KFUPM

SE 513 – Modeling & Systems Identification

Course Project

Identification of a Magnetic Levitation System

For

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By

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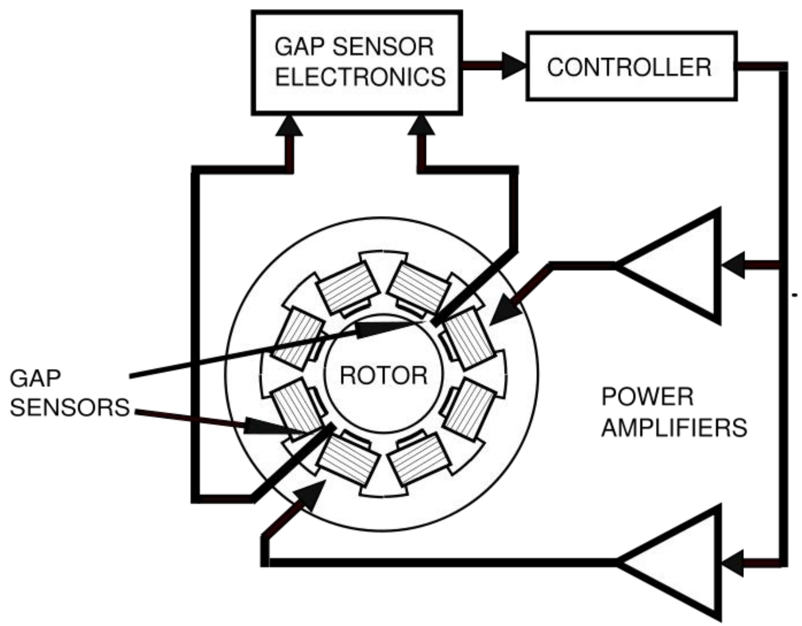
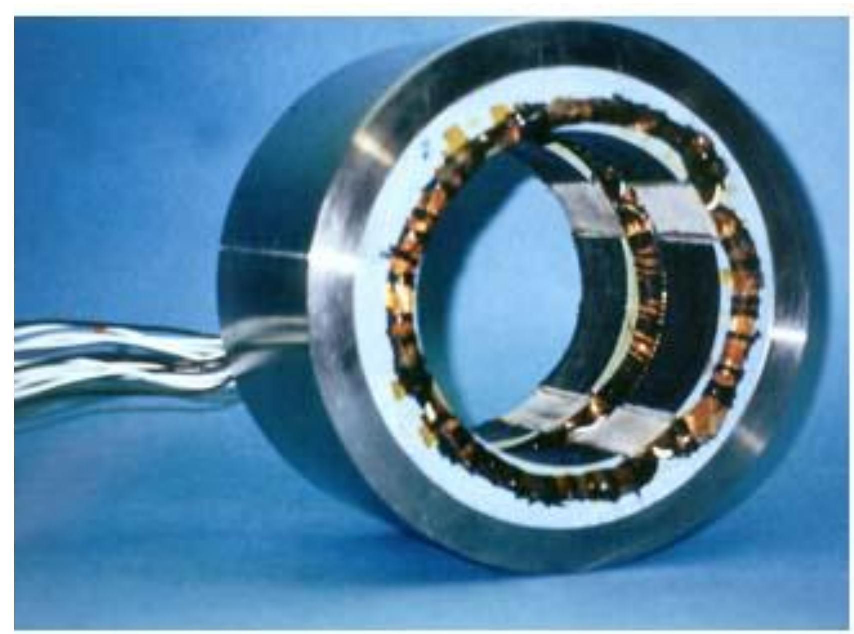
Maglev Trains

JR-Maglev MLX01 reached 581 km/h (Japan)

superconducting magnets which allow for a larger gap, and repulsive-type **Electro-Dynamic Suspension** (EDS).

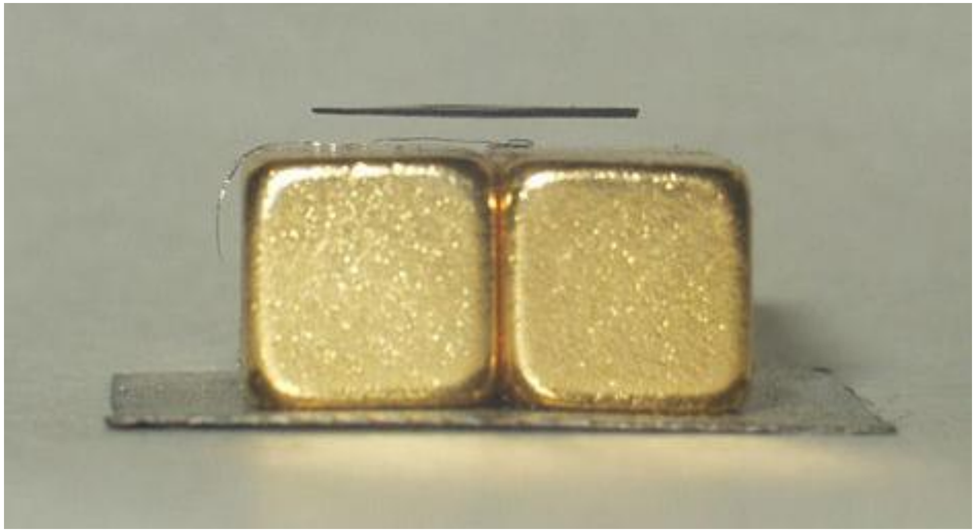
Magnetic Bearings





-support moving machinery without physical contact
- advantages include very low and predictable friction, ability to run without lubrication and in a vacuum
- industrial machines such as compressors, turbines, pumps, motors and generators

Research Experimentation



Outline

1. **System Dynamic Model**
    1. Nonlinear Model
    2. Linearized Model
2. **System in the LAB**
    1. Feedback® MAGLEV System
    2. Control Loop
3. **Experiment**
    1. Hardware
    2. Software
    3. Data
4. **Identification**
    1. Models
    2. Results
    3. Analysis
5. **Future Directions**

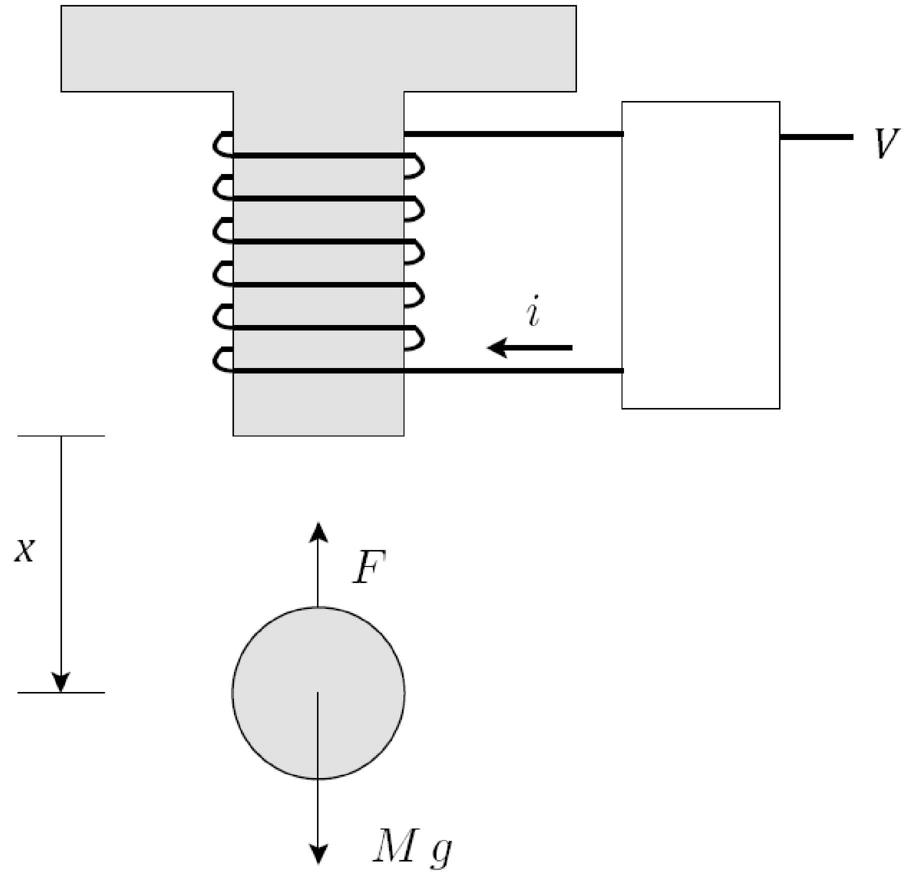
System Model

References for Model:

1- P. S. Shiakolas, R. S. Van Schenck, D. Piyabongkarn, and I. Frangeskou, "**Magnetic Levitation Hardware in the Loop and MATLAB Based Experiments for Reinforcement of Neural Network Control Concepts**", IEEE Transactions on Education, 2004

2- A. Bittar and R. M. Sales, “**H2 and H, control applied to an electromagnetically levitated vehicle**”, IEEE International Conference on Control Applications, Connecticut, USA, 1997

Free-Body Diagram



Free-Body Diagram

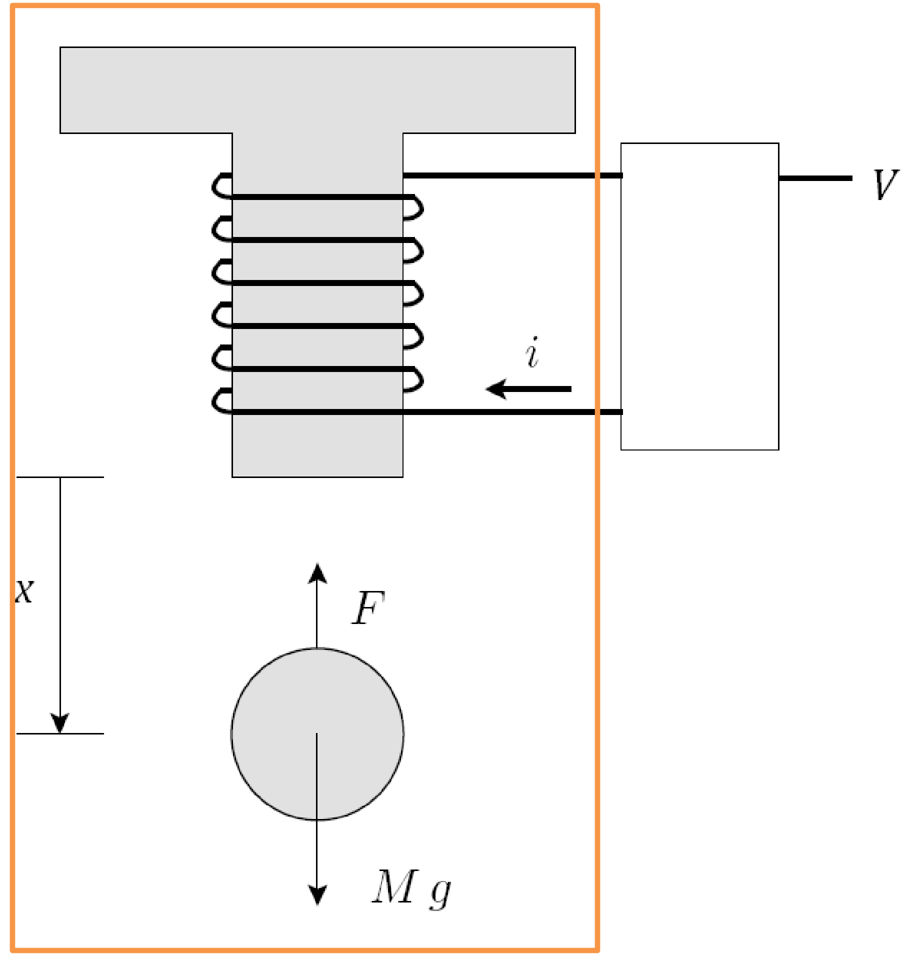
Input: Voltage / **Output**: Ball Position

$$M\ddot{x} = Mg - F(x,i)$$

$$F(x,i) = -\frac{i^2}{2}\frac{dL(x)}{dx}$$

$$with\ L(x) = L_c + \frac{L_0 X_0}{x}$$

$$\Longrightarrow F(x,i) \cong K_L \frac{i^2}{x^2}$$



$L(x)$ Total Inductance

L_c Coil Inductance

$L_0 X_0$ Operating Points

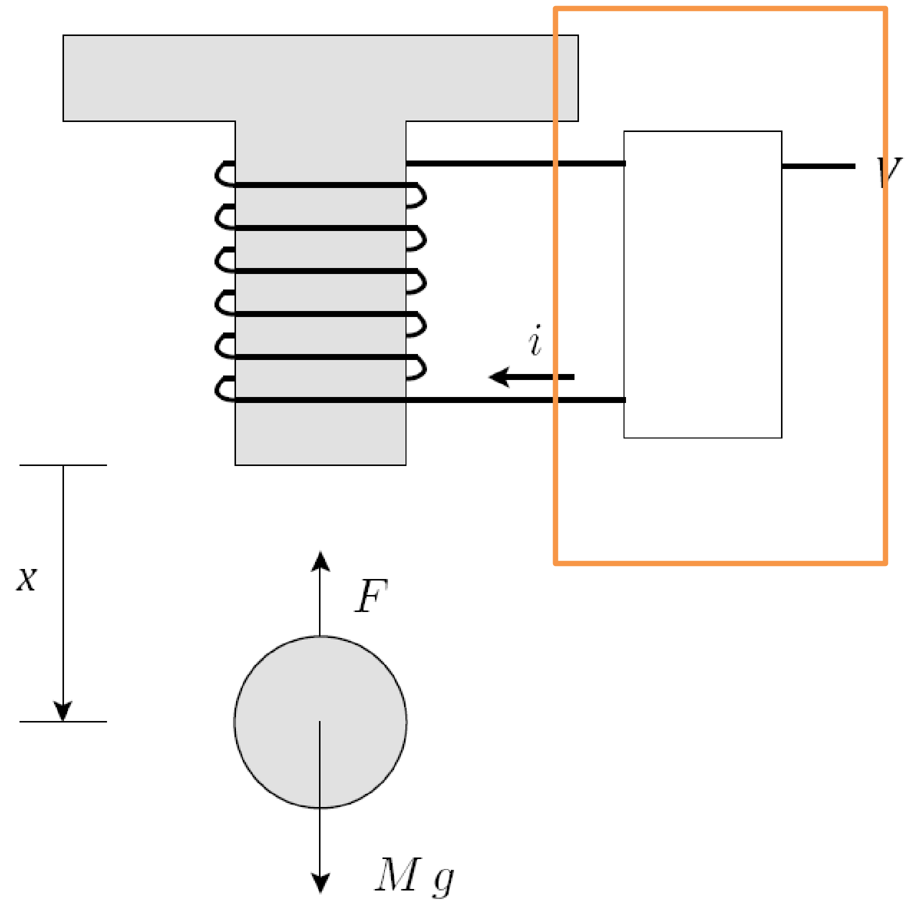
Free-Body Diagram

Input: Voltage / **Output**: Ball Position

$$M\ddot{x} = Mg - K_L \frac{i^2}{x^2}$$

$$with\, V = R_c i + L_c \frac{di}{dt} \cong K_c i$$

Assume no dynamics



R_c Coil Resistance

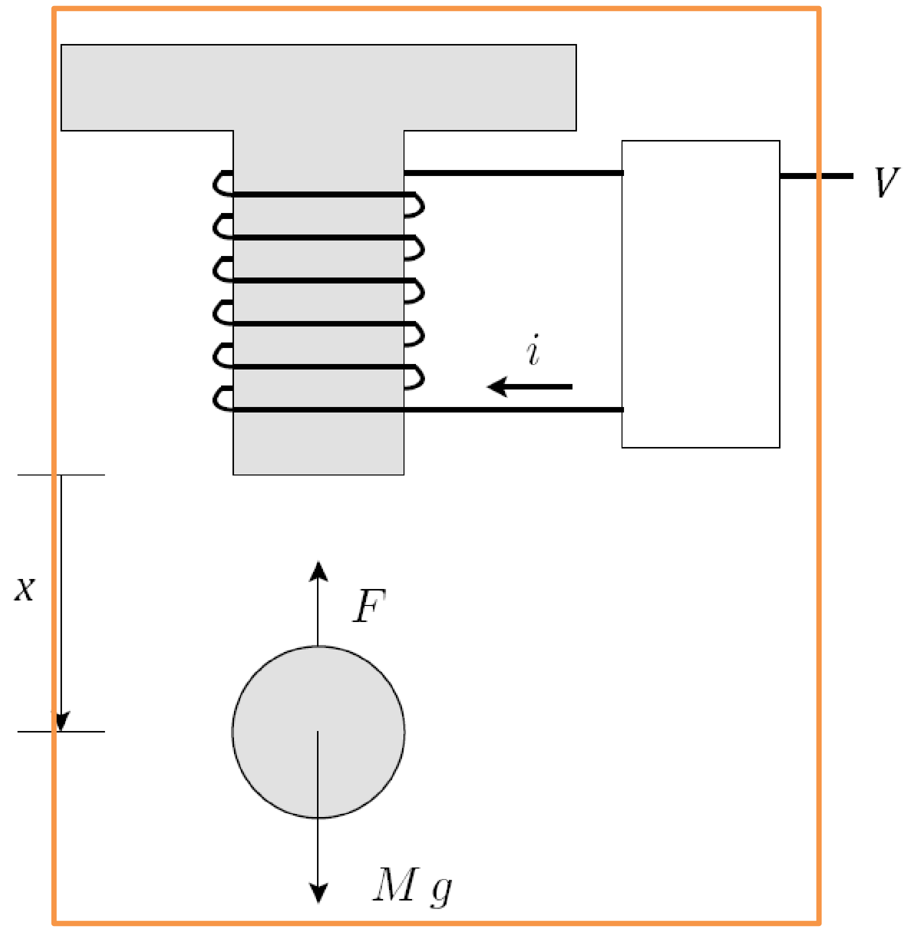
V **Input**: Voltage

Nonlinear Model

$$\ddot{x} = g - \frac{K_L K_c^2}{M} \frac{V^2}{x^2}$$

$$\ddot{x} = g - K_s \frac{V^2}{x^2}$$

Input: Voltage / **Output**: Ball Position



Linearization

$$\ddot{x} = g - K_s \frac{V^2}{x^2}$$

For some Operating Points X_0, V_0

$$\ddot{x} = f(x, V)$$

$$\ddot{x} = \left.\frac{\partial f}{\partial x}\right|_{X_0,V_0} \cdot x + \left.\frac{\partial f}{\partial V}\right|_{X_0,V_0} \cdot V$$

$$\ddot{x} = \frac{2K_s V_0^2}{X_0^3} x - \frac{2K_s V_0}{X_0^2} V$$

Transfer Function

$$\ddot{x} = \frac{2K_s V_0^2}{X_0^3} x - \frac{2K_s V_0}{X_0^2} V$$

$$\frac{x(s)}{V(s)} = \frac{\left(\frac{-2K_s V_0}{X_0^2}\right)}{\left(S^2 - \frac{2K_s V_0^2}{X_0^3}\right)}$$

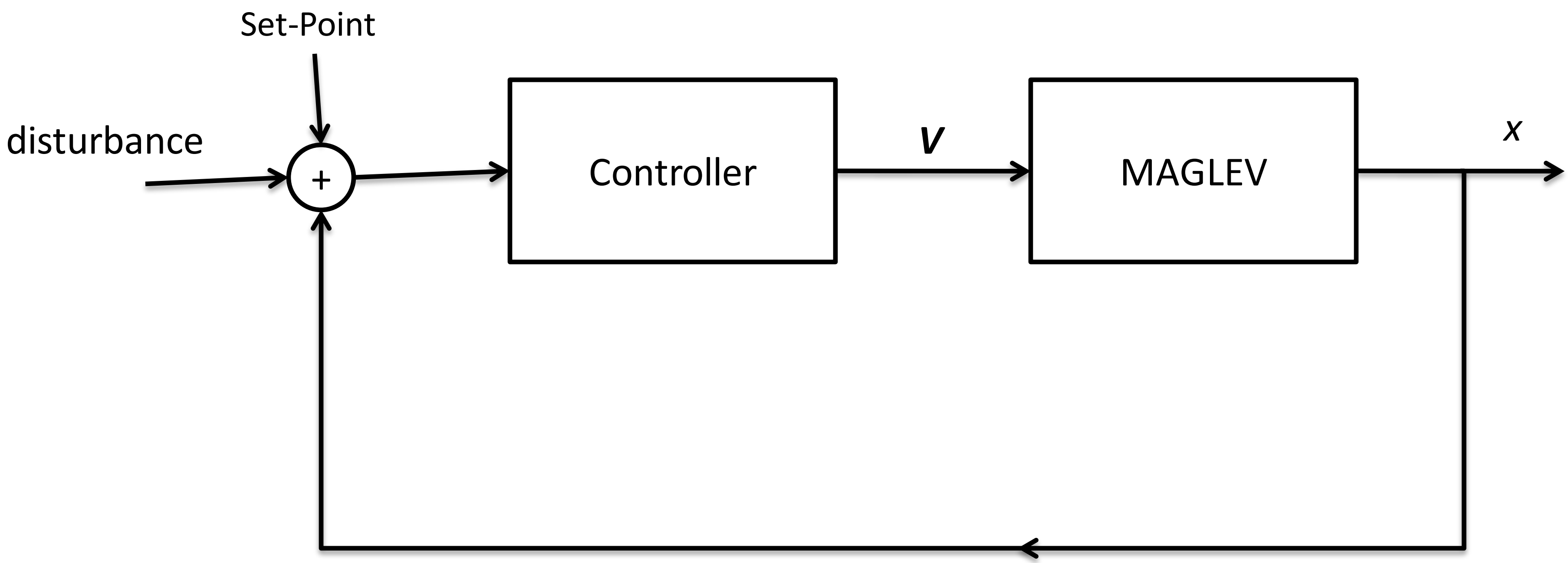
So, $$\boxed{\frac{x(s)}{V(s)} = \frac{b}{(s^2 + a^2)}}$$

2nd order system

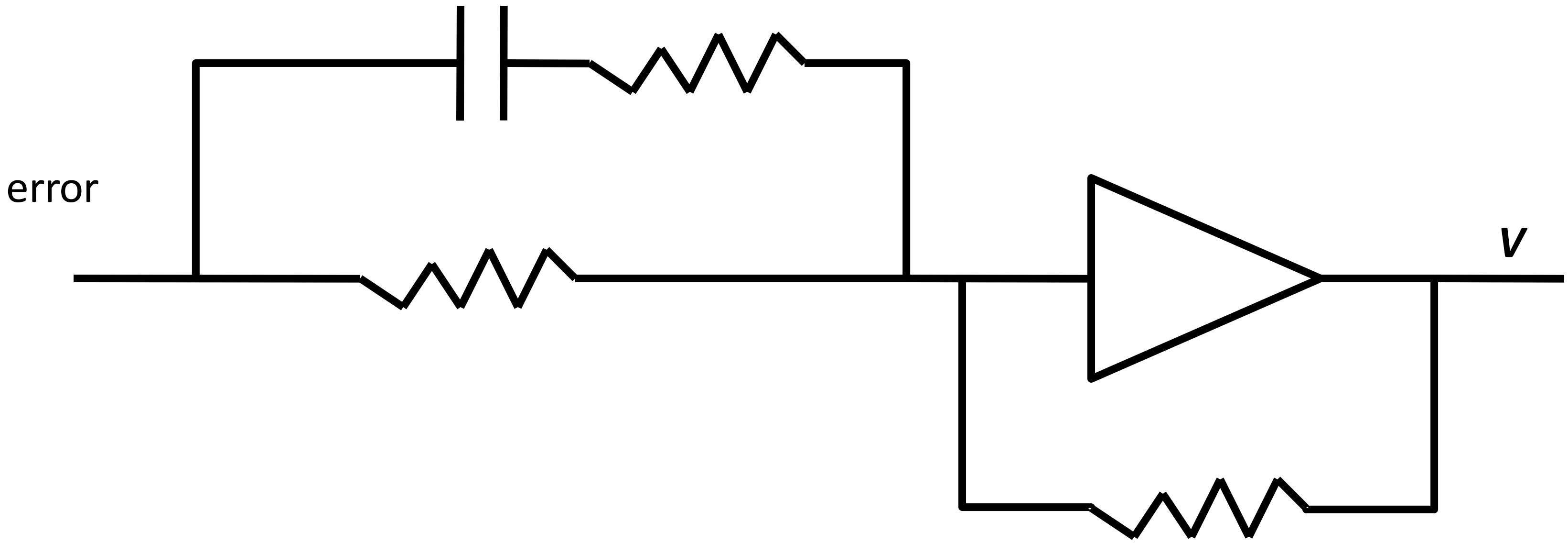
MAGLEV in Lab

- In closed-loop
- Photosensor (IR) for position
  - Sensor = 2.5V -> furthest from magnet
  - Sensor = -2.5 -> closest to magnet
- Set-point manually changed
- Analog Controller onboard

Closed-Loop System



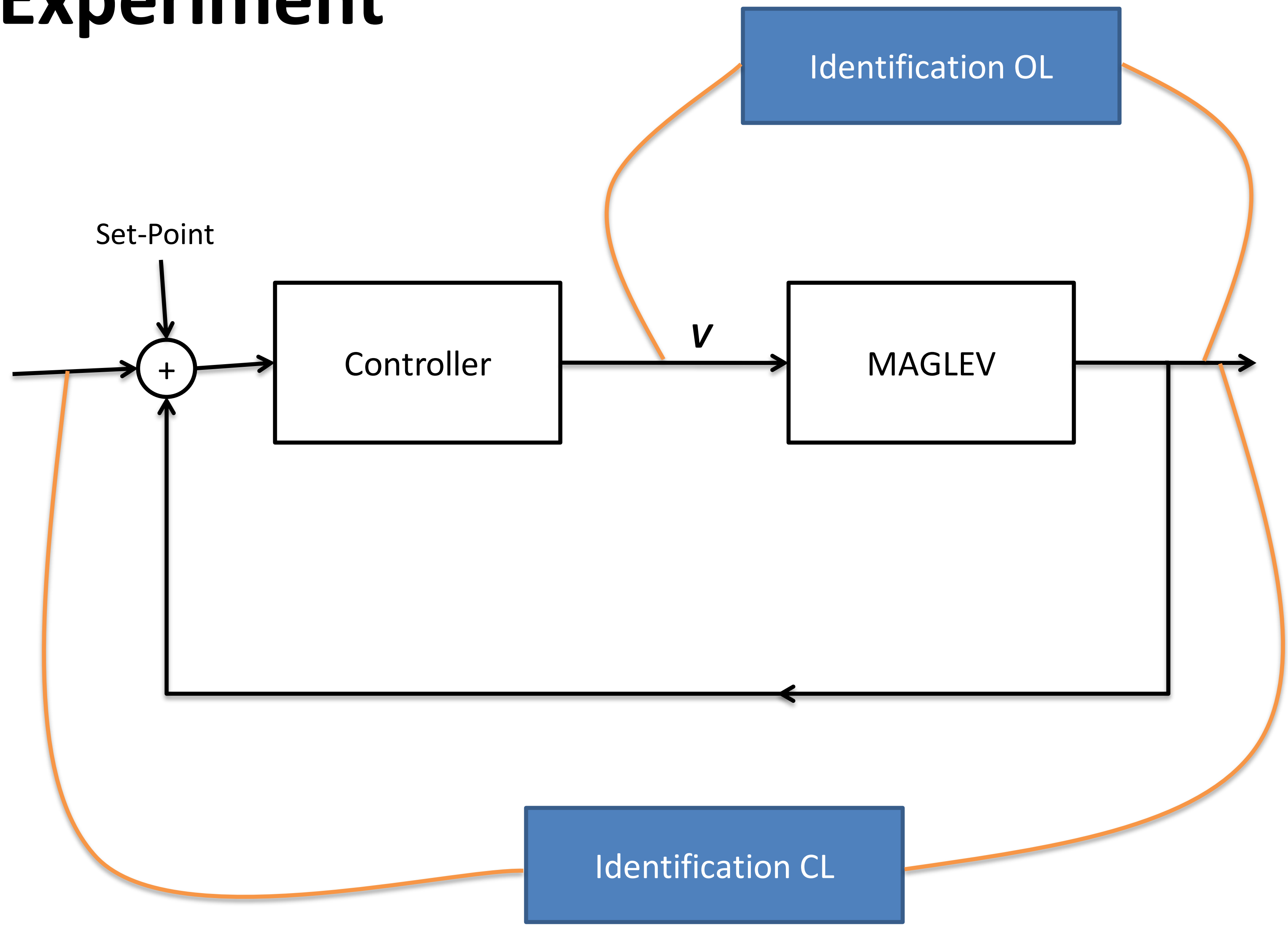
Controller



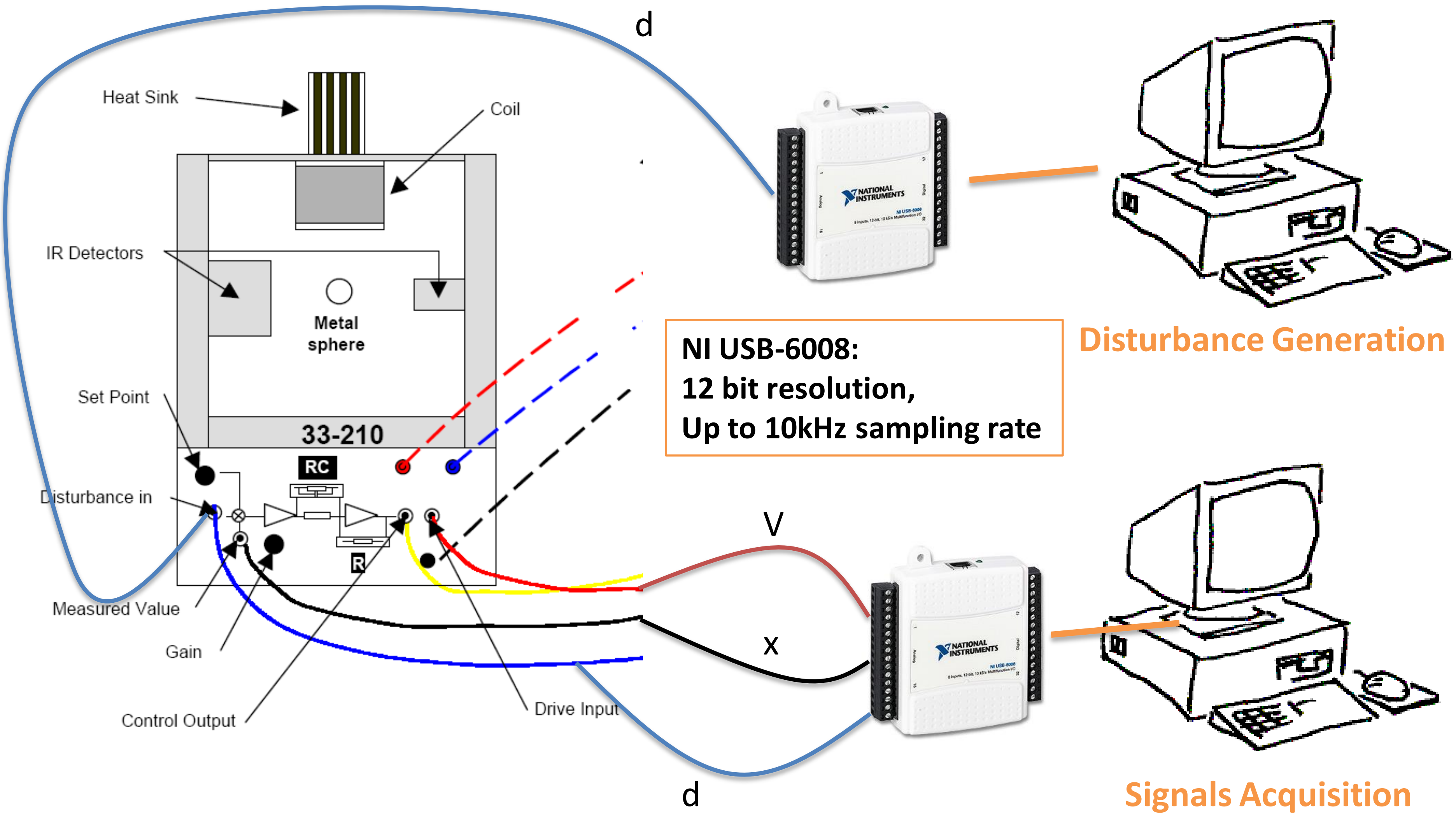
$$G_c(s) = \frac{K(s + k_1)}{s + k_2}$$

Lead/Lag Compensator

Experiment


Identification OL
Set-Point
+
Controller
V
MAGLEV
Identification CL

Experiment



NI USB-6008:
12 bit resolution,
Up to 10kHz sampling rate

2 PCs!!

Software

- Collected data Using:
  - **“VI Logger”**
- Data-logging software
- Scheduling features
- Flexible adjustments
- Choose sampling speed

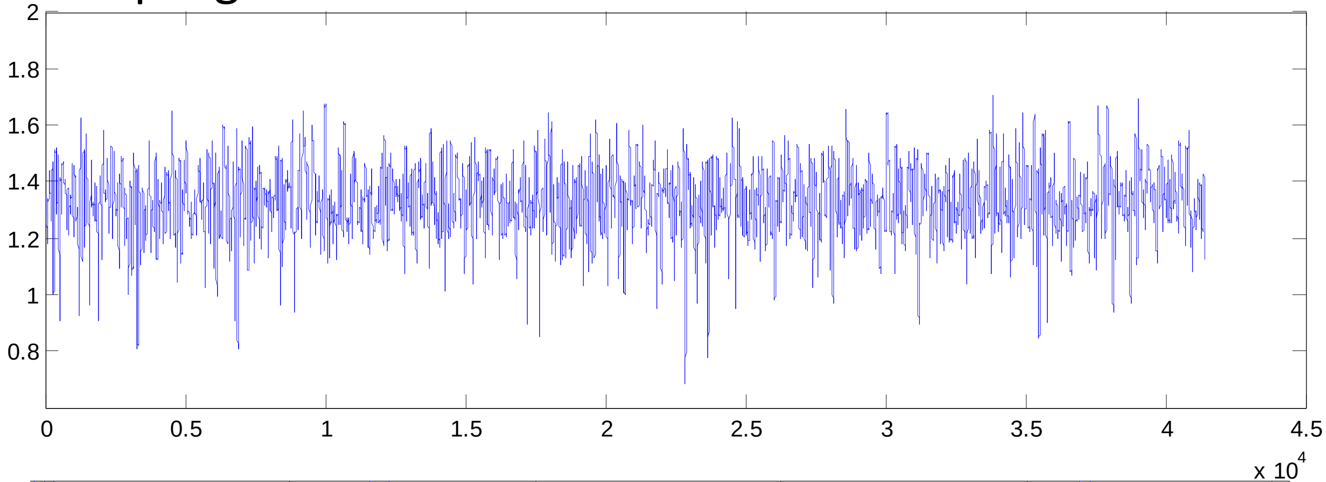
- Disturbance Generation:
  - **“LabVIEW”**
- You can generate any kind of signals as required:
  - Random Sequence,
  - sinusoids,
  - Etc

Data

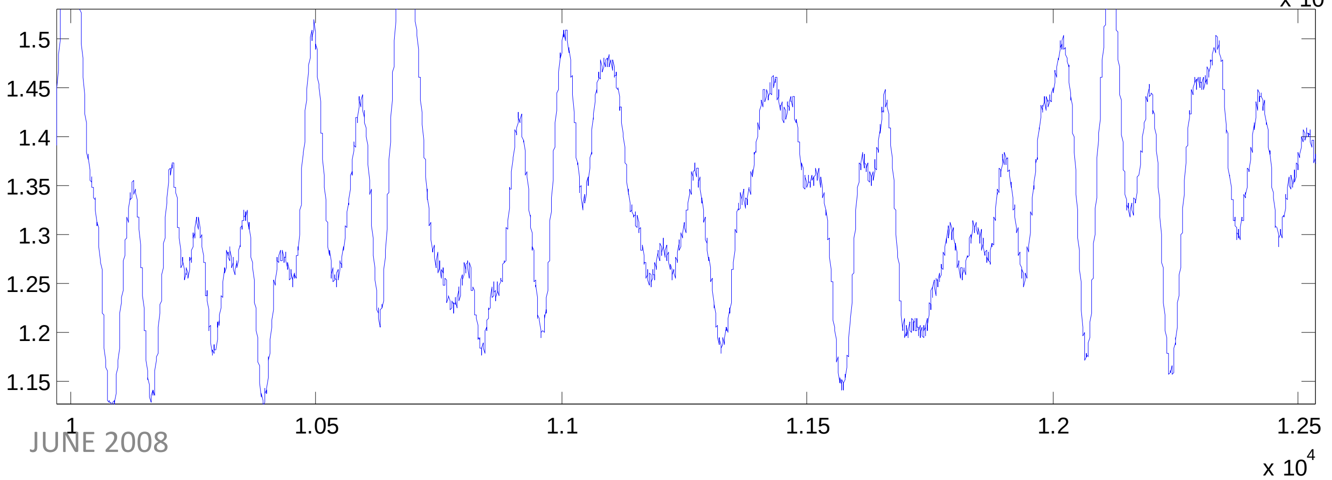
- Three set-points:
  - 0, 1, -1
- Sampling rate:
  - 1kHz, i.e. 1000 samples per second
- Disturbance = **Random Sequence with small amplitude**
- Data Collected for:
  - Disturbance (d)
  - System Output (x)
  - Control Input (V)

Data

- Data(0) = 3 × 41431 samples
- Data(1) = 3 × 41309 samples
- Data(-1) = 3 × 39257 samples
- Sampling Period = 1ms



System Output for set-point 0



Output Magnified

SYSTEM IDENTIFICATION

Model Structure

- Recall

$$\frac{x(s)}{V(s)} = \frac{b}{(s^2 + a^2)}$$

- Due to *discretization*

$$G(z) = \frac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

Other Information

- As hardware sampling period is 1ms
  - we can artificially enlarge the sampling period by 'skipping' samples

- Convenient speeds 1~10ms

- It is expected to have:
  - Poles around **unit circle**

MAGLEV Identification

- Open-loop System Input: V, Output: x

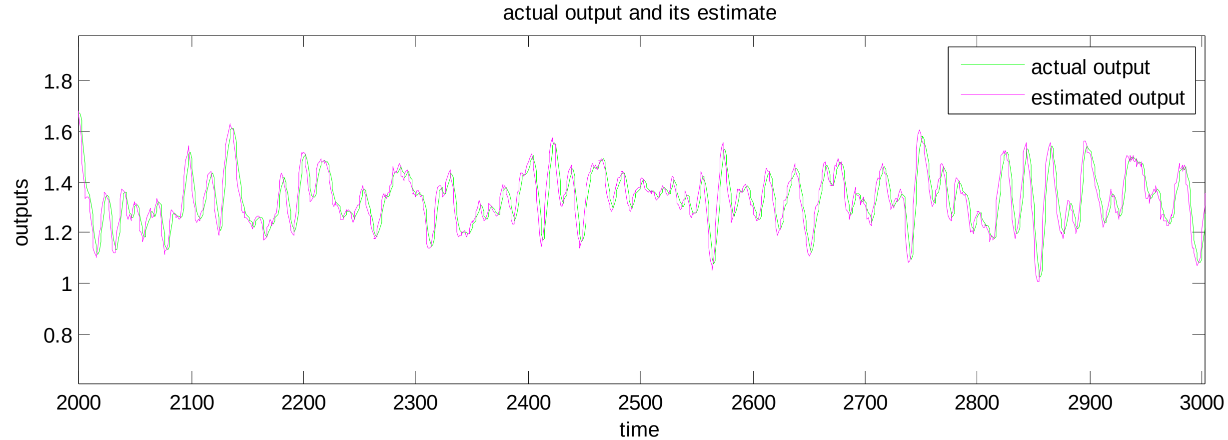
$$G_0(z) = \frac{4.869 \times 10^{-5} + 0.0001446z^{-1}}{1 - 1.899z^{-1} + 0.8996z^{-2}}$$

$$G_1(z) = \frac{-2.9 \times 10^{-6} + 0.0001233z^{-1}}{1 - 1.837z^{-1} + 0.8374z^{-2}}$$

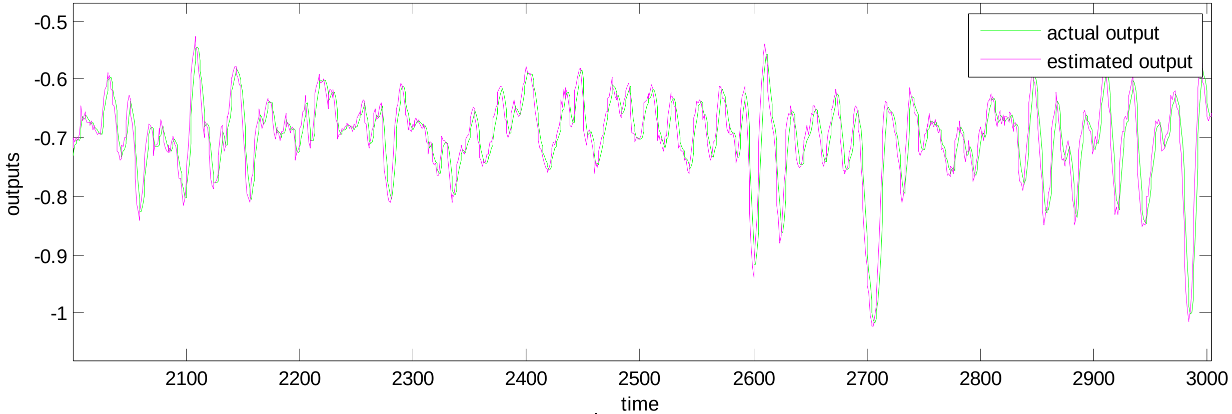
$$G_{-1}(z) = \frac{4.37 \times 10^{-5} + 0.0001342z^{-1}}{1 - 1.911z^{-1} + 0.911z^{-2}}$$

Results Plots

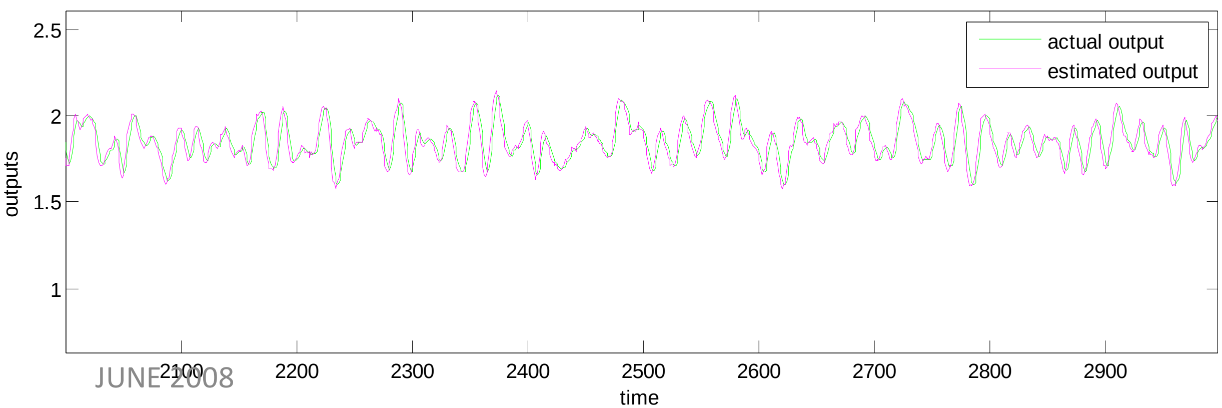
Samples 2000-3000 showing



Set-point = 0



Set-point = 1



Set-point = -1

Results Analysis

- System 1 Poles:
  - 0.9932, 0.9057
- System 2 Poles:
  - 0.9968, 0.8401
- System 3 Poles:
  - 0.9958, 0.9148

- All poles proved to be near the unit circle

Identification Approach 2

- Here, lets make

$$G(z) = \frac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + z^{-2}}$$

$$a_2 = 1$$

- To make poles *exactly* at the unit circle

$$y(k) + y(k-2) = -a_1 y(k-1) + b_o u(k) + b_1 u(k-1)$$

Unknown parameters

- ***Y*** & ***A*** matrices will be different

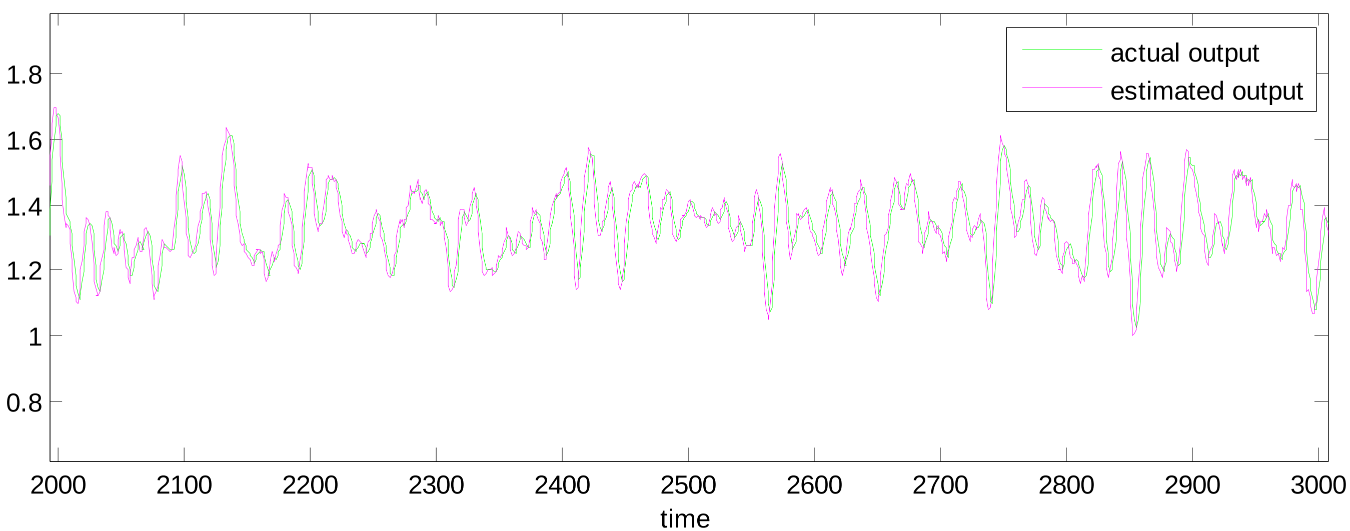
Results 2

- Tested for Set-Point 0,

$$G_0(z) = \frac{4.534 \times 10^{-5} + 0.0001398z^{-1}}{1 - 1.999z^{-1} + z^{-2}}$$

- Poles

$$0.9997 \pm j0.0257 \rightarrow |0.9997 \pm j0.0257| = 1$$



Closed-Loop Identification

- Input: ***Disturbance***, Output: ***x***

$$G_{CL}(z) = \frac{0.00296 + 8.902 \times 10^{-5} z^{-1}}{1 - 2.289z^{-1} + 1.723z^{-2} - 0.4331z^{-3}}$$

- Poles

$$0.9955, 0.6467 \pm j0.1297$$

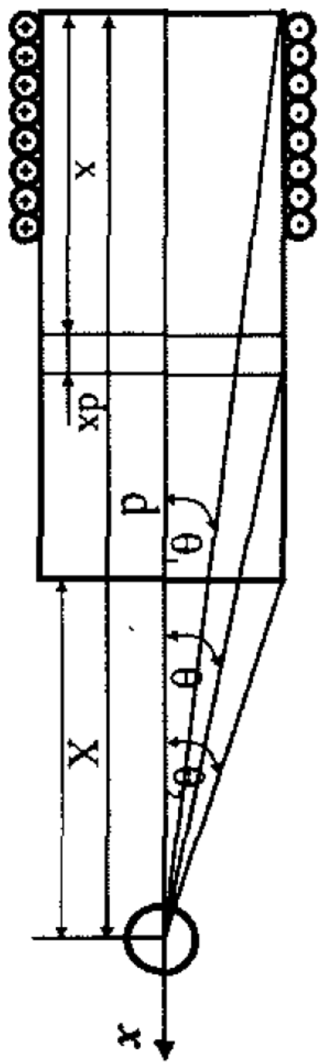
- Controller should be tuned!

Future Directions

- Horizontal Motion Dynamics
  - Maybe need of another sensor
  - Or, observable model –> Horizontal motion can be estimated

- Going to Continuous-time Analysis:
  - Study effect of discretization

- Improve Controller Design
  - More stable design



Final Remarks

- Acknowledgement:
  - Thanks for Prof. Doraiswami for constant advising

- Interesting Project!
  - Included many concepts together: Modeling, Magnetic Fields, Op-amps, Nonlinearities, Numerical Methods, LabVIEW, Discrete-time Analysis, and of course **Identification**, etc.

THANKS!

- *Q & A*