SELF-BALANCING ROBOT

Capstone Project

Presented by

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Rafik Hariri University
جامعة رفيق الحريري

OUTLINE

BACKGROUND: SELF-BALANCING ROBOTS

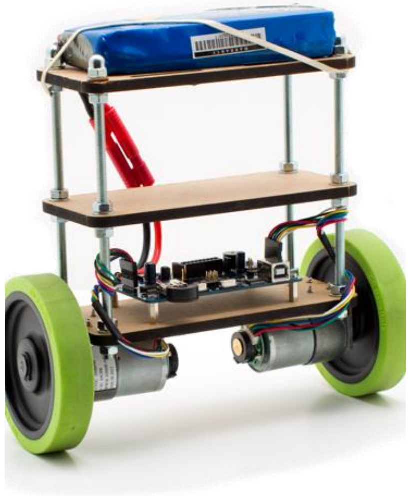
Require control systems

Invention started from 1980s

Non-linear & unstable

Sustainable Design

Used in multiple fields



Balanduino

Segway

Hover Boards

Legway

MOTIVATION

Newly and continuously growing field

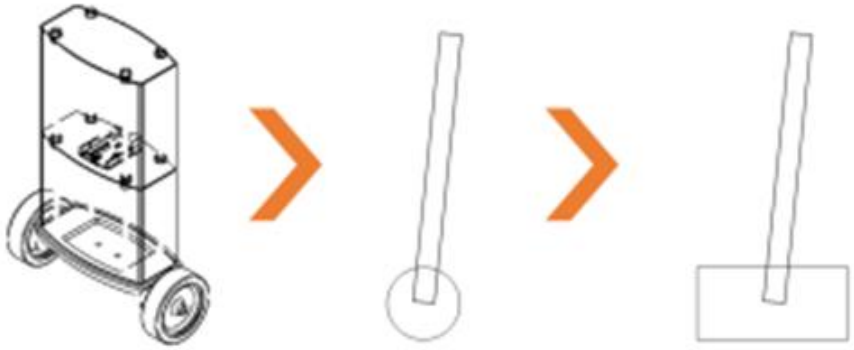
Considered a sustainable and multi-purpose robot

Using Simscape platform to implement a modeled version of the robot

Possibility of comparing different control algorithms

OUTLINE

PRINCIPLE OF INVERTED PENDULUM IP



Other than TWSBRs, IP's applications:

- Human Walking Robots
- Earthquake resistant building design
- Missile Launchers

OUTLINE

- Background & Motivation
- Principle of Inverted Pendulum
- Literature Review
- Purpose
- Control Methods
- Modeling of the 2WD Robot
- Simulation: PID
- Simulation: LQR
- Comparison and Discussion
- Conclusion & Future Perspectives

LITERATURE REVIEW

An & Li 2013

LQR & PID Simulations' Comparison

- Controlling self-balance
- PID's feedback: either tilt angle or tilt angle rate
- LQR: involves combining tilt angle tilt angle rate and position
- LQR achieved steady state faster than PID

Bature et al., 2014

LQR PID & FLC Comparison

- Implemented on a two-wheeled inverted pendulum mobile robot
- Feedback composed of tilt angle and position
- FLC showed less overshoot and faster response but consumed higher energy
- LQR showed faster response and less overshoot than PID

Rahman et al., 2018

LQR PID & FLC Comparison

- Implemented on a TWSBR using ROS and Gazebo
- PID gave the most stable response in the real time Pitch angles plot
- LQR was the faster
- FLC was non-stable due to inefficient tuning

Jiménez et al., 2020

LQR & PID Comparison

- TWSBR MATLAB simulation and real implementation
- Both met the specifications: less than 200 ms setting time &less than 5 degrees tilt
- PID had higher overshoot but less steady state error
- LQR had less overshoot and minimal steady state error

ETH Zurich University, 2022

Design and implement of a new form of a self balancing robot (2whld robot – 4whld robot, and quadruped)

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Background & Motivation

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Purpose

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Modeling of the 2WD Robot

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Simulation: LQR

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Conclusion & Future Perspectives

PURPOSE

Modeling the OSOYOO 2WD Robot using Simscape → Simulate different control algorithms (PID & LQR) to ensure system stability → Compare the algorithms' performances

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CONTROL METHODS

PID

- SISO
- Minimize error
- Can be tuned using Kp, Ki & Kd parameters
- Kp: Present
- Ki: Past
- Kd: Future

LQR

- MIMO/SIMO
- Based on States
- Feedforward & Feedback Controls
- Governed by gains that minimize the cost function :
  - $J = \int \{x'Qx \ + \ u'Ru \ + \ 2 * x'Nu\} \, dt$

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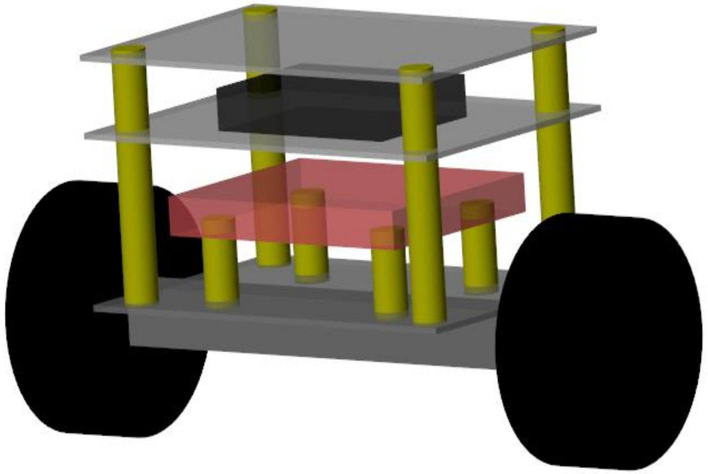
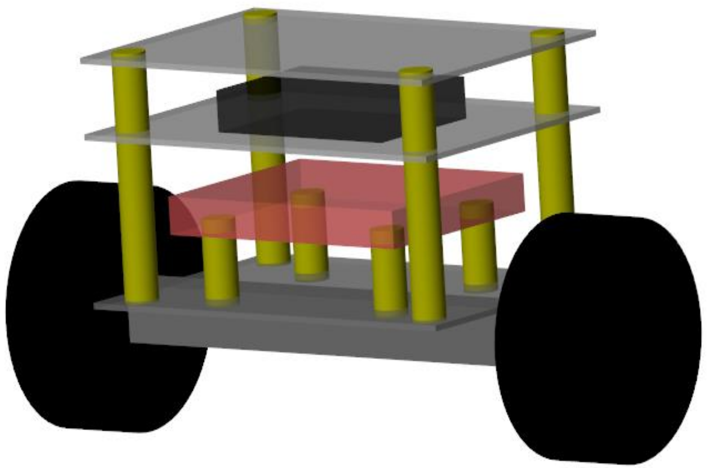
MODELING OF THE 2WD ROBOT

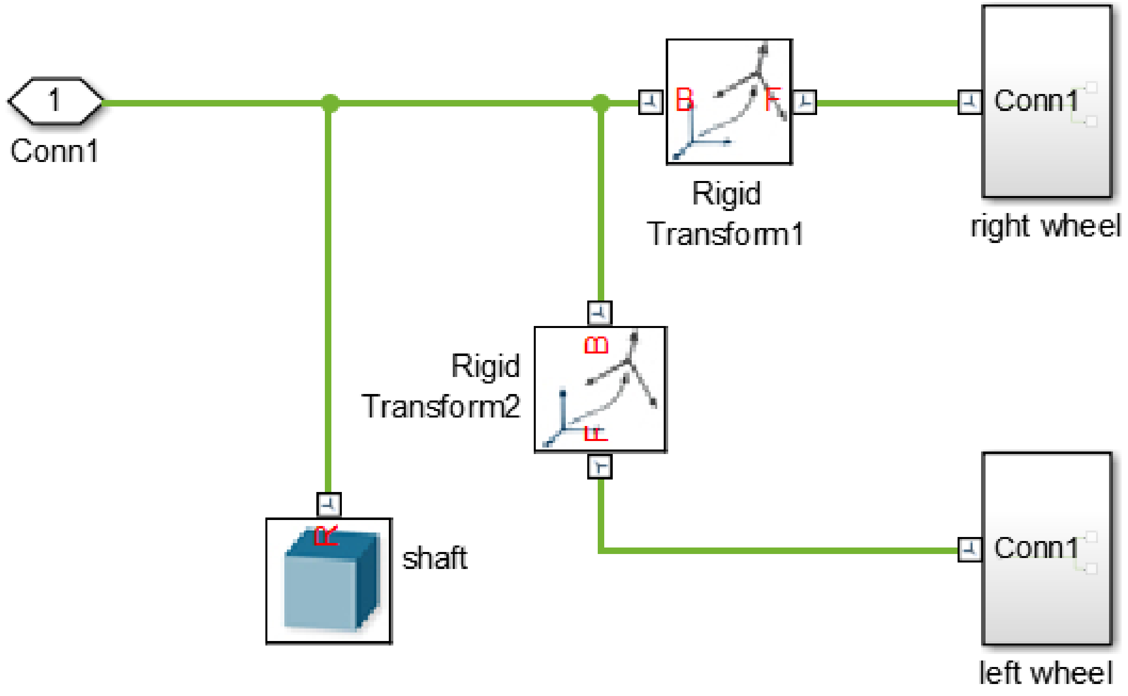


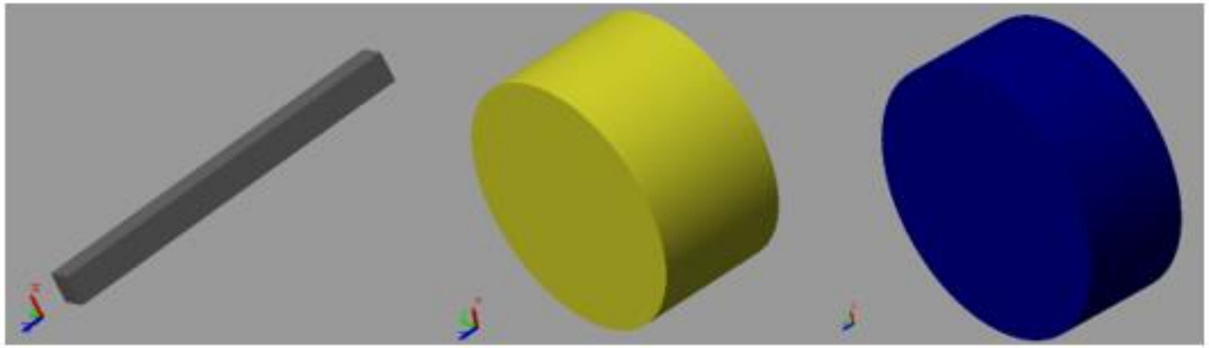
MODELING: CART

Shaft			Unit
Shape	Brick		
Dimensions	[1.5,1.5,18]		cm
Mass	345		g
Left & Right Wheels			**Unit**
	Wheel Body	**Wheel Tire**	
Shape	Cylinder		
Radius	2.36	3.2	cm
Length	2.57	2.6	cm
Mass	23.4	25.6	g



MODELING: CART

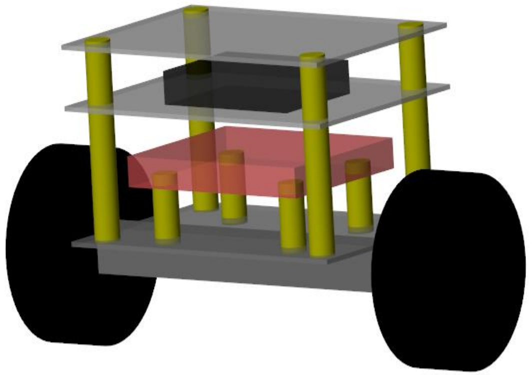




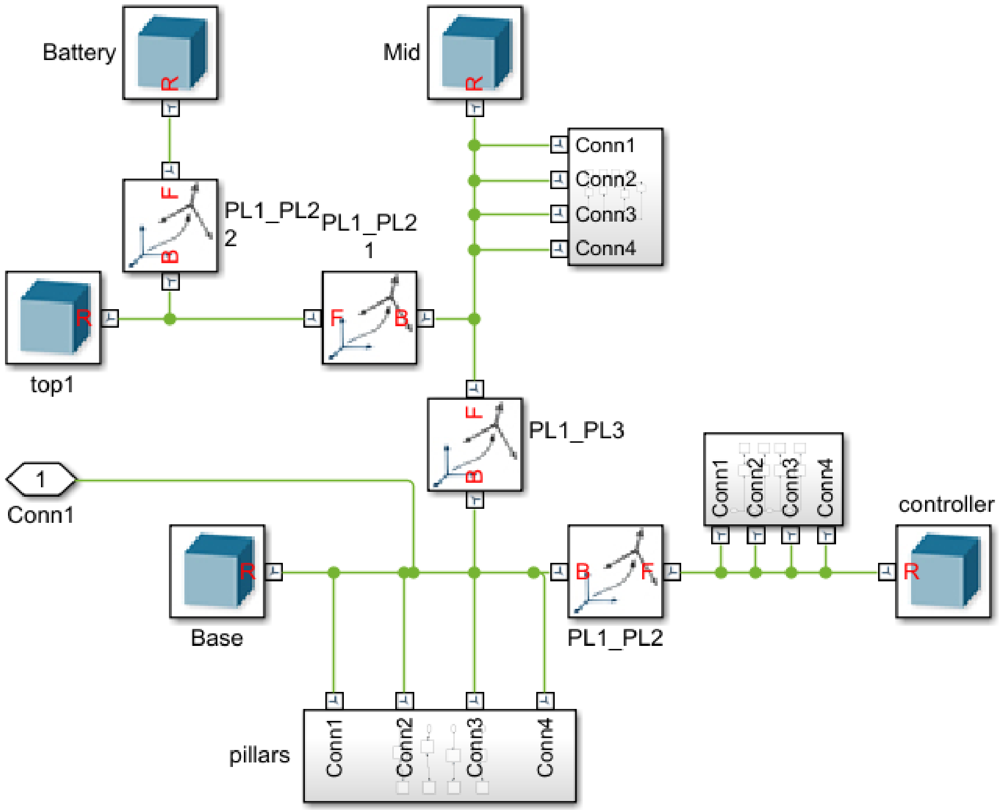
MODELING: CHASSIS

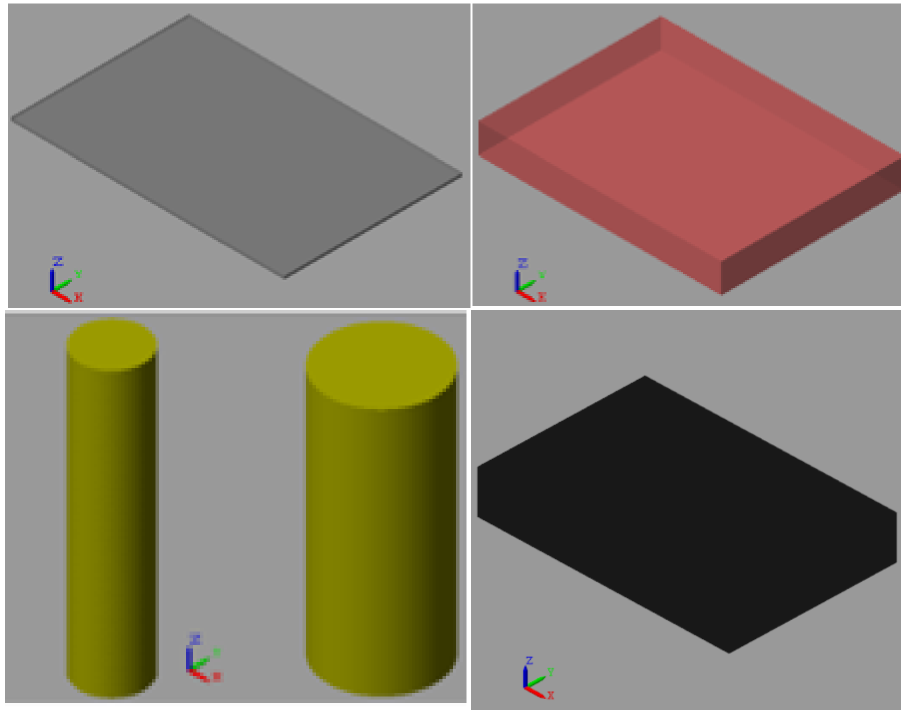
Levels						Unit
	Base	Controller	Middle	Top	Battery	
Shape	Brick					
Dimensions	[12.58,8.2, 0.16]	[8.22 6.19 1]	[12.58,8.2, 0.16]	[12.58,8.2,0.16]	[6,4,1.1]	cm
Mass	107.8	69.6	63	63	105	g

Rods			Unit
	1st Set	2nd Set	
Shape	Cylinder		
Radius/rod	0.5	0.5	cm
Length/ rod	4.4	2.3	cm
Mass/ rod	6.1	2.9	g
Number/Set	4	8	Rods



MODELING: CHASSIS





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SIMULATION: PID

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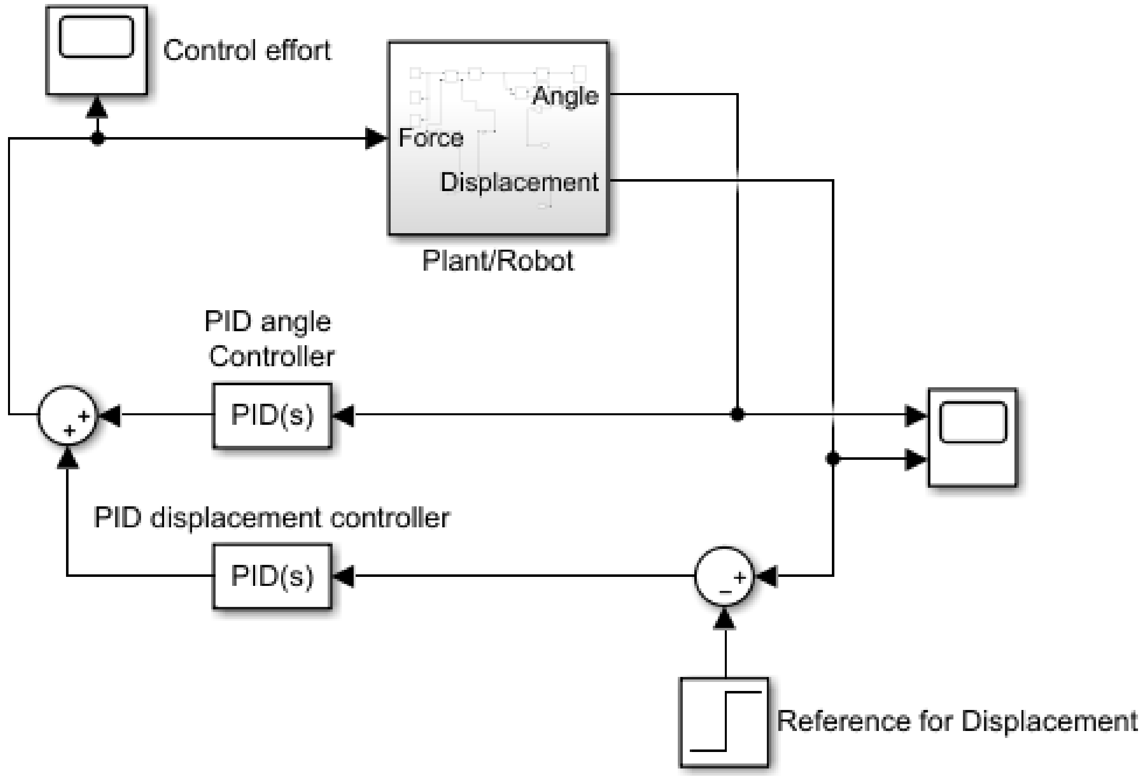
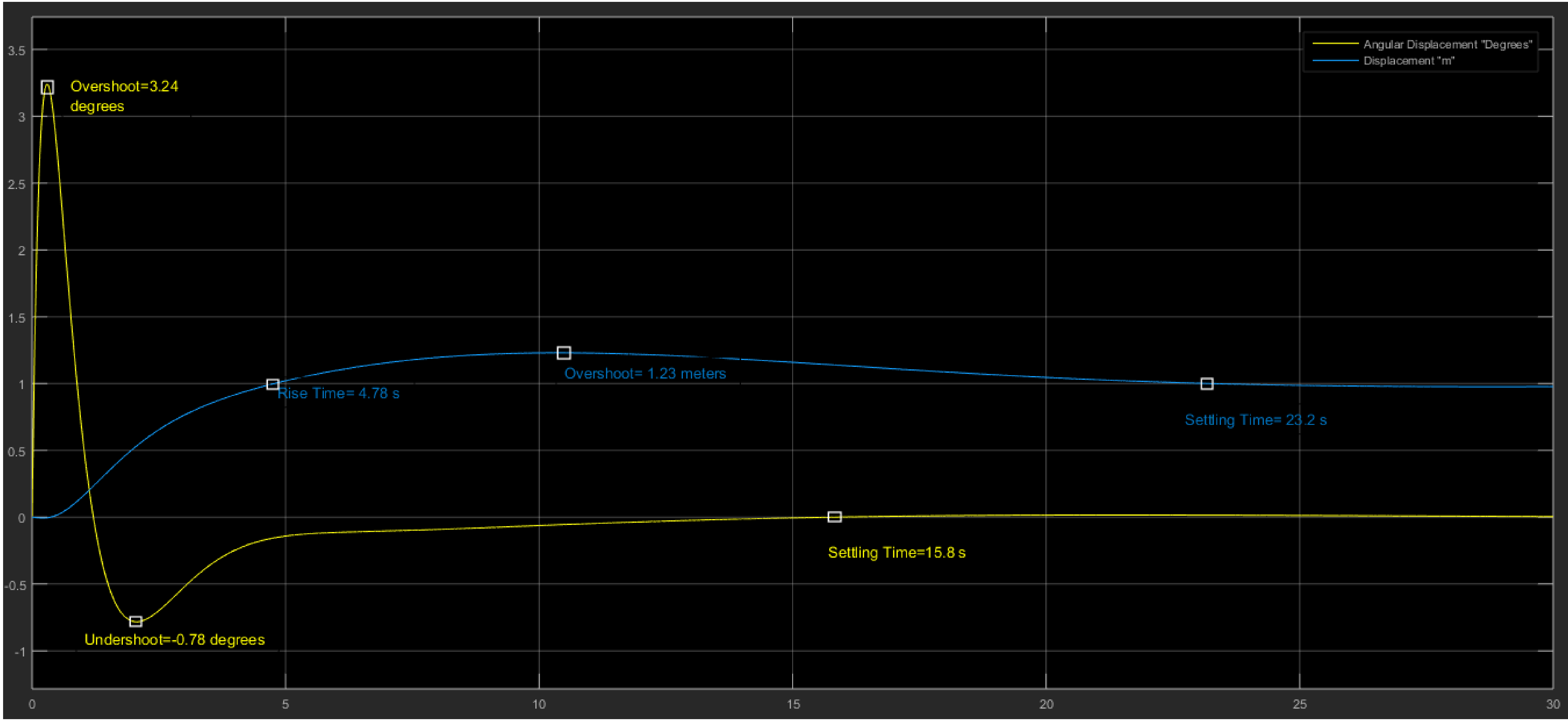
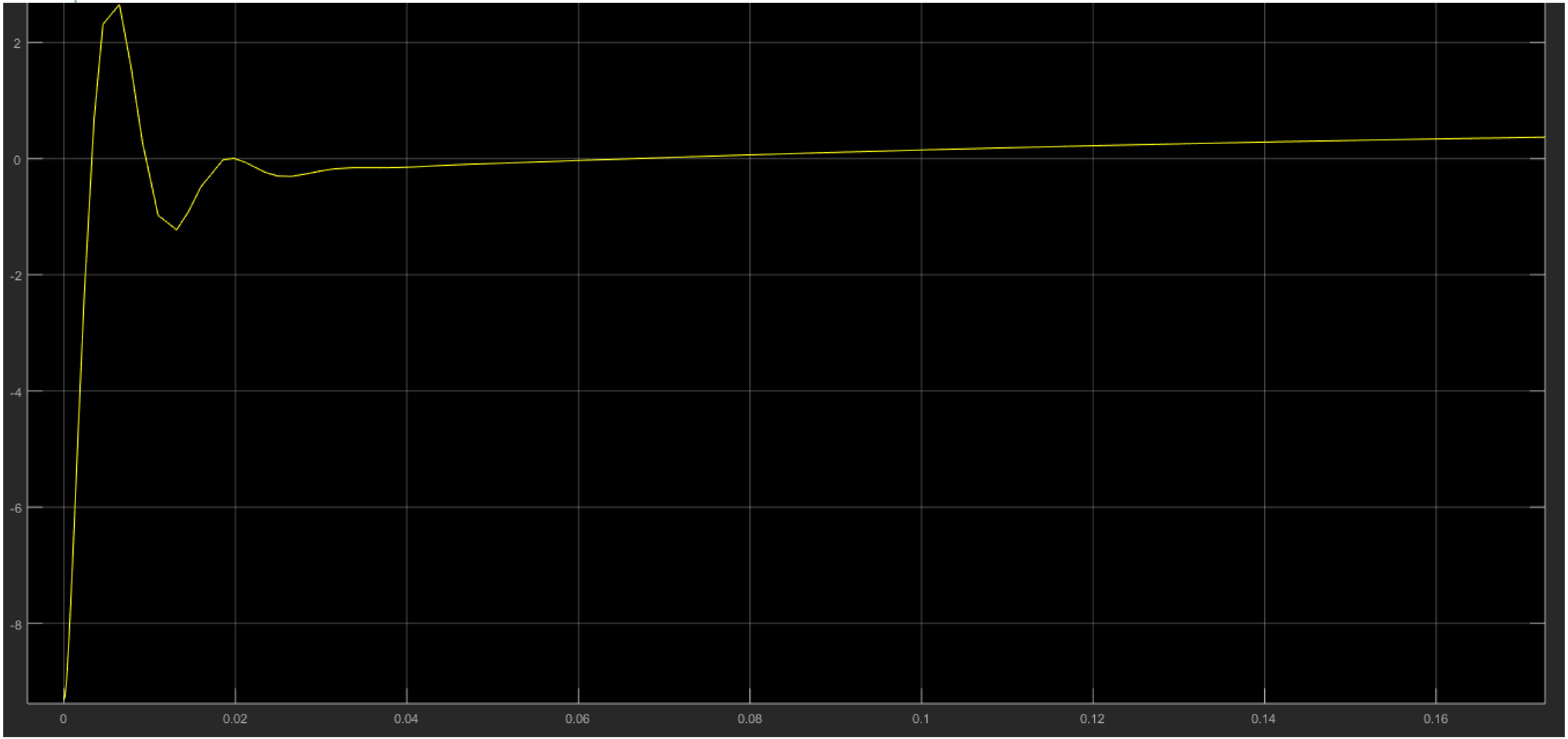
- Recording "angle", "displacement", and "control effort" responses with respect to time
- The robot is controlled via displacement force "f"
- PID Feedback is received from position sensor & gyroscope "p" & "q"
- Kp, Kd and Ki gains are adjusted in each of the PID controllers




Angular Displacement "Degrees"
Displacement "m"
Overshoot=3.24
degrees
Overshoot= 1.23 meters
Rise Time= 4.78 s
Settling Time= 23.2 s
Settling Time=15.8 s
Undershoot=-0.78 degrees
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
-1
0
5
10
15
20
25
30



2
0
-2
-4
-6
-8
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16

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SIMULATION: LQR

LQR

SIMO system

State Variables: x, $\dot{x}$, $\emptyset$, $\dot{\emptyset}$

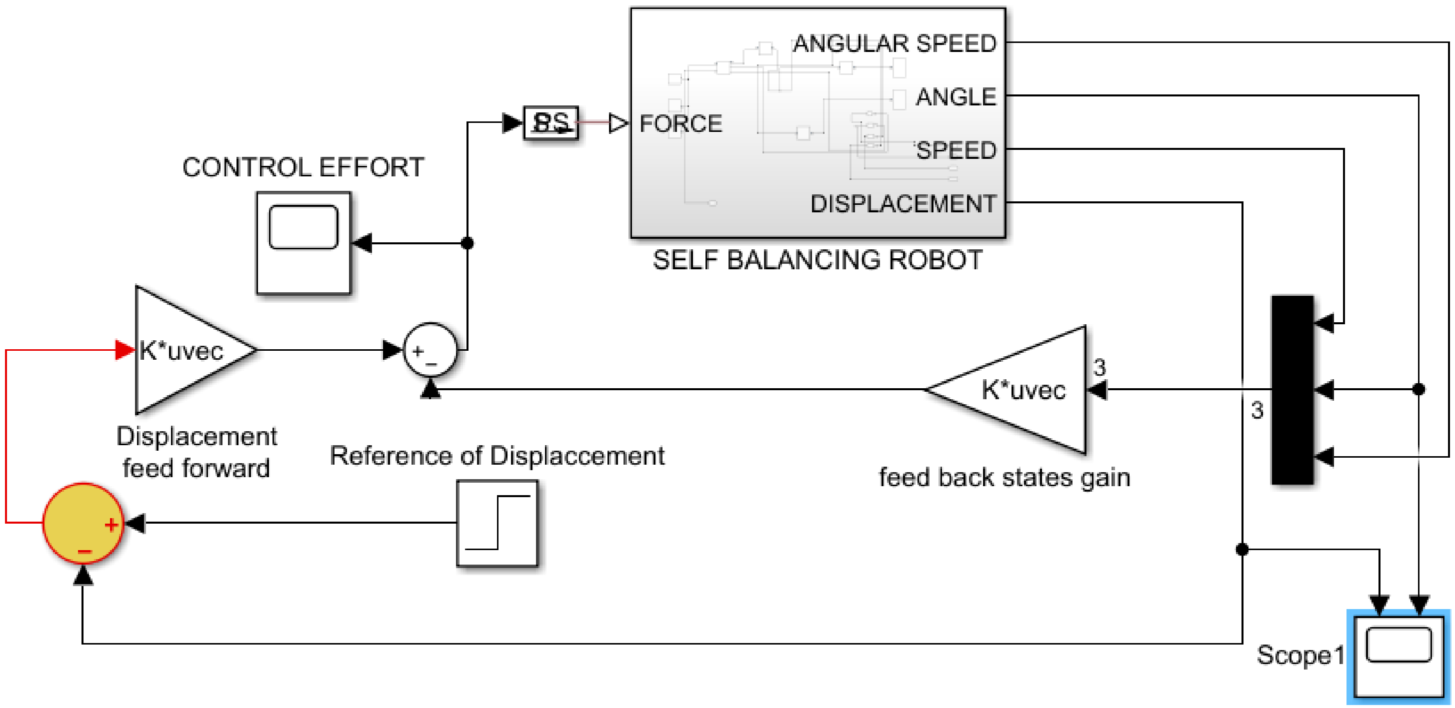
Additional sensors

Consists of feed forward & feedback controls

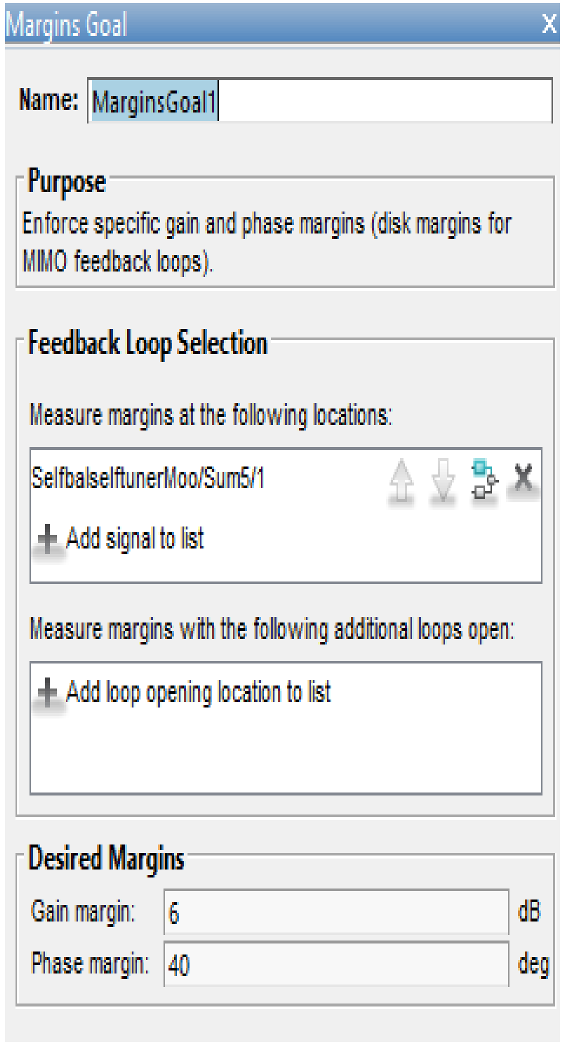
Gains are calculated based on the "Control Analysis" in MATLAB based on specific contract

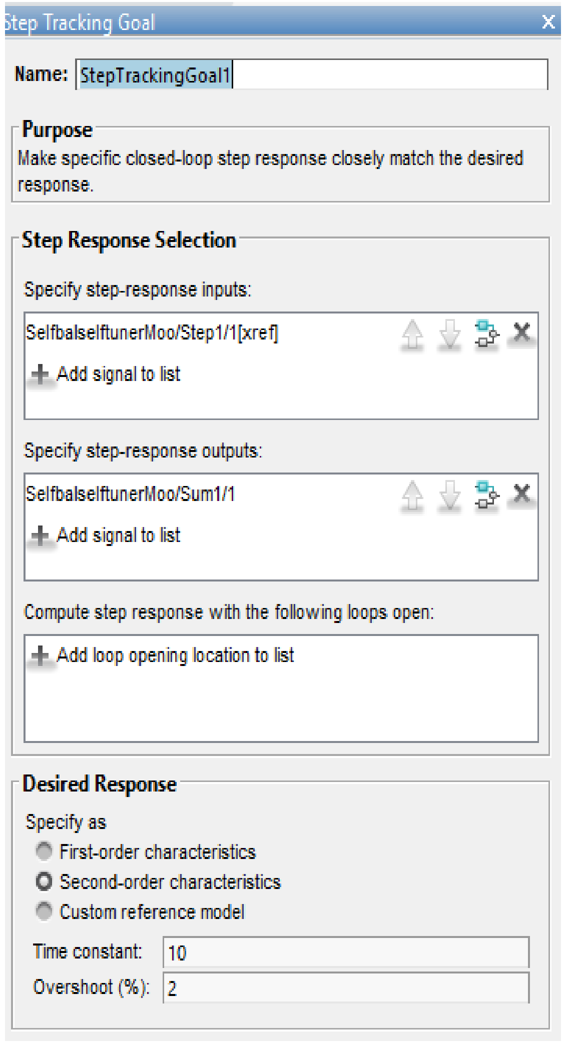
$\boldsymbol{u} = -\boldsymbol{Kx}$ minimizes the cost function

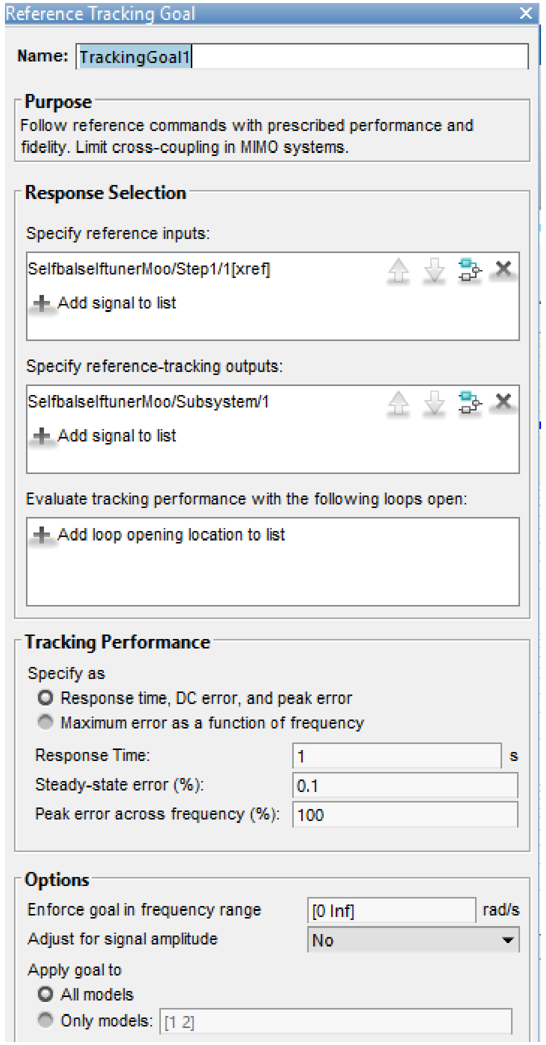
$$J = \int\{x'Qx + u'Ru + 2 * x'Nu\}\, dt$$

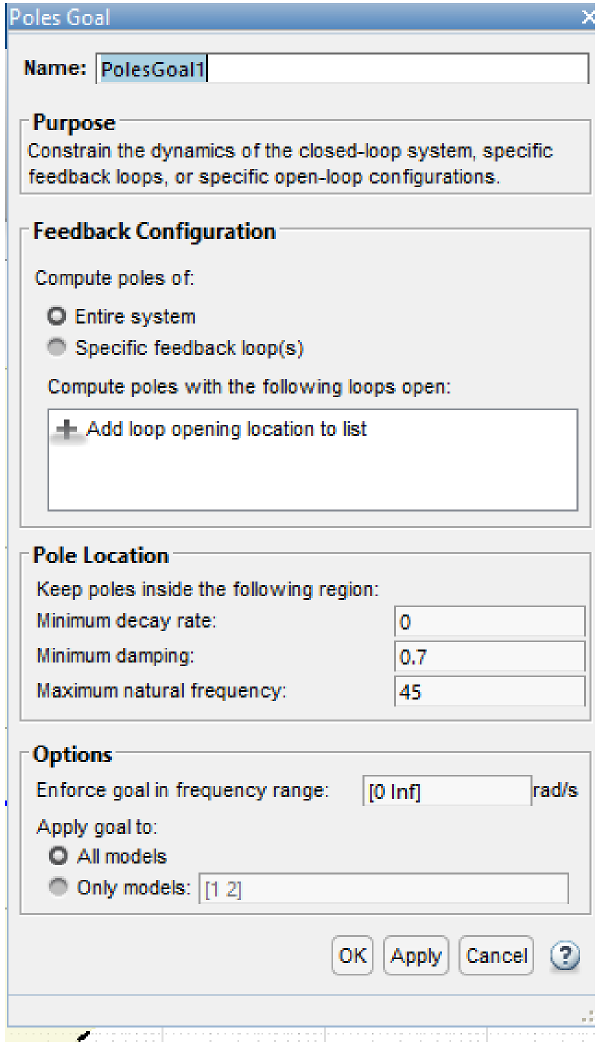


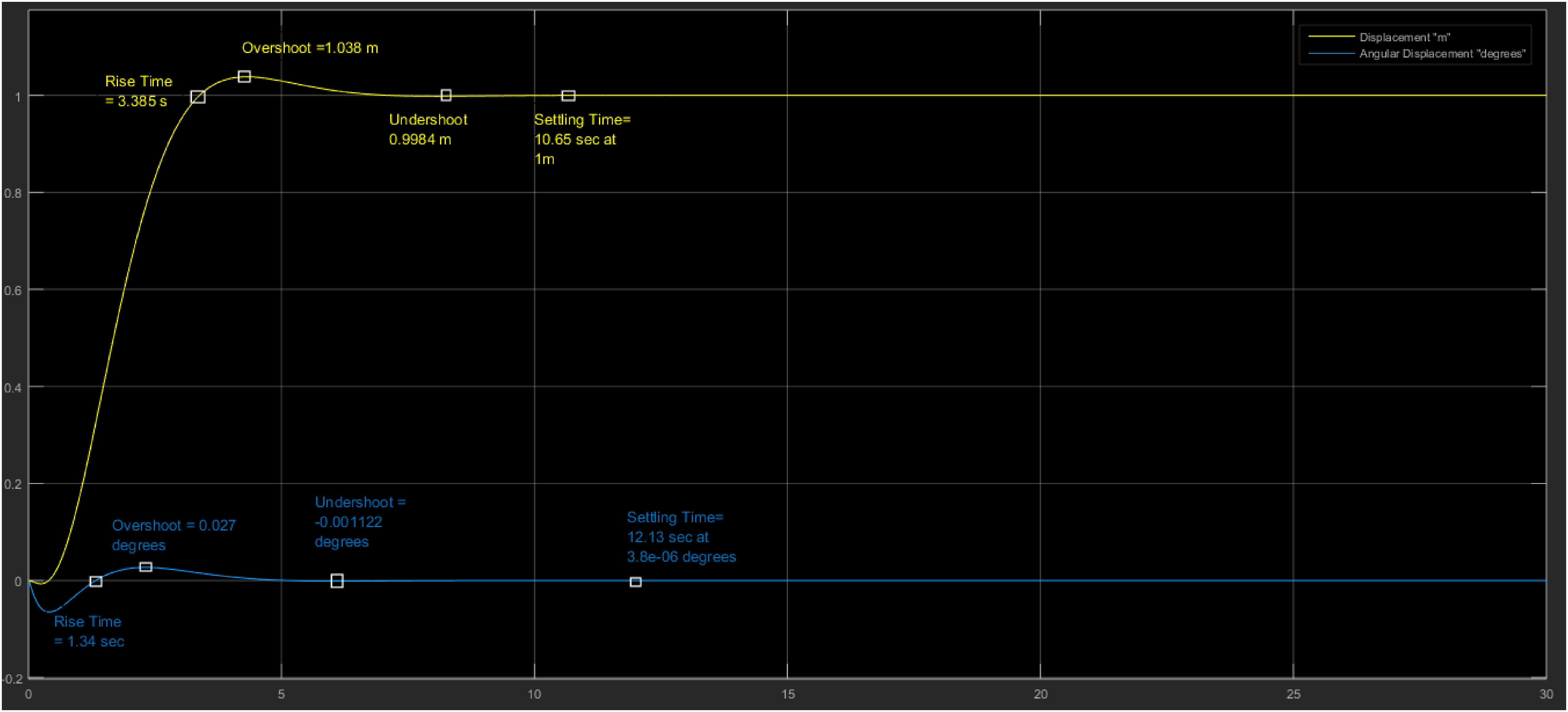
LQR CONTROLLER SPECS



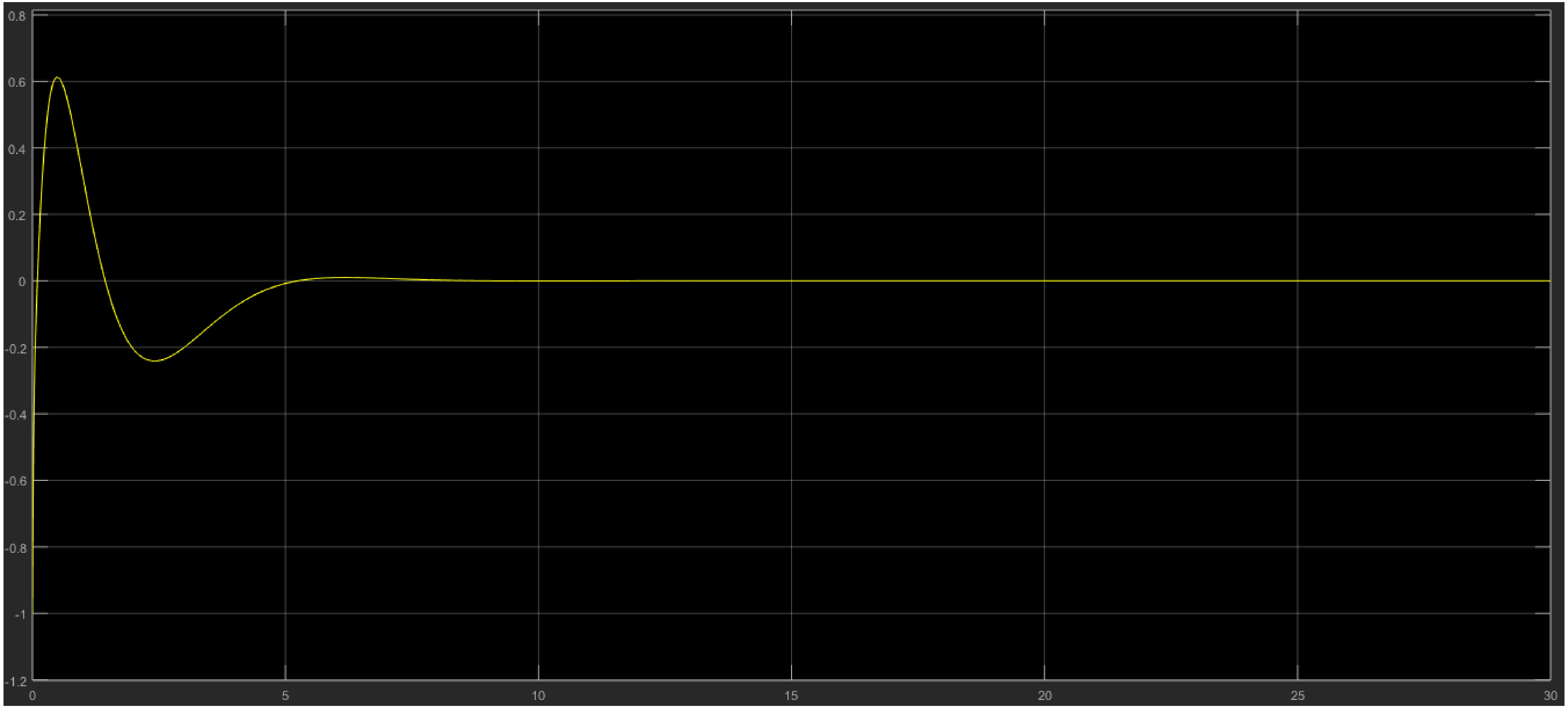







Displacement "m"
Angular Displacement "degrees"
Overshoot =1.038 m
Rise Time
= 3.385 s
Undershoot
0.9984 m
Settling Time=
10.65 sec at
1m
Undershoot =
-0.001122
degrees
Overshoot = 0.027
degrees
Settling Time=
12.13 sec at
3.8e-06 degrees
Rise Time
= 1.34 sec
1
0.8
0.6
0.4
0.2
0
-0.2
0
5
10
15
20
25
30

CONTROL EFFORT



LQR

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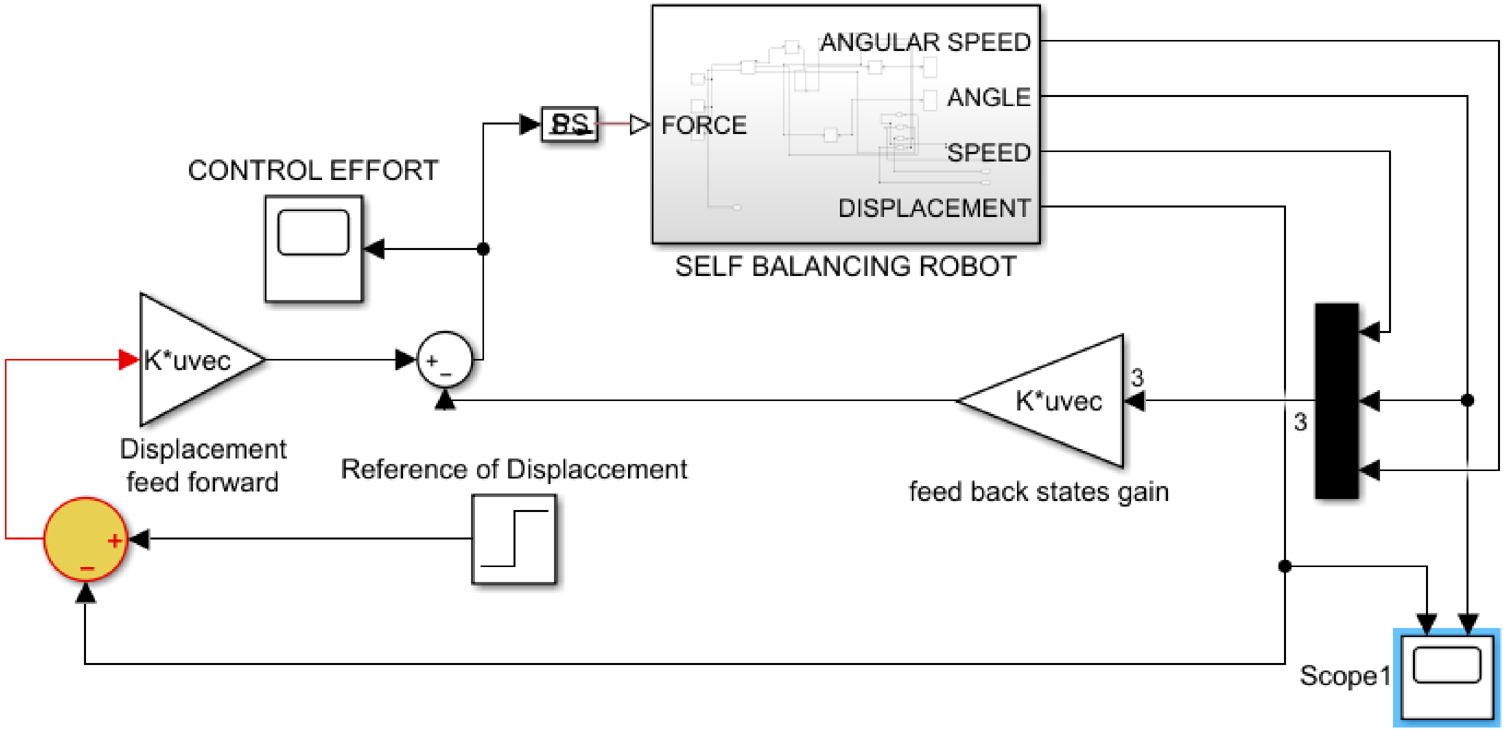


LQR WITH MOO

x and Ø are observed

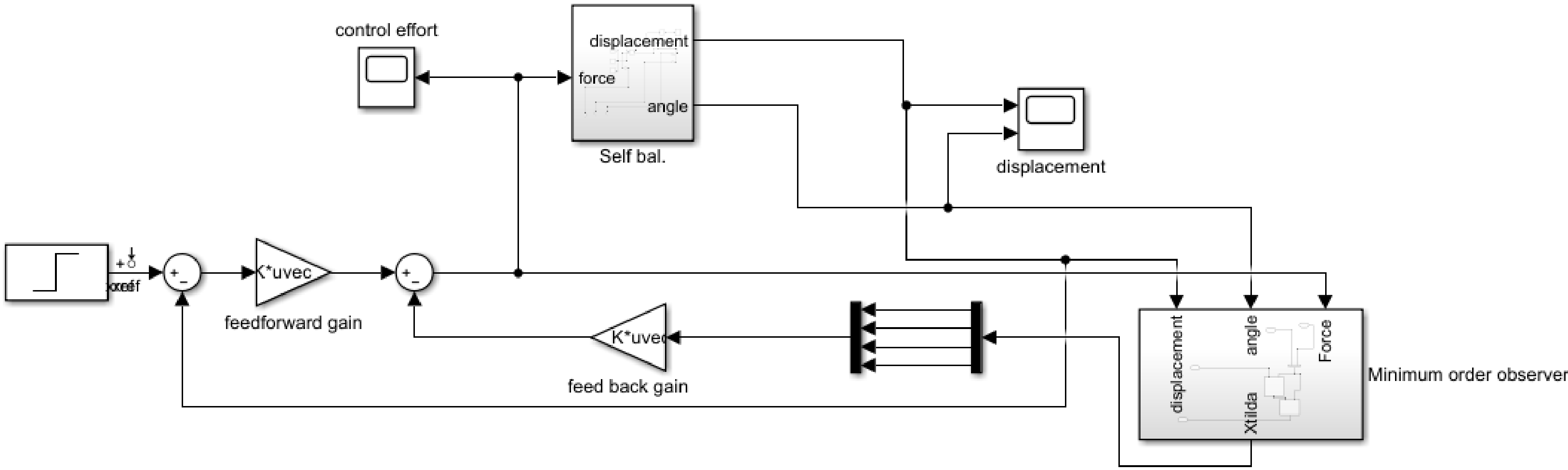
$\dot{x}$ and $\dot{Ø}$ are to be estimated

"Ethatilda" block gets the state variables required to acquire the estimated states by:

$$\dot{\tilde{\boldsymbol{\eta}}} = \hat{\mathbf{A}}\tilde{\boldsymbol{\eta}} + \hat{\mathbf{B}}y + \hat{\mathbf{F}}u$$

The above "Ethatilda" and the measured states "y" are then fed to the transformation block which will output the estimated states "xtilda"

$$\tilde{\mathbf{x}} = \hat{\mathbf{C}}\tilde{\boldsymbol{\eta}} + \hat{\mathbf{D}}y$$



INVERTED PENDULUM TRANSFER FUNCTIONS

Result after applying newton's second law then linearization on Pendulum and car separately

$$(I + ml^2)\ddot{\emptyset} - mgl\,\emptyset = ml\ddot{x}$$

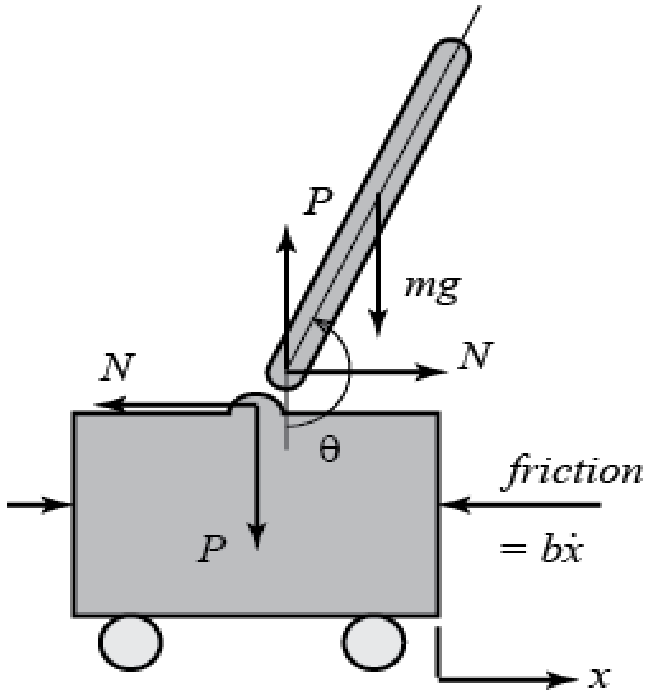
$$(M + m)\ddot{x} + b\dot{x} - ml\,\ddot{\emptyset} = F$$

Laplace Transfrom

$$\frac{\Phi(s)}{U(s)} = \frac{\frac{ml}{q}s}{s^3 + \frac{b(l+ml^2)}{q}s^2 - \frac{mgl(M+m)}{q}s - \frac{bmgl}{q}}\left[\frac{rad}{N}\right]$$

$$\frac{X(s)}{U(s)} = \frac{\frac{(I+ml^2)s^2 - gml}{q}}{s^4 + \frac{b(l+ml^2)}{q}s^3 - \frac{mgl(M+m)}{q}s^2 - \frac{bmgl}{q}s}\left[\frac{m}{N}\right]$$

Where q= [(M+m)(I+ml^2)-$(ml)^2$]



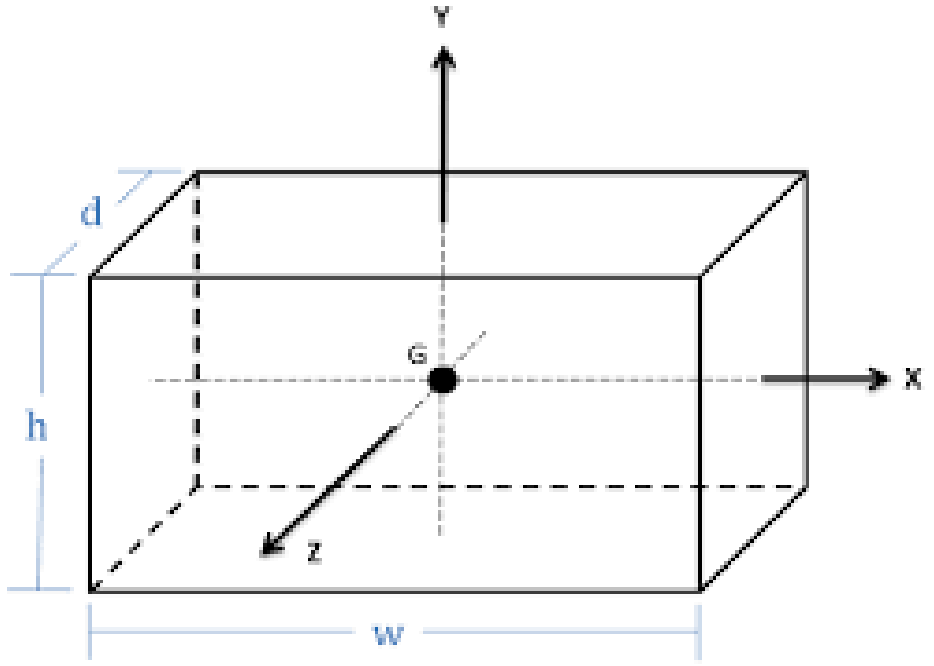
INVERTED PENDULUM STATE SPACE MODEL

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\varnothing} \\ \ddot{\varnothing} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{-(I+ml^2)b}{I(M+m)+Mml^2} & \frac{m^2gl^2}{I(M+m)+Mml^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{-mlb}{I(M+m)+Mml^2} & \frac{mgl(M+m)}{I(M+m)+Mml^2} & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \varnothing \\ \dot{\varnothing} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{(I+ml^2)}{I(M+m)+Mml^2} \\ 0 \\ \frac{ml}{I(M+m)+Mml^2} \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \varnothing \\ \dot{\varnothing} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u$$

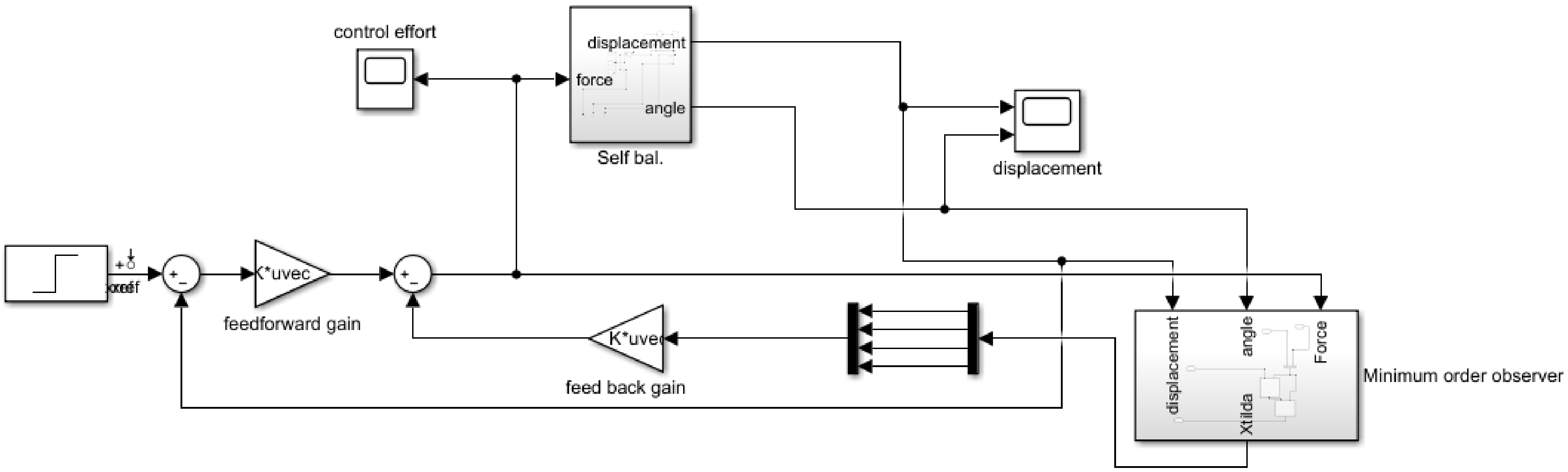
ROBOT'S CHARACTERISTICS

	Label	Value	Unit
Mass of the Cart	M	0.5500	Kg
Mass of the Chassis	m	0.4696	Kg
Length to chassis center of mass	l	3.59	cm
Coefficient of friction of the cart	b	0.1	N/m/sec
Mass moment of inertia of the Chassis	I	0.0004648 7	Kg.m^2



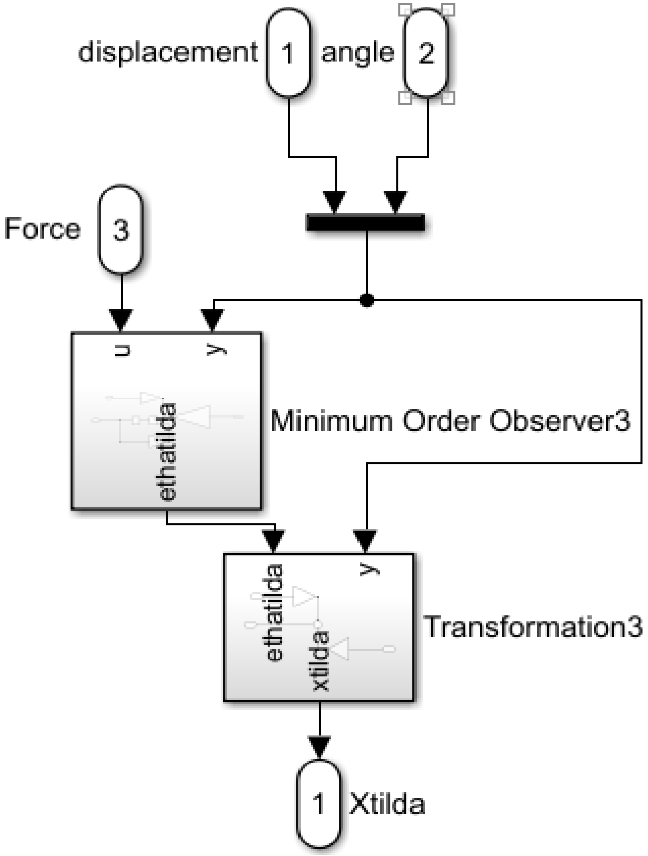
$$I=\frac{1}{12}m(h^2+d^2)$$

LQR WITH MOO



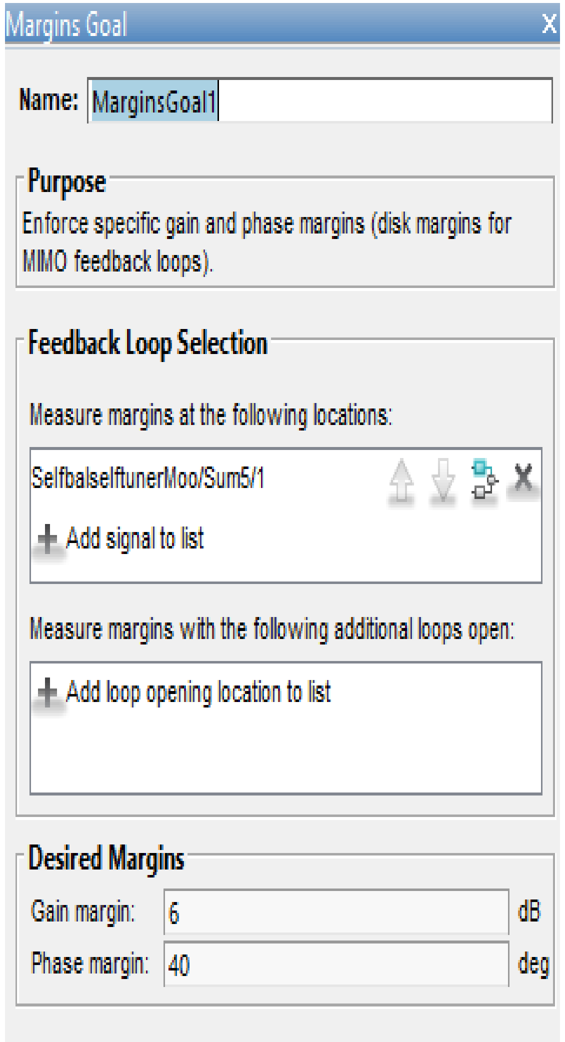
$$\dot{\tilde{\boldsymbol{\eta}}} = \hat{\mathbf{A}}\tilde{\boldsymbol{\eta}} + \hat{\mathbf{B}}y + \hat{\mathbf{F}}u$$

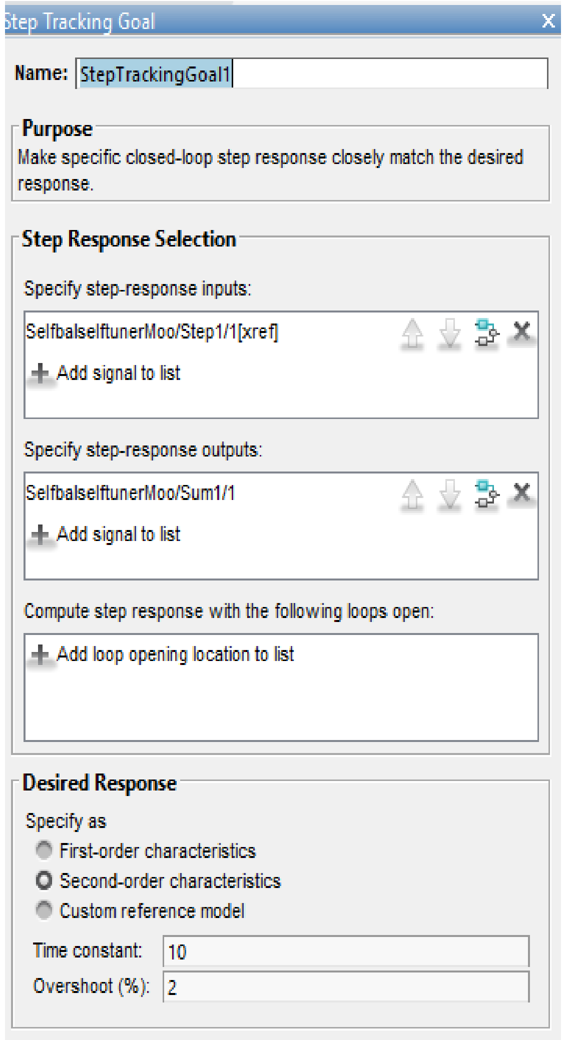
$$\tilde{\mathbf{x}} = \hat{\mathbf{C}}\tilde{\boldsymbol{\eta}} + \hat{\mathbf{D}}y$$

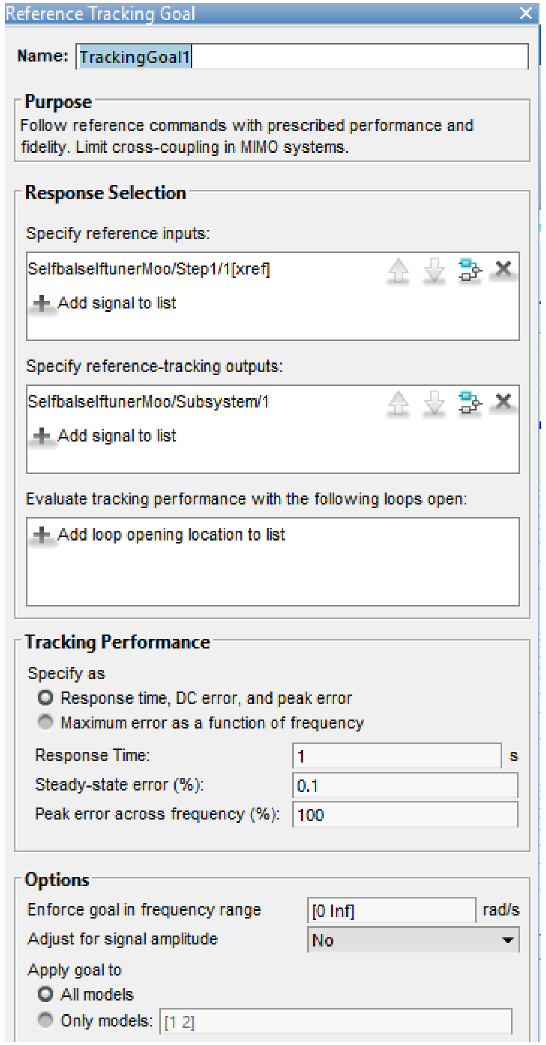


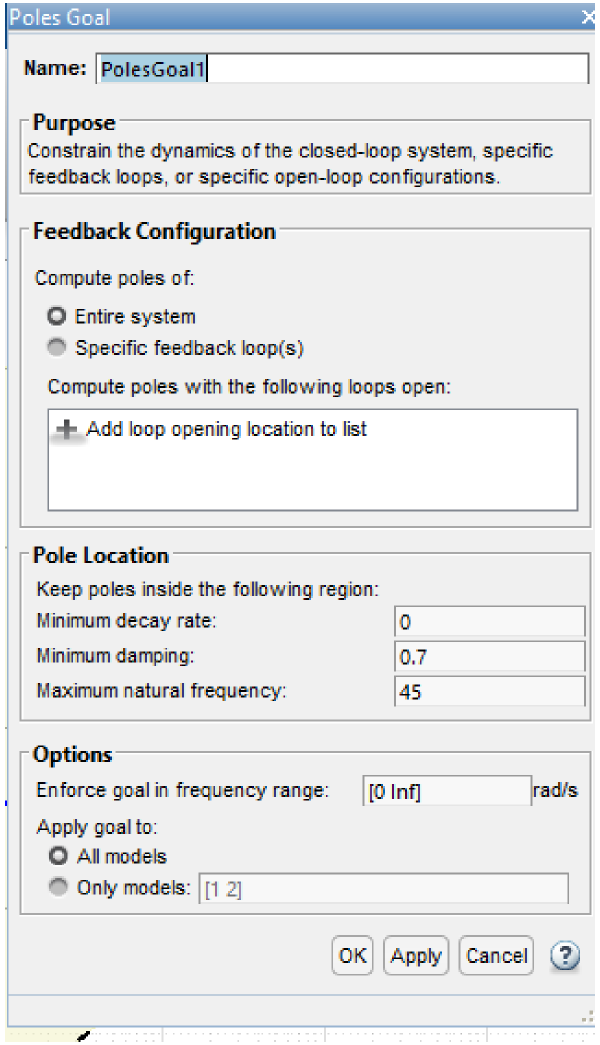
Minimum Order Observer

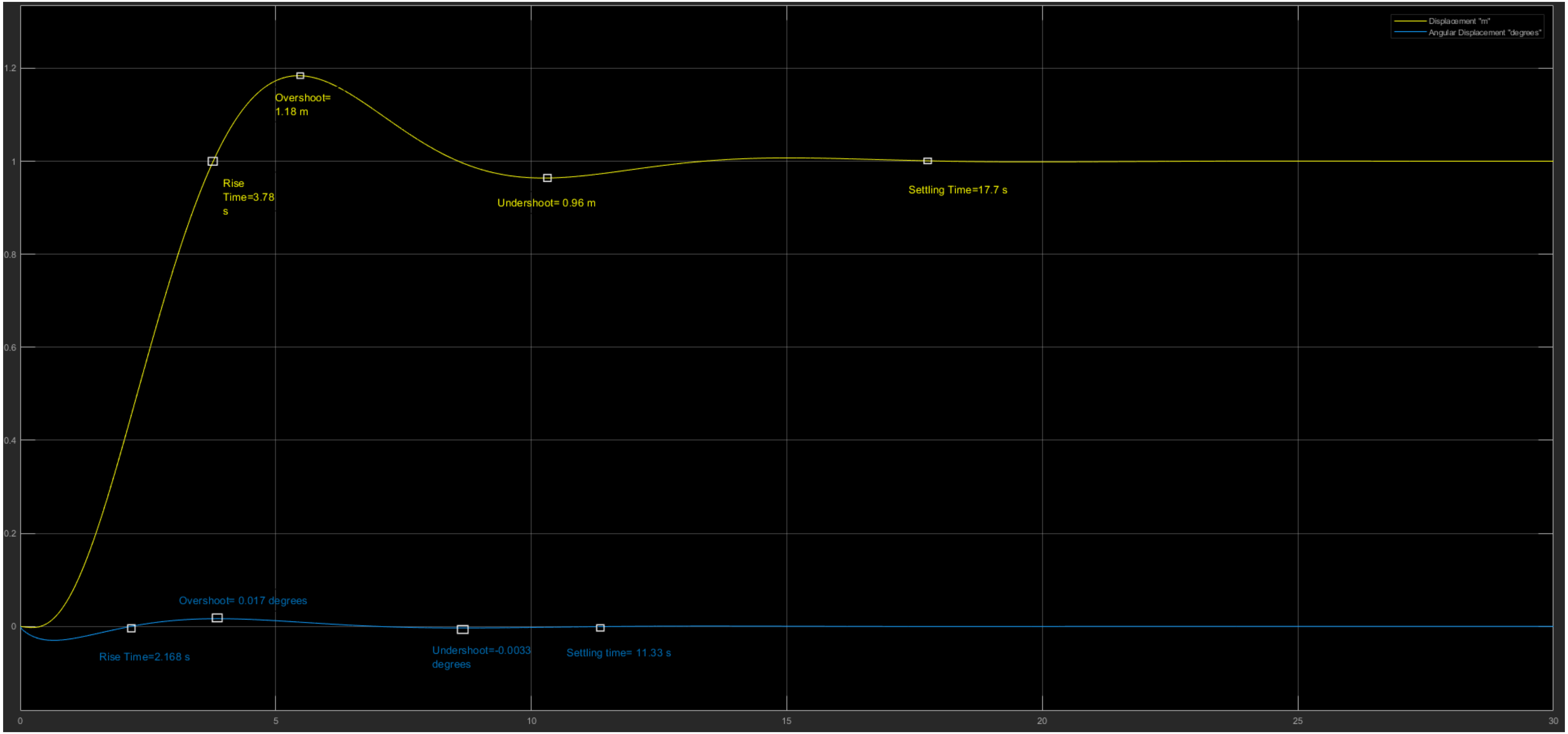
LQR CONTROLLER SPECS





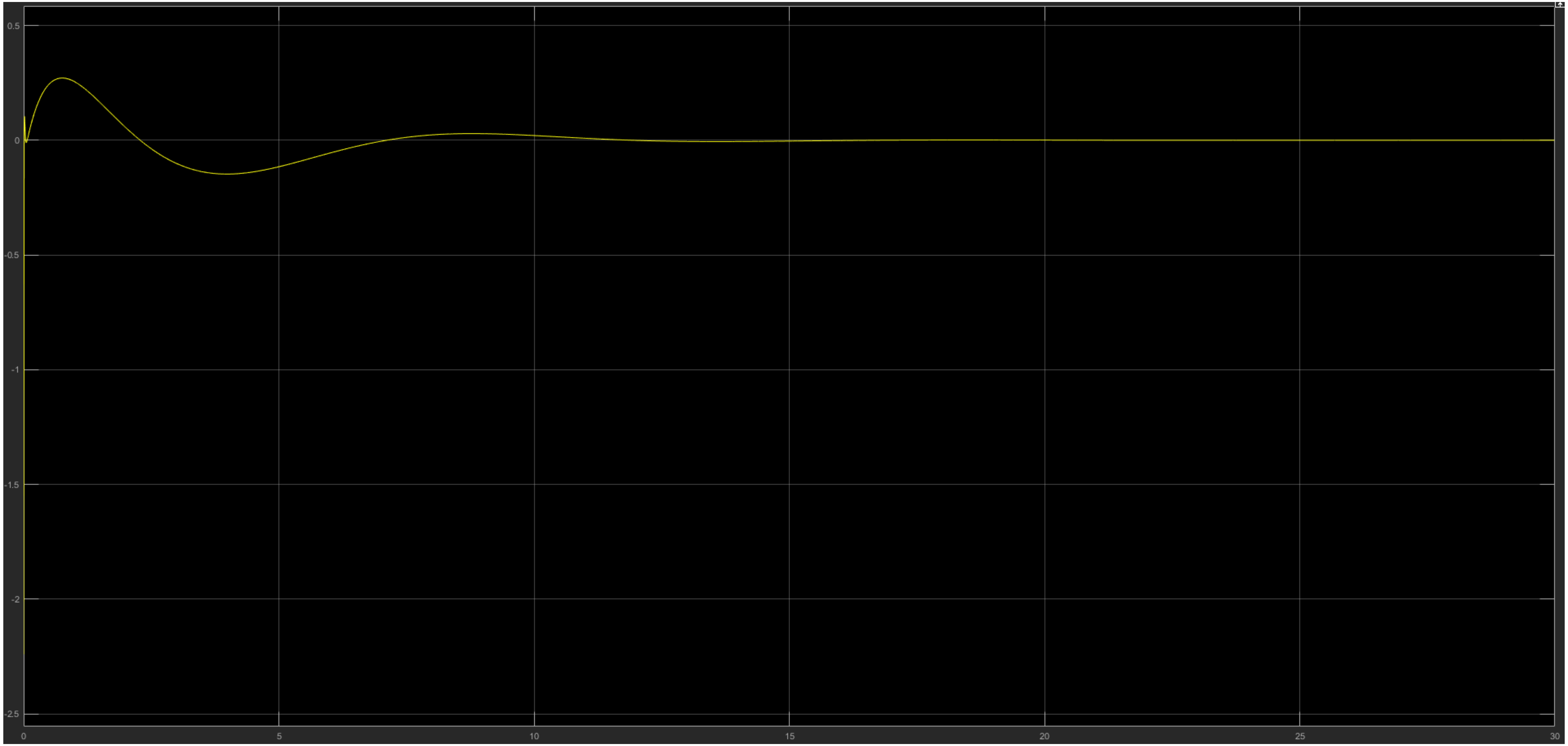






Displacement "m"
Angular Displacement "degrees"
Overshoot=
1.18 m
Rise
Time=3.78
s
Undershoot= 0.96 m
Settling Time=17.7 s
Overshoot= 0.017 degrees
Rise Time=2.168 s
Undershoot=-0.0033
degrees
Settling time= 11.33 s
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30

CONTROL EFFORT



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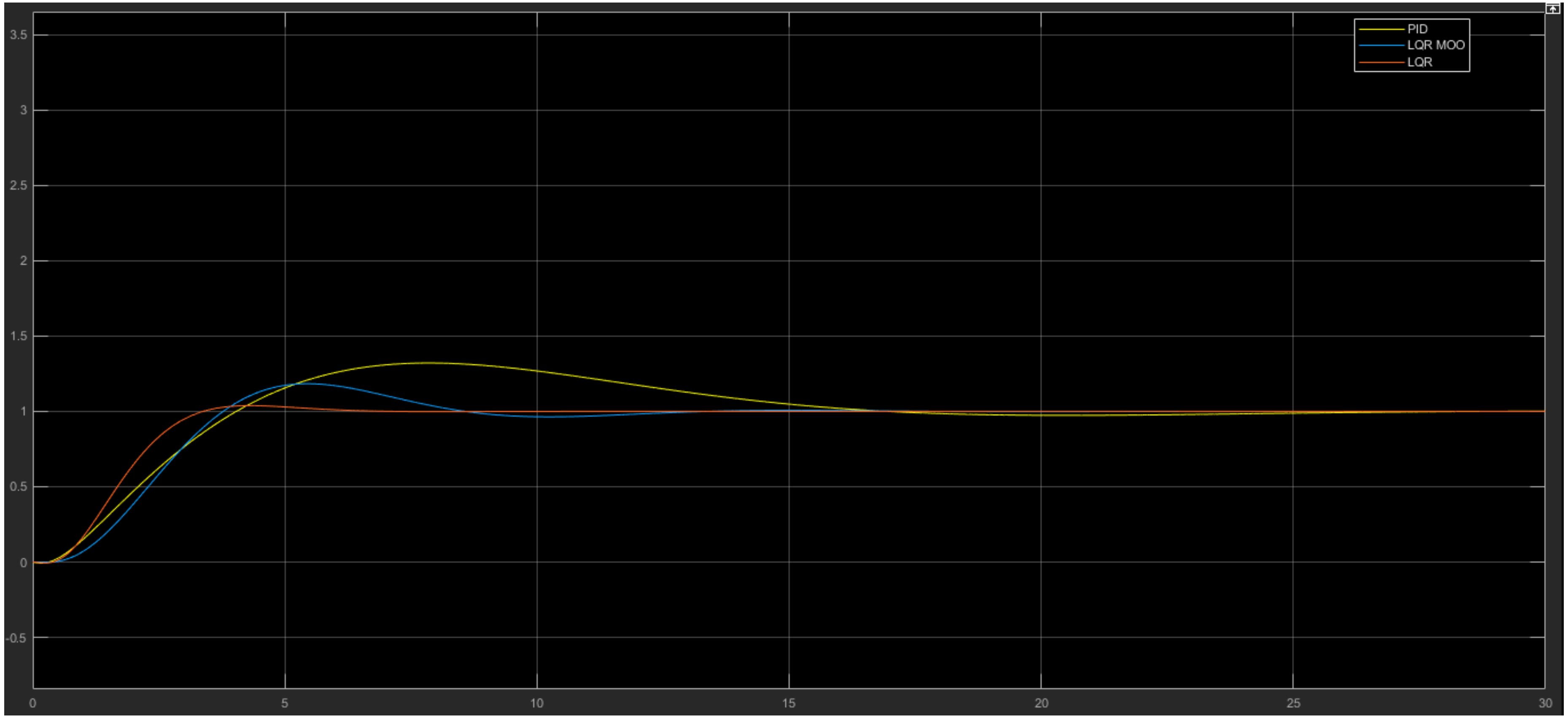
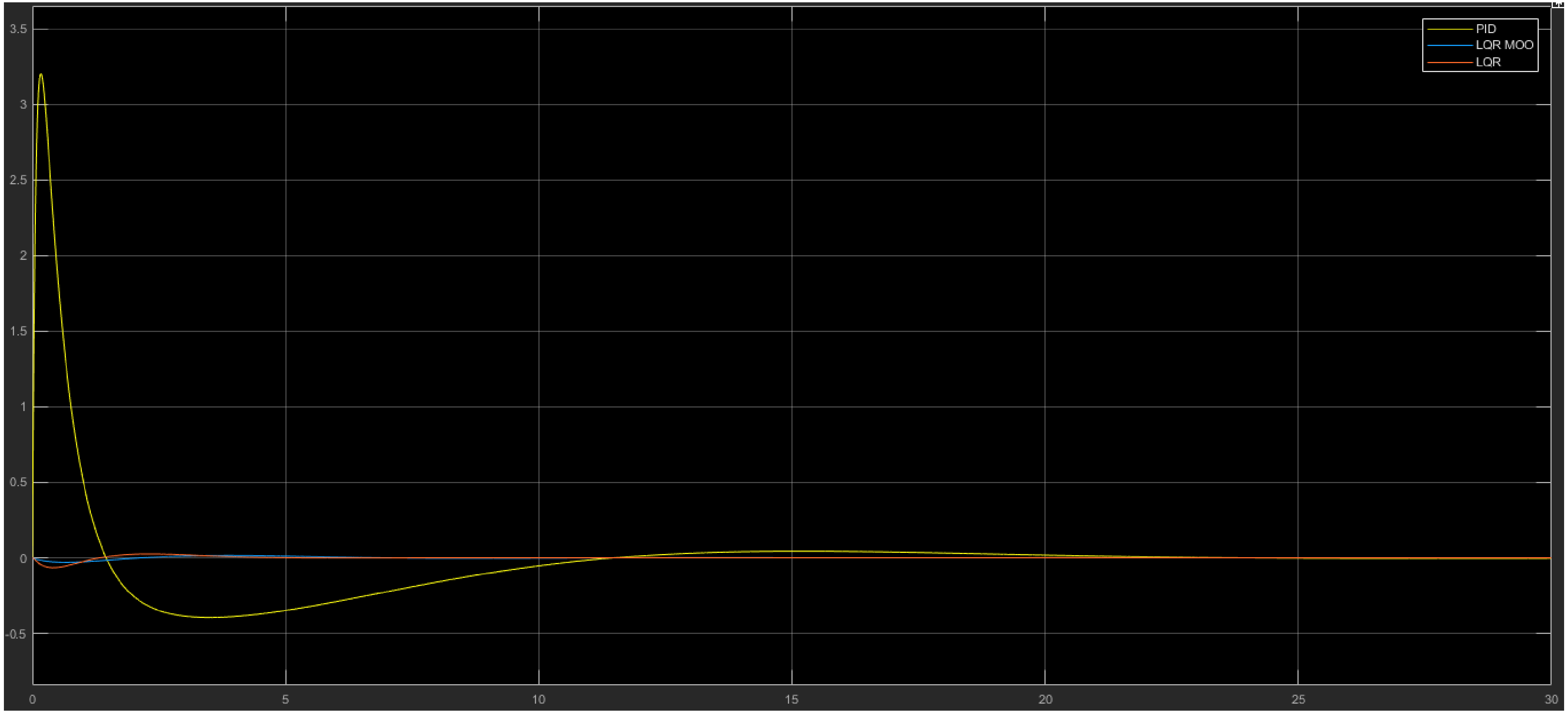
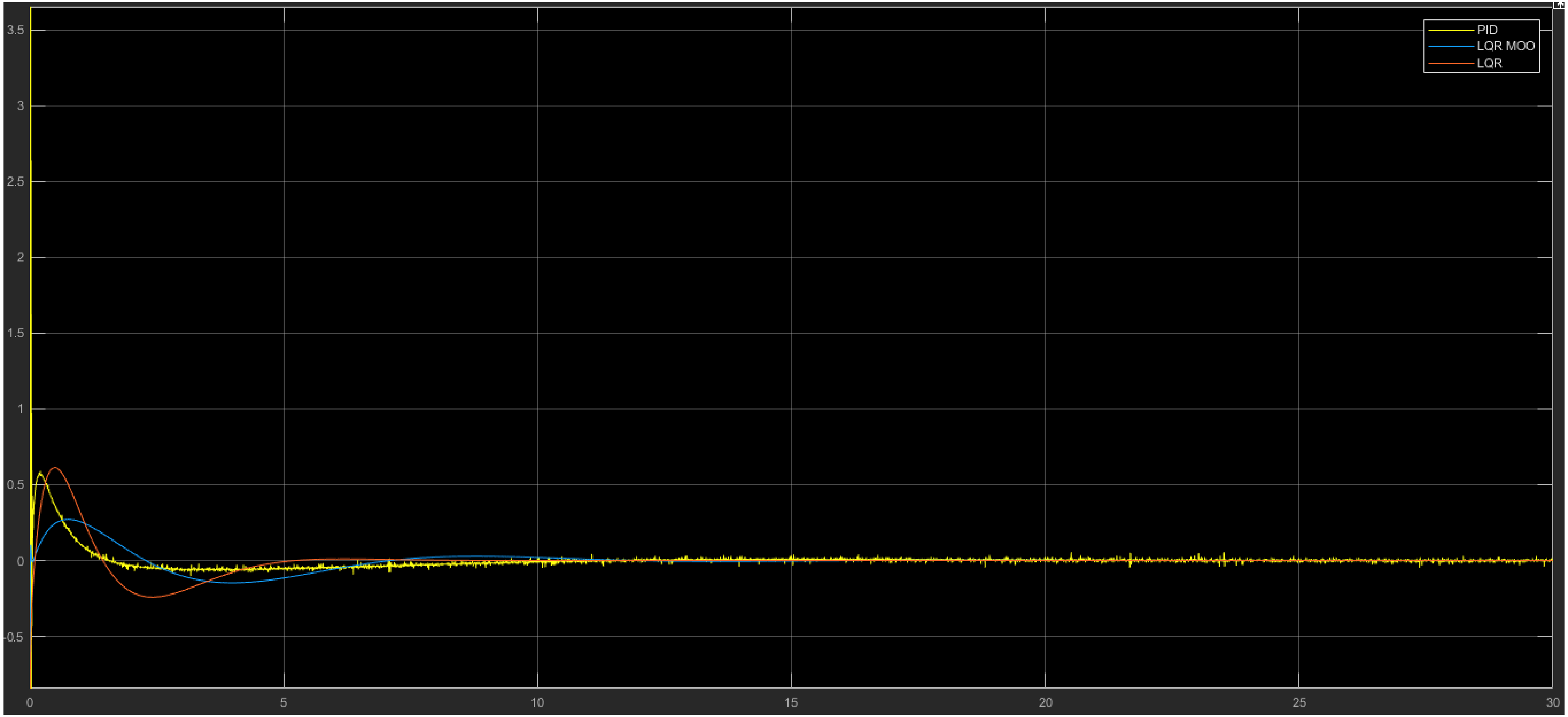
DISPLACEMENT



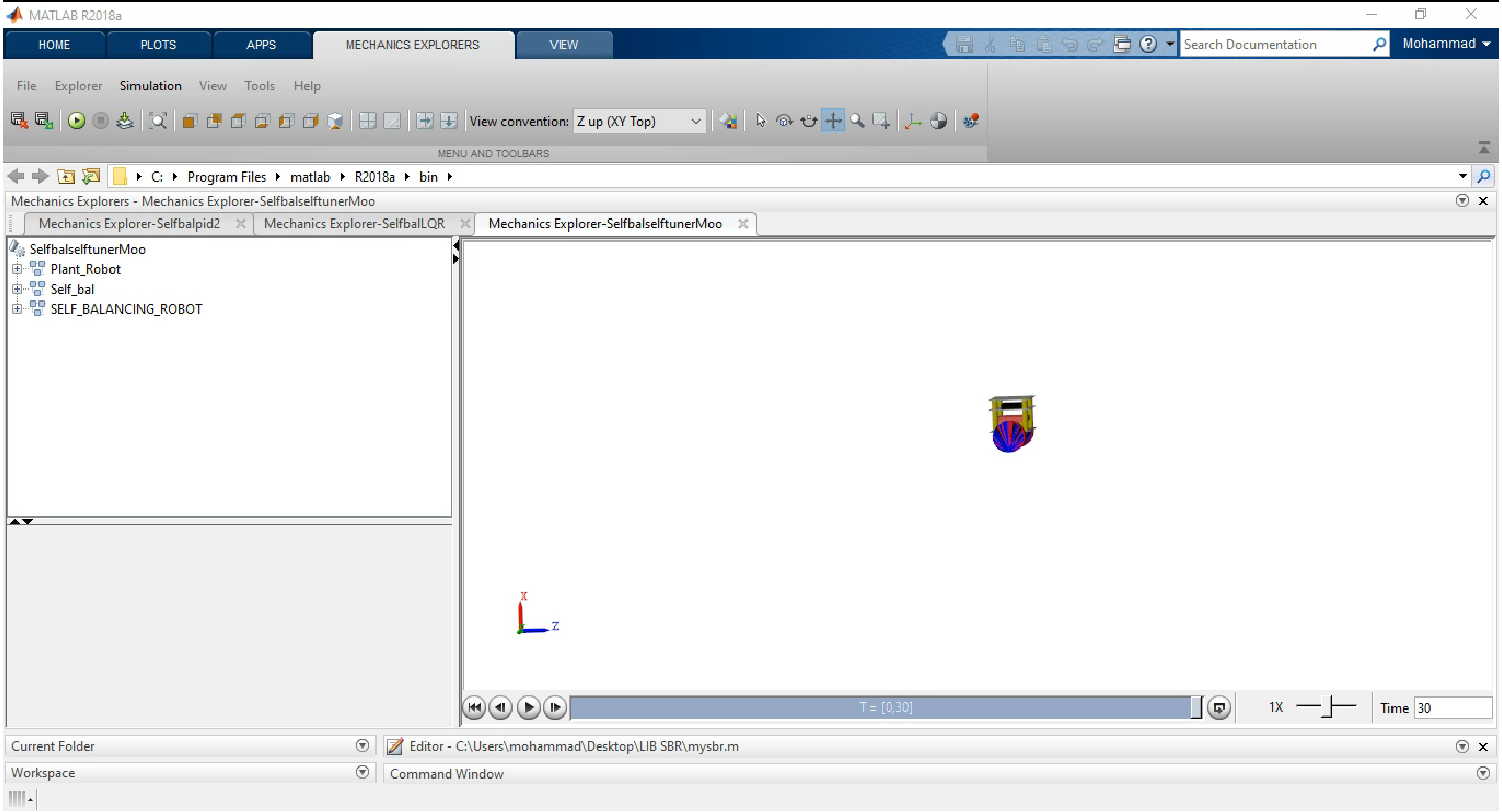
ANGLE



CONTROL EFFORT



VIDEO


MATLAB R2018a
HOME
PLOTS
APPS
MECHANICS EXPLORERS
VIEW
Search Documentation
Mohammad
File Explorer Simulation View Tools Help
View convention: Z up (XY Top)
MENU AND TOOLBARS
C: Program Files matlab R2018a bin
Mechanics Explorers - Mechanics Explorer-SelfbalselftunerMoo
Mechanics Explorer-Selfbalpid2
Mechanics Explorer-SelfbalLQR
Mechanics Explorer-SelfbalselftunerMoo
SelfbalselftunerMoo
Plant_Robot
Self_bal
SELF_BALANCING_ROBOT
X
Z
T = [0,30]
1X
Time 30
Current Folder
Editor - C:\Users\mohammad\Desktop\LIB SBR\mysbr.m
Workspace
Command Window

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CONCLUSION & FUTURE PERSPECTIVES

- LQR somehow gave the most promising results
- However, LQR is the most expensive in terms of sensors
- There is no optimal controller that meets all user requirements
- User must compromise based on his application and choose the best controller

Future Perspectives

- Real implementation on the actual robot
- Performance comparison between actual and empirical results

THANK YOU