Single-Wheeled Self-Balancing Platform

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Presentation Outline

- Motivation
- Introduction
- Problem Statement & Objectives
- Scope of Project
- Project Applications
- Methodology
- Results
- Analysis of Results
- Future Enhancements
- Conclusion
- References

Motivation

Manual Unicycle

Motorized Unicycle

- Travelling short distance using light weight vehicles
- Less pollution due to electric system
- Light weight and portable
- Use of less mechanical components making system less expensive and more mechanically reliable

Introduction

- Improved technology in the field of transportation

- Such unicycle facilitates micro-mobility

- PID control algorithm is used obtained the desired output

Problem Statement & Objectives

- **Problem Statement:**
  - To integrate all the modules like reading data from sensors, calculating the PID values and controlling the actuators in order to get required output
  - To balance the system upright

- **Project Objectives:**
  - To design a PID controller that balances a single wheeled platform
  - To analyse the system behaviour during application of external forces

Scope of Project

- **Project Capabilities:**

  - Is capable of self-balancing at standstill position

  - Can overcome external disturbances

- **Project Limitations:**

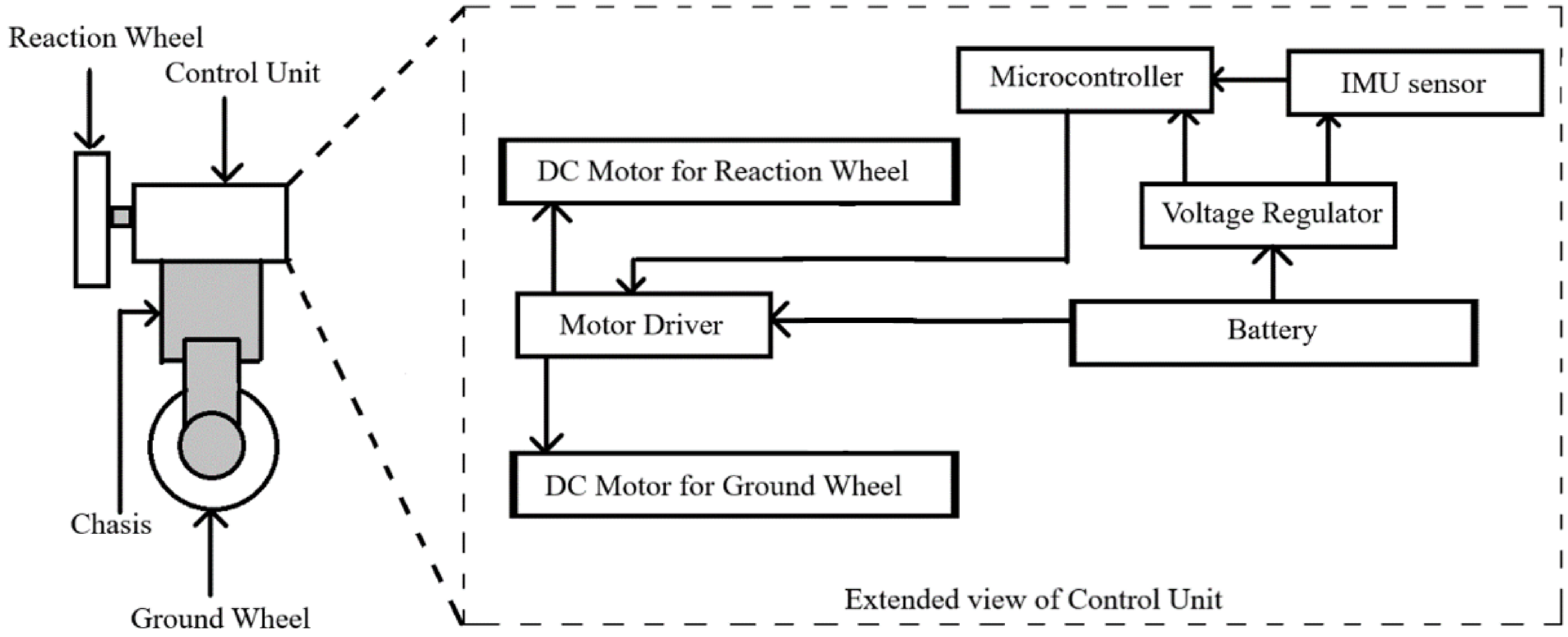
  - Cannot be controlled remotely

  - Is not capable of navigating autonomously

Potential Project Applications

- Commuting Robots
  - Faster and easier than walking
  - To transport around areas where vehicles are not allowed
- Patrol Transporters
  - Can be used as an alerting device while patrolling
- Service Robots
  - Autonomous trolley at malls, hospitals, airports
- Explorer Robots
  - To get through narrow paths where multi-wheeled systems don’t fit

Methodology - [1]
(System Block Diagram)



Methodology - [2]
(Hardware Requirements)

S.N.	General Component	Component Name	Qty	Usage of the component in the project
1.	IMU Sensor	MPU 6050	1	To measure the angular velocity and acceleration of the bot in three axes
2.	Microcontroller	Arduino Nano	1	To interface with the sensor and motor driver and to do the necessary calculation
3.	DC Motor	12V DC Geared Motor	2	To control the two wheels of the bot: ground wheel & reaction wheel
4.	DC Motor Driver	L298N	1	To control the two DC motors used
5.	Battery	Lithium Polymer (mAh)	3	To give a power source to the system
6.	Ground Wheel	Spoke Wheel for Toys	1	To generate necessary displacement in order to balance the bot in pitch axis
7.	Reaction Wheel	Acrylic sheet(circular)	1	To generate necessary torque in order to balance the bot in roll axis

Methodology - [3]
(Software Requirements)

S.N.	General Software	Software used	Purpose
1.	IDE & Compiler	Arduino IDE	To generate the machine level instruction for microcontroller
2.	Libraries	I^2C	To establish communication between sensor unit & microcontroller
3.	Programming Language	C/C++	To write programming logic for the system in high level language
4.	CAD and Simulation	Autodesk Fusion 360 and MATLAB	For the design, testing and simulation of the system in order to get the required output

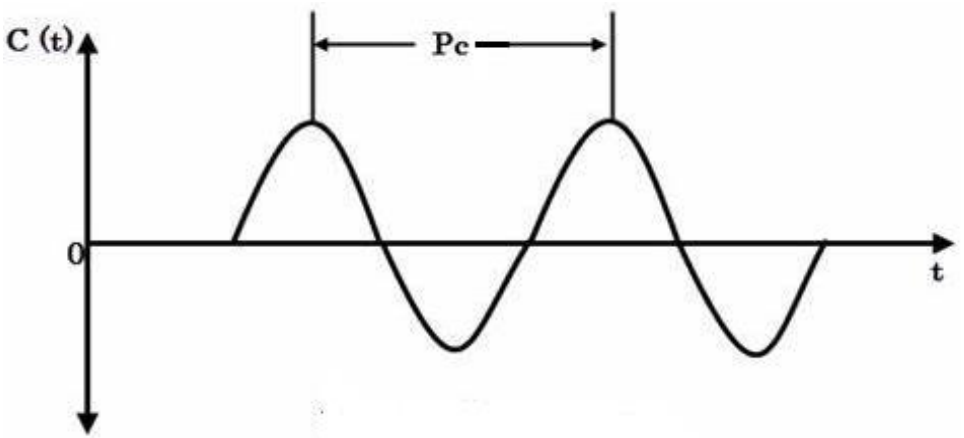
Methodology - [4]
(PID Tuning)

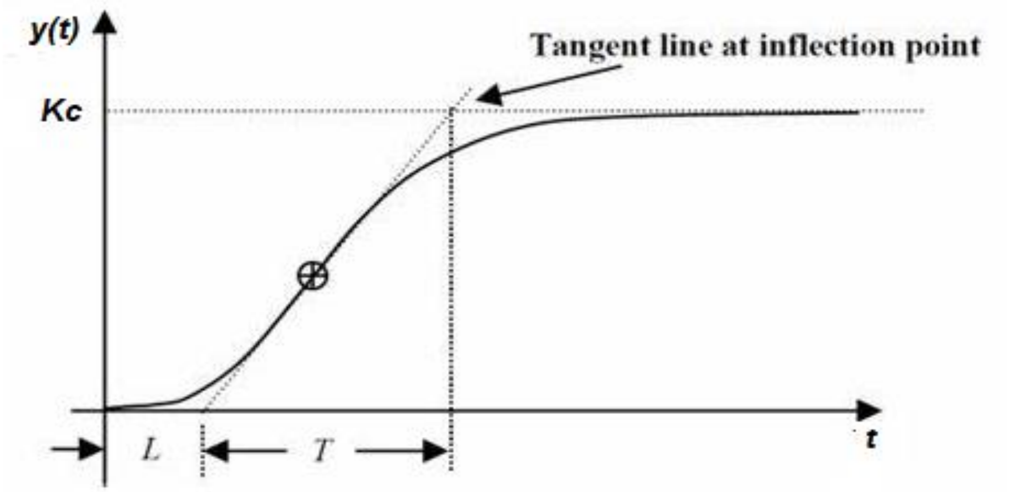
- **Ziegler-Nichols tuning method**
  - To determine initial set of working parameters
  - To adjust and correct the error between the measured value and the desired value

- **Advantages**
  - Tuning rules are very simple

- **Disadvantages**
  - Very sensitive to parameter variations
  - Further fine tuning is needed

Methodology - [5]
(Critical Value Estimation in Ziegler- Nichols)

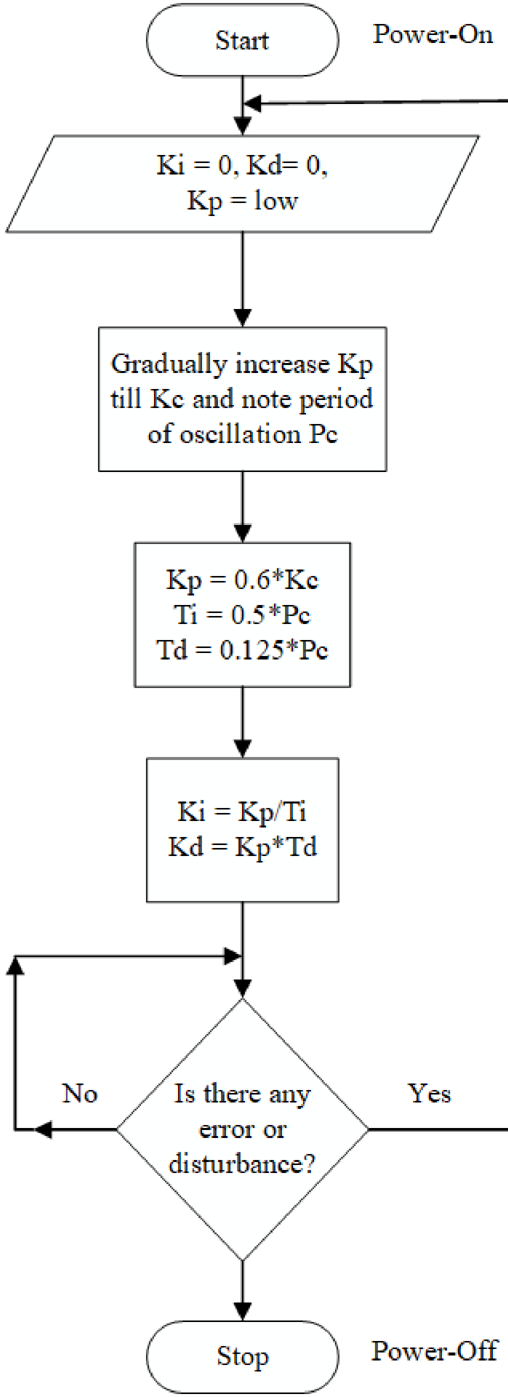




- Proportional Gain is increased till the output response is sinusoidal
- The corresponding gain is called critical gain (Kc)
  - time period of the output response is denoted as Pc
  - Both are used to determine the PID tuning parameters

- A tangent line is drawn at the inflection point of the S-shaped curve
- The value of delay time (L) and time constant (T) is determined from the graph
  - values of Kp, Ki and Kd are adjusted

Methodology - [6] (Flowchart for PID Tuning)



Type of Controller	K_p	T_i	T_d
P	$0.5\ K_C$	∞	0
PI	$0.45\ K_C$	$0.83\ P_C$	0
PID	$0.6\ K_C$	$0.5\ P_C$	$0.125\ P_C$

S.N.	Parameters	Description
1.	K_p	Proportional Gain
2.	K_i	Integral Gain
3.	K_d	Derivative Gain
4.	K_C	Critical Gain
5.	T_i	Time constant of integration
6.	T_d	Time constant of derivation
7.	P_C	Period of oscillation

Methodology - [7]
(Linearized Equation of Roll Dynamics)

$$\ddot{\theta}_r = \frac{-\tau_{lat}}{-J_{eq,lat}} + \frac{(m_1 L_1 + m_2 L_2) g(\theta_r)}{J_{eq,lat}}$$

- In the above equation, θ_r is roll angle of unicycle and $\ddot{\theta}_r$ is double derivative of roll angle

$$\ddot{\varphi}_{rw} = \left[\frac{1}{J_2} + \frac{1}{J_{eq,lat}}\right](\tau_{lat}) - \frac{(m_1 L_1 + m_2 L_2) g \sin(\theta_r)}{J_{eq,lat}}$$

- In the above equation, $\ddot{\varphi}_{rw}$ is double derivative of reaction wheel angle of unicycle

Methodology - [8]
(State Space Representation of Roll Dynamics)

$$\begin{bmatrix} \dot{\theta}_r \\ \ddot{\theta}_r \\ \dot{\varphi}_{rw} \\ \ddot{\varphi}_{rw} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 2.5428 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -2.5428 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta_r \\ \dot{\theta}_r \\ \varphi_{rw} \\ \dot{\varphi}_{rw} \end{bmatrix} + \begin{bmatrix} 0 \\ -1.1714 \\ 0 \\ 1262.8851 \end{bmatrix} (\tau_{lat})$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \theta_r \\ \dot{\theta}_r \\ \varphi_{rw} \\ \dot{\varphi}_{rw} \end{bmatrix}$$

Methodology – [9]
(Linearized Equation of Pitch Dynamics)

$$\ddot{\theta}_p = \frac{m_4 g L_4}{J_{eq,lon_2}}\left(\theta_p\right) + (-J_{eq,lon} + m_4 r L_4)(\tau_{lon})$$

- In the above equation, θ_p is pitch angle of unicycle and $\ddot{\theta}_p$is double derivative of pitch angle

$$\ddot{\varphi}_{dw} = \frac{-(J_{eq,lon} + m_4 r L_4) m_4 g L_4}{(J_{eq,lon}{}^2 + J_{eq,lon_2})}\theta_p + \frac{(J_{eq,lon} + m_4 r L_4)^2}{J_{eq,lon}{}^2 J_{eq,lon_2}} + \frac{1}{J_{eq,lon}}(\tau_{lon})$$

- In the above equation, $\ddot{\varphi}_{dw}$ is drive wheel angle of unicycle

Methodology - [10]
(State Space Representation of Pitch Dynamics)

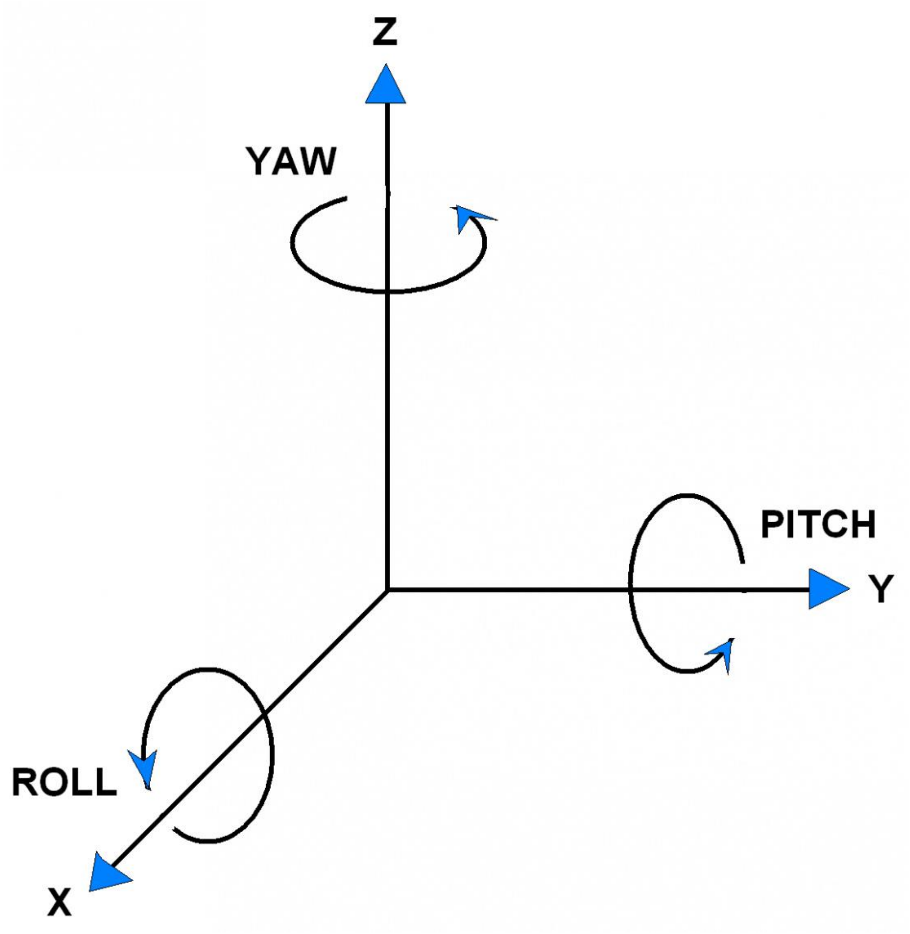
$$\begin{bmatrix} \dot{\theta}_p \\ \ddot{\theta}_p \\ \dot{\varphi}_{dw} \\ \ddot{\varphi}_{dw} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1.7006 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -5.4413 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \theta_p \\ \dot{\theta}_p \\ \varphi_{dw} \\ \dot{\varphi}_{dw} \end{bmatrix} + \begin{bmatrix} 0 \\ 0.0042 \\ 0 \\ 306.7075 \end{bmatrix} (\tau_{lon})$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \theta_p \\ \dot{\theta}_p \\ \varphi_{dw} \\ \dot{\varphi}_{dw} \end{bmatrix}$$

Methodology - [11]
(Physical Parameters)

Symbol	Parameter	Value
m_1	Mass of body with Reaction Wheel as Pendulum	0.856kg
m_2	Mass of Reaction Wheel	0.283kg
m_3	Ground Wheel	0.078kg
m_4	Mass of body with Ground Wheel as Pendulum	1.061kg
r_r	Radius of Reaction Wheel	0.075m
r	Radius of Ground Wheel	0.053m
L_1	Length between COG and body end	0.19m
L_2	Length between COG and center of Reaction Wheel	0.21m
L_4	Length between COG and center of Ground Wheel	0.13m
g	Acceleration due to Gravity	9.8m/s^2
J_1	Inertia of the Body with Reaction Wheel as Pendulum	0.8103kgm^2
J_2	Inertia of Reaction Wheel	0.0008kgm^2
J_3	Inertia of Ground Wheel	0.0002kgm^2
J_4	Inertia of Body with Ground Wheel as Pendulum	0.8109kgm^2
$J_{eq, Lat}$	Equivalent Inertia in Lateral Direction	0.0523kgm^2
$J_{eq,Lon}$	Equivalent Inertia in Longitudinal Direction	0.0034kgm^2

Methodology - [12]
(Reference Co-ordinate System)

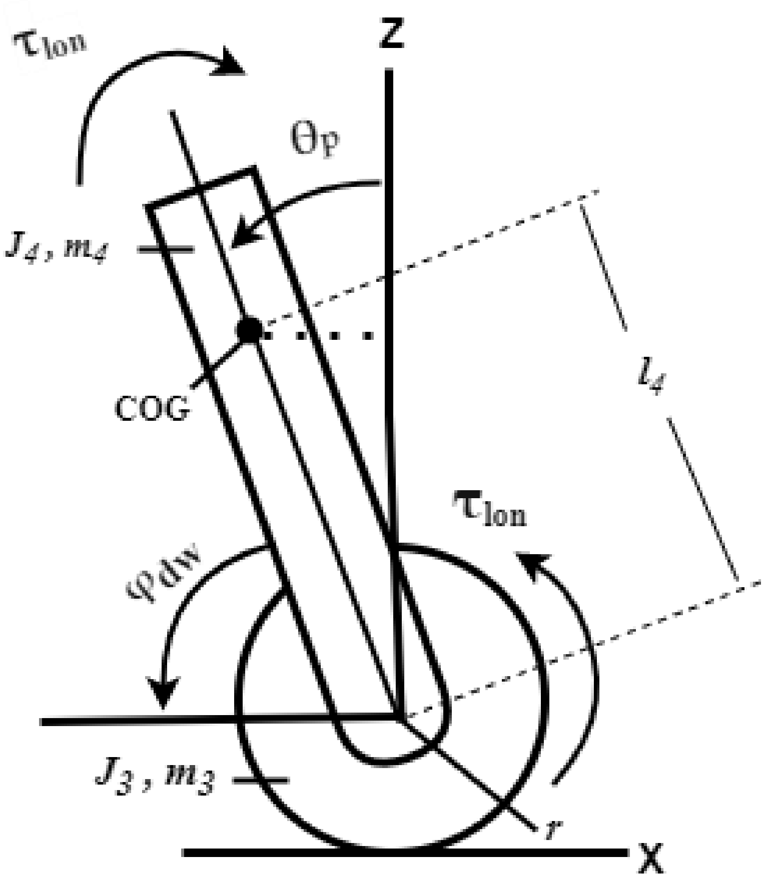


- Roll is the rotation of bot around x-axis with respect to initial starting position of bot

- Pitch is the rotation around y-axis

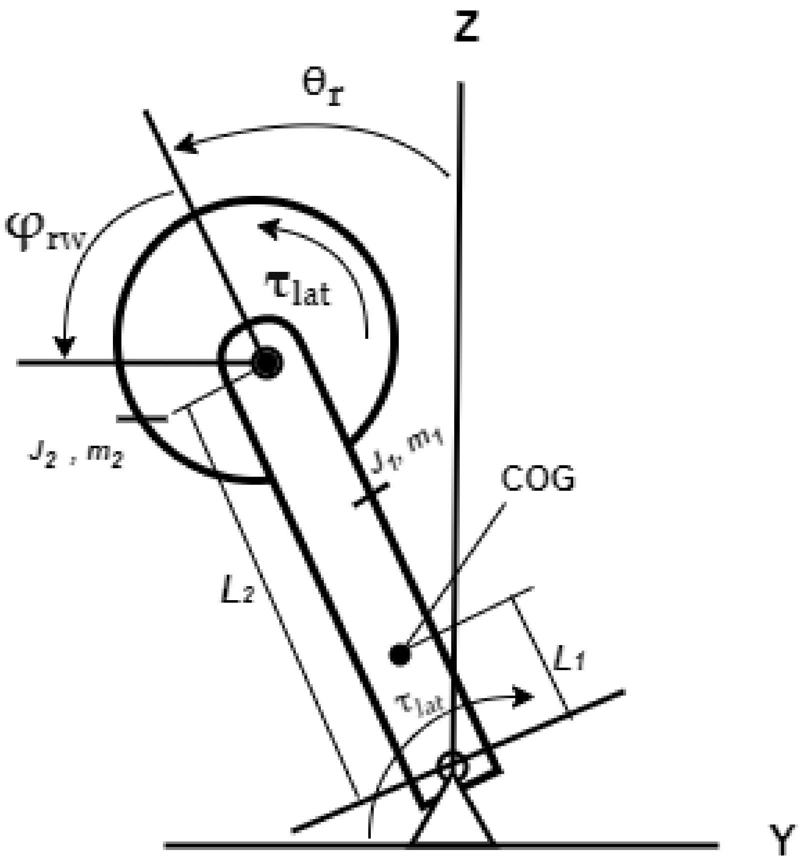
- Rotation around z-axis is not required

Methodology - [13]
(Free Body Diagram of Pitch Dynamics)



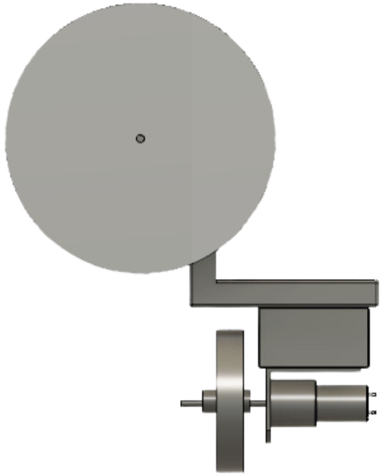
S.N.	Symbol	Description
1.	τ_{lon}	Torque applied in longitudinal direction (Nm)
2.	J_i	Rotational inertia (kgm^2)
3.	L_4	Distance between COG of body & point of rotation of pitch angle (m)
4.	m_4	Mass of body (kg)
5.	m_3	Mass of Ground wheel(kg)
6.	θ_p	Pitch angle of unicycle (rad)
7.	COG	Center of Gravity

Methodology - [14] (Free Body Diagram of Roll Dynamics)

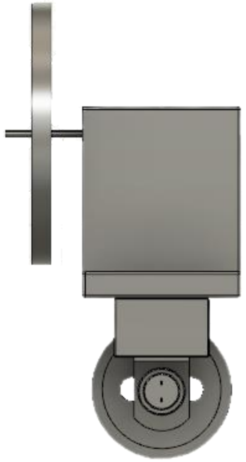


S.N.	Symbol	Description
1.	τ_{lat}	Torque applied in lateral direction (Nm)
2.	Ji	Rotational inertia (kgm2)
3.	L_1	Distance between COG of body & point of rotation of roll angle (m)
4.	L_2	Distance between COG of body & center of reaction wheel(m)
4.	m_1	Mass of body (kg)
5.	m_2	Mass of Reaction wheel(kg)
6.	θ_r	Roll angle of unicycle (rad)
7.	COG	Center of Gravity

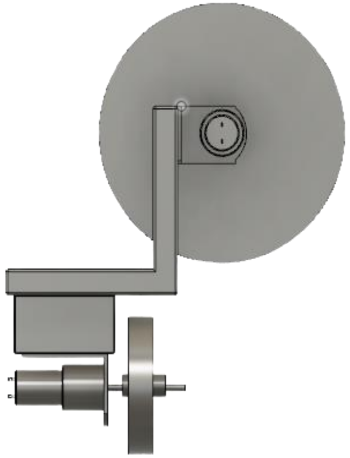
Methodology - [15] (CAD Models of System)



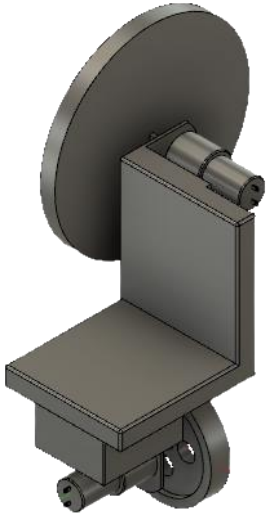
Front View



Right Side View



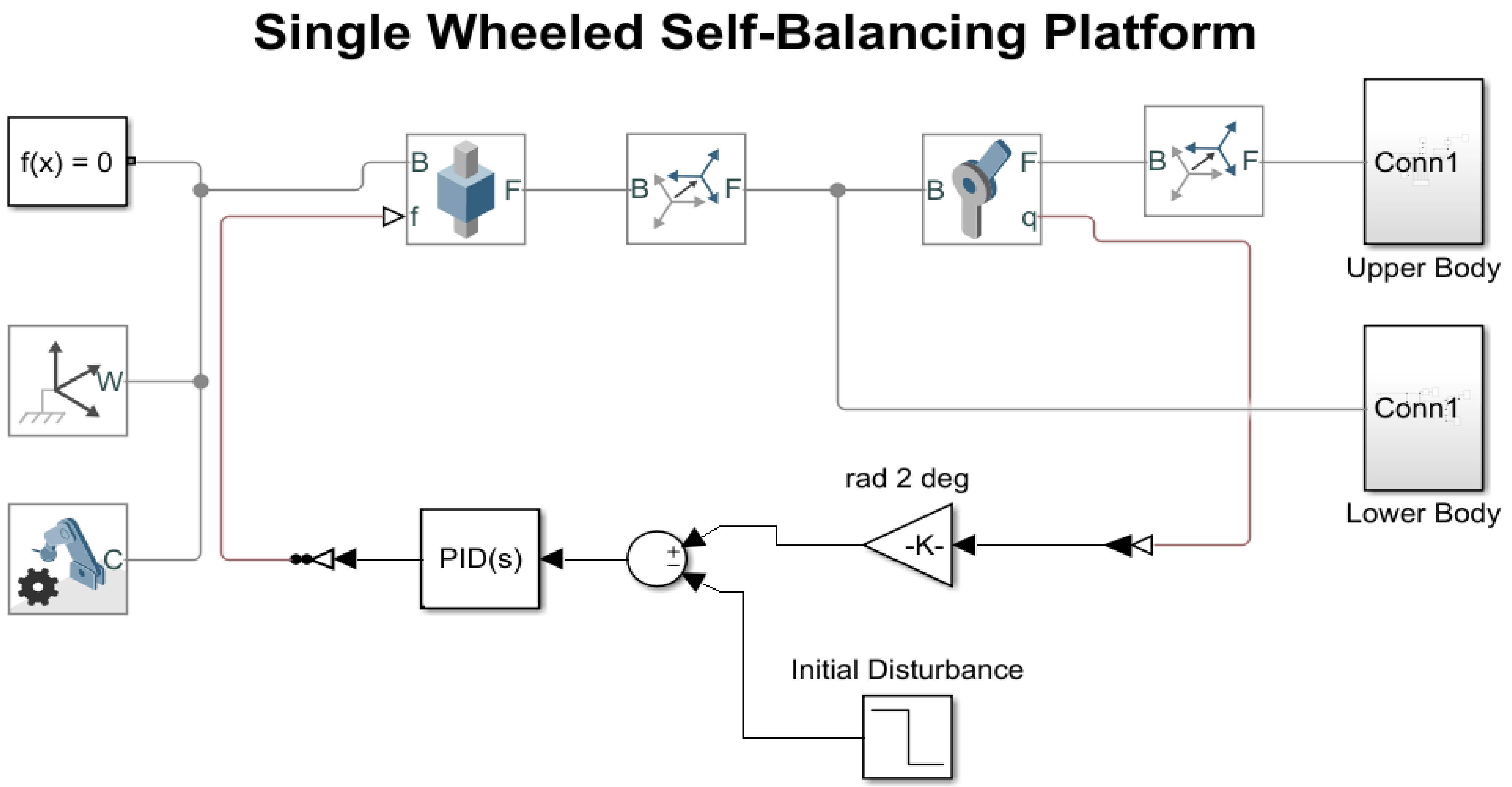
Back View



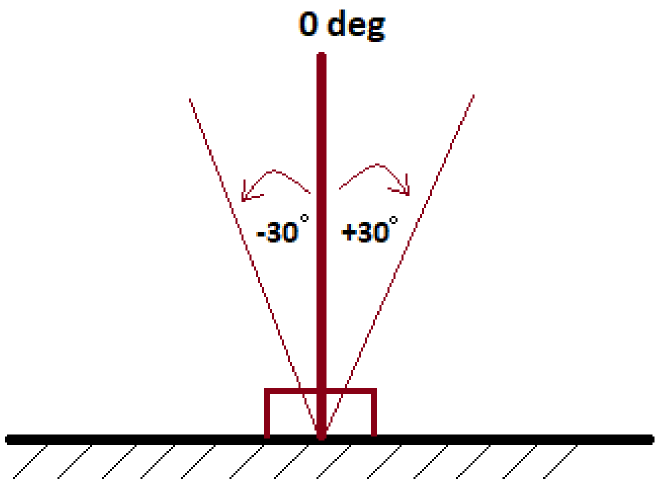
Left View

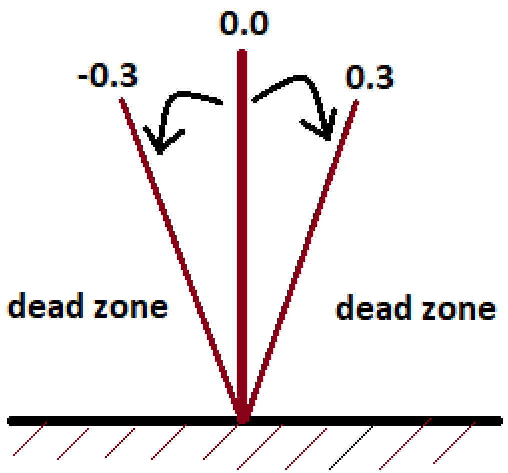
- The CAD designs aided to visualize the structure of system before it was built physically.

Methodology – [16]
(Simulink Block Diagram for Animation)



Methodology - [17] (Interpretation of IMU Orientation)





- Data from bipolar ADC of IMU of a axis in the form of angles from initial starting position

- Angles in the factors of g(1g = 9.8 m/s^2) with respect to z axis

Methodology- [18] (System Model)

Front View

Back View

Right Side View

- Front view shows circuit elements, ground wheel motor, and reaction wheel
- Back view displays positioning of the battery
- Side view clearly shows the ground wheel, as well as reaction wheel motor

Methodology - [19] (IMU value specification)

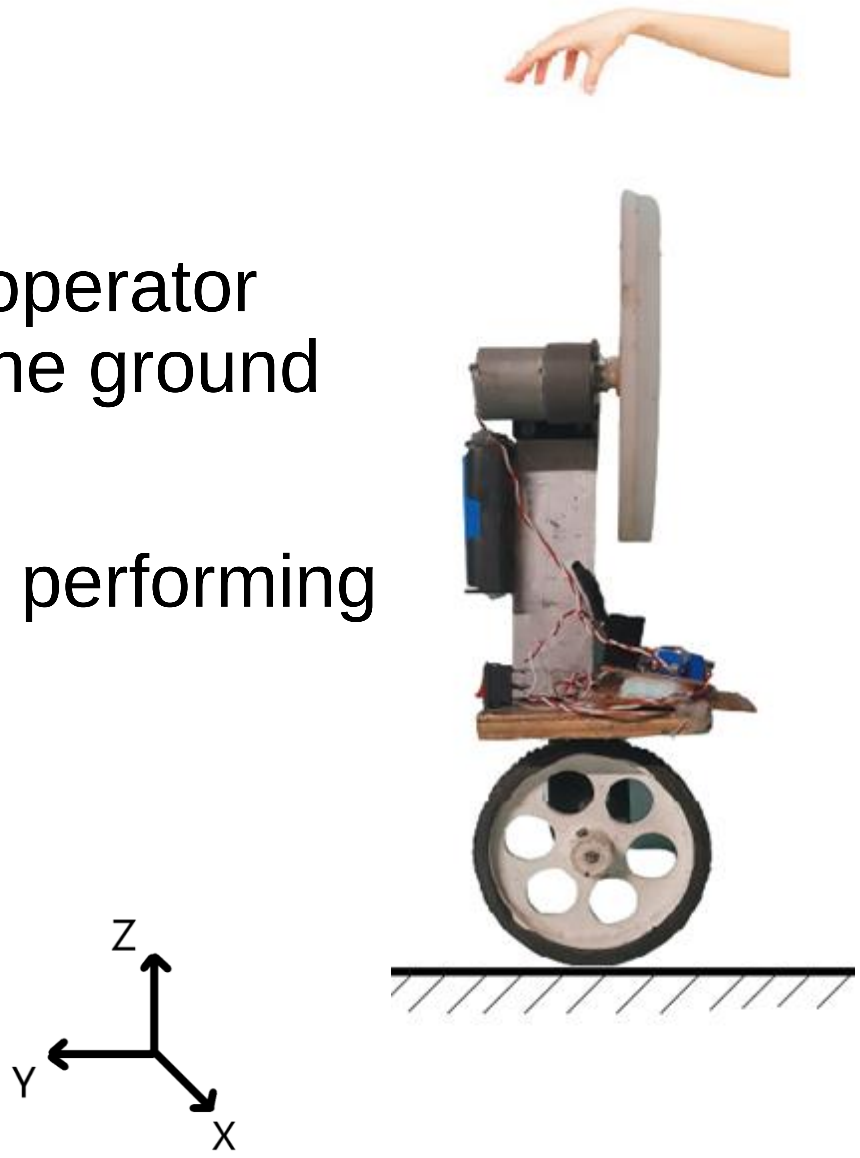
Accel full scale range (g)	Accel sensitivity (LSB / g)
±2	16384
±4	8192
±8	4096
±16	2048

- Sensor is set between full scale range of ±2 g
- The data is read accordingly within this range

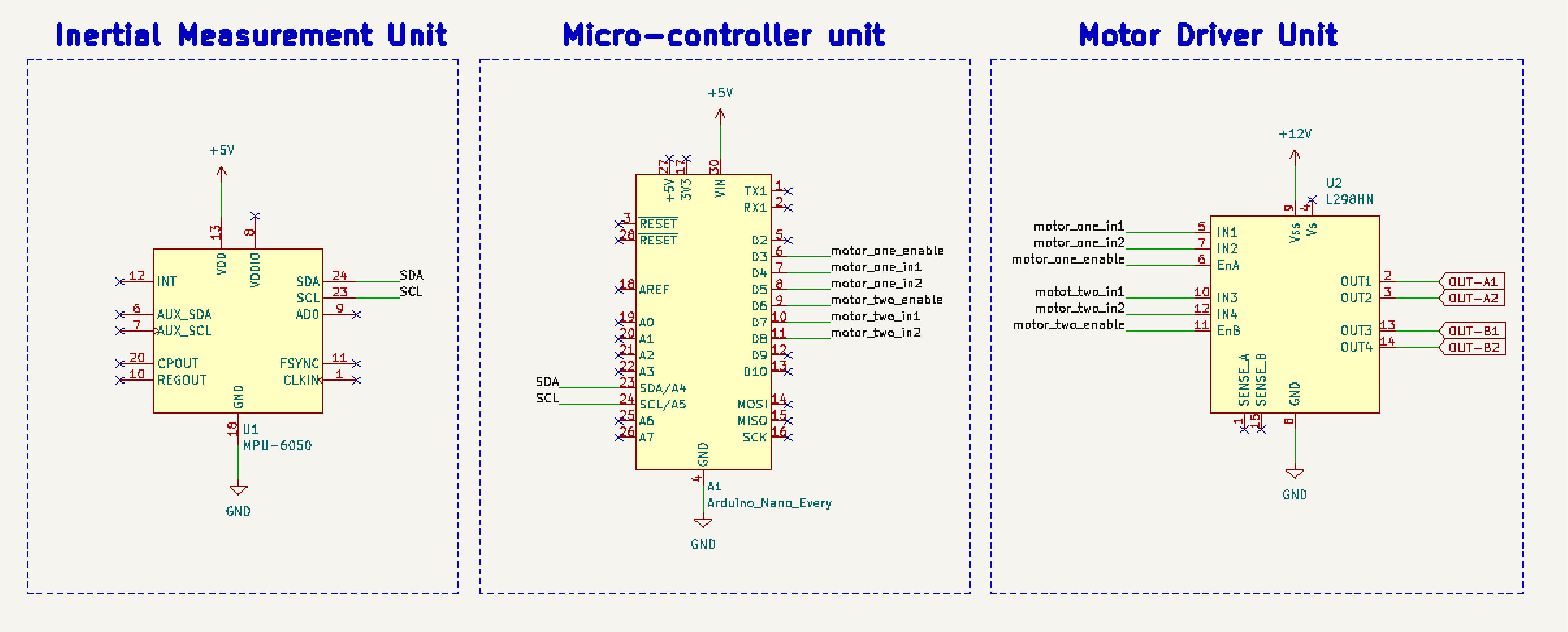
Methodology[20] (Initial Positioning)

- The bot is initially placed by the operator approximately perpendicular to the ground

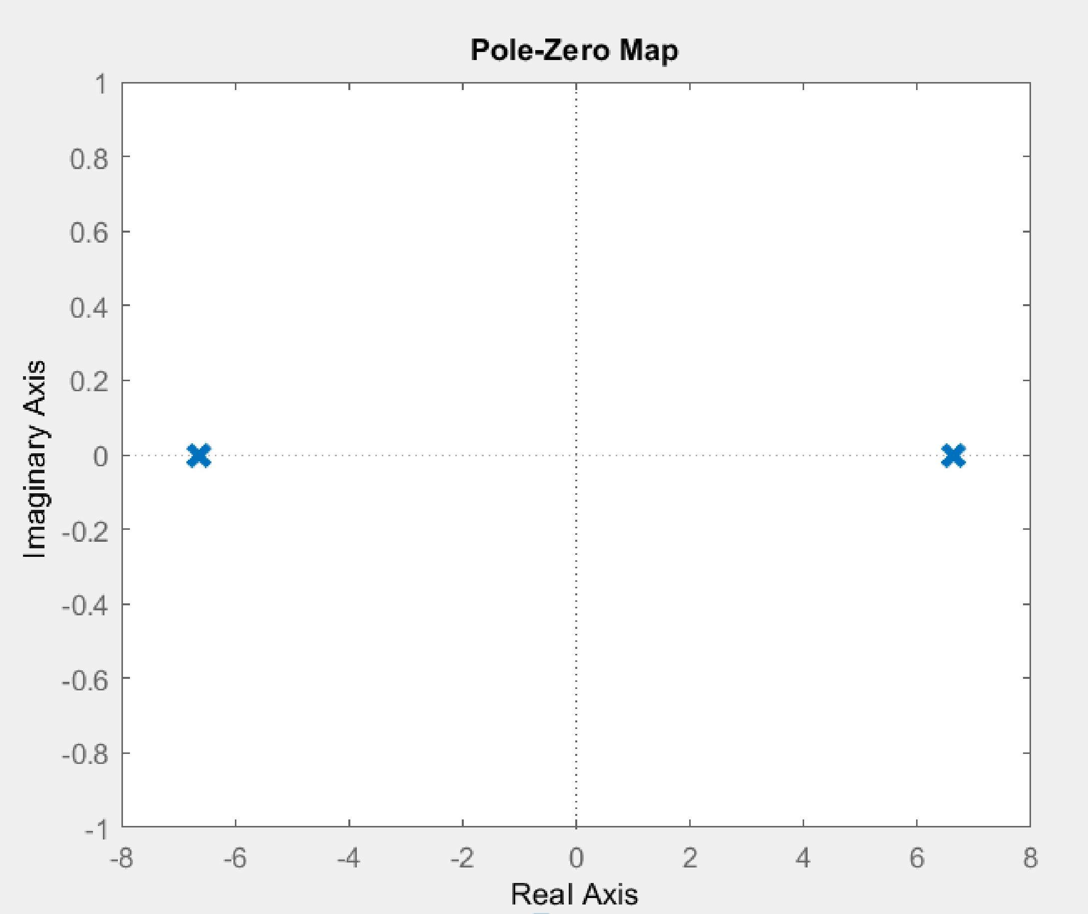
- Afterward it tries to balance itself performing the necessary calculations.

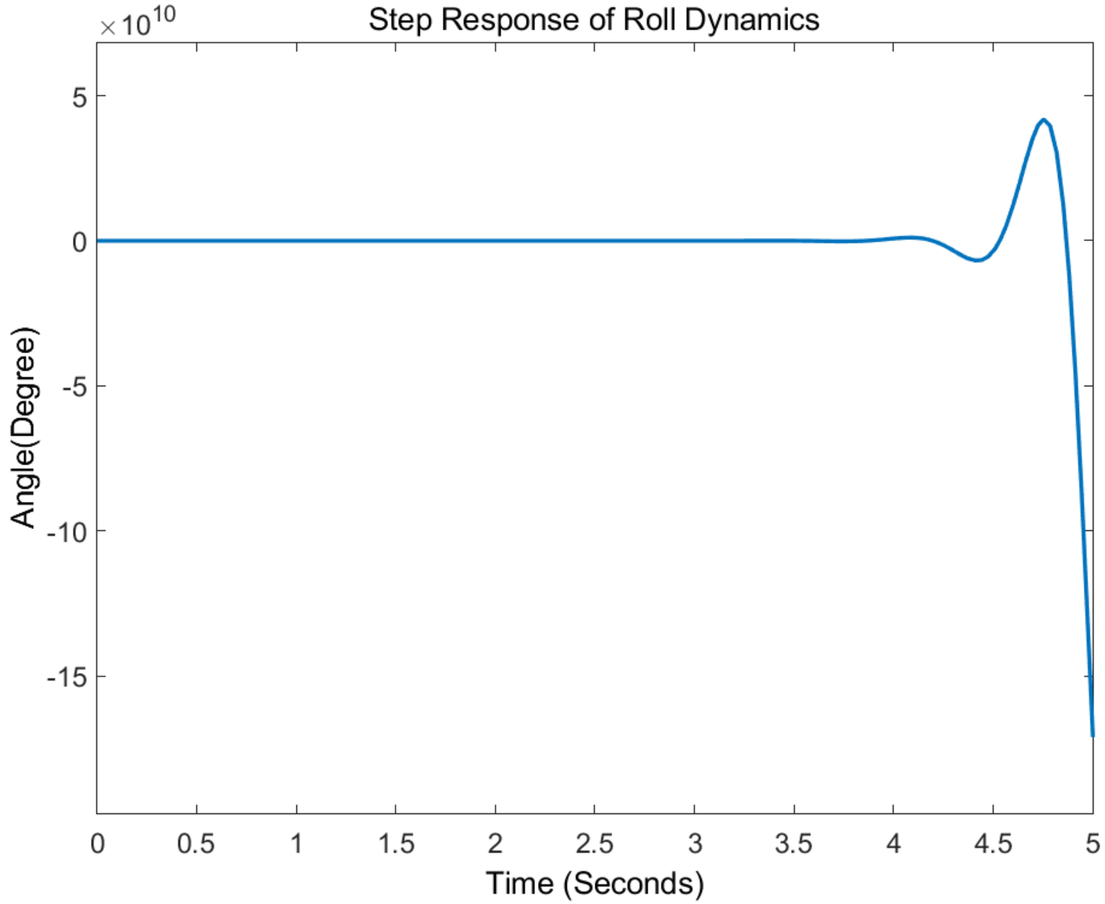


Methodology - [21]
(Circuit Schematic)

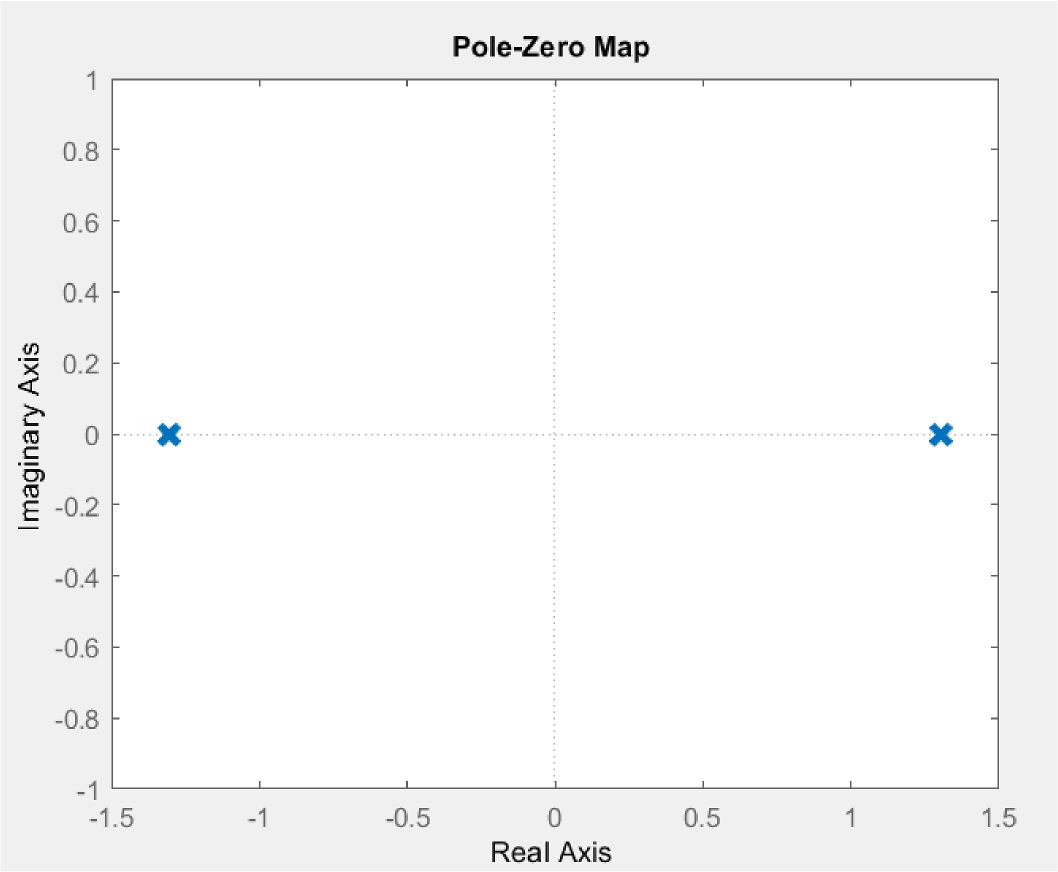


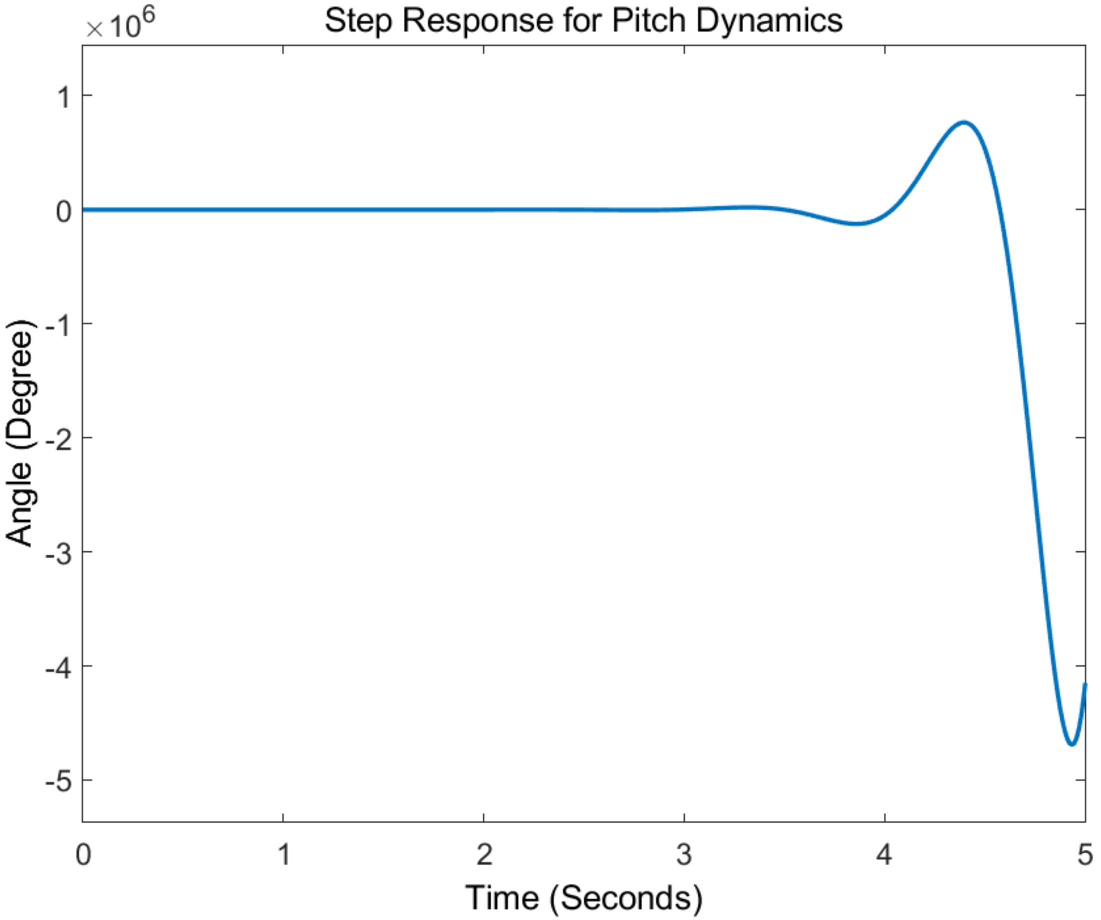
Results [1] (Roll Dynamics Before Tuning)



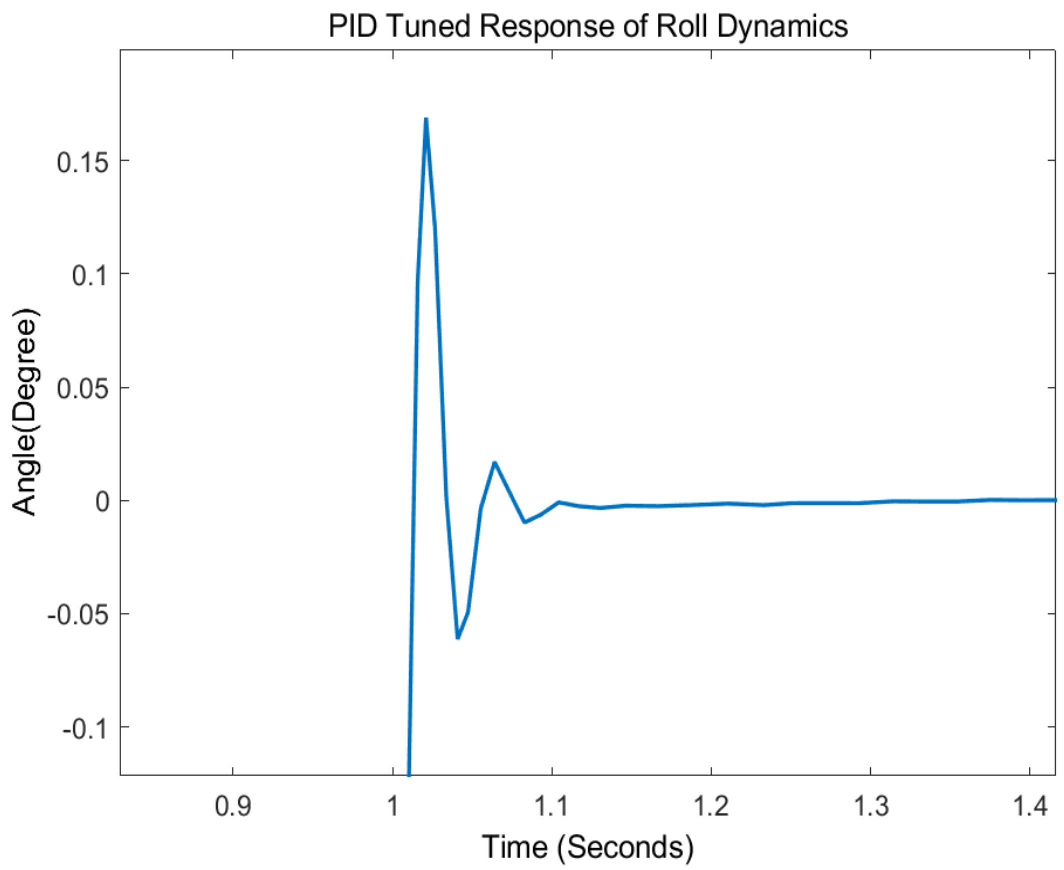


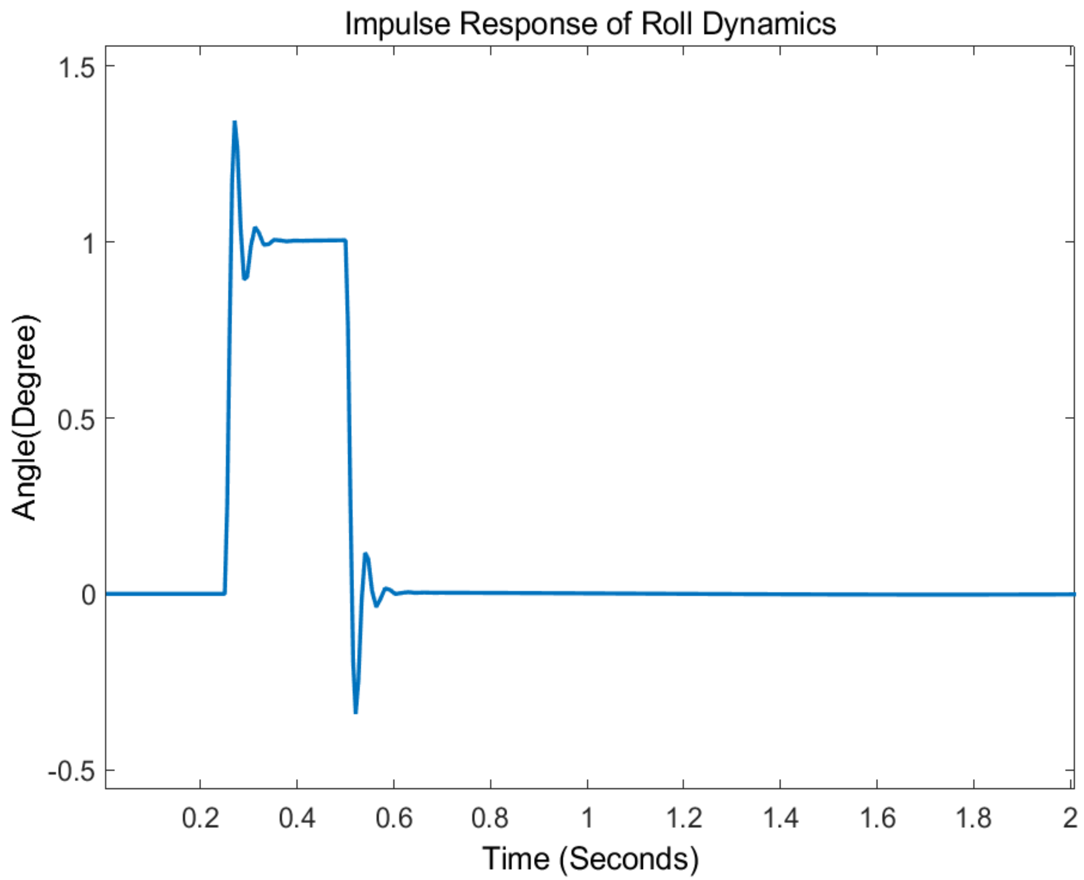
Results [2]
(Pitch Dynamics Before Tuning)



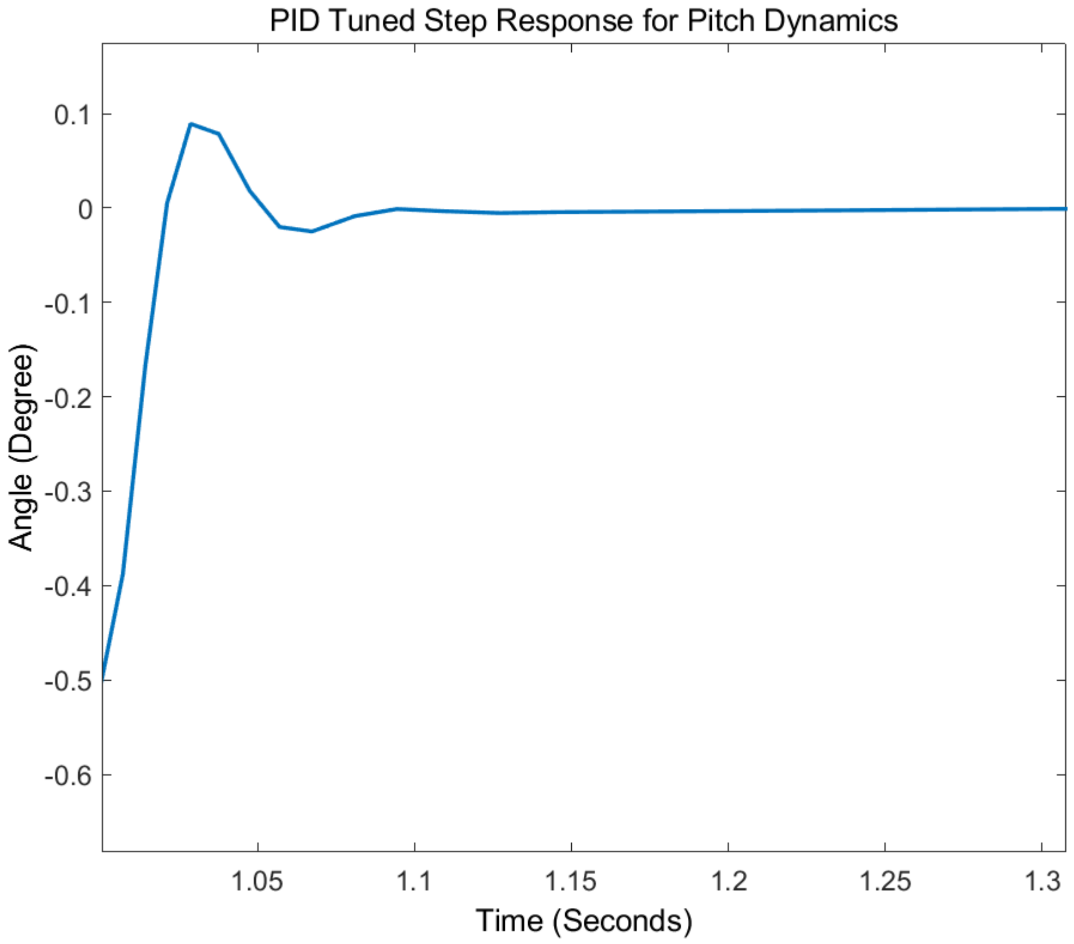


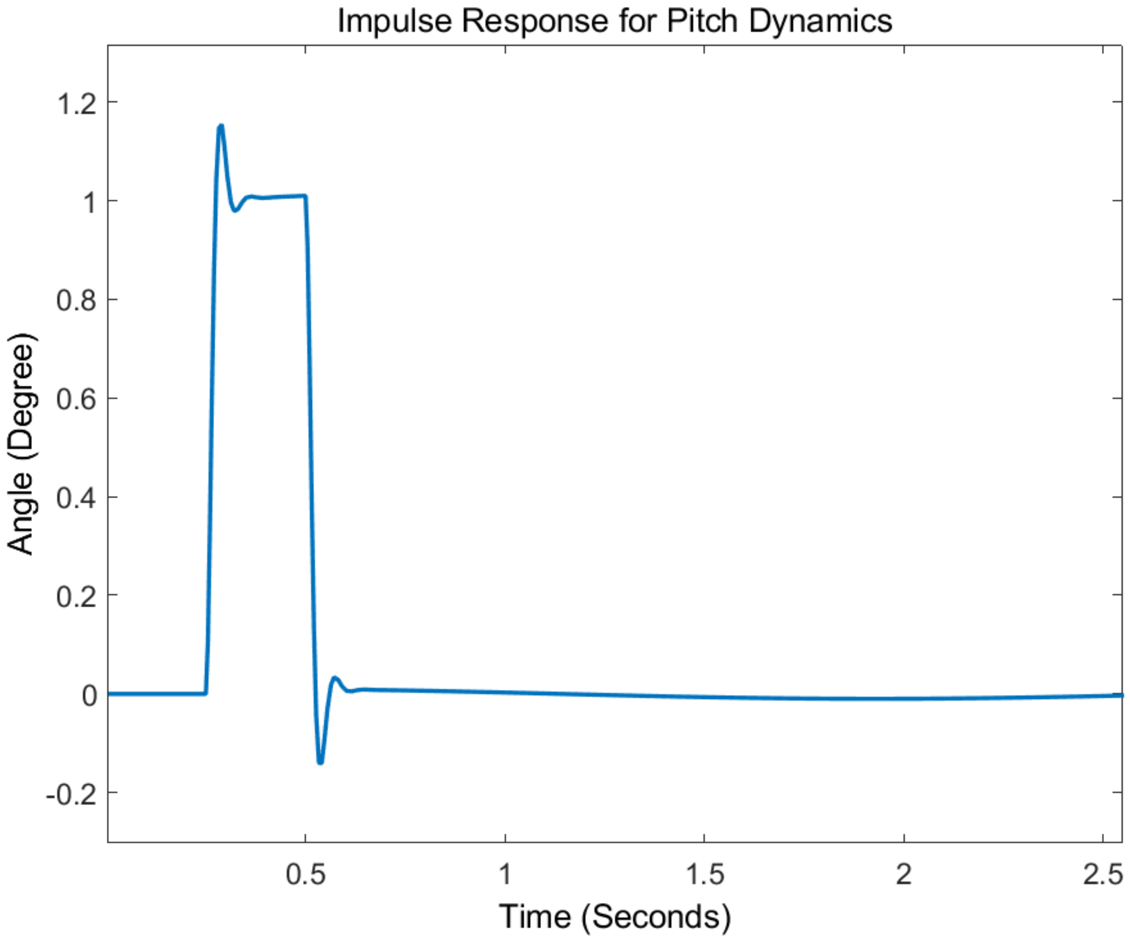
Results [3]
(Roll Dynamics Post PID tuning)



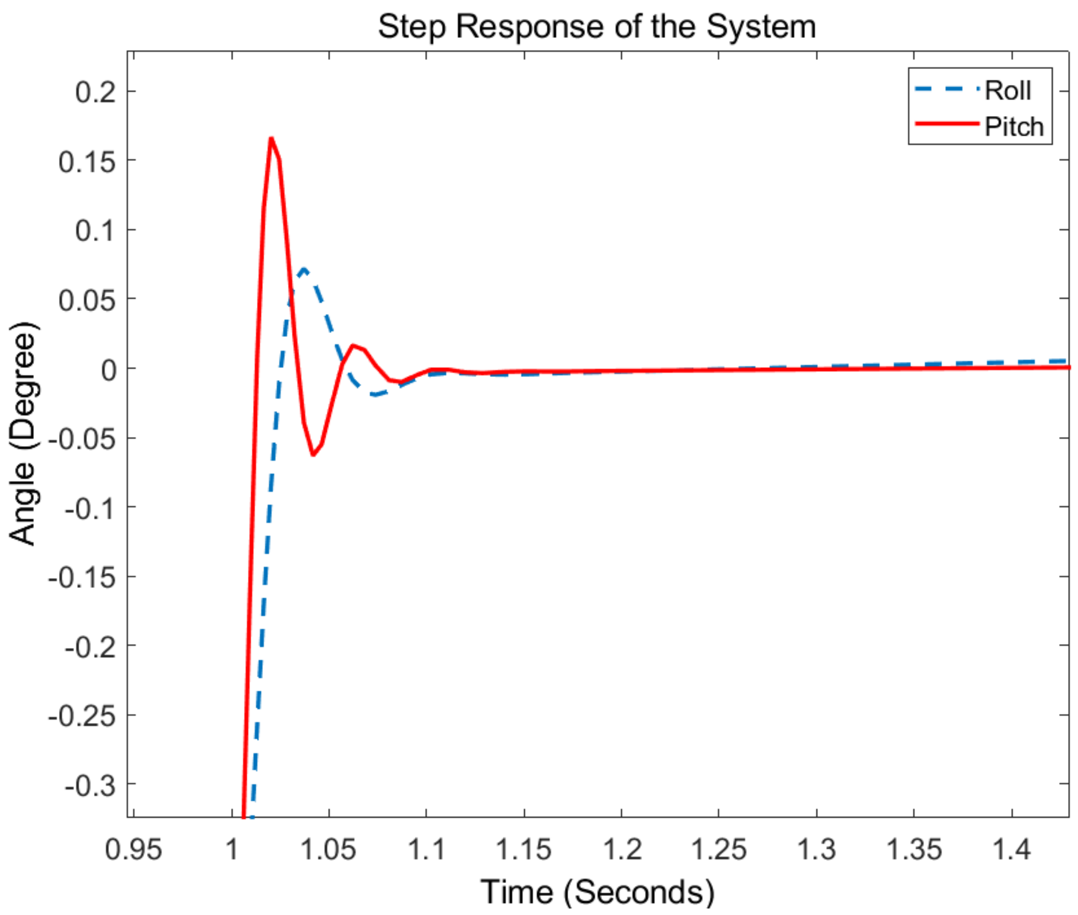


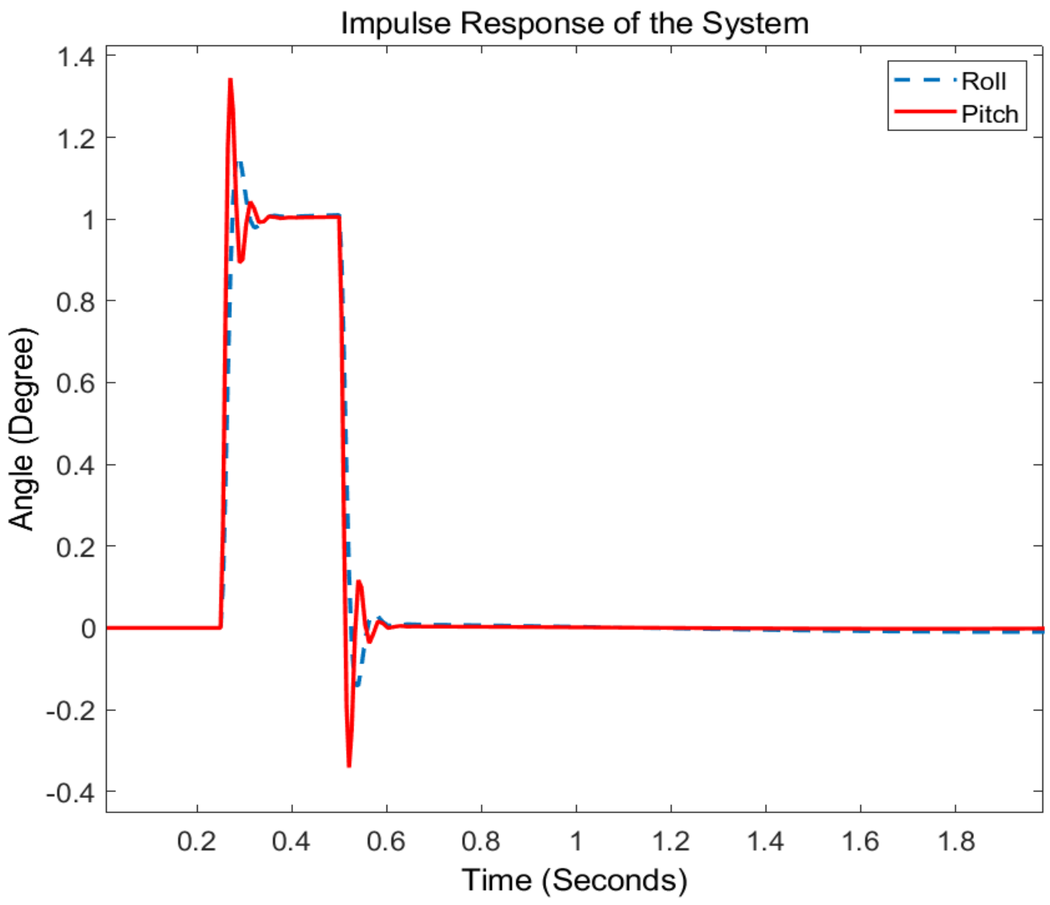
Results [4]
(Pitch Dynamics Post PID tuning)



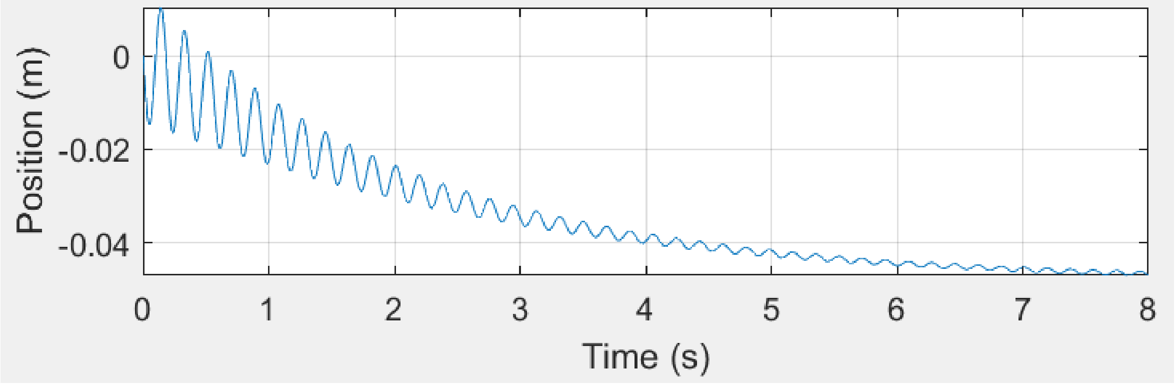


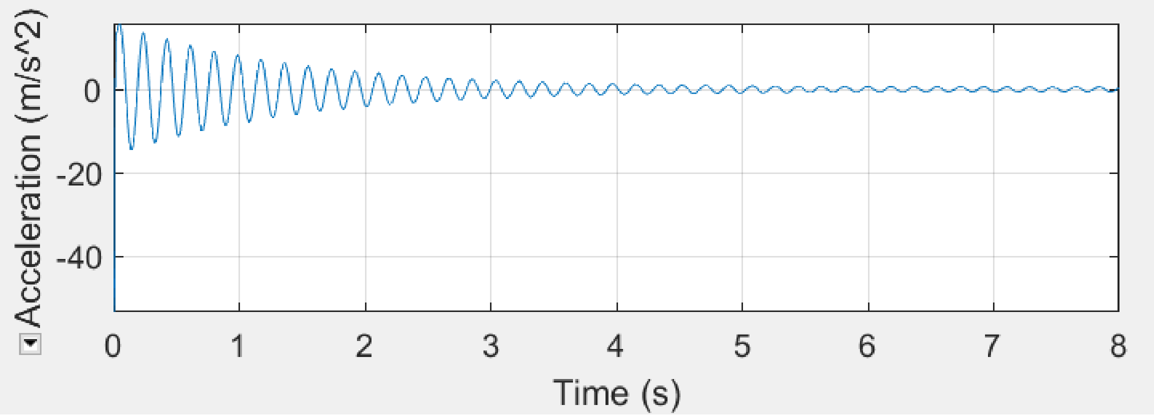
Results [5]
(Roll Dynamics and Pitch Dynamics)

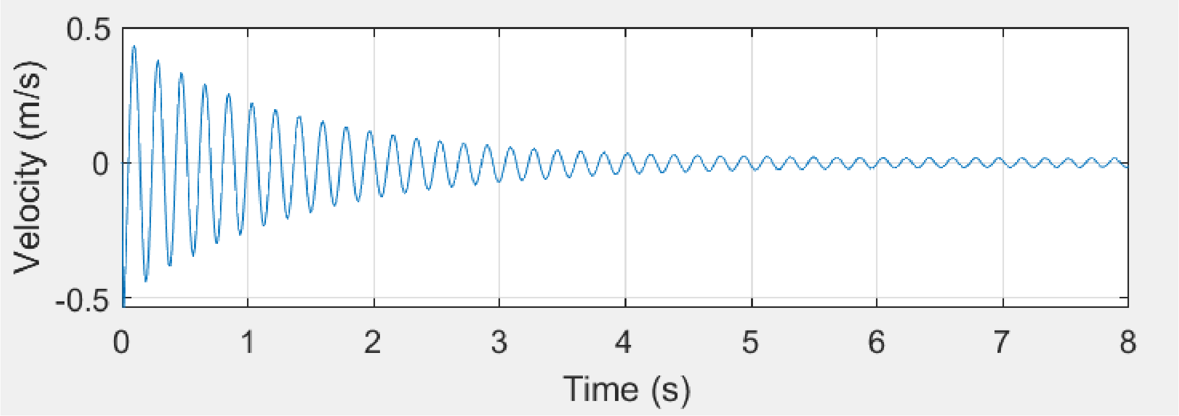


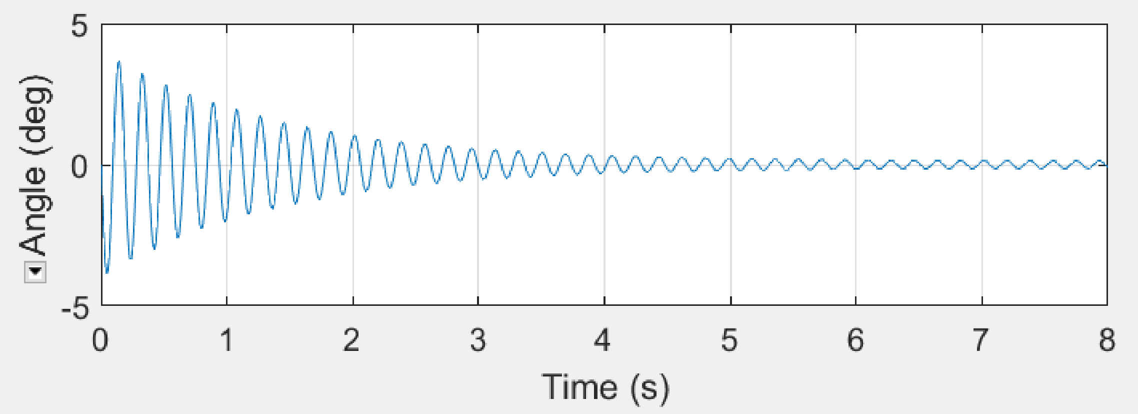


Results [6]
(Graph from Animation for Roll Dynamics)

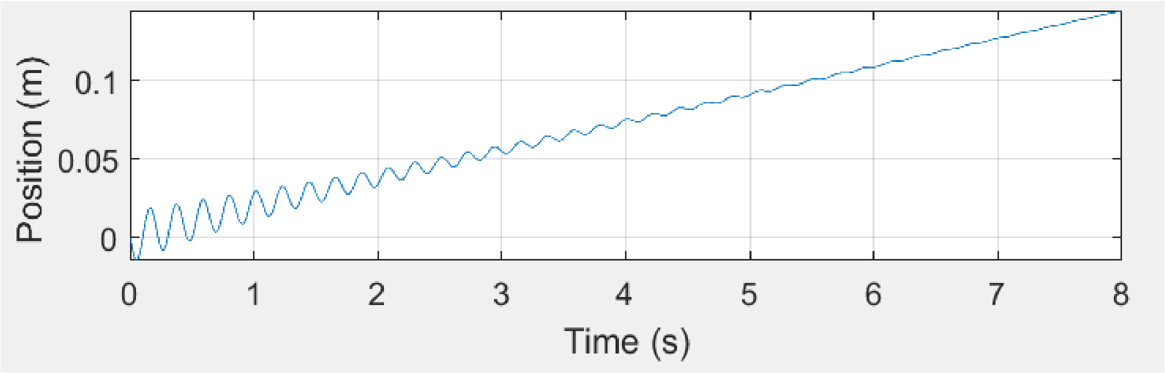


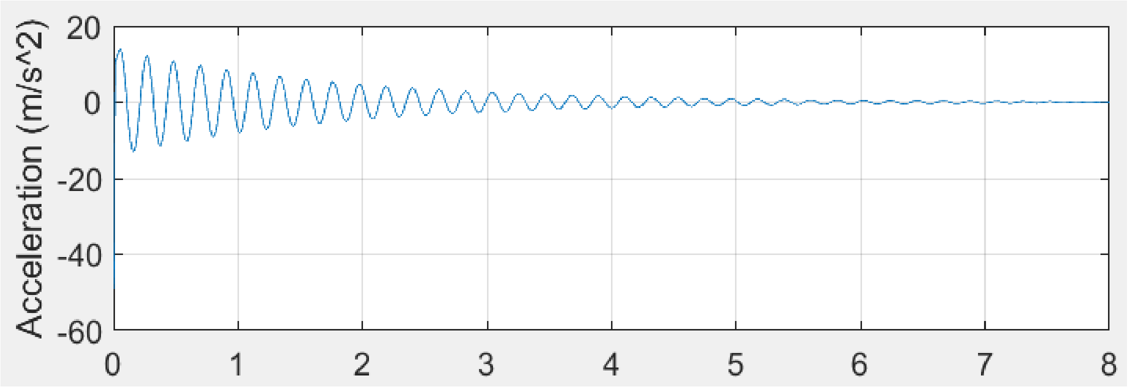


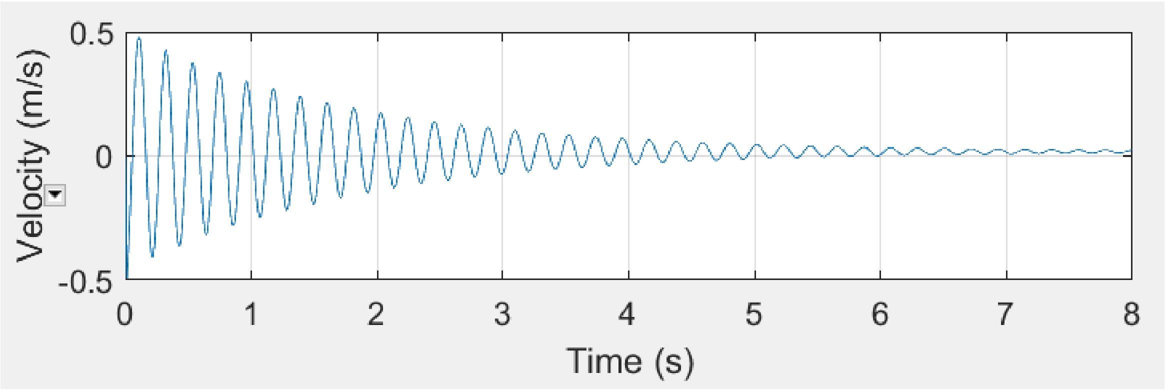


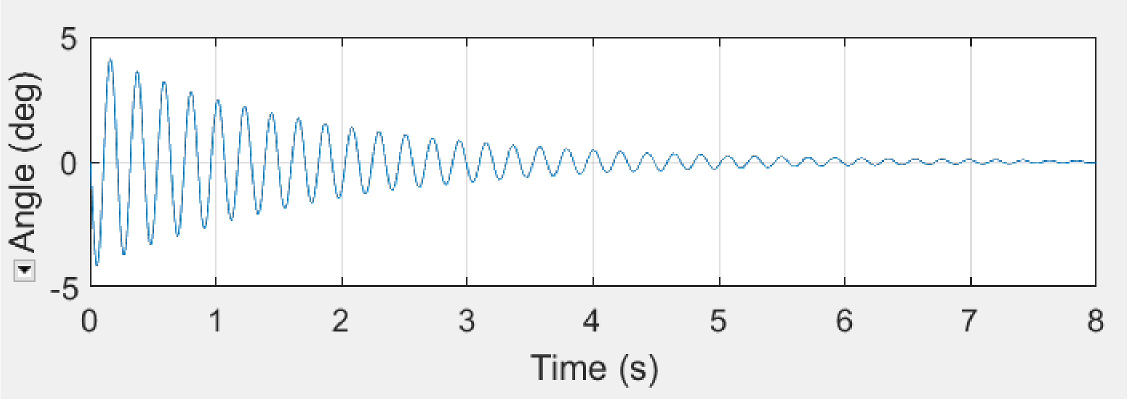


Results [7]
(Graph from Animation for Pitch Dynamics)









Results [7]
(PID values from MATLAB visualization)

PID Values	K_p	K_i	K_d
Roll Dynamics	0.006	0.772	0.193
Pitch Dynamics	0.012	1.2785	0.3196

Results [8]
(Observed PID values from IMU data and code)

PID Values	**K_p**	**K_i**	**K_d**
Roll Dynamics	300	200	12000
Pitch Dynamics	400	250	16000

Analysis of Results

- Currently, the system is not able to hold itself upright
  - With the motors according to the orientation of IMU sensor
- There are various reasons
  - Design of the actual mechanical body
  - Performance of motors
  - Errors from sensor data
- The PID values in simulation and real hardware differ

Future Enhancements

- To withstand increasing load on top of the body
- To balance itself on sloppy/rugged surfaces
- A fully functioning automated unicycle can be built
- To be able to control these system remotely

Conclusion

- Design, construction, working and stability of a single wheeled self-balancing system
- First objective completed in both simulation and hardware
- Attempt of second objective resulted in unsuccessful results

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