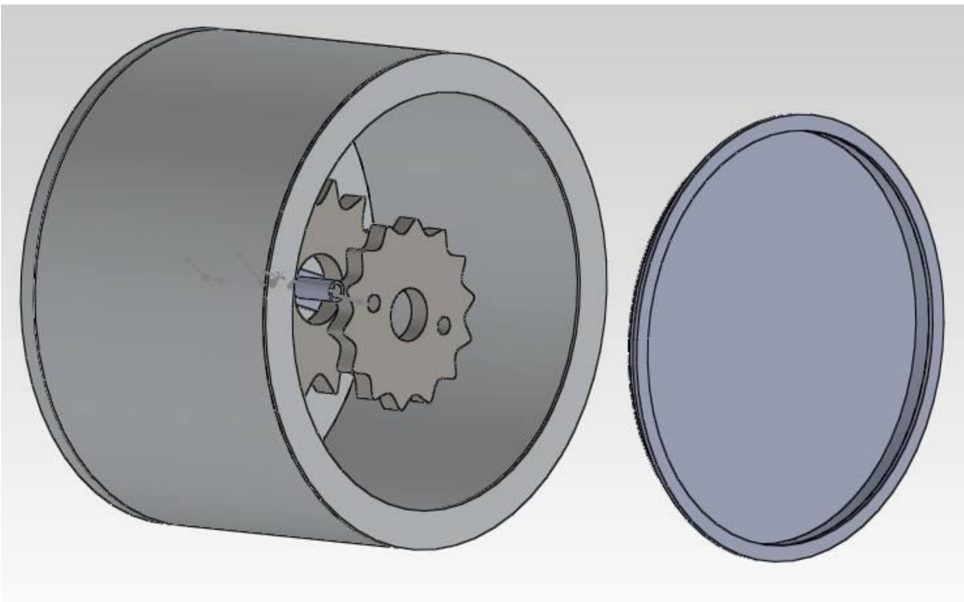


Figure 3.4 Uni Directional Model

Chapter 4: Mathematical Modeling and Simulation

Mathematical model was derived using Lagrangian equations. This model was validated using matlab Simulink.

4.1 Mathematical Model for Sphere

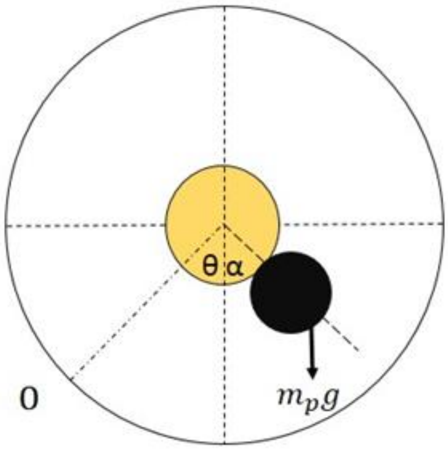


Figure 4.1 Orientation of Wheels

(x, y)	Center of sphere
R	Radius of the sphere
l	Length between the centers of two wheels
m_s	Mass of the spherical shell
m_i	Mass of the inner driving unit
m_p	Mass of the pendulum wheels
m_r	Mass of the rotating wheels
J_s	Moment of inertia of spherical shell around its center
J_r	Moment of inertia of rotating wheels around its center
J_p	Moment of inertia of pendulum wheels around its center
J_i	Moment of inertia of inner driving unit around the center of the sphere
τ	Torque of the motor
T	Kinetic energy

P Potential energy

Q Total external non conservative force

Kinematic equations

$x = -R\theta$

$y = R$

Assuming no slip between ground and sphere

$\dot{x} = -R\dot{\theta}$

Dynamic model

Using Lagrangian function

$L = T - P$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right) - \frac{\partial L}{\partial q} = Q$$

Kinetic energy of the system

Kinetic energy of the sphere

$$T_s = \frac{1}{2}J_s\dot{\theta}^2 + \frac{1}{2}m_sR^2\dot{\theta}^2$$

Kinetic energy of the inner driving unit

$$T_i = \frac{1}{2}J_i\dot{\theta}^2 + \frac{1}{2}m_iR^2\dot{\theta}^2$$

Kinetic energy of the rotating wheels

$$T_r = \frac{1}{2}J_r\dot{\alpha}^2 + \frac{1}{2}m_rR^2\dot{\theta}^2$$

Kinetic energy of the pendulum wheel

$$T_p = \frac{1}{2} J_p \dot{\alpha}^2 + \frac{1}{2} m_p \left[\left(l\dot{\alpha} - R\dot{\theta}\cos\alpha \right)^2 + \left(-R\dot{\theta}\sin\alpha \right)^2 \right]$$

Total kinetic energy

$$T = T_s + T_i + T_r + T_p$$

Total potential energy

$$P = -m_p g l \cos\alpha$$

Substituting to Lagrangian equation

$$L = \tfrac{1}{2} J_s \dot{\theta}^2 + \tfrac{1}{2} m_s R^2 \dot{\theta}^2 + \tfrac{1}{2} J_i \dot{\theta}^2 + \tfrac{1}{2} m_i R^2 \dot{\theta}^2 + \tfrac{1}{2} J_r \dot{\alpha}^2 + \tfrac{1}{2} m_r R^2 \dot{\theta}^2 + \tfrac{1}{2} J_p \dot{\alpha}^2 + \tfrac{1}{2} m_p \left[\left(l\dot{\alpha} - R\dot{\theta}\cos\alpha \right)^2 + \left(-R\dot{\theta}\sin\alpha \right)^2 \right] + m_p g l \cos\alpha$$

$$L = \tfrac{1}{2} \left\{ \left[J_s + J_i + \left(m_s + m_i + m_r + m_p \right) R^2 \right] \dot{\theta}^2 + \left(J_r + J_p + + m_p l^2 \right) \dot{\alpha}^2 - 2 m_p l R \dot{\alpha} \dot{\theta} \cos\alpha \right\} + m_p g l \cos\alpha$$

Generalized coordinate system

$$q_1 = \theta\, , q_2 = \alpha$$

$$L = \tfrac{1}{2} \left\{ \left[J_s + J_i + \left(m_s + m_i + m_r + m_p \right) R^2 \right] \dot{q_1}^2 + \left(J_r + J_p + m_p l^2 \right) \dot{q_2}^2 - 2 m_p l R \dot{q_2} \dot{q_1} \cos q_2 \right\} + m_3 g l \cos q_2$$

Robot rolls in clockwise direction

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q_1}} \right) - \frac{\partial L}{\partial q_1} = -\tau$$

Pendulum rotates in anticlockwise direction

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q_2}} \right) - \frac{\partial L}{\partial q_2} = \tau$$

$$\frac{\partial L}{\partial \dot{q}_1} = \left[J_s + J_i + \left(m_s + m_i + m_r + m_p\right)R^2\right]\dot{q}_1 - m_p l R \dot{q}_2 \cos q_2$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_1}\right) = \left[J_s + J_i + \left(m_s + m_i + m_r + m_p\right)R^2\right]\ddot{q}_1 + m_p l R \dot{q}_2{}^2 \sin q_2 - m_p l R \ddot{q}_2 \cos q_2$$

$$\frac{\partial L}{\partial q_1} = 0$$

$$\frac{\partial L}{\partial \dot{q}_2} = \left(J_r + J_p + m_p l^2\right)\dot{q}_2 - m_p l R \dot{q}_1 \cos q_2$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_2}\right) = \left(J_r + J_p + m_p l^2\right)\ddot{q}_2 + m_p l R \dot{q}_1\, \dot{q}_2 \sin q_2 - m_p l R \ddot{q}_1 \cos q_2$$

$$\frac{\partial L}{\partial q_2} = m_p l R \dot{q}_1 \dot{q}_2 \sin q_2 - m_p g l \sin q_2$$

Substitution

$$\left[J_s + J_i + \left(m_s + m_i + m_r + m_p\right)R^2\right]\ddot{q}_1 + m_p l R \dot{q}_2{}^2 \sin q_2 - m_p l R \ddot{q}_2 \cos q_2 = -\tau$$

$$\left(J_r + J_p + m_p l^2\right)\ddot{q}_2 + m_p l R \dot{q}_1\, \dot{q}_2 \sin q_2 - m_p l R \ddot{q}_1 \cos q_2 - m_p l R \dot{q}_1 \dot{q}_2 \sin q_2 + m_p g l \sin q_2 = \tau$$

$$\left(J_r + J_p + m_p l^2\right)\ddot{q}_2 - m_p l R \ddot{q}_1 \cos q_2 + m_p g l \sin q_2 = \tau$$

Since, $\dot{x} = -R\dot{\theta}$

Coordinate system can be changed as, $q_1 = \theta$, to be $q_1 = x$

$$\left[\left(\frac{J_s + J_i}{R^2}\right) + \left(m_s + m_i + m_r + m_p\right)\right]\ddot{q}_1 - m_p l \dot{q}_2{}^2 \sin q_2 + m_p l \ddot{q}_2 \cos q_2 = \left(\frac{1}{R}\right)\tau$$

$$\left(J_r + J_p + m_p l^2\right)\ddot{q}_2 + m_p l R \ddot{q}_1 \cos q_2 + m_p g l \sin q_2 = \tau$$

Matrix form

$$M(q)\ddot{q} + C(q, \dot{q}) = B\tau$$

$$\begin{bmatrix} \left[\left(\frac{J_s + J_i}{R^2}\right) + \left(m_s + m_i + m_r + m_p\right)\right] & m_p l \cos q_2 \\ m_p l R \cos q_2 & \left(J_r + J_p + m_p l^2\right) \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} -m_p l \dot{q}_2{}^2 \sin q_2 \\ m_p g l \sin q_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{R} \\ 1 \end{bmatrix} [\tau]$$

$q_1 = x$, $q_2 = \alpha$

Since cylinder represents the motion of a sphere in uni direction, to derive cylindrical model, simply the mass and inertia of the sphere can be replaced by mass and inertia of cylinder.

4.2 Matlab Simulation Results of the Plant

Simulations were observed for different types of input signals using matlab simulink. The presented results were obtained using unit step function with magnitude of 8V. To motor it was possible to apply up to 12V. But, when applying 12V, motor rpm increased up to 80 rpm and that caused the pendulum to rotate 180^o.

So, this was the maximum input voltage which can be given, while maintaining the motion of the robot in controllable state. Maximum velocity of the cylinder that can be obtained was around 0.7 m/s. But that velocity can’t be maintained for a long time. Maximum constant velocity that the robot can roll was around 0.4 m/s.

However these values can be increased by, increasing the mass of the pendulum wheel or increasing the length between two centers of the reaction wheel and the extra mass (pendulum wheel). When increasing those values cylinder rotates faster that the current velocity and this prevents the pendulum wheel from rotating 180^o.

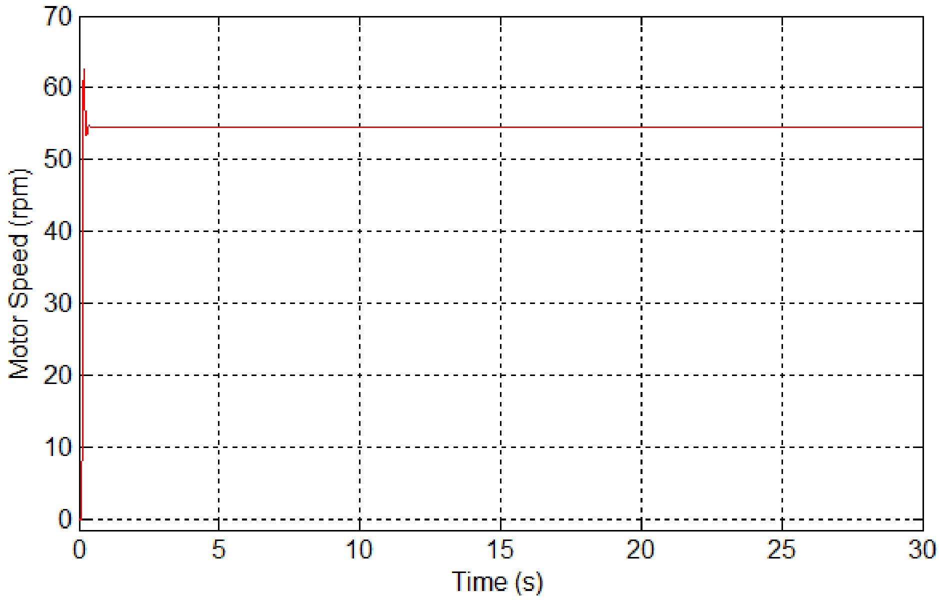


Figure 4.2 Speed of the Motor

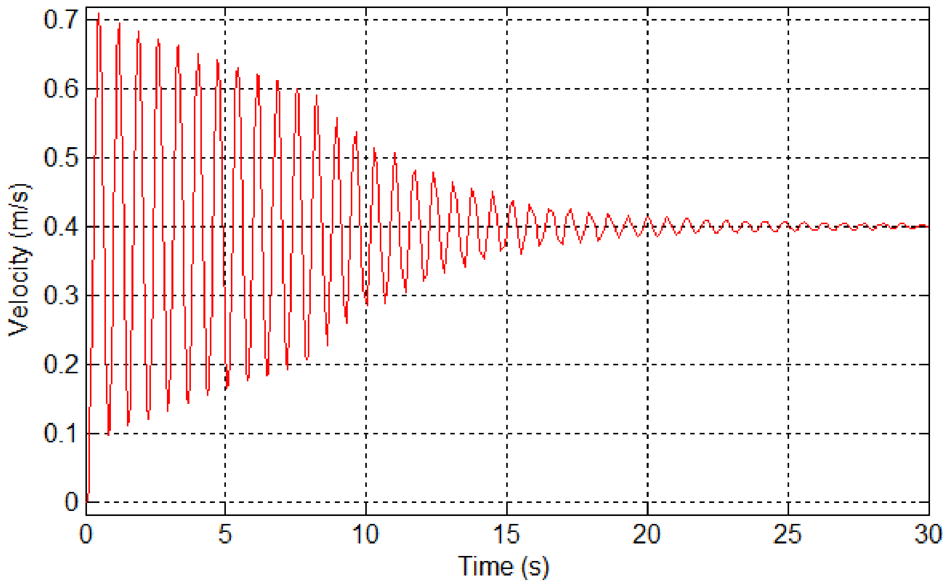


Figure 4.3 Velocity of the Cylinder

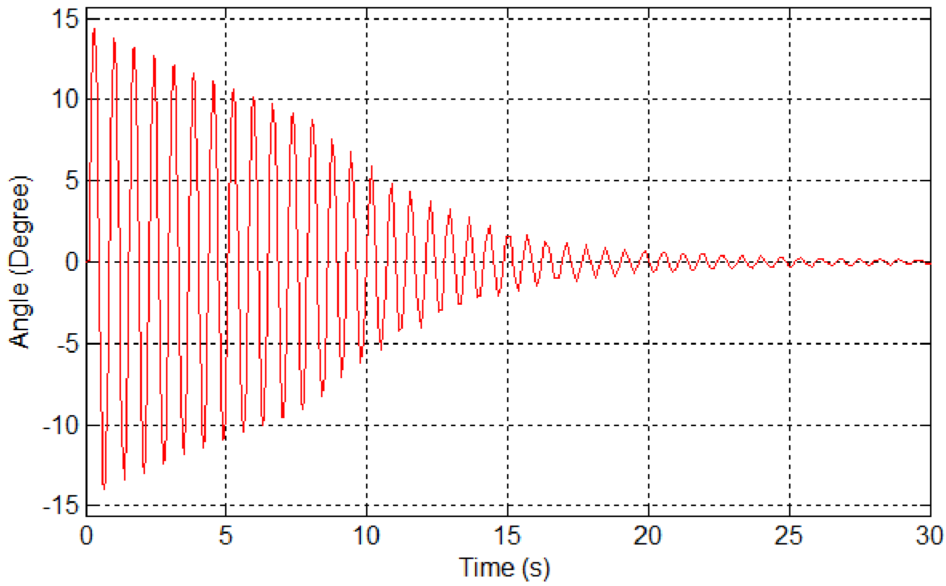


Figure 4.4 Angle of the Pendulum with Respect to Ground

According to the simulation results, pendulum angle didn't exceed 180^{o} and robot is controllable by varying the input voltage below 8V.

Chapter 5: Hardware Implementation and Controller Design

Hardware was implemented for a cylindrical robot as mentioned earlier. This consisted of two processing units, DC motor, reaction wheel and pendulum wheel, motor driver unit, encoder, accelerometer and gyroscope. Power was supplied from a power supply unit, using long wires.

5.1 Hardware Structure

STM32F4-Discovery board was applied as main processing unit. According to received feedback values, DSP generated require PWM and directly applied to the motor driver IC. Motor driver unit applied the pulse to motors. Initially the plan was to use both motor speed and cylinder velocity as feedbacks. But due to incorrect output values of encoder, only cylindrical speed was used to serve the purpose.

Gyroscope and accelerometer were used to measure the speed of the cylinder. Using sensor fusion technique signals were processed in Arduino board and send to Discovery board as serial data. Using bot accelerometer and gyroscope, considerably accurate feedback was gained.

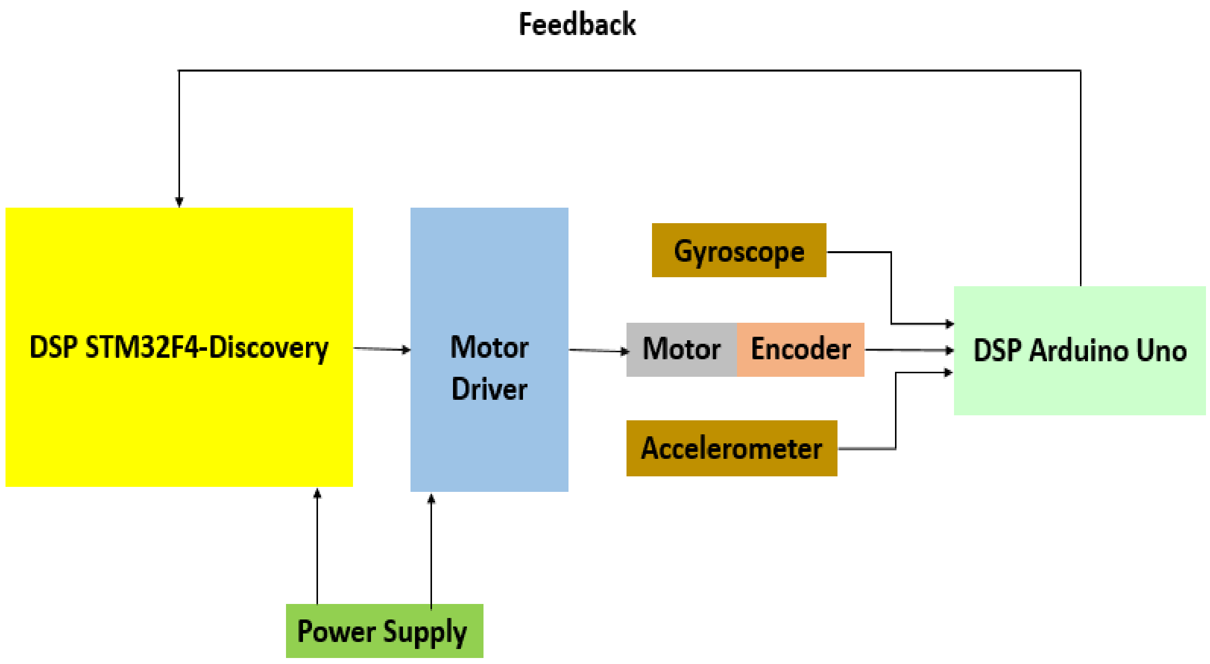


Figure 5.1 Hardware Structure of the Robot

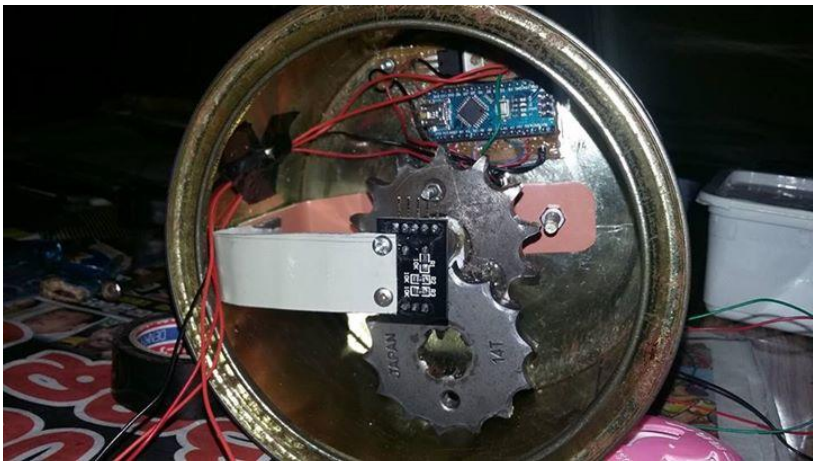


Figure 5.2 Cylindrical Robot

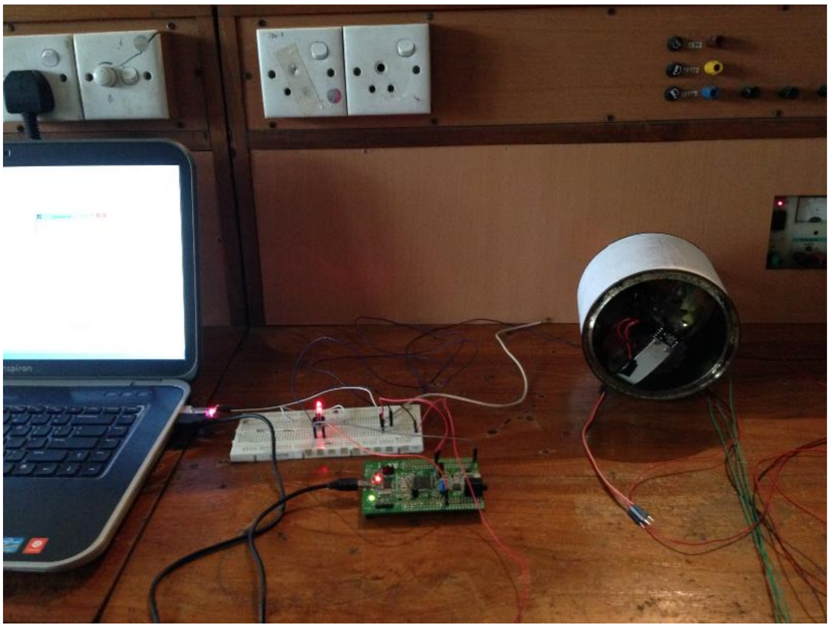


Figure 5.3 Robot with Control Board

5.2 Parameter Estimation

Parameters of the motor and cylinder were estimated as accurately as possible. But there were some mismatches. For motor parameter estimation unit step response was used. Matlab and DSpace were used to aid the process.

5.2.1 Motor Parameters

Table 5.1 Motor Parameter Values

Moor Parameter	Value
Inductance	0.28 H
Resistance	12 Ω
Back emf Constant	1.4
Torque Constant	1.4
Moment of Inertia	0.00212 Kgm^2

5.2.2 System Parameters

Table 5.2 System Parameter Values

System Parameter	Value
Mass of Cylindrical Shell	0.075 Kg
Mass of IDU	0.2 Kg
Mass of Pendulum Wheel	0.1 Kg
Mass of Reaction Wheel	0.1 Kg
Moment of Inertia of IDU and Shell	0.004 Kgm^2
Moment of Inertia of Pendulm and Reaction Wheels	0.0018 Kgm^2

In system parameter values, mass values were measured using a balance and inertia values were obtained using Solidwork software package. Inertia values has a greater effect on the system and needed to be more accurate than mass values.

To verify obtained model parameters, simulations were done using matlab. Figure 5.4 shows resulting velocities for a given input, which was 8V pulse applied for 2s. Due to limitations in hardware setup, it was difficult to obtain the response for a step function. But this results can be considered to be acceptable.

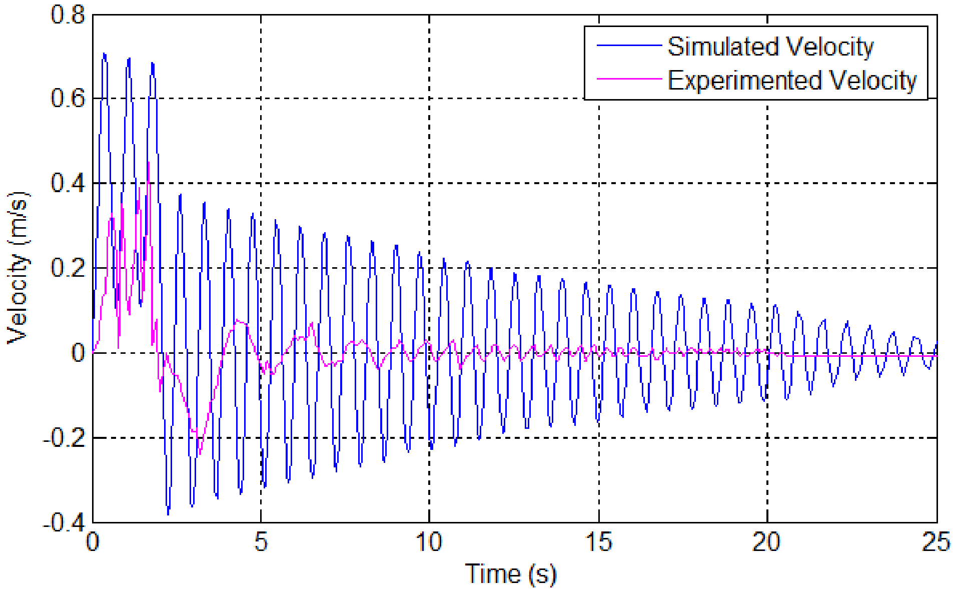


Figure 5.4 Simulated and Experimented Velocities

5.3 Controller Design

A PID controller was designed and implemented for the robot. Since, this is a nonlinear system a transfer function can't be obtained. Values of the controller were manually tuned with the aid of matlab

Table 5.3 PID parameter values

PID Parameter	Value
K_p	1
K_i	0.5
K_d	0.2

Since this is a nonlinear system and can't make reasonable assumptions for system to be considered as linear, this plant model doesn't have poles. But however using a feedback linearization method poles of the whole system can be placed in desired locations.

With the increasing of K_d values system tend to be stable and regulate for a short period of time and roughly after 150s, error between desired value and the actual value started to increase continuously up to maximum error. There for in actual system it's essential to pay attention for that fact and should make sure that system won't behave in an undesirable manner.

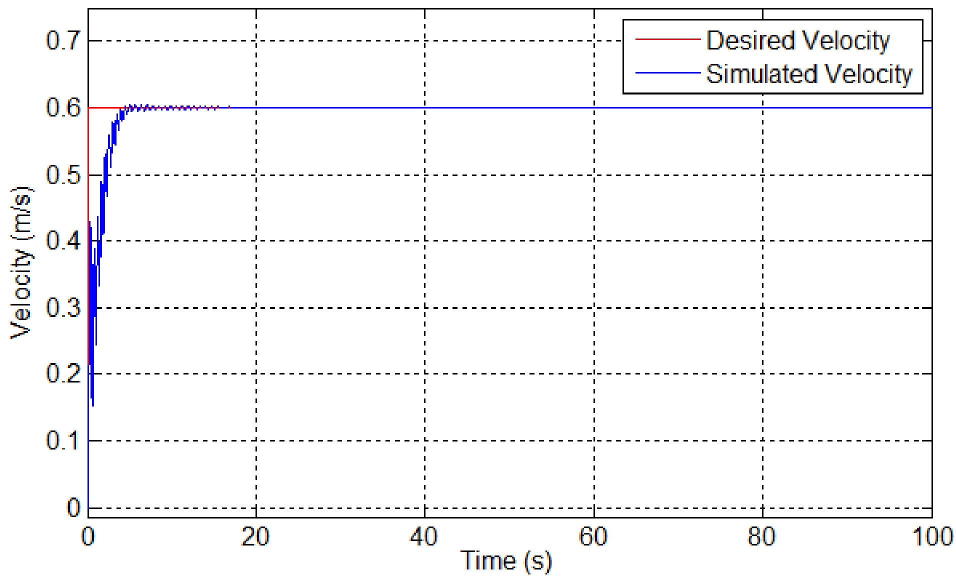


Figure 5.5 Regulating Task

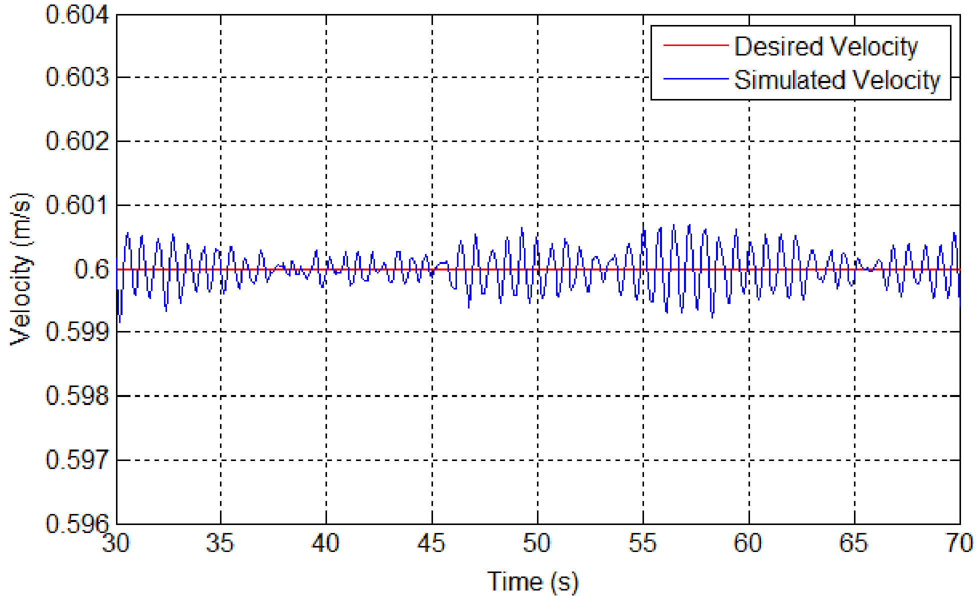


Figure 5.6 Steady State Error

Figure 5.6 shows the steady state error of the system for the above result. Unlike in a linear system steady state error was not a constant value. It looked like a random sinusoidal shape value. So, using proposed PID controller this error can’t be reduced. The reason is integration in the steady state error part is nearly zero.

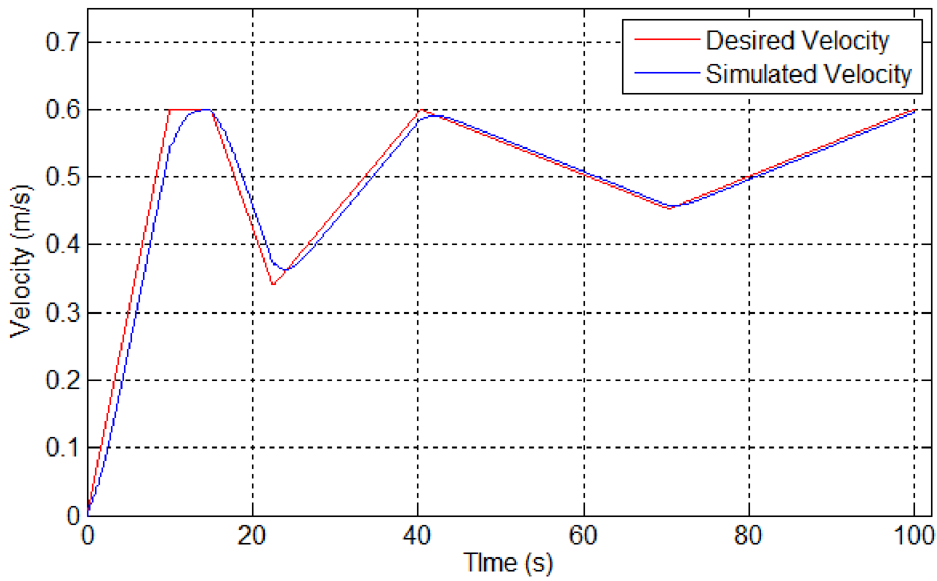


Figure 5.7 Tracking Task

Designed controller was capable of tracking the signal in an accurate manner. However the maximum acceleration or deceleration the system can track is roughly 0.05 m/s^2. When accelerating and decelerating the system it's essential to check whether the pendulum angle exceeds 180^o. Because risk of exceeding that value is higher when accelerating or decelerating than rolling in a constant velocity.

Chapter 6: Results

As the final step of the project for this semester, simulation results and experimented results were compared.

6.1 Comparison of Results

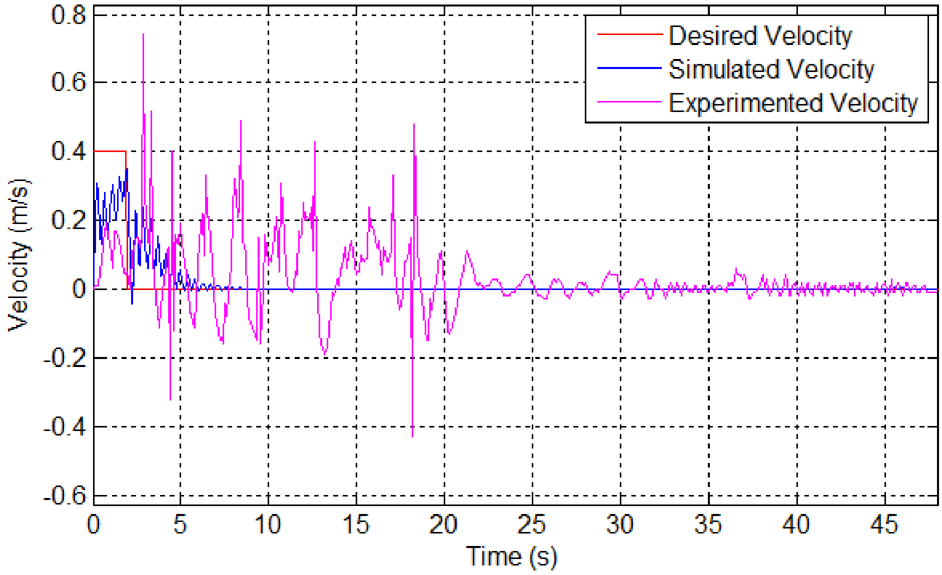


Figure 6.1 Results for Small Pulse

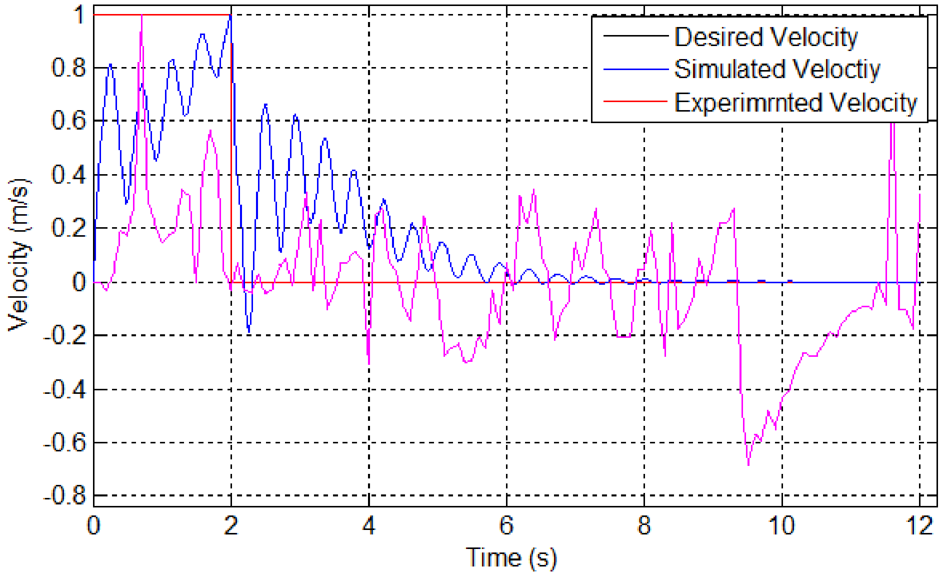


Figure 6.2 Results for Medium Pulse

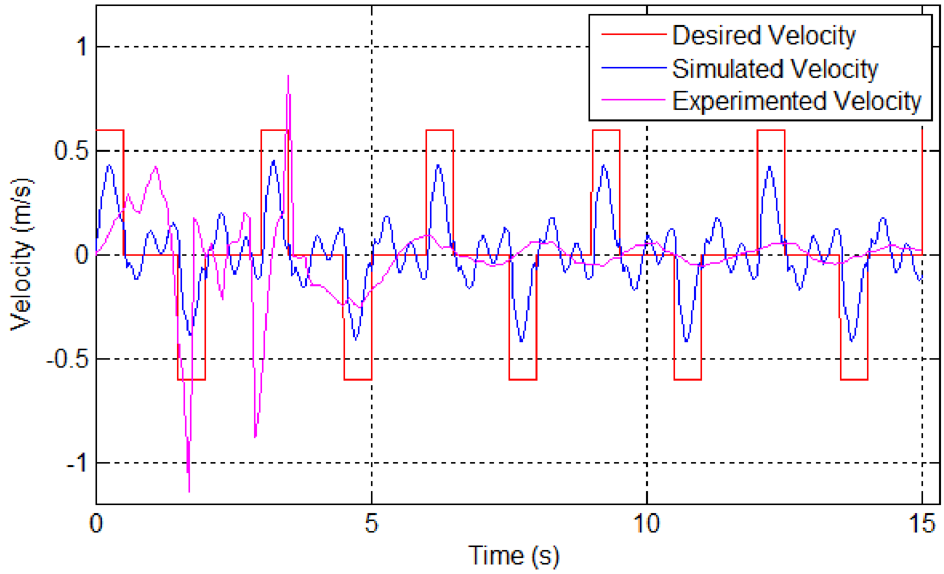


Figure 6.3 Results for Continuously Applied Pulse

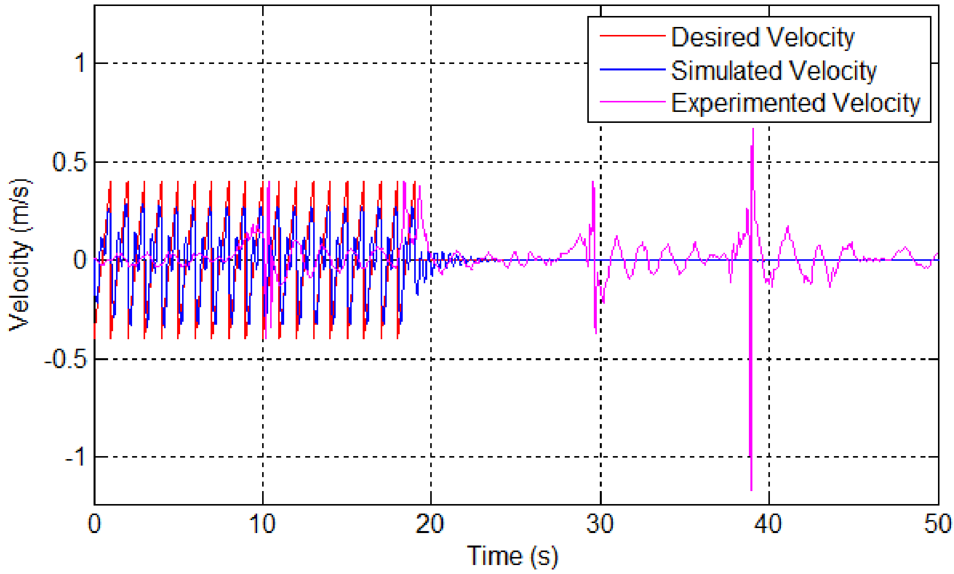


Figure 6.4 Results for a Saw Tooth Signal

Since battery hasn't used to supply power, long wires were used. Because of that it was difficult to obtain results for a long period of time. However with small desired velocity values results were obtained for a longer time period.

Using signals which have positive and negative values also, results were obtained for a longer time period.

6.2 Discussion of Results

Even though there are mismatches these results are acceptable level. When modeling the system frictional effects and some other effects were neglected for the simplicity of the modelling. That causes mismatches is results. These sensors and circuits are not flawless. So it also contribute to reduce the quality of results. Estimated parameter values are also not perfect. Due to time limitations we didn’t get a chance to pay much attention on those issues. But improving model parameters errors can be greatly reduced.

Chapter 7: What's Next?

As the 2nd phase of this project we are planning to model and implement the robot for two dimensional locomotion using 4 wheels. Since spherical prototype should be implemented for that more accuracy is going to be needed. COG of the robot without pendulum wheels should be located at the center of the sphere. Otherwise it'll effect undesirably for the locomotion of the robot.

Since we are planning to locate wheels in opposite directions, when moving along x or y direction other two set of wheels should be stationed to cancel out any contribution to change COG. Otherwise robot can deviate from the desired path. To achieve motor very encoders should be used to measure the position of the wheel. To overcome these sensor error issues we are planning to implement kalman filter. Using sensor fusion also one target.

As controller, we are planning to use a more suitable nonlinear controller, which will benefit very much in path planning. In above mentioned method, robot can't simply rotate along z-axis and change its orientation. Despite of time limitations, we are hoping to attach two more wheels to remedy that problem. In that case robot should be in perfect shape for controlling.

Chapter 8: Conclusions

Spherical robot is a very interesting research area. But these kinds of robots are not much implemented in industrial applications. Main reason for this is limitations of their mobility. To improve the quality of spherical robots their undesirable effects should be minimized. There are more than enough opportunities to develop industrial applications using spherical robots. These robots has many appealing features over other robots. Especially in military applications and apace applications these kind of robots are really useful.

We hope many more researches will be attracted to this area and in near future there will be more and more industrial applications, which uses spherical robots.

Finally, we would like to say our attitude on final year project, is very good and it provided us an enormous opportunity to sharp our theory knowledge with practical applications. And also we am happy to say, now we have confidence in in on completing tasks and it will be benefit for us to face as an engineer in the real world coming up in the future.

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Appendix

Simulink Models

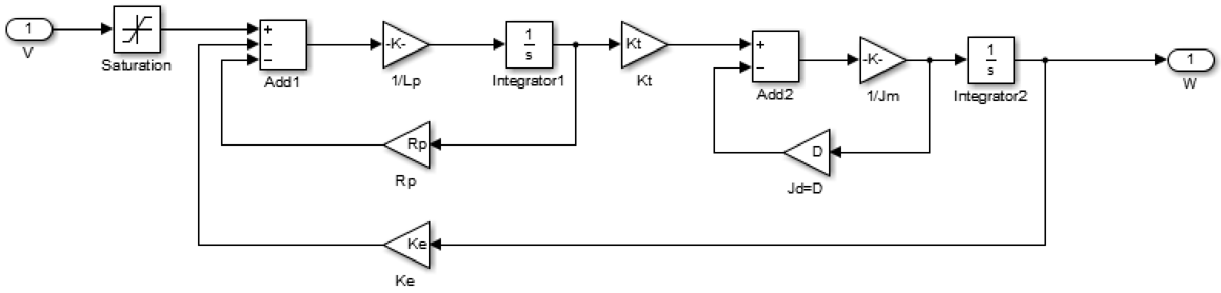

Figure (a) : Motor Model

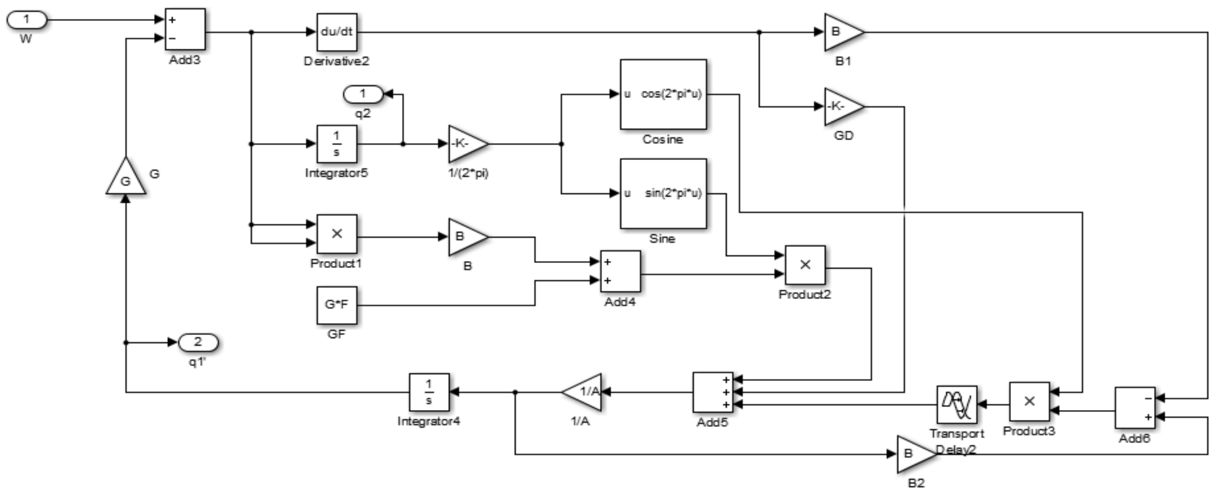

Figure (b) : Plant Model

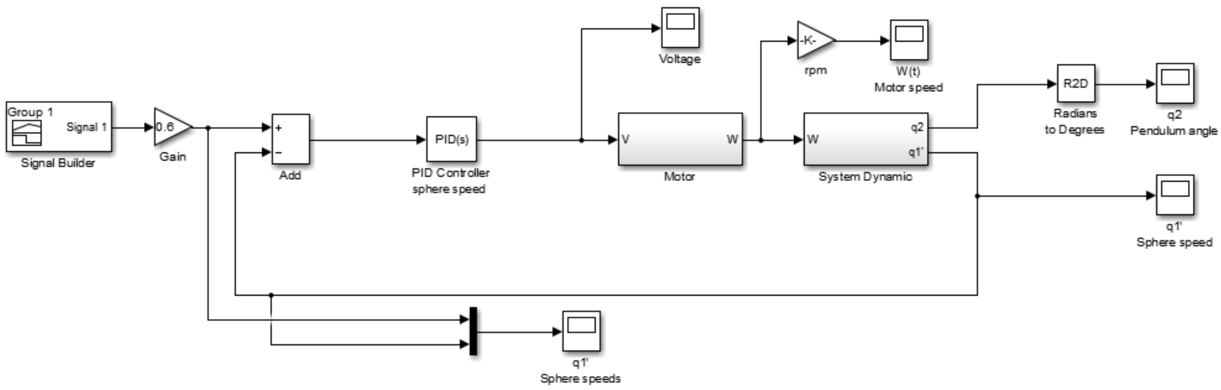

Figure (c) : Complete System Model With Controller

Discovery Model

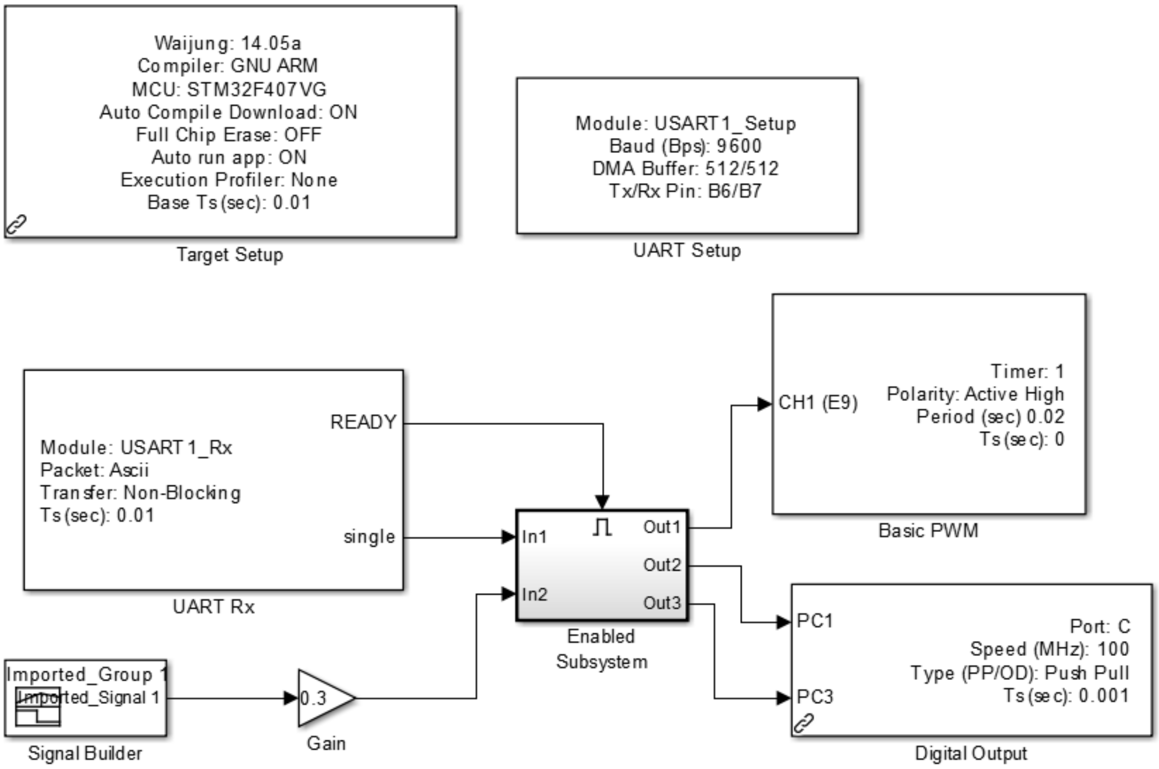

Figure (d) : Uploaded Discovery Model