Final Presentation

Course: Electrical Engineering lab (Automatic Control)
Semester: Fall, 2018
Instructor: Feng-Li Lian
Final Project: **Wheeled Inverted Pendulum**
Date: Jan, 2019
Classroom: EE1 Room 401

B05502097	B04502031	B04502139	B04502097
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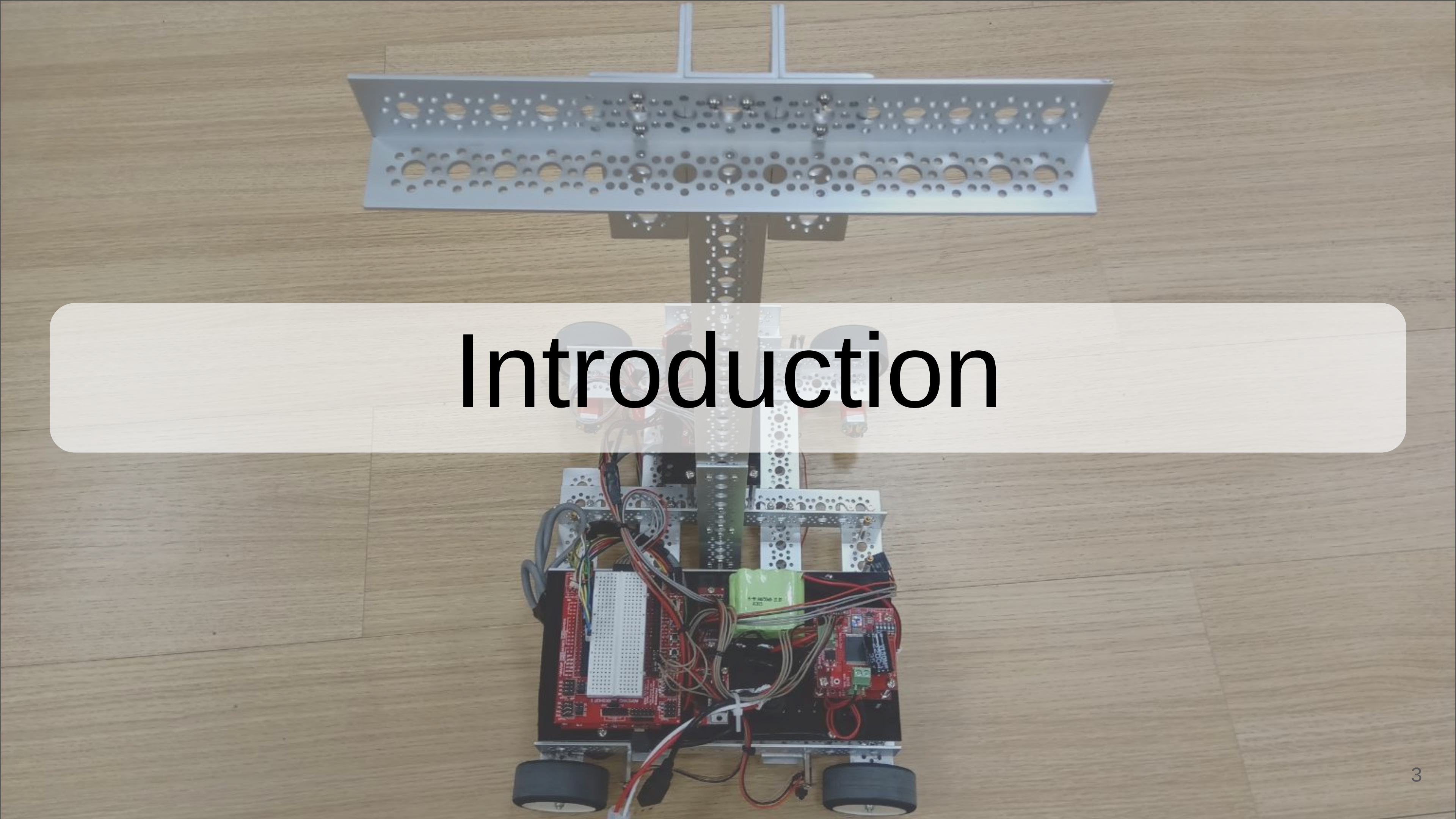
Outline

- ❖ Introduction
- ❖ Design principal
- ❖ System ID
- ❖ Modeling
- ❖ P controller design
- ❖ PID controller design
- ❖ Experiment result
- ❖ Live demo

Introduction

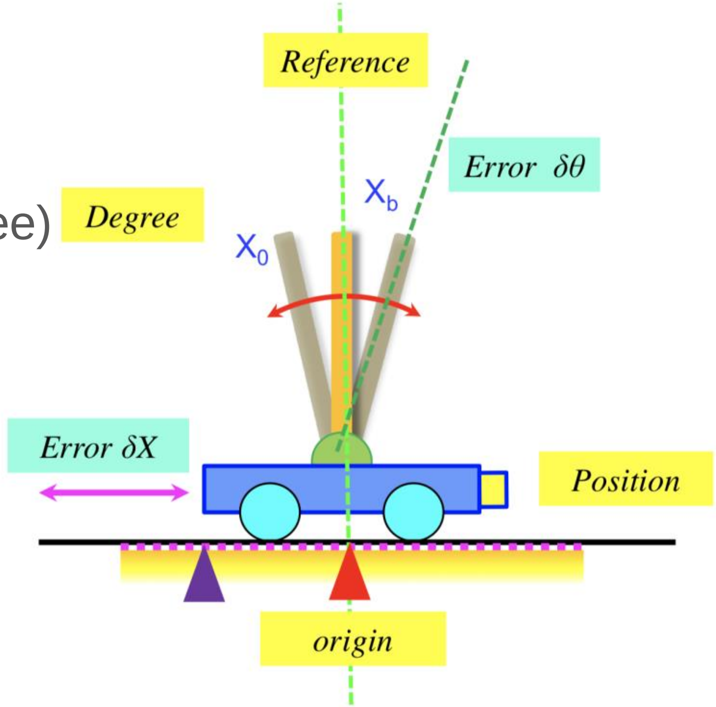


Wheeled Inverted Pendulum

Actuator: Motor (speed)

Sensor: Pendulum Encoder (degree)
Motor Encoder (degree)

Controller: Arminno



Wheeled Inverted Pendulum

Actuator: Motor (speed)

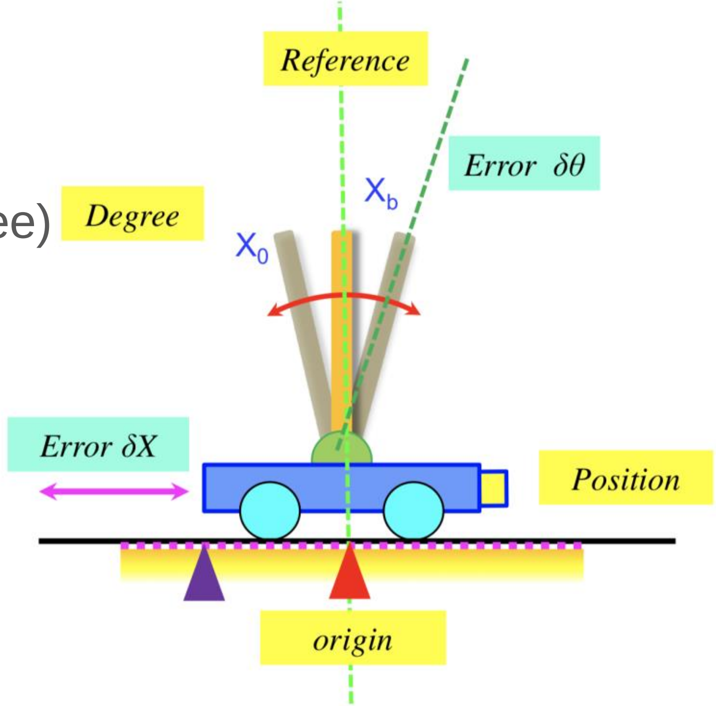
Sensor: Pendulum Encoder (degree)

Motor Encoder (degree)

Controller: Arminno

Error: $\delta\theta$, δx

Objective: $\delta\theta$=0, δx = 0

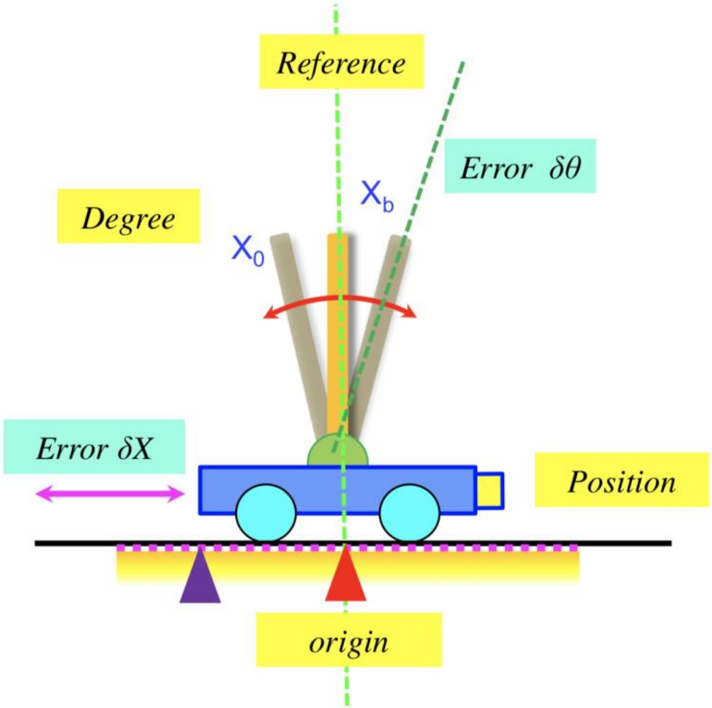


Challenge

1. Nonlinear System (due to pendulum)

2. Unstable equilibrium point

3. Other nonlinear effects: motor friction etc.



Time domain spec

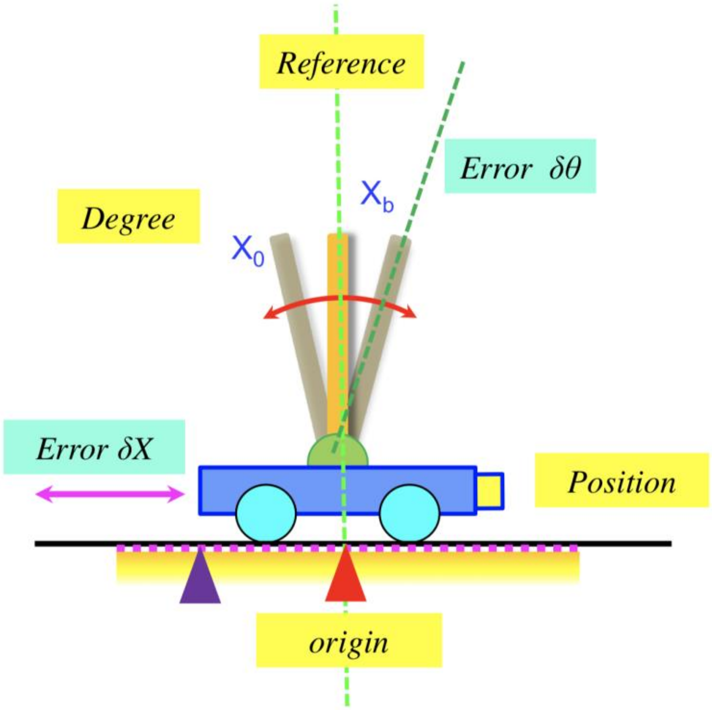
Pendulum Angle θ

— settling time < 10 sec.

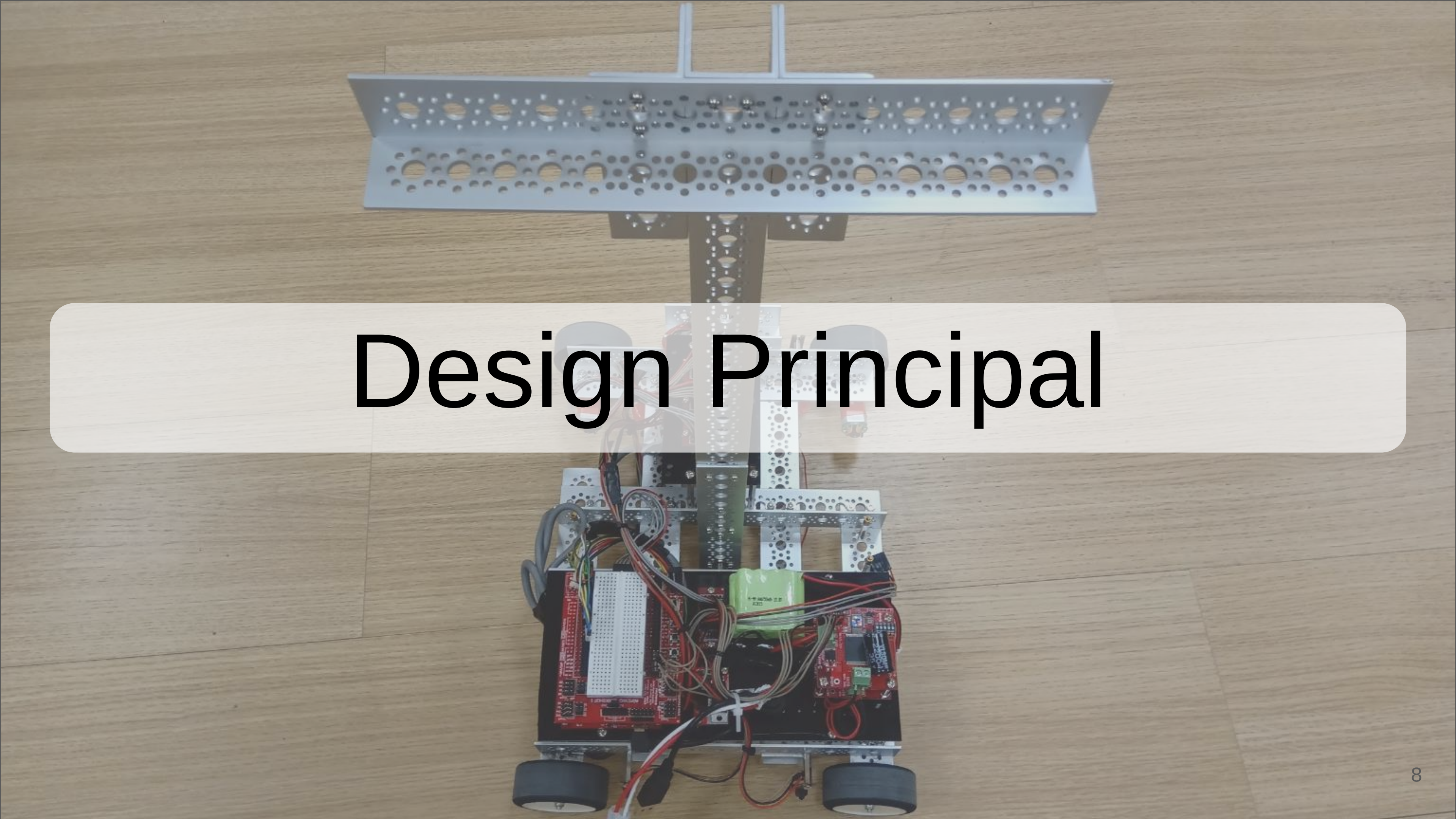
—steady state error < 5º

Vehicle Position x

— settling time < 30 sec.



Design Principal



Controller Design SOP

System identification from linearization around the equilibrium point

System ID

Modeling

Modelling from Lagrangian

System ID / **Modeling** → **P Controller Design** → **PD controller Design** → **PID controller Design**

P Controller Design

Find the equilibrium point.

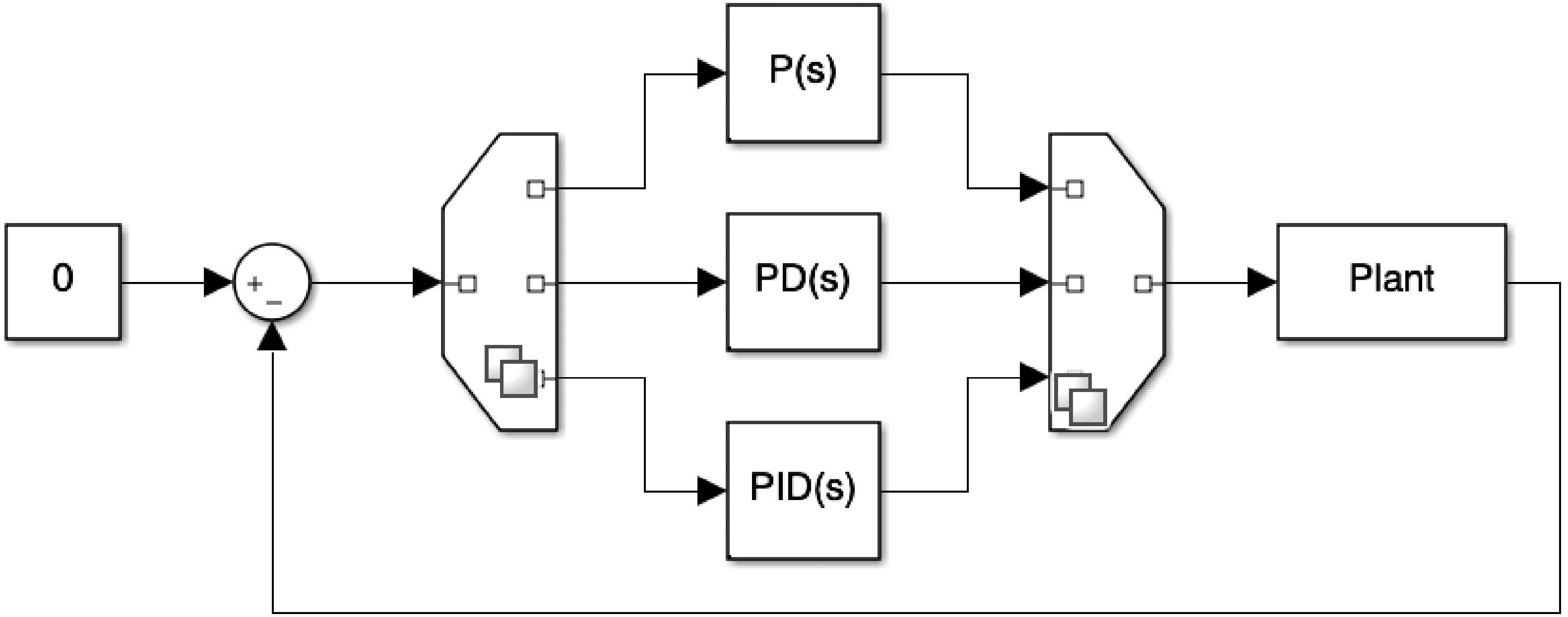
PD controller Design

From the linearized model around the equilibrium point, design a PD controller with greater errors.

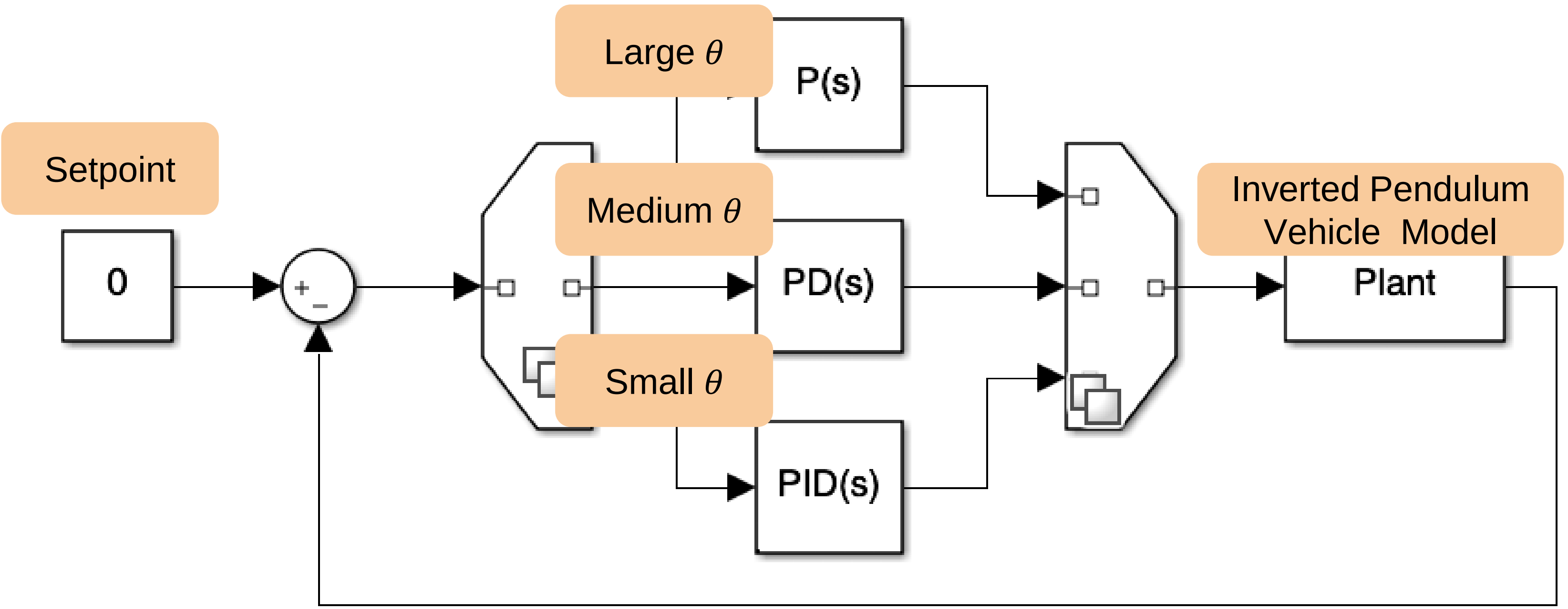
PID controller Design

Design a PID controller from the linearized model around the equilibrium point.

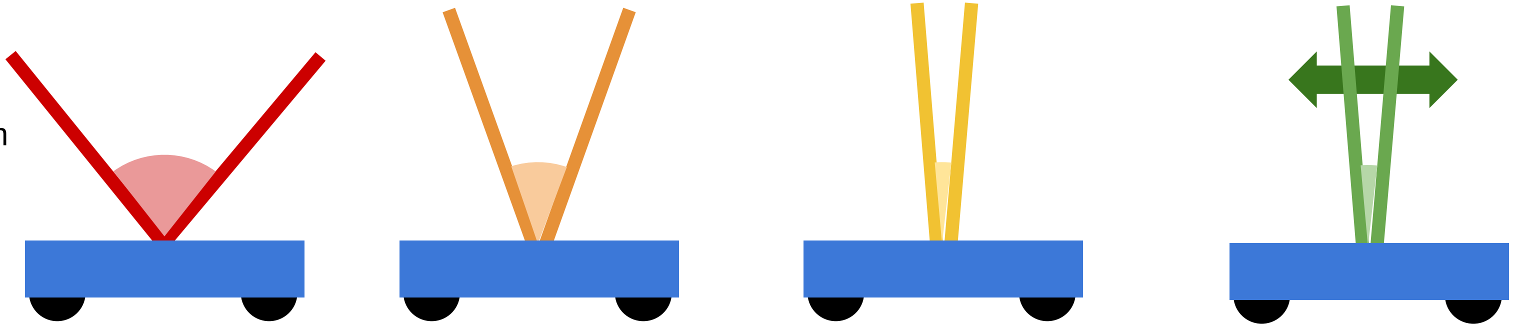
Controller Block Diagram—tracking θ



Controller Block Diagram—tracking θ



Controller Design SOP for Position tracking



System identification from linearization around the equilibrium point

System ID

Modeling

Modelling from Lagrangian

P Controller Design

Find the equilibrium point.

PD controller Design

From the linearized model around the equilibrium point, design a PD controller with greater errors.

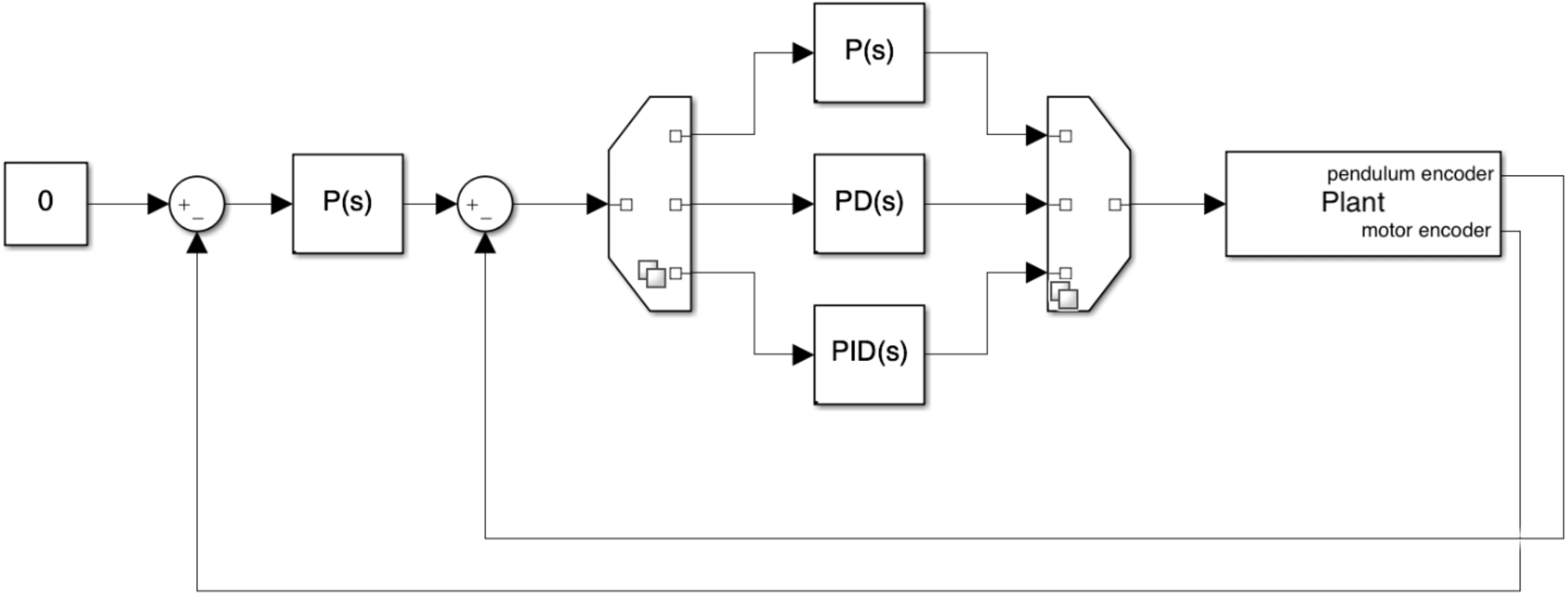
PID controller Design

Design a PID controller from the linearized model around the equilibrium point.

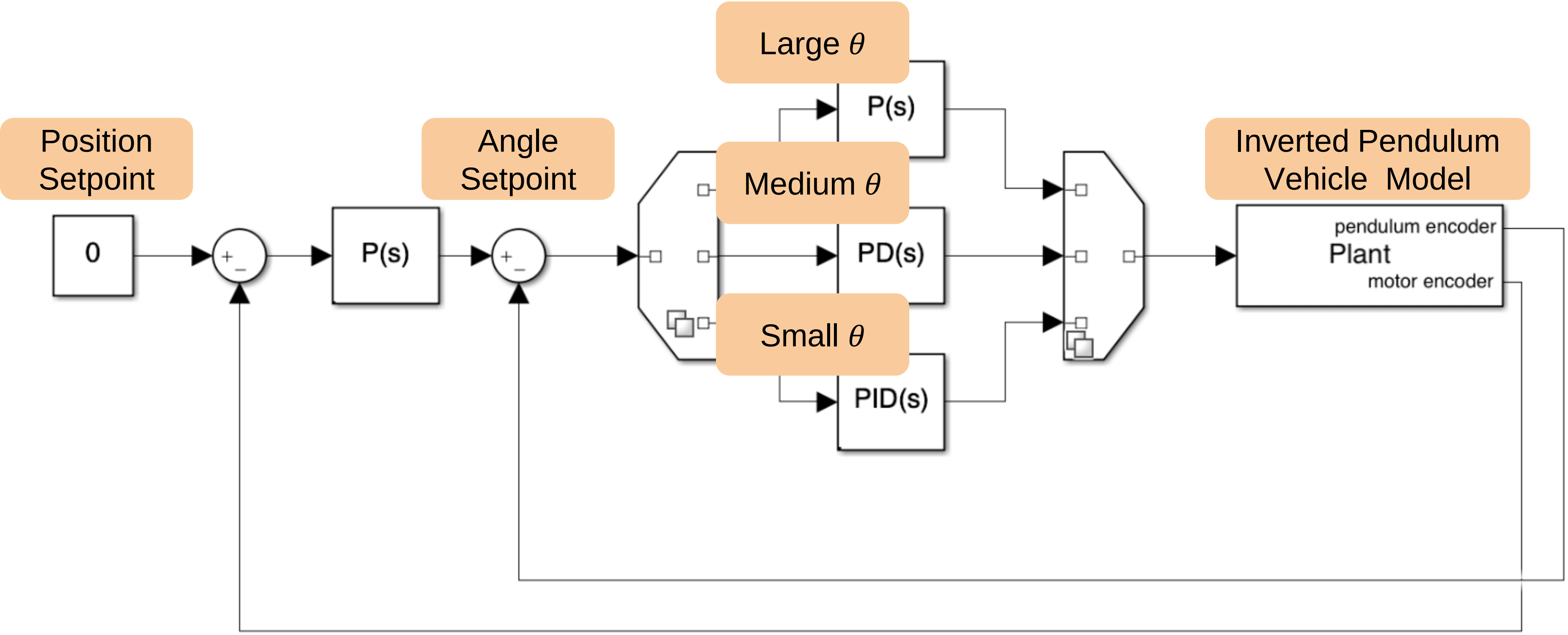
P controller Design (Position)

Use the setpoint position to control from feedbacks

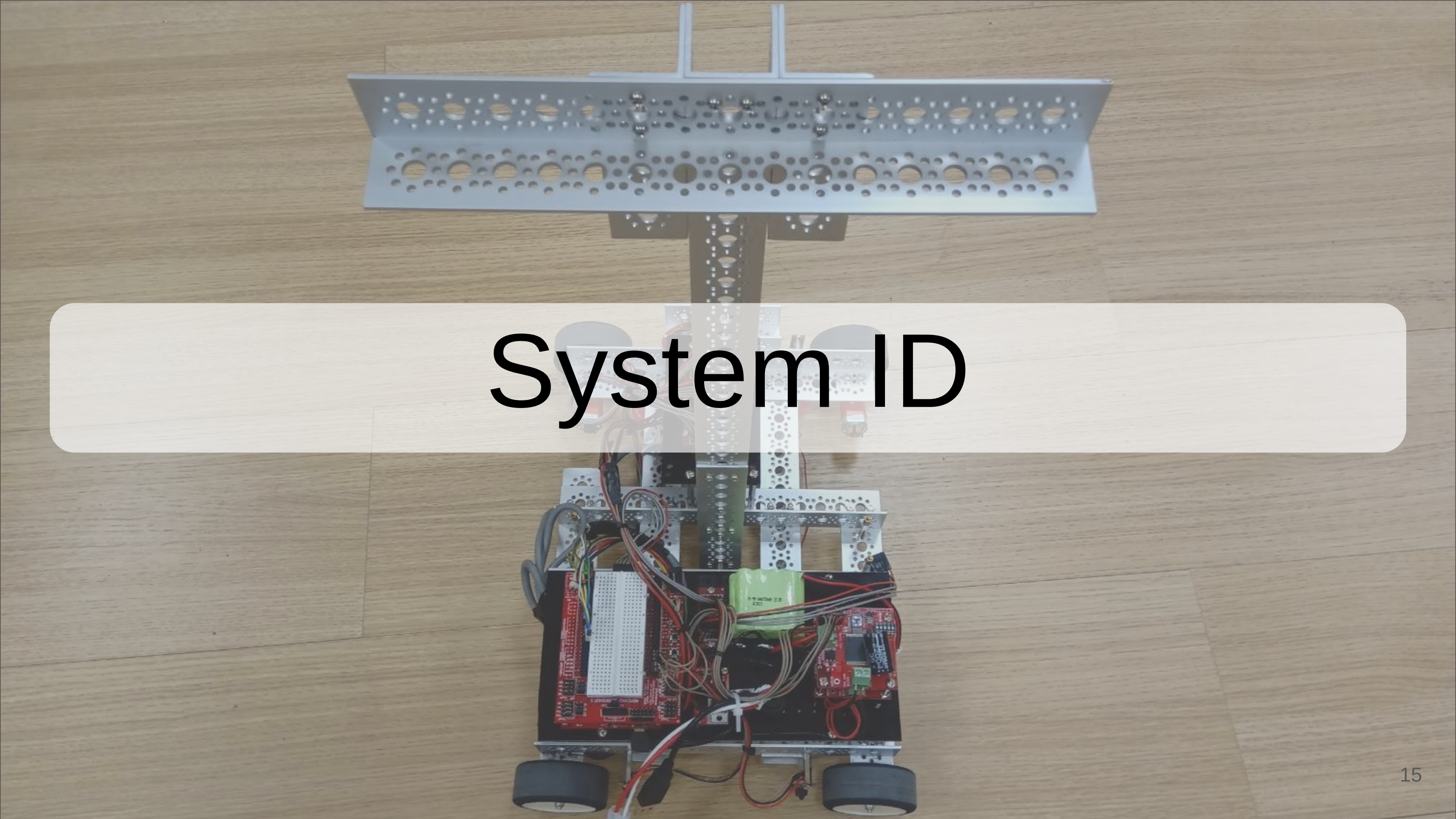
Controller Block Diagram—tracking θ & x



Controller Block Diagram—tracking θ & x



System ID



System

Time axis

Left Encoder

Right Encoder

Input Speed

	A	B	C	D	E
1	tmValue	IPdecValue	LdecValue	RdecValue	int(direction)*speed
2	458	0	0	0	0
3	6642181	0	0	0	100
4	12366044	0	22	14	100
5	17373888	0	94	58	0
6	21963747	0	163	117	100
7	26819513	1	228	185	100
8	31515748	2	309	254	0
9	36453164	1	393	335	100
10	41250104	-1	465	411	100
11	45963693	1	547	489	0
12	50720404	1	630	571	0
13	55710127	-1	700	642	100
14	60571922	2	769	712	0
15	65097052	2	839	776	100
16	70104102	0	910	849	100
17	3016683	0	992	925	100
18	7788989	0	1078	1009	0
19	12418820	0	1160	1089	0
20	17248851	1	1229	1160	100
21	22103644	0	1297	1229	100
22	26829926	0	1379	1300	0
23	31648049	2	1460	1377	0
24	36653542	2	1525	1447	100
25	41299016	2	1588	1510	0
26	46067766	-1	1663	1576	100
27	50772267	8	1727	1643	0
28	55690195	-2	1807	1710	0
29	60173741	3	1862	1765	100
30	65413592	2	1927	1832	0
31	69820527	0	1990	1886	0
32	2878127	7	2041	1940	100
33	7666431	0	2097	1994	0
34	12290520	1	2162	2049	100
35	17502802	3	2229	2117	0

speed_100_new

System

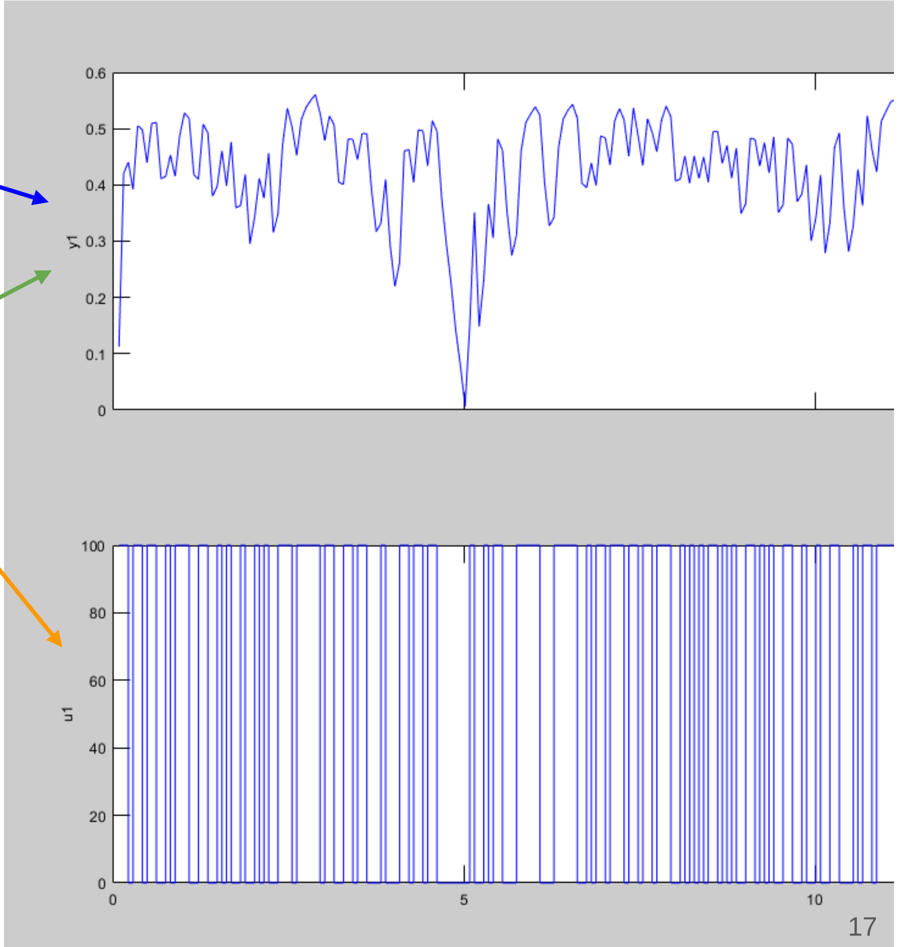
	1	2	3	4
1	0.0923	0.1126	0.0716	100
2	0.1718	0.4211	0.2573	100
3	0.2413	0.4403	0.3765	0
4	0.3051	0.3920	0.4101	100
5	0.3725	0.5051	0.4303	100
6	0.4377	0.4982	0.4804	0
7	0.5063	0.4396	0.4640	100
8	0.5729	0.5095	0.4846	100
9	0.6384	0.5110	0.5049	0
10	0.7045	0.4108	0.4167	0
11	0.7738	0.4156	0.4217	100
12	0.8413	0.4530	0.4142	0
13	0.9041	0.4153	0.4270	100
14	0.9737	0.4888	0.4531	100
15	1.0419	0.5277	0.5155	100
16	1.1082	0.5187	0.5060	0
17	1.1725	0.4184	0.4305	0
18	1.2396	0.4102	0.4162	100
19	1.3070	0.5081	0.4399	100
20	1.3726	0.4923	0.4680	0
21	1.4396	0.3803	0.4096	0
22	1.5091	0.3972	0.3972	100
23	1.5736	0.4606	0.4053	0
24	1.6398	0.3984	0.4171	100
25	1.7052	0.4764	0.3990	0
26	1.7735	0.3593	0.3593	0
27	[illegible]	[illegible]	[illegible]	[illegible]

Time axis

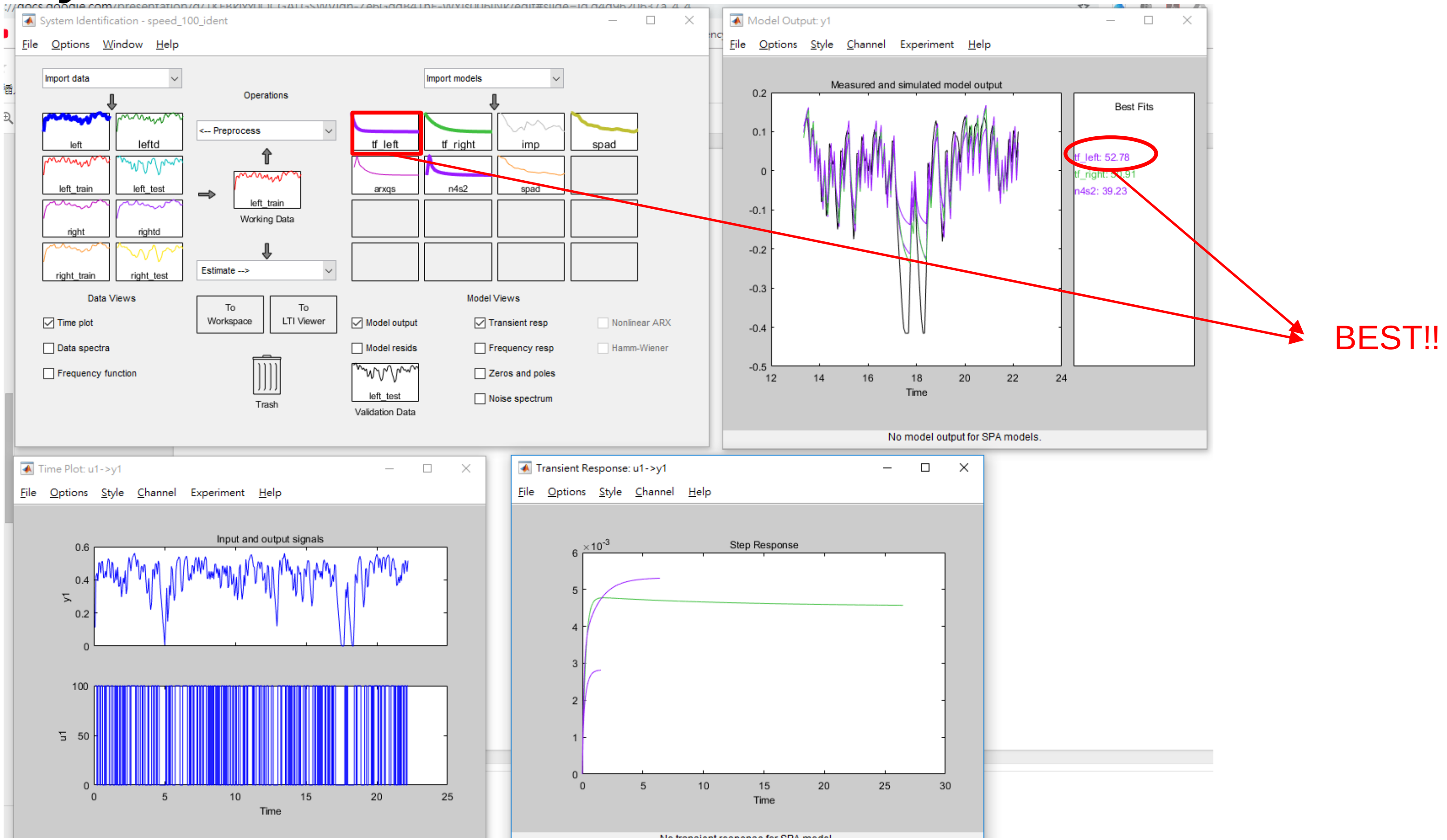
Left Speed

Right Speed

Input Speed



System Identification



Transfer Function

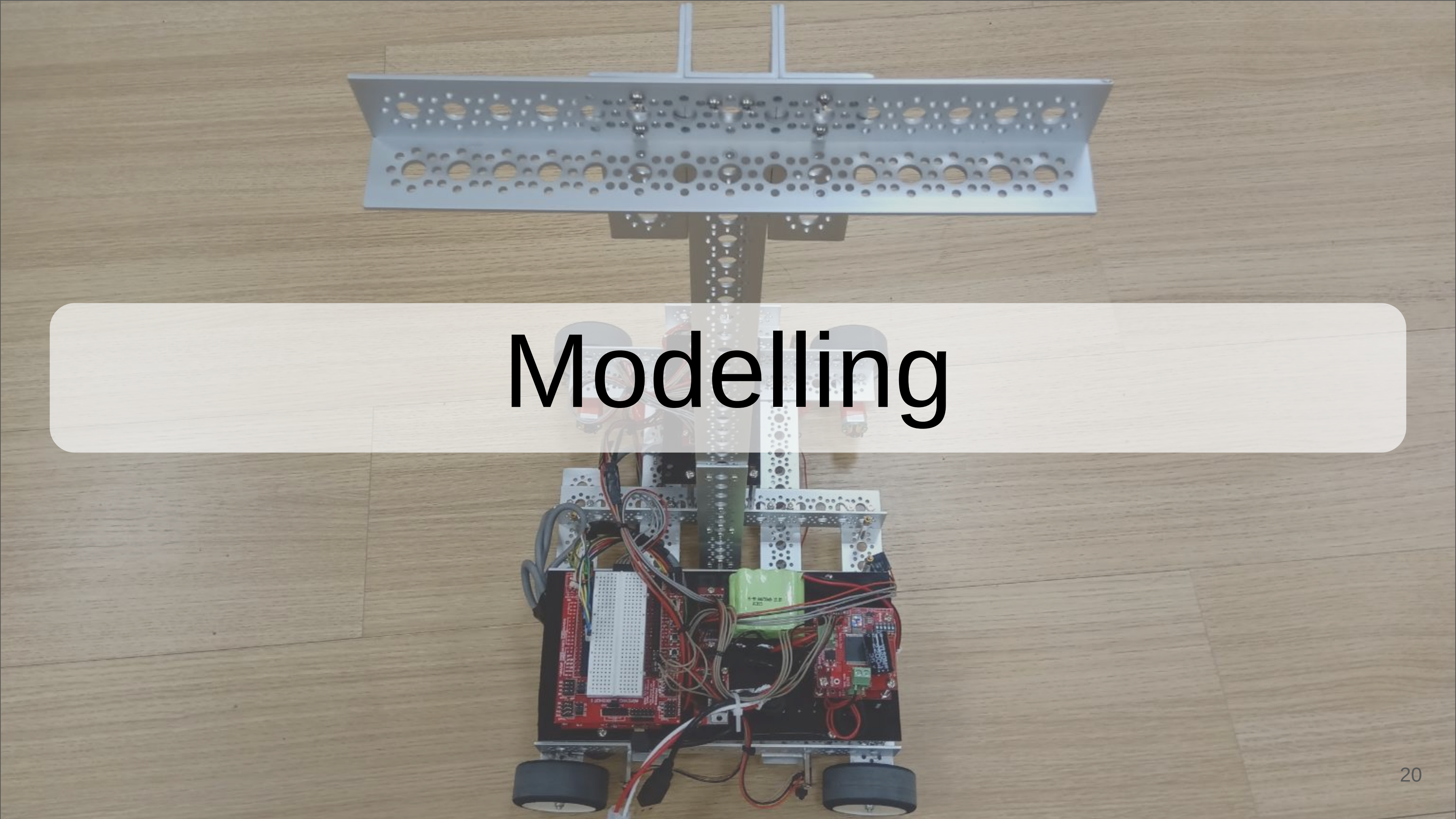
Input : drive speed

Output : actual speed

From input to output "y1":

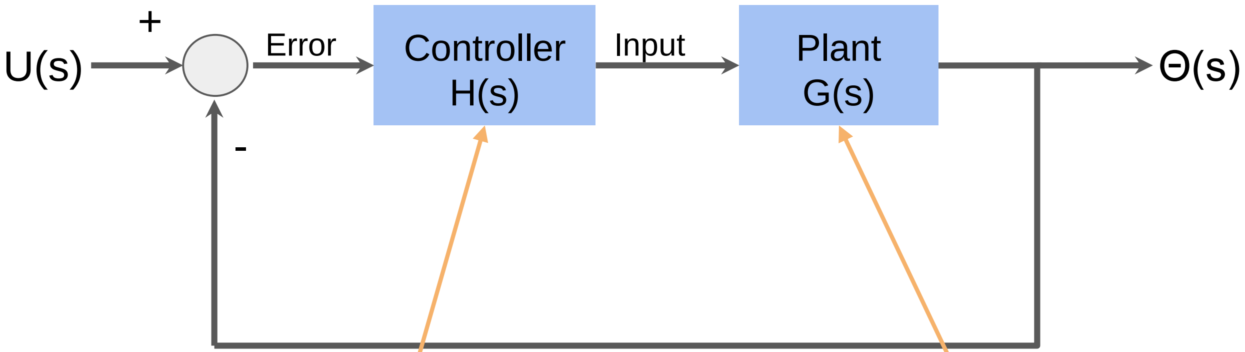
$$\frac{V(s)}{input} = \frac{-7.043\ s^3 + 0.5402\ s^2 + 236.4\ s - 18.13}{3.421\ s^3 + 117.4\ s^2 + 329\ s}$$

$$\frac{A(s)}{input} = \frac{V(s)}{input} \times s$$



Modelling

Overall Model



Θ(s) = Angle of the Pendulum
A(s) = Acceleration of the Vehicle
Input(s) = Input speed

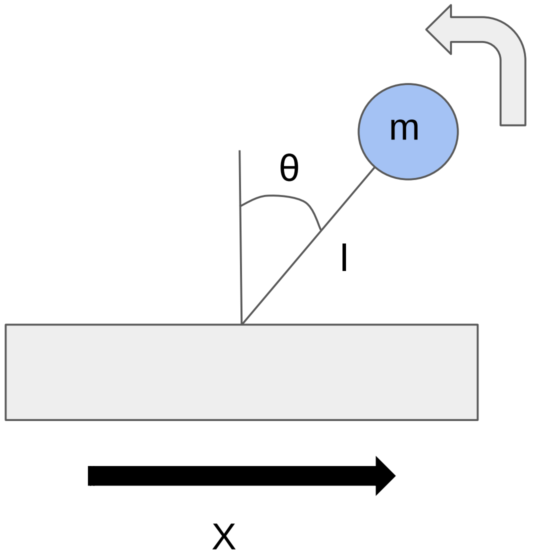
PID Controller

$$G(s) = \frac{\Theta(s)}{Input(s)} = \frac{\Theta(s)}{A(s)} \frac{A(s)}{Input(s)}$$

Derived physics model

From System Identification tool

Physics Model[2]



From Newton's Law,

$$\ddot{\theta} = \frac{g \cdot sin(\theta)}{l} - \frac{\ddot{x} \cdot cos(\theta)}{l}$$

θ ≈ 0

$$-\ddot{x} = l\ddot{\theta} - g\theta$$

Laplace

$$\frac{\Theta(s)}{X(s)} = \frac{-s^2}{ls^2 - g}$$

or

$$\frac{\Theta(s)}{A(s)} = \frac{-1}{ls^2 - g}$$

Physics Model

According to the measurement :

l = 0.2923 m

g = 9.81 m/s^2

m = 0.289 kg

$$\Rightarrow \quad \frac{\Theta(s)}{A(s)} = \frac{-3.421}{s^2 - 33.56}$$

One of the poles > 0
→ Unstable system

System Model

Transfer function(speed command to acceleration)

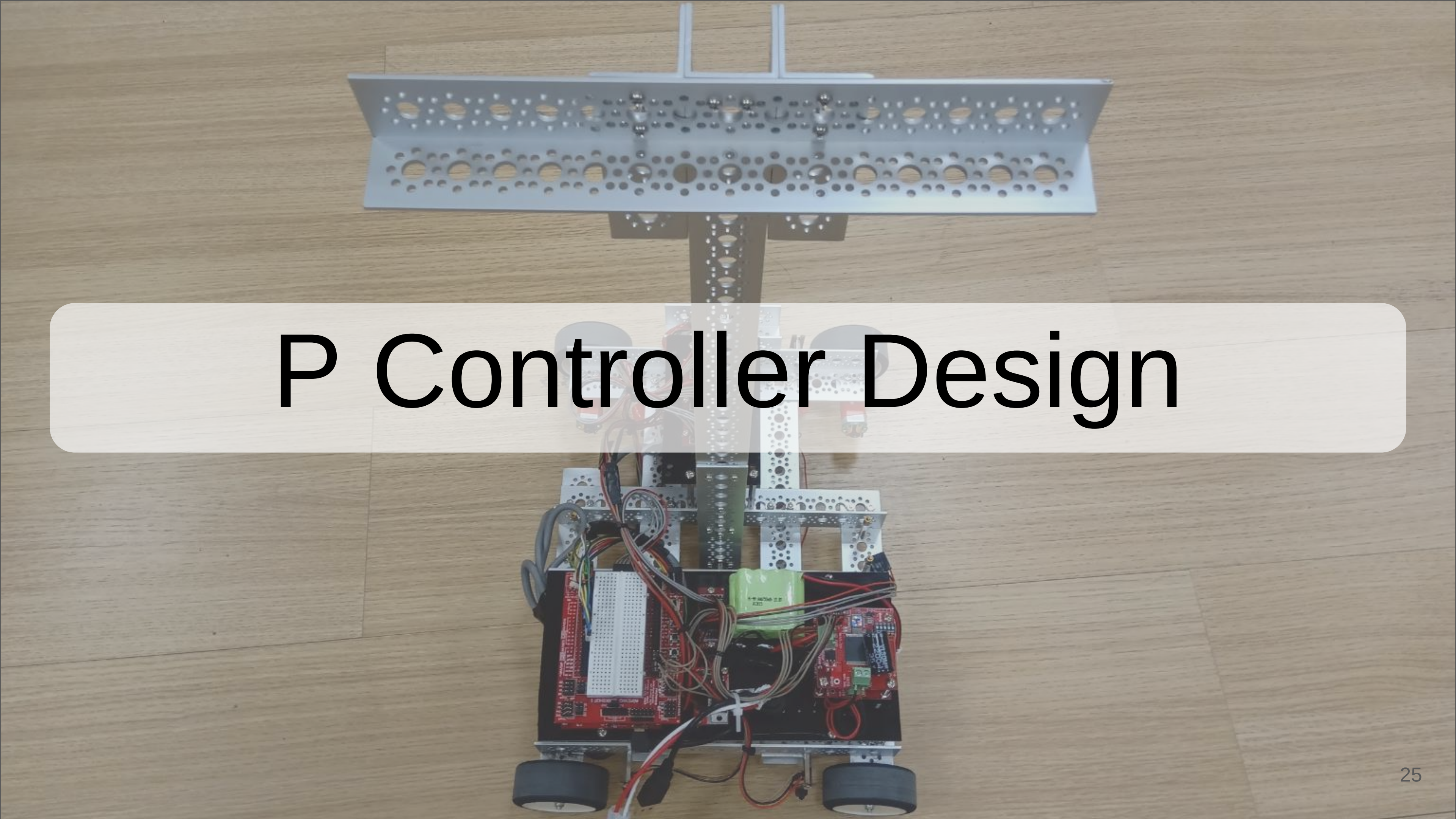
$$\frac{-7.043s^3 + 0.5402s^2 + 236.4s - 18.13}{3.421s^2 + 117.4s + 329}$$

Transfer function(acceleration to pendulum degree)

$$\frac{-3.421}{s^2 - 33.56}$$

Overall transfer function = $$\frac{7.043s - 0.5402}{s^2 + 34.32s + 96.16}$$

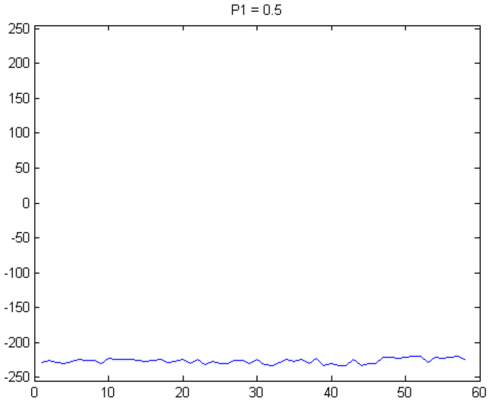
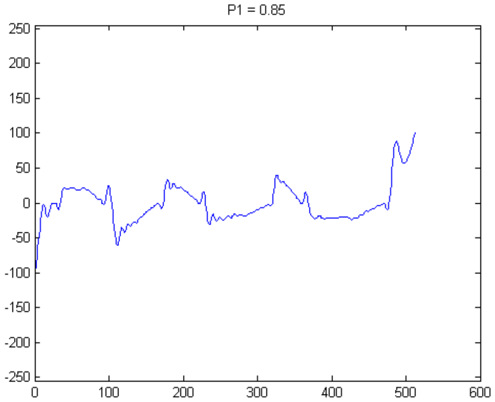
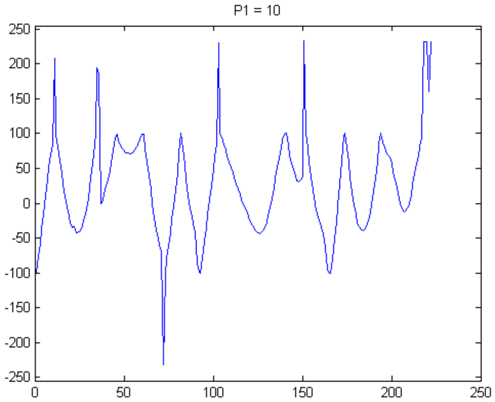
P Controller Design



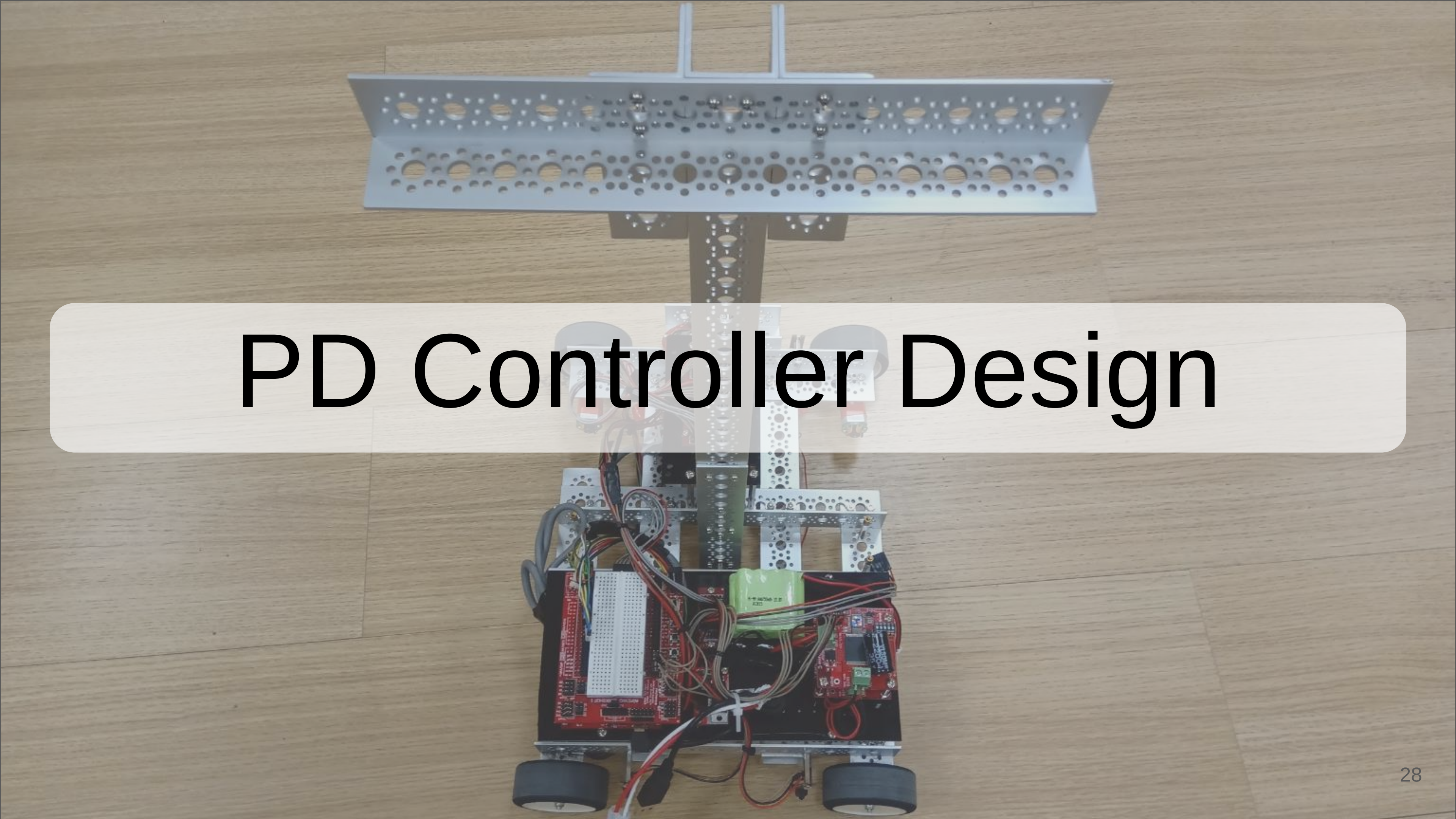
P Controller (θ>9º)

- 最外層的P Controller之目的便是讓倒單擺擺起來，使其到均衡點，進入線性區域。
- P Controller 所使用的區域不適用於線性模型，因此我們也做出了諸多特別的設計來彌補。
- 我們設計讓P Controller在作用之前，先往反方向運動，以增加其速度變化量，如此較容易達成將倒單擺擺起來的目的。

What happened if the value of Kp is too small or too large?

small Kp	moderate Kp	large Kp
		
倒單擺無法進入線性區域，或是進入線性區之速度過小，很快便又跌出來	倒單擺成功地以適當腳速度進入線性區，達成平衡	倒單擺進入線性區之速度過大，很快地衝入另一邊的非線性區，無法達成平衡

PD Controller Design

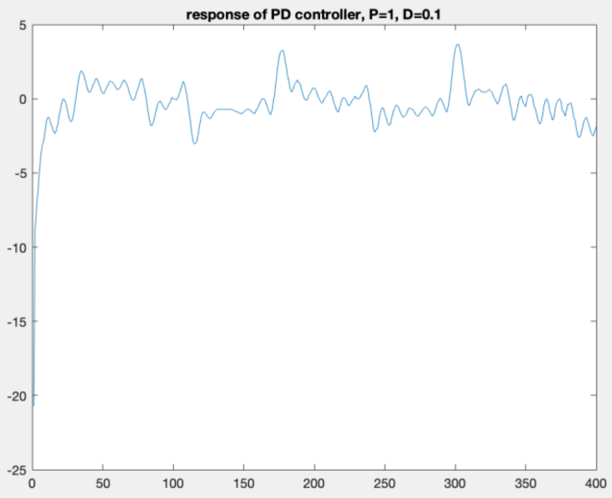


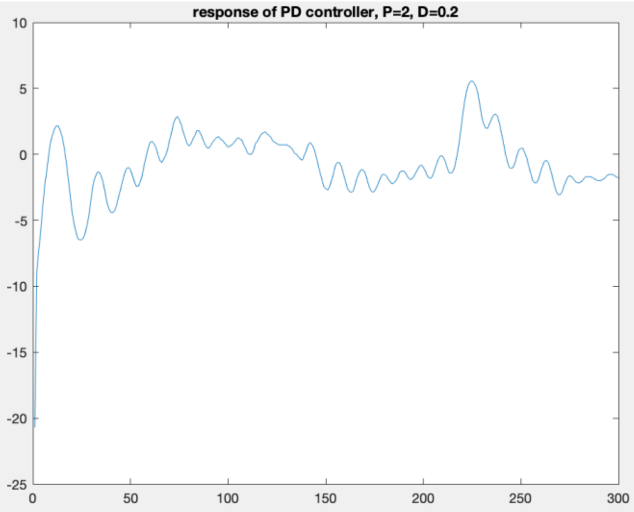
PD controller design (5º<θ<9º)

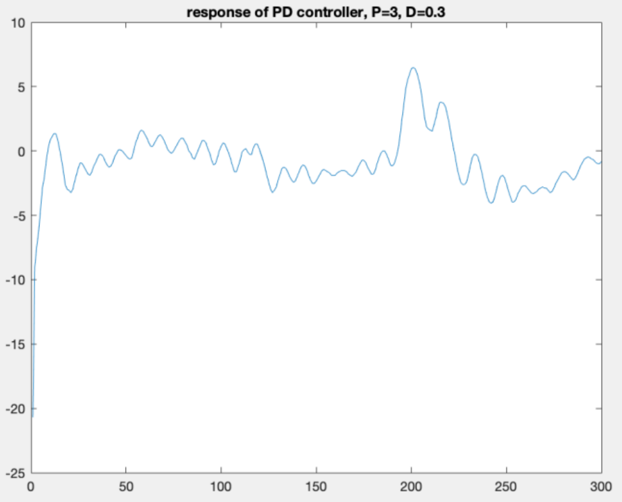
filename	KP	KD	Overshoot(deg)
PD_1_0.1.csv	1	0.1	3.69
PD_1_0.2.csv	1	0.2	4.59
PD_1_0.05.csv	1	0.05	6.84
PD_1_0.15.csv	1	0.15	4.5
PD_2_0.2.csv	2	0.2	5.58
PD_2_0.3.csv	2	0.3	5.56
PD_2_0.4.csv	2	0.4	6.03
PD_3_0.3.csv	3	0.3	6.48
PD_3_0.5.csv	3	0.5	6.75
PD_3_0.7.csv	3	0.7	6.66

PD controller design

Rising time: 3>2>1
Overshoot: 1<2<3

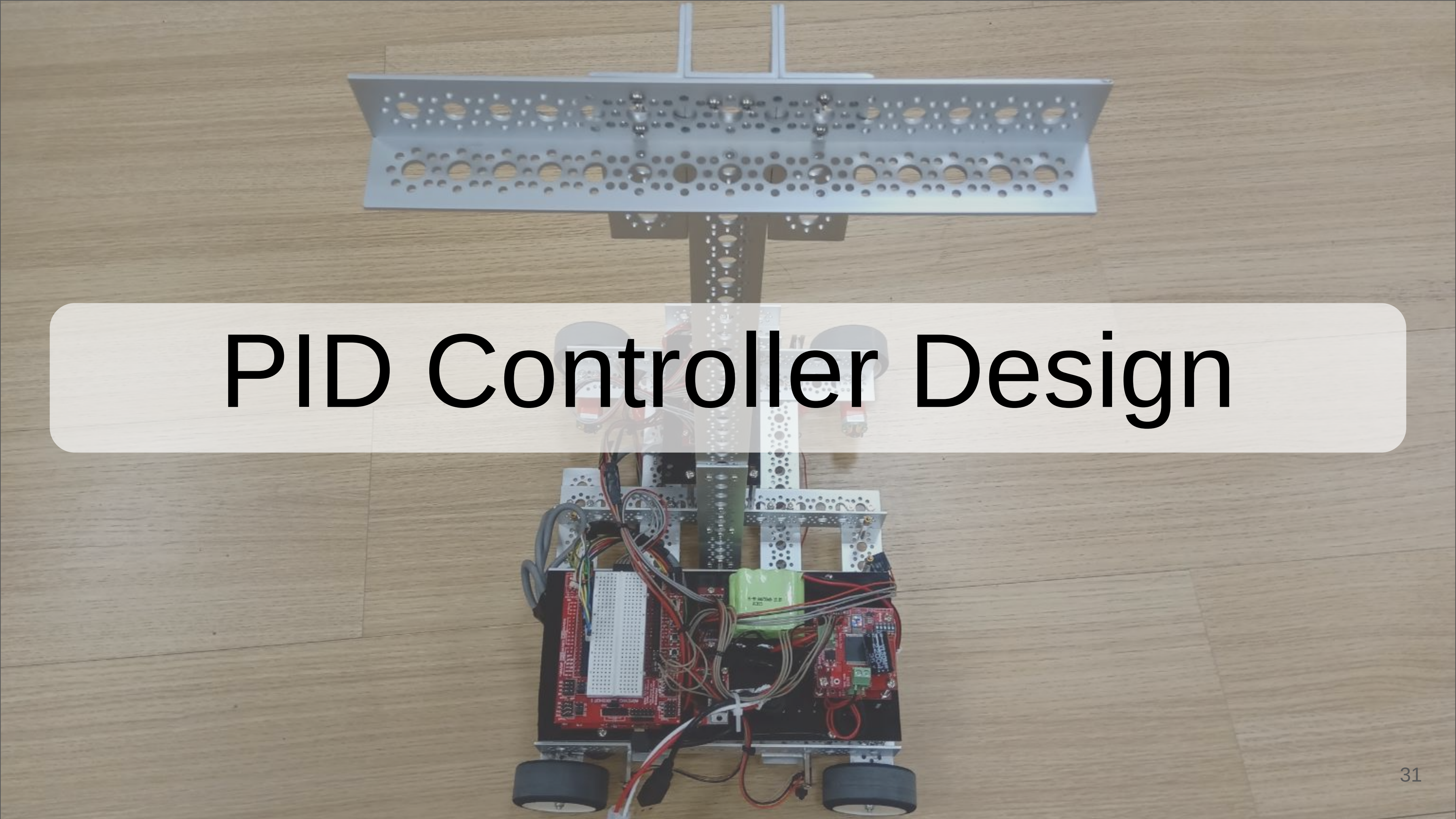






$1 + 0.1s$ $\quad$ $2 + 0.2s$ $\quad$ $3 + 0.3s$

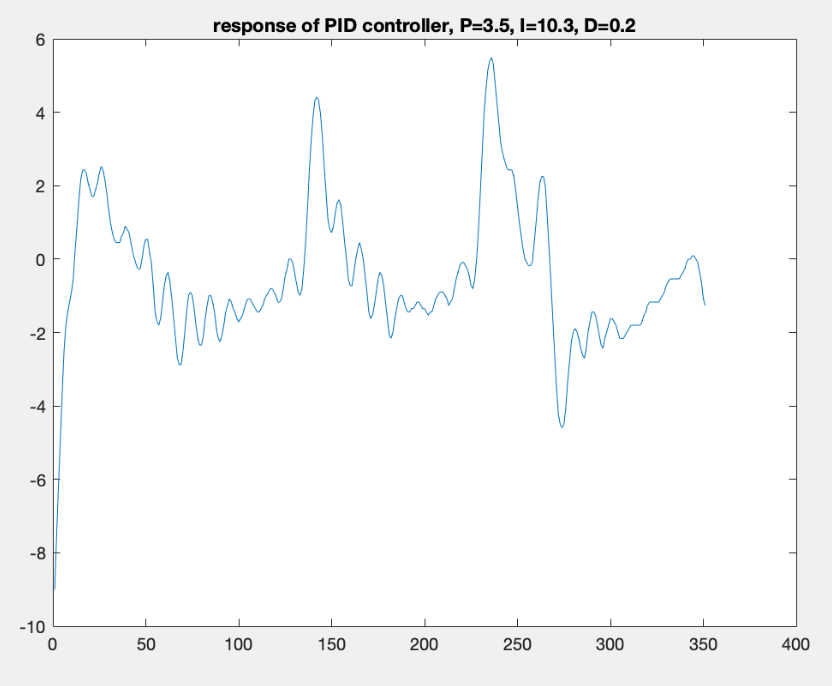
PID Controller Design

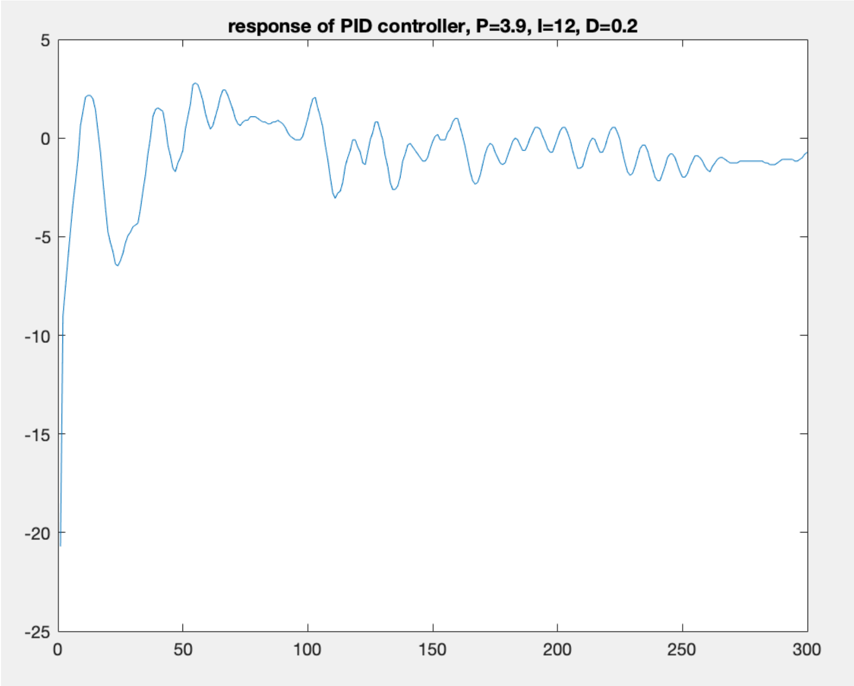


PID controller design ($\theta < 5^\circ$)

filename	KP	KI	KD	Overshoot(deg)
PID_3.5_9_0.2.csv	3.5	9	0.2	5.49
PID_3.5_10.3_0.2.csv	3.5	10.3	0.2	5.94
PID_3.9_10.3_0.2.csv	3.9	10.3	0.2	6.84
PID_3.9_10.3_0.4.csv	3.9	10.3	0.4	6.48
PID_3.9_10.3_0.05.csv	3.9	10.3	0.05	9.18
PID_3.9_12_0.2.csv	3.9	12	0.2	2.79
PID_4.3_10.3_0.2.csv	4.3	10.3	0.2	3.06

PID controller design (θ<5º)

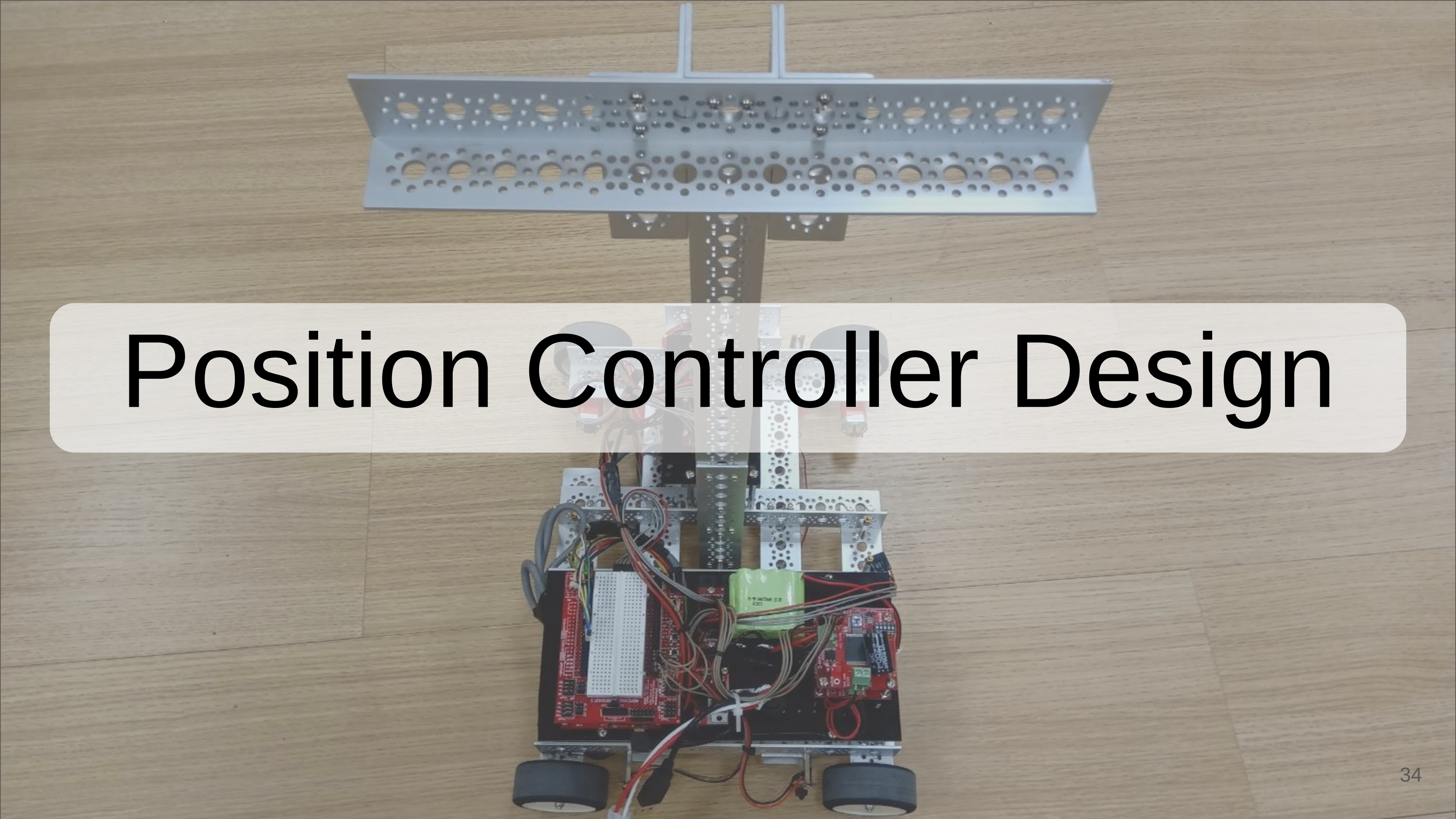




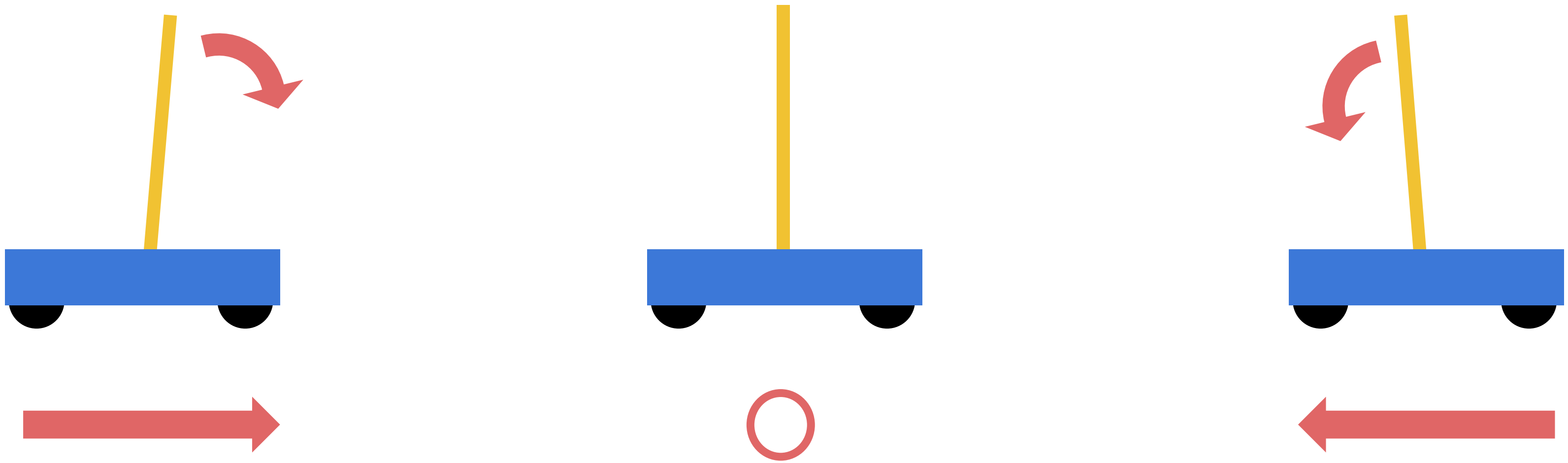
$$3.5 + \frac{10.3}{s} + 0.2s$$

$$3.9 + \frac{12}{s} + 0.2s$$

Position Controller Design



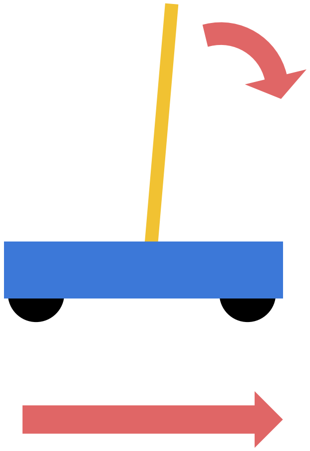
Inspiration



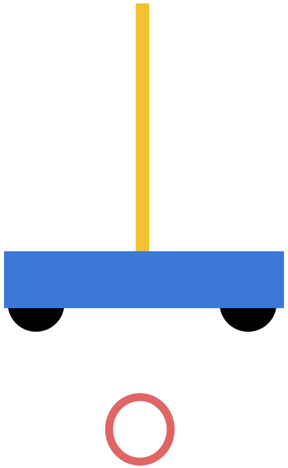
Inspiration

Using P control to achieve better performance

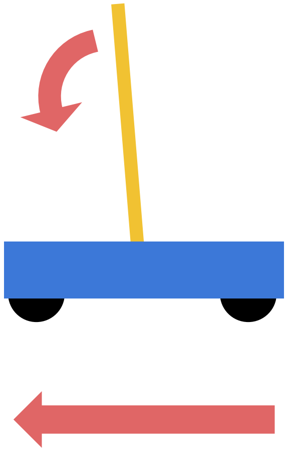
Setpoint > 0



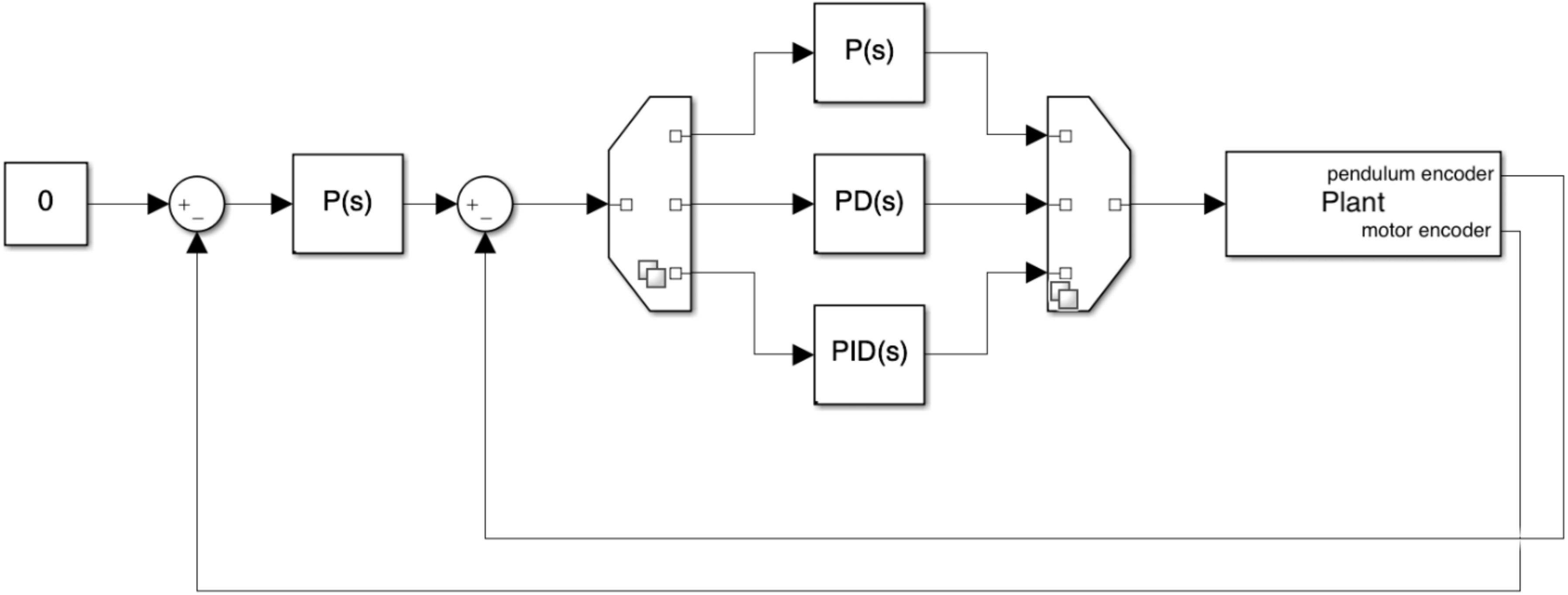
Setpoint = 0



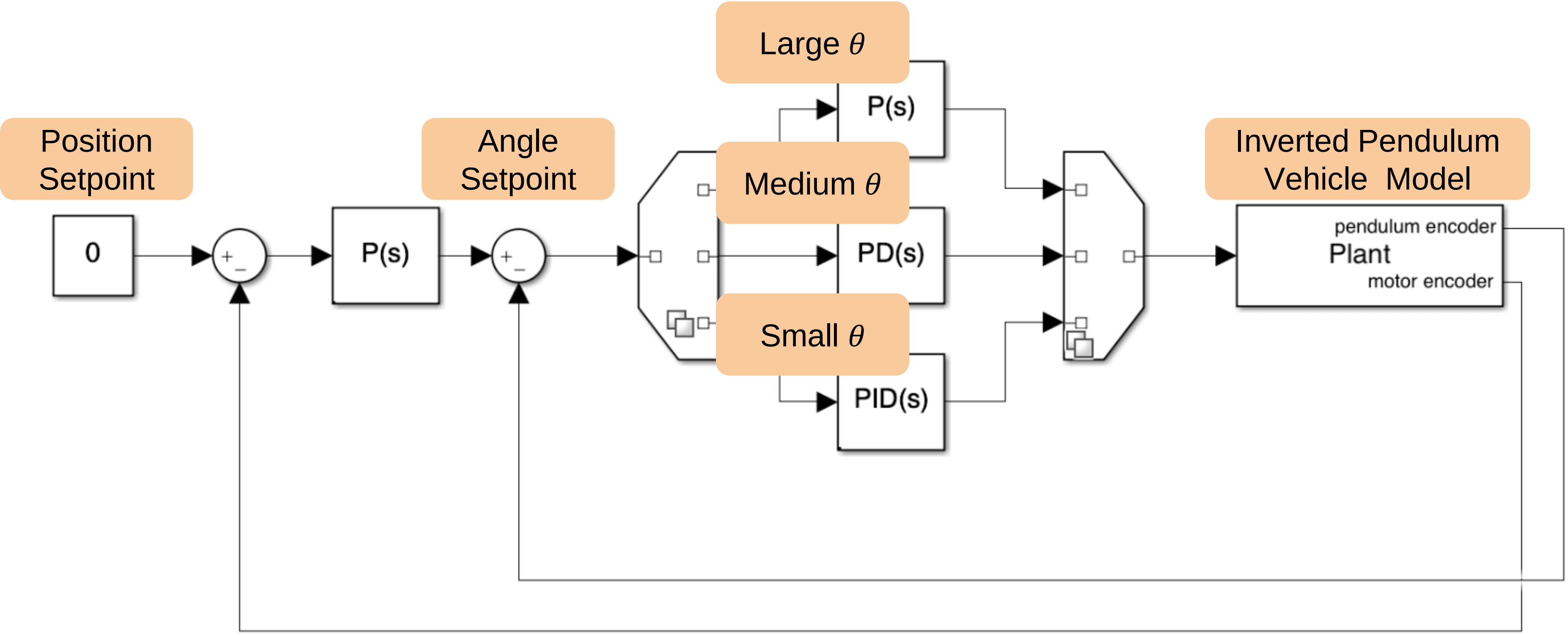
Setpoint < 0



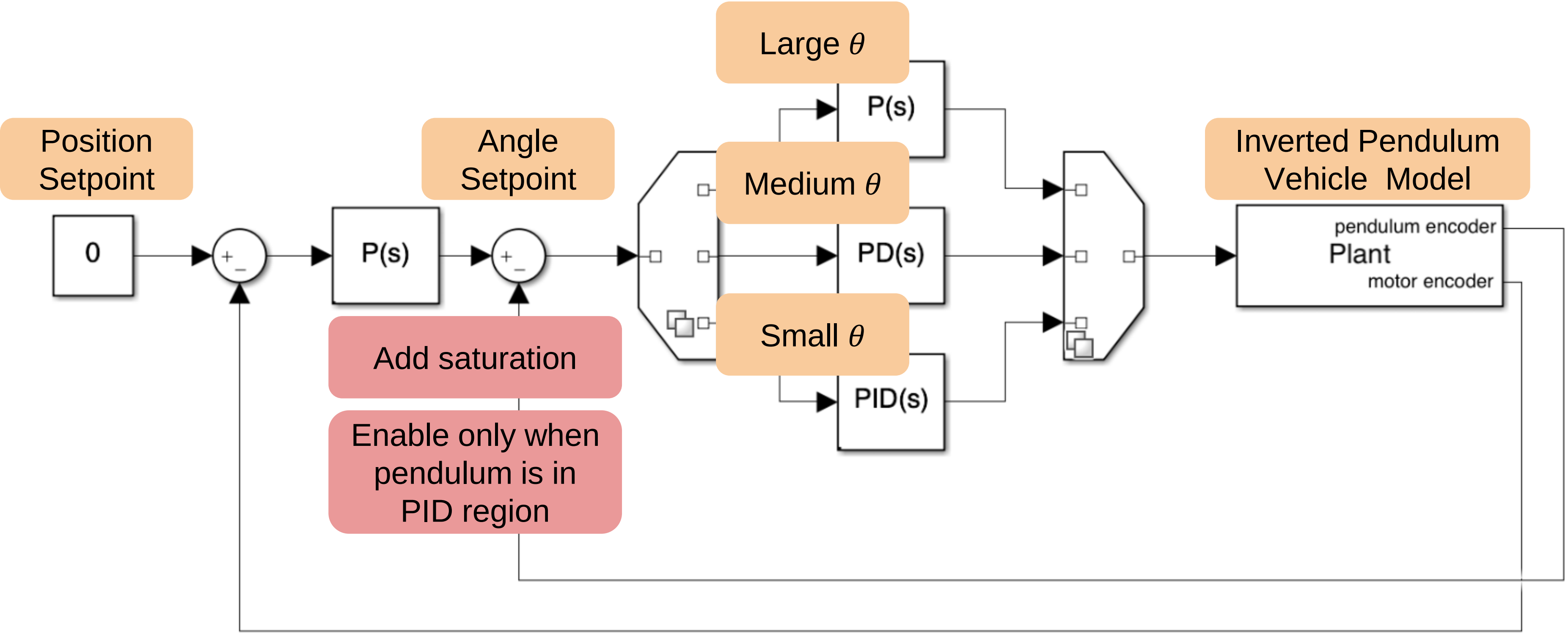
Position controller design



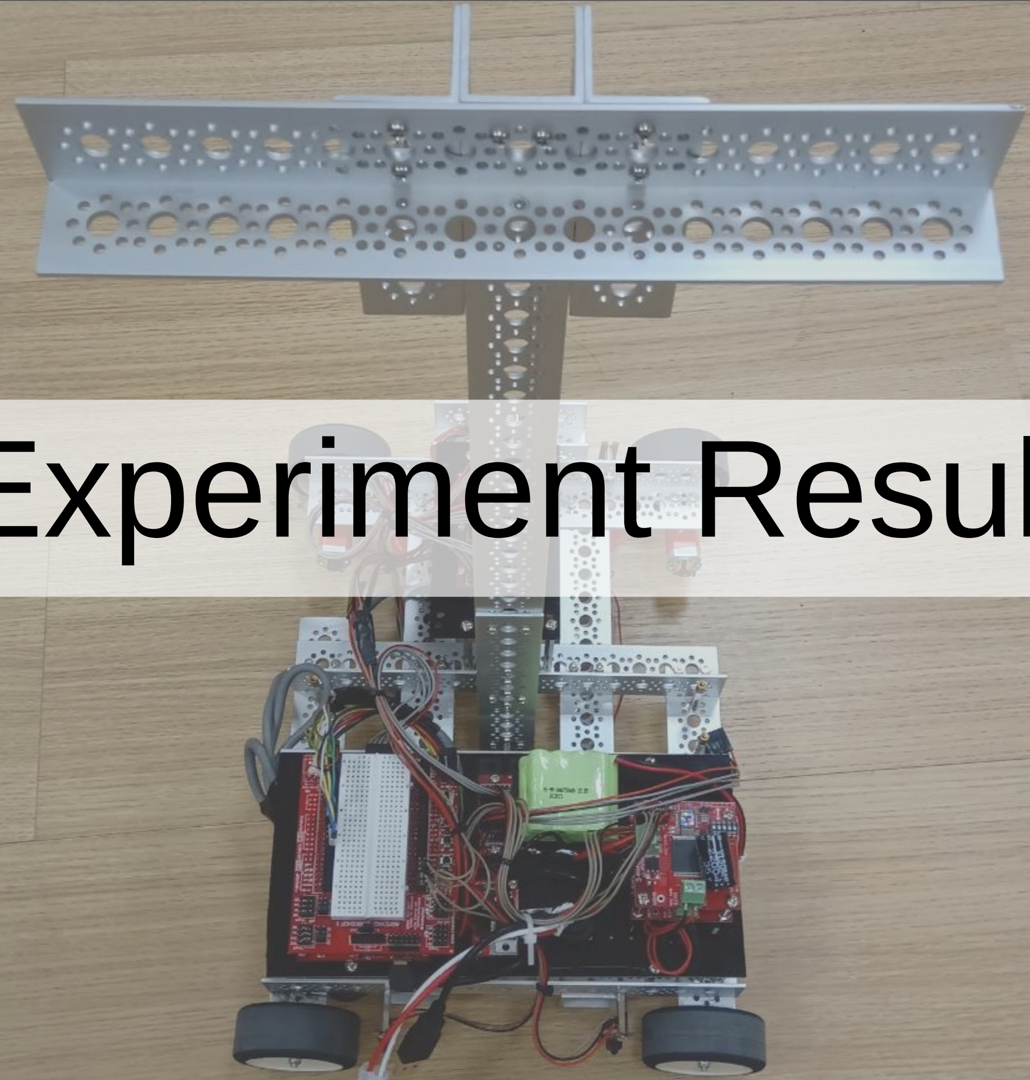
Position controller design—detail



Position controller design—further detail

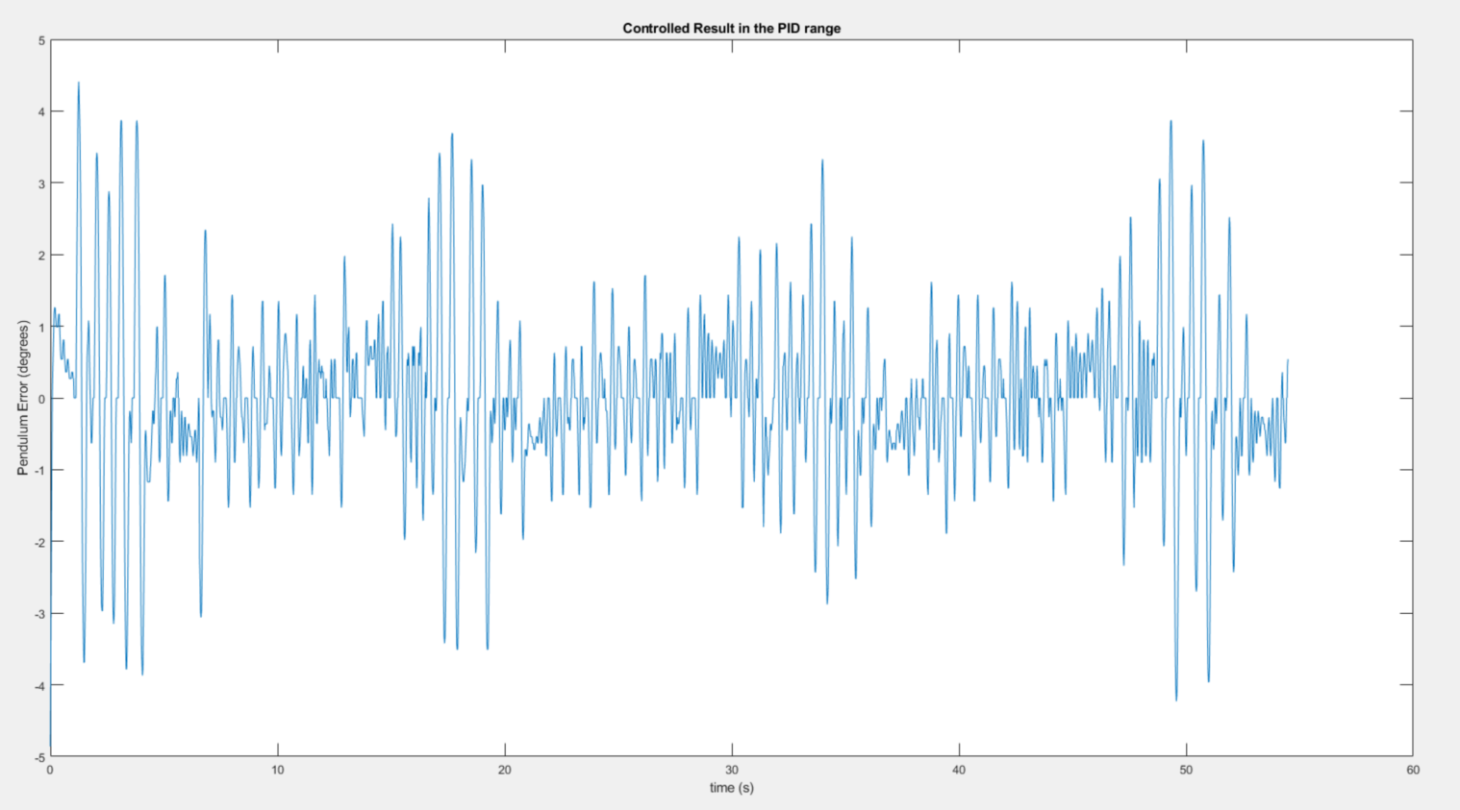


Experiment Result

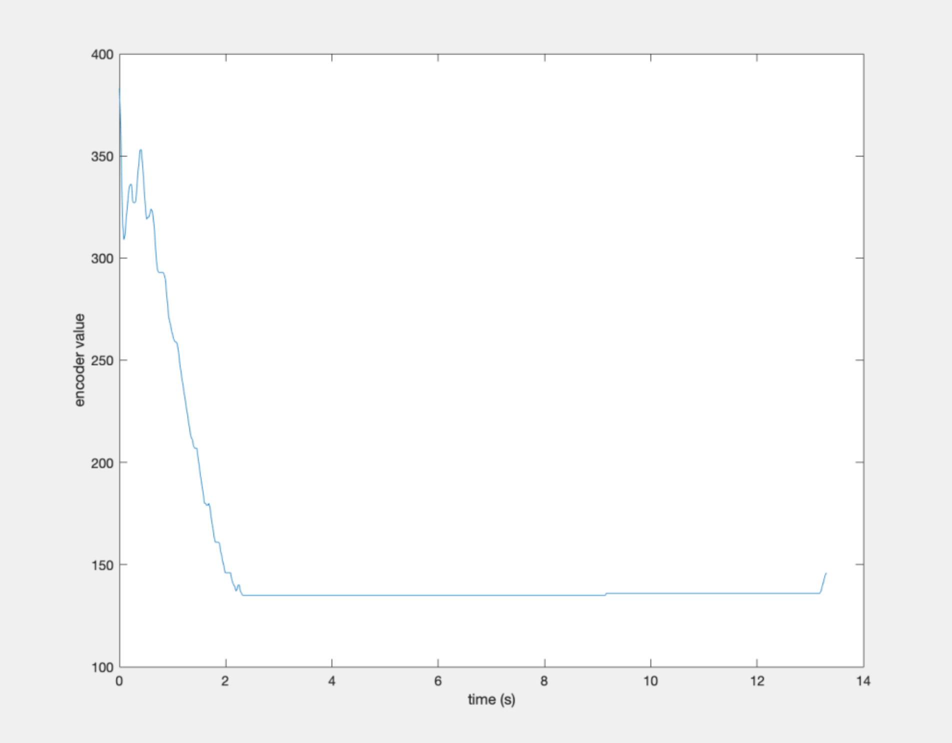


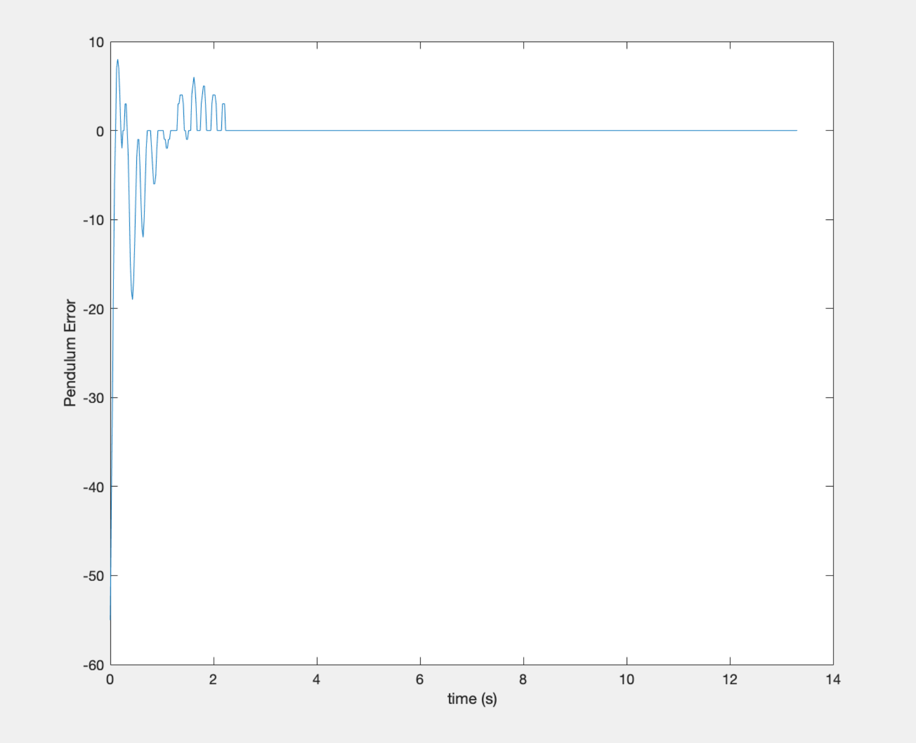
Pendulum degree

Max Error : 4.41 degrees
Min Error : -4.86 degrees
Ave Error : -0.00074 degree
Std : 1.1228

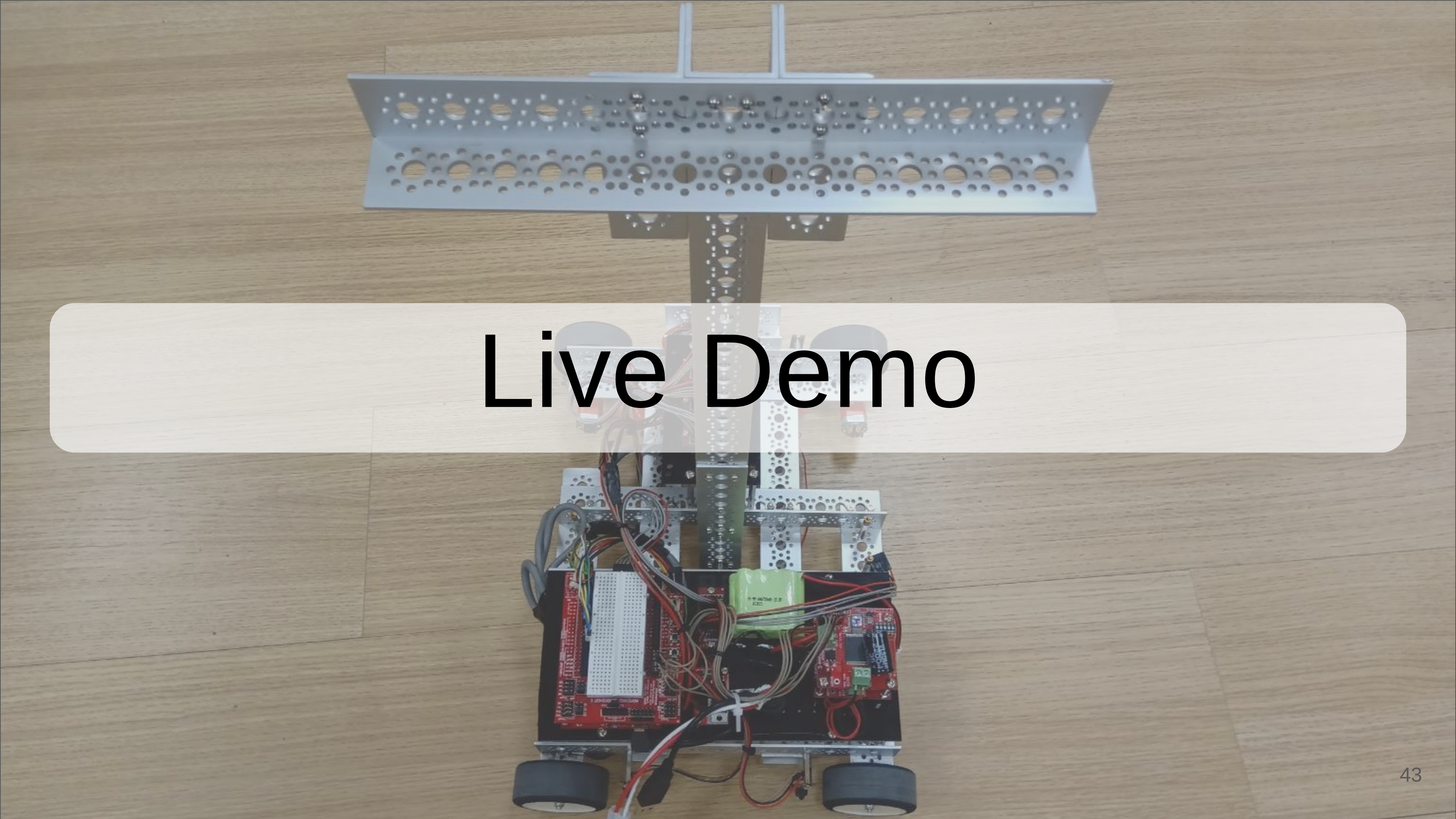


Vehicle Position

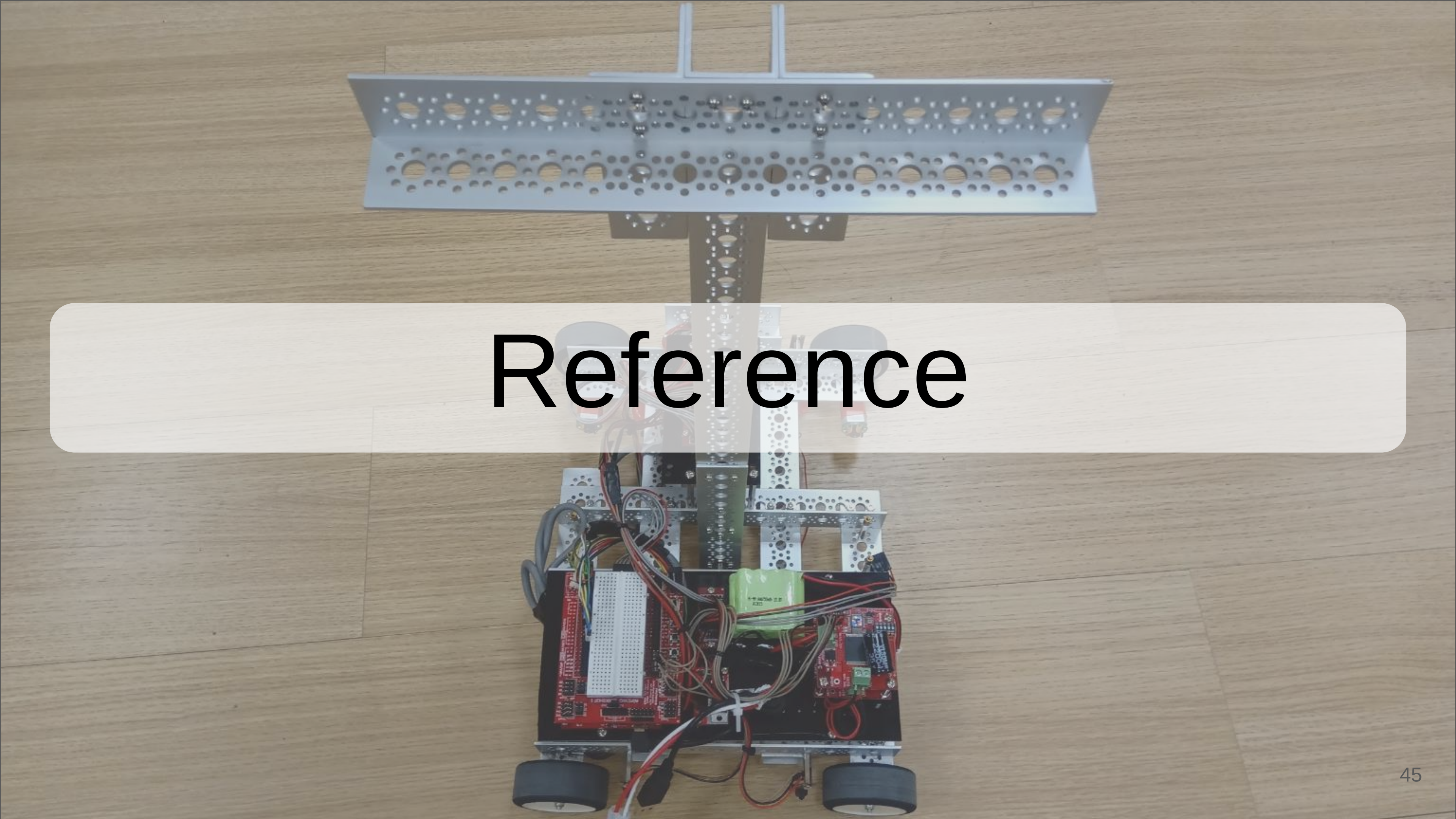




Live Demo



https://youtu.be/Kn8Ok2zyNI4



Reference

Reference

[1] 自動控制Final Project實驗講義

[2] Kent Lundberg, “The Inverted Pendulum System” ,
http://web.mit.edu/klund/www/papers/UNP_pendulum.pdf