# Introduction to Continuous Control Systems

EEME E3601

Week 1


Homayoon Beigi

*Homayoon.Beigi@columbia.edu*

*https://www.RecoTechnologies.com/beigi*

Mechanical Engineering dept.

&

Electrical Engineering dept.

Columbia University, NYC, NY, U.S.A.

# Course

- Classroom: 329 Pupin
- Class Time: Wednesdays ***4:10*** PM – ***6:40*** PM
- Instructor: ***Homayoon Beigi*** *<hb87@columbia.edu>*
- TA 1: *Venkat Suprabath Bitra <vsb2127@columbia.edu>*
- TA 2: *Garvit Vyas <gv2361@columbia.edu>*
- TA 3: *Jiabao Shen <js6626@columbia.edu>*
- CA: *Feihao Wang <fw2430@columbia.edu>*
- Website: ***https://www.RecoTechnologies.com/beigi***

# Office Hours

1. Homayoon Beigi (Prof.)

   Email: *hb87@columbia.edu*

   Days: Tuesdays & Wednesdays Time: 10:15AM to 11:15 AM on zoom:

   Link: https://columbiauniversity.zoom.us/j/91269329516?pwd=WTaeQAsnbMui17aX9jKP1yN6CGgLTu.1

   And Thursdays: 4PM-5PM by appointment only

2. Venkat Suprabath Bitra (TA)

   Email: *vsb2127@columbia.edu*

   Days: Tuesdays and Fridays 3PM to 4PM

   Link: https://meet.google.com/cem-cpgk-zzm

3. Garvit Vyas (TA)

   Email: *gv2361@columbia.edu*

   Days: Tuesdays & Wednesdays Time: 11:30AM to 12:30PM

   Link: https://meet.jit.si/ColumbiaEEME009yyycy19Fo

4. Jiabao Shen (TA)

   Email: *js6626@columbia.edu*

   Days: Monday & Thursdays 1PM to 2PM

   Link: https://meet.jit.si/ColumbiaEEME00OIw7TzRRbF

# Background

- **Columbia University –** Professor of Professional Practice Since 2025
  *Adjunct Professor* – 1995-2024
  *Courses*: Speech Recognition, Signal Recognition, Speaker Recognition, Handwriting Recognition, Continuous Control, Discrete Control, Nonlinear and Adaptive Control, Math of Machine Learning Learning, Signals, and Control, Applied Signal Recognition Digital Control
  Depts: ME, EE, CS, and CE
- **Recognition Technologies, Inc.** – *President / Head of Research & Dev.* – since 2003
- **Internet Server Connections, Inc.** - *Vice President* – since 2001
- **IBM T.J. Watson Research Center** – Research Staff Member - 1991-2001
- **Columbia University** –Center for Telecommunications Research - 1990-1991
- **Columbia University** – BS (1984), MS (1985) & PhD (1990)
- **Various Patent Advisory and Expert Services**

# Research and Development Activities

**IBM – T.J. Watson Research Center**
*Research Staff Member* – 1991-2001

**Unconstrained Online Handwriting Recognition** – *Lead Researcher 1991 – 1997*

**Speaker Recognition** – *Speech Recognition Group – Lead Researcher 1997 – 2001*

**Adventurous System and Software Research** – *Award in Adventurous Research*

**Pen-Based Music Composition**
An award to conduct an independent research for two years (1995 – 1997)
(initially 1 year and renewed for a second year)

Many **Patents** *and* **Publications** *including* **top 10% patent value to IBM**

# Research and Development Activities

**Nonlinear Control** – *Adaptive, Learning, and Repetitive techniques*

**Face, Object, and Emotion Recognition** – *Recognition technologies, Inc.*

**Speech and Speaker Recognition** – *Recognition Technologies, Inc. and IBM Research*

**Music Recognition** – *Mode Recognition, Transcription, and Timbre Transfer*

**Online Handwriting Recognition** – *Recognition Technologies, Inc. and IBM Research*

**Structural Health Monitoring** – *Joint Project with the Civil Engineering Dept. of Columbia University*

**Language Proficiency Rating** – *Recognition Technologies, Inc.*

**Large-Scale Portfolio Optimization** –Internet Server Connections, Inc.

**Neural Network and Deep Learning** – *Pioneered Deep Nonlinear Learning Formulation*

**Iterative Learning Control** – *Pioneered the Adaptive Learning Control Field*

**Machine Health Prognosis** – *Machinery Components*

**Lossless Image Compression** – *A Project for the Library of Congress*

**Zero-Gravity Fluid Research** – *A joint project with the NASA Space Lab*

**Kinematics** – *A Unification Formulation for all types of Four Bar Linkages*
*Joint research with the late Prof. F. Freudenstein*

# Selected Professional Activities

## Standards:

**U.S. Delegation of ISO/SC 37 JTC 1 W3C**
*Active Liaison*

**ANSI / INCITS *Standards for Biometric Data Interchange Format***
*Active Liaison & Driving Force for Speaker Recognition*

**VoiceXML Forum *Standards for Speaker Biometric***
*Active Liaison & Driving Force for Speaker Recognition*

## Other Committees:

**FBI / NIST Speaker Recognition Advisory Panel**
*Invited Member – 2009*

**Biometric Operations and Support Services Unrestricted (BOSS-U)**
*Computer Sciences Corporation Team*

**Voice Identification Policy Group (VIPG)**
*Advisory Team*

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# Grading
## *(Tentative)*

Homework – 30%

*Small Problems and/or Coding Assignments*

Midterm Exam – 30% – Nov. 5, 2025

*In-Class Problems and/or Coding Assignments*

Final Exam – 40% – Dec. 17, 2025

*In-Class Problems*

Exams are closed book.
Only TI-30xs calculators are allowed.

*Modifications to percentages and calculation of the final grade may be made, depending on the collective performance of the class.*

# Tools

## Matlab

It will be useful to have Matlab installed on your computer.

- Student license should be available through Columbia.

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# Books

Textbooks:

*Required:*

F. Gornaraghi and B.C. Kuo, "Automatic Control Systems," 10th Edition, McGraw Hill Education, New York, 2024.

*Reference Books:*

H. Beigi, "Fundamentals of Speaker Recognition," Springer-Verlag, New York, 2011.

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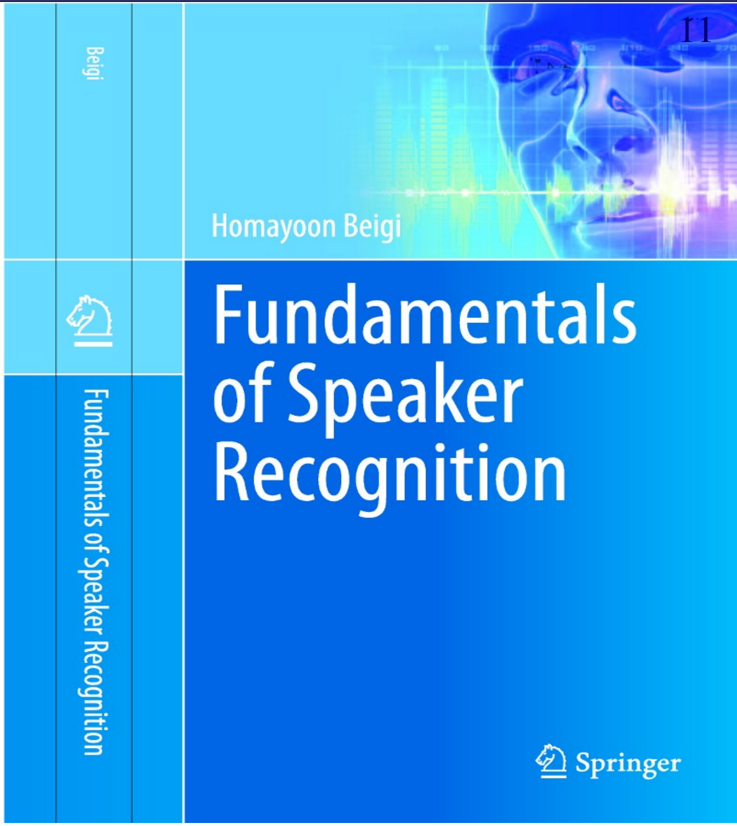
# Textbook

**~1000** Pages – **26** chapters **– 177** illustrations

*100,000+ downloads of online version*

*www.FundamentalsOfSpeakerRecognition.org*




ISBN: 978-0-387-77591-3

Part I – Basic Theory

1. Introduction
2. Anatomy of Speech
3. Signal Representation of Speech
4. Phonetics and Phonology
5. Signal Proc. & Feature Extraction
6. Probability Theory and Statistics
7. Information Theory
8. Metrics and Divergences
9. Decision Theory
10. Parameter Estimation
11. Unsuperv. Clust. & Learning
12. Transformation
13. Hidden Markov Modeling
14. Neural Networks
15. Support Vector Machines

Part II – Advanced Theory

16. Speaker Modeling
17. Speaker Recognition
18. Signal Enhancement & Comp.

Part III – Practice

19. Evaluation & Representation of Results
20. Time Lapse Effects
21. Adaptation over Time
22. Overall Design

Part IV – Background Material

23. Linear Algebra
24. Integral Transforms
25. Optimization Theory
26. Standards

# Terminology

Open-Loop vs Closed-Loop

Linear vs Nonlinear

Time-Variant vs Time-Invariant

Continuous-Time vs Discrete-Time

Single-Input Single-Output (SISO) vs Multi-Input Multi-Output (MIMO)

# Controllers

- Adaptive Control Systems
  - Self-tuning Regulators
  - Model-Reference Control
  - Fuzzy Control Systems and Gain Scheduling Systems
  - Nonlinear Adaptive Control – Based on Deep Learning and Nonlinear Modeling such as PINN

- Repetitive Processes
  - Iterative Learning Control
  - Adaptive Learning Control
  - Repetitive Control

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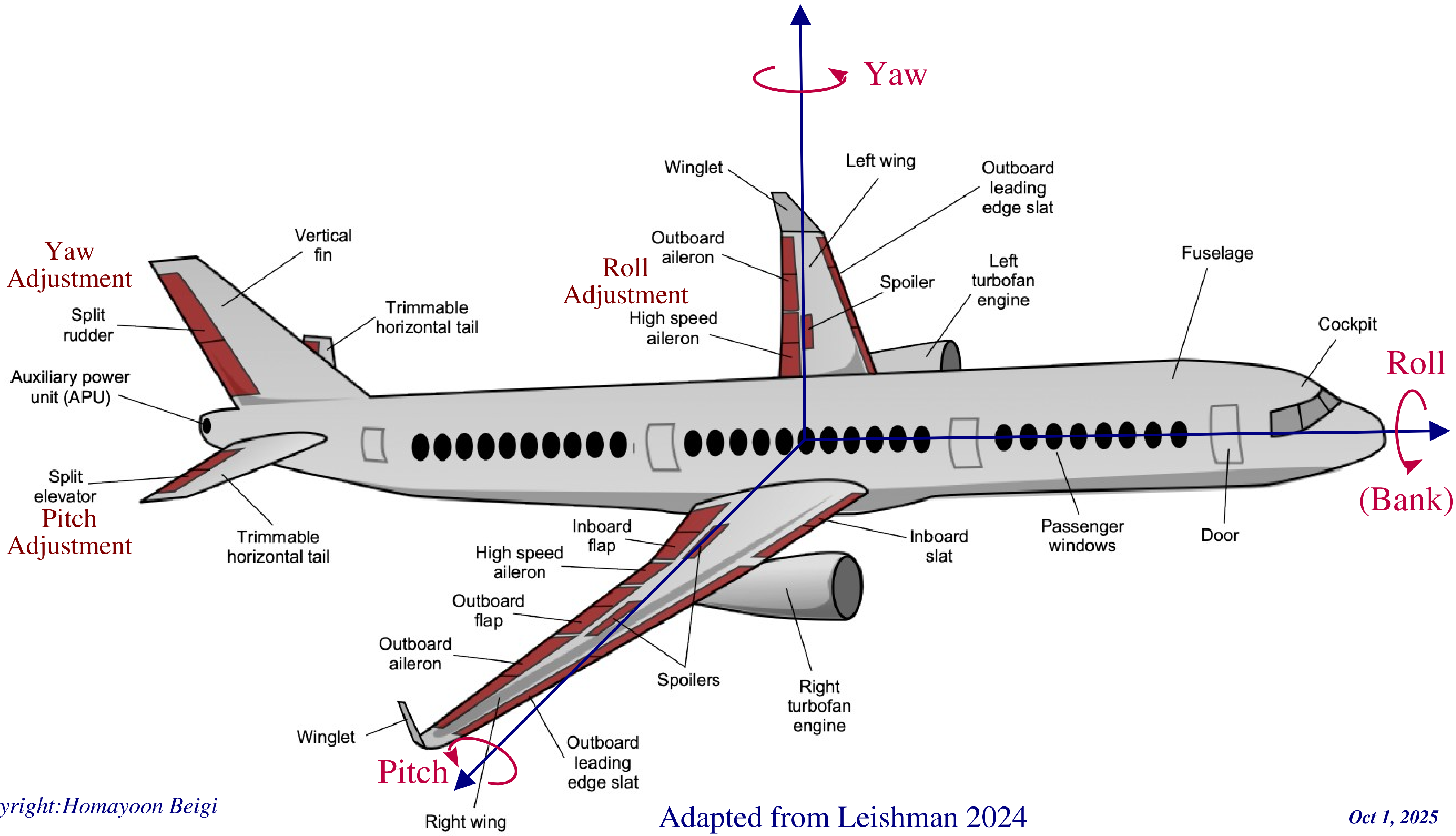
# Sample Plant
# (Telescope)

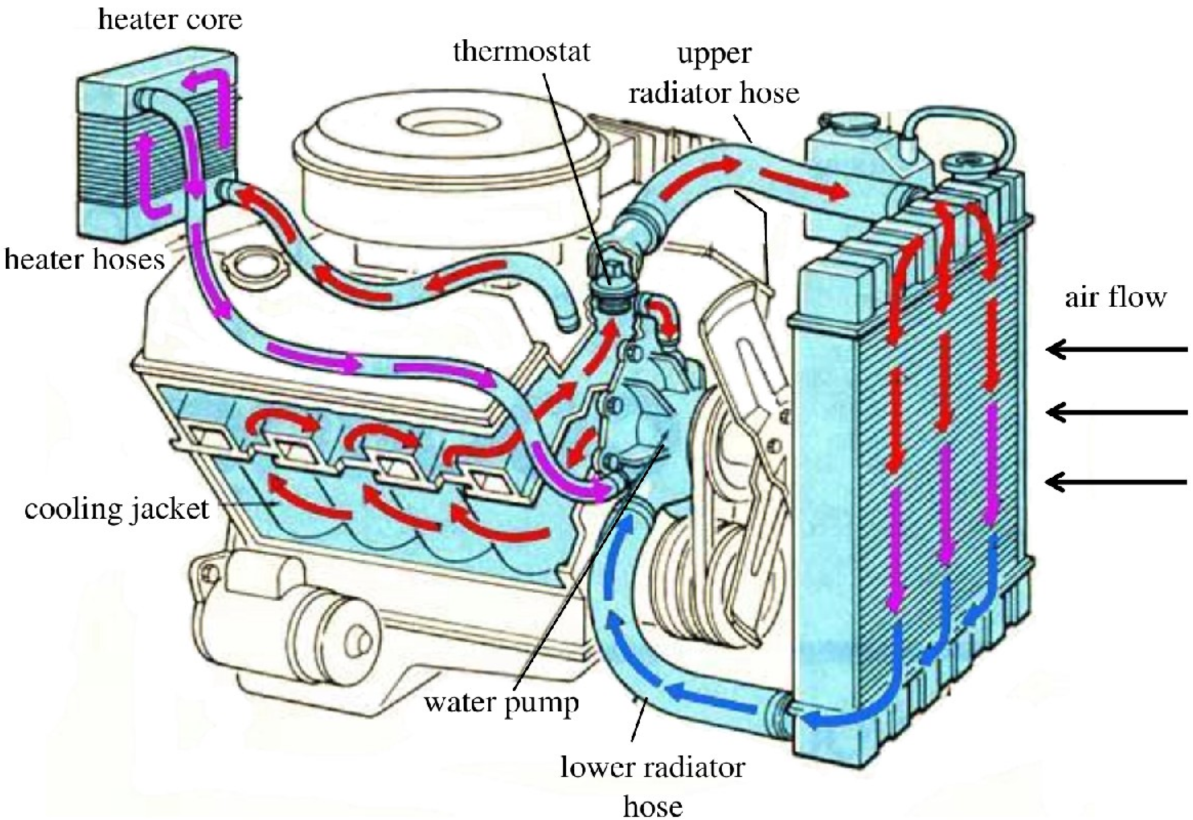
# Sample Plant
# (Telescope)

# Sample Plant
# (Commercial Airplane)




Adapted from Leishman 2024

# Sample Plant
# (Engine Cooling System)




*Source: Bencs 2021*

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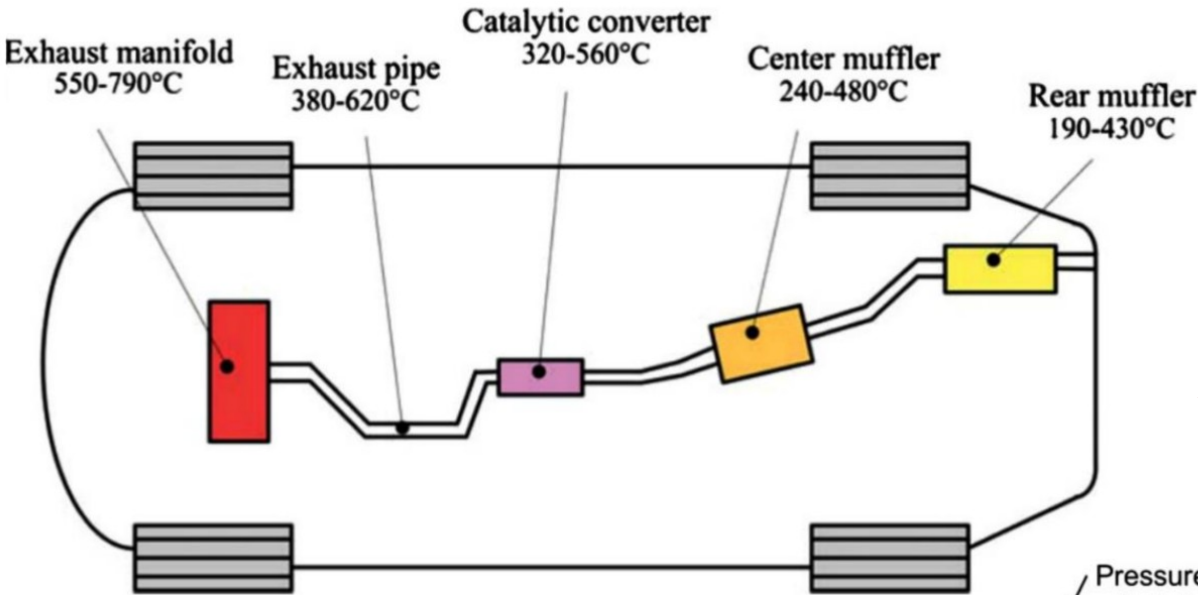
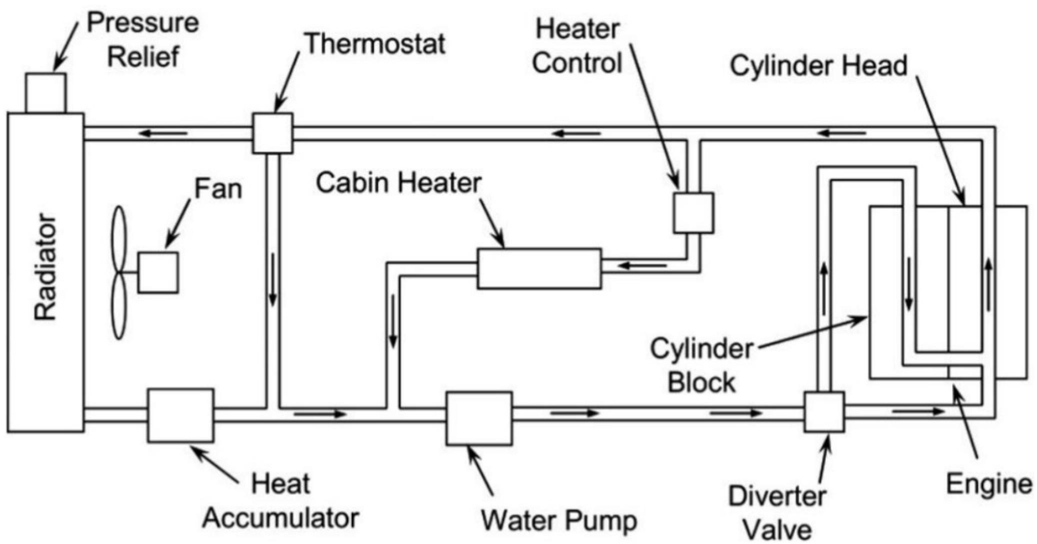
# Sample Plant
# (Engine Cooling System)



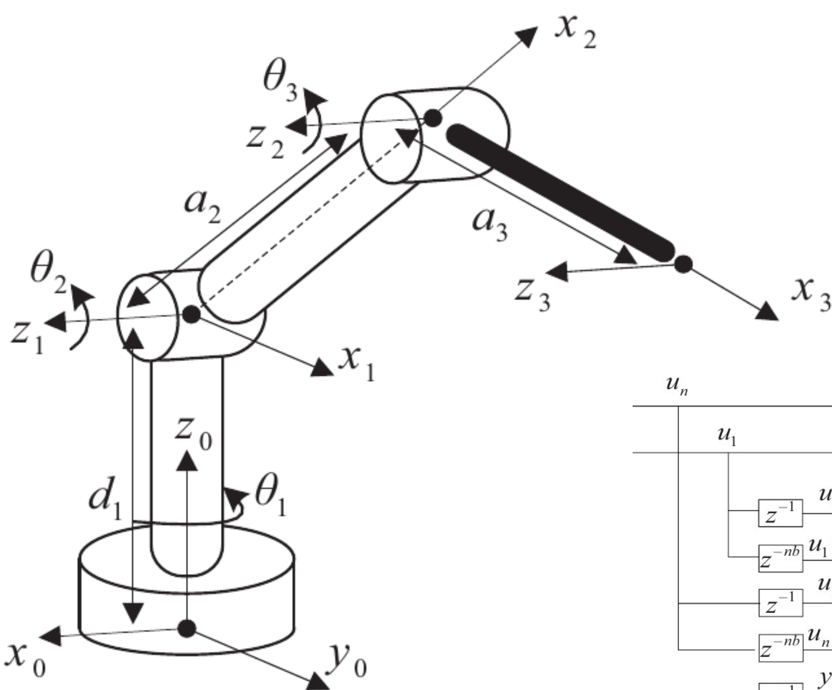

Use Phase Change Material (PCM)
for heat accumulation during cooling

Utilize the temperature difference in
the exhaust system for the PCM

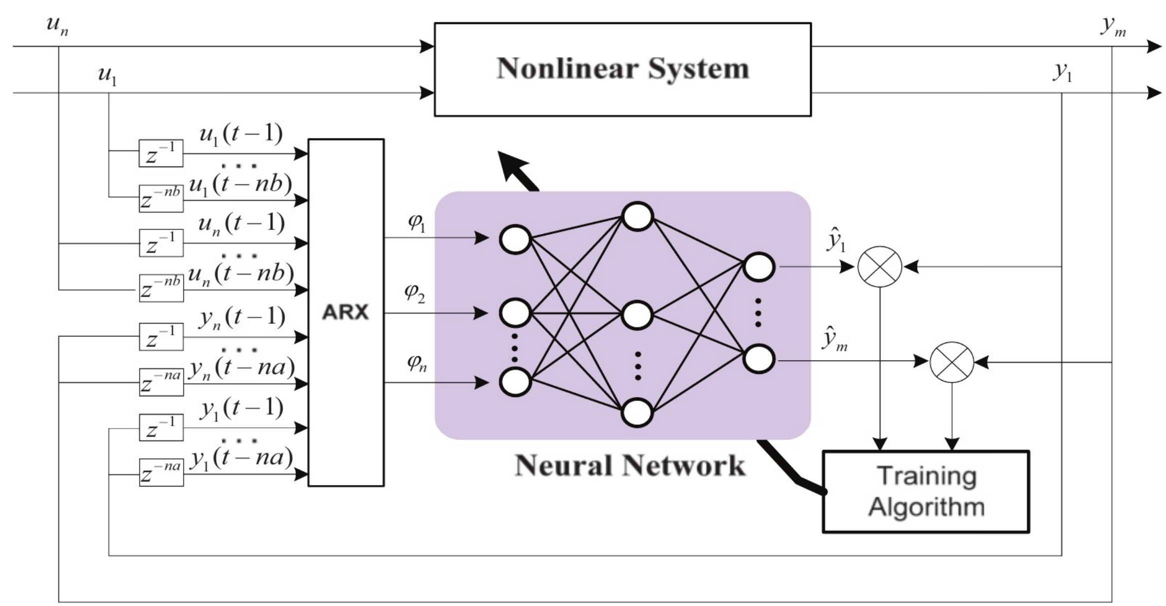



Source: Bencs 2021

# Robot Manipulator Control



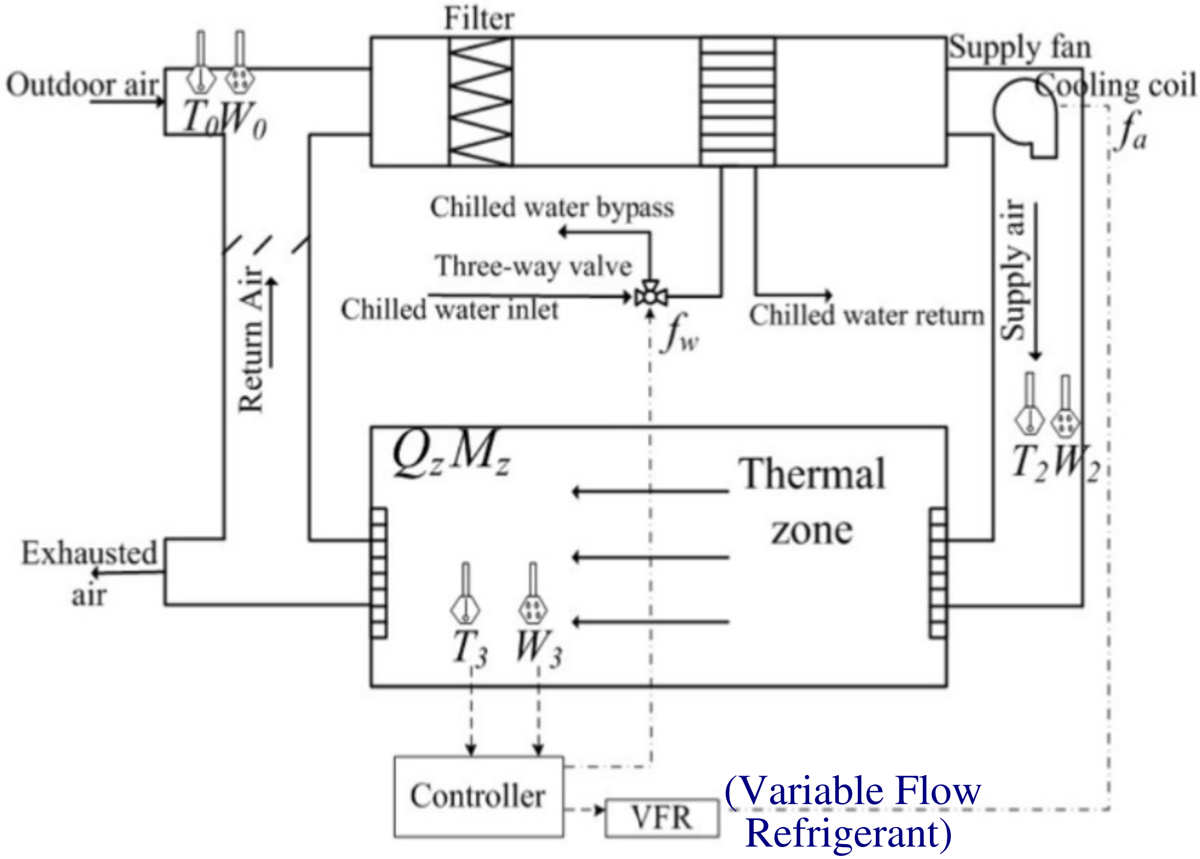

3-DOF Industrial Robot




Nonlinear System ID using Neural Networks for Robot Control

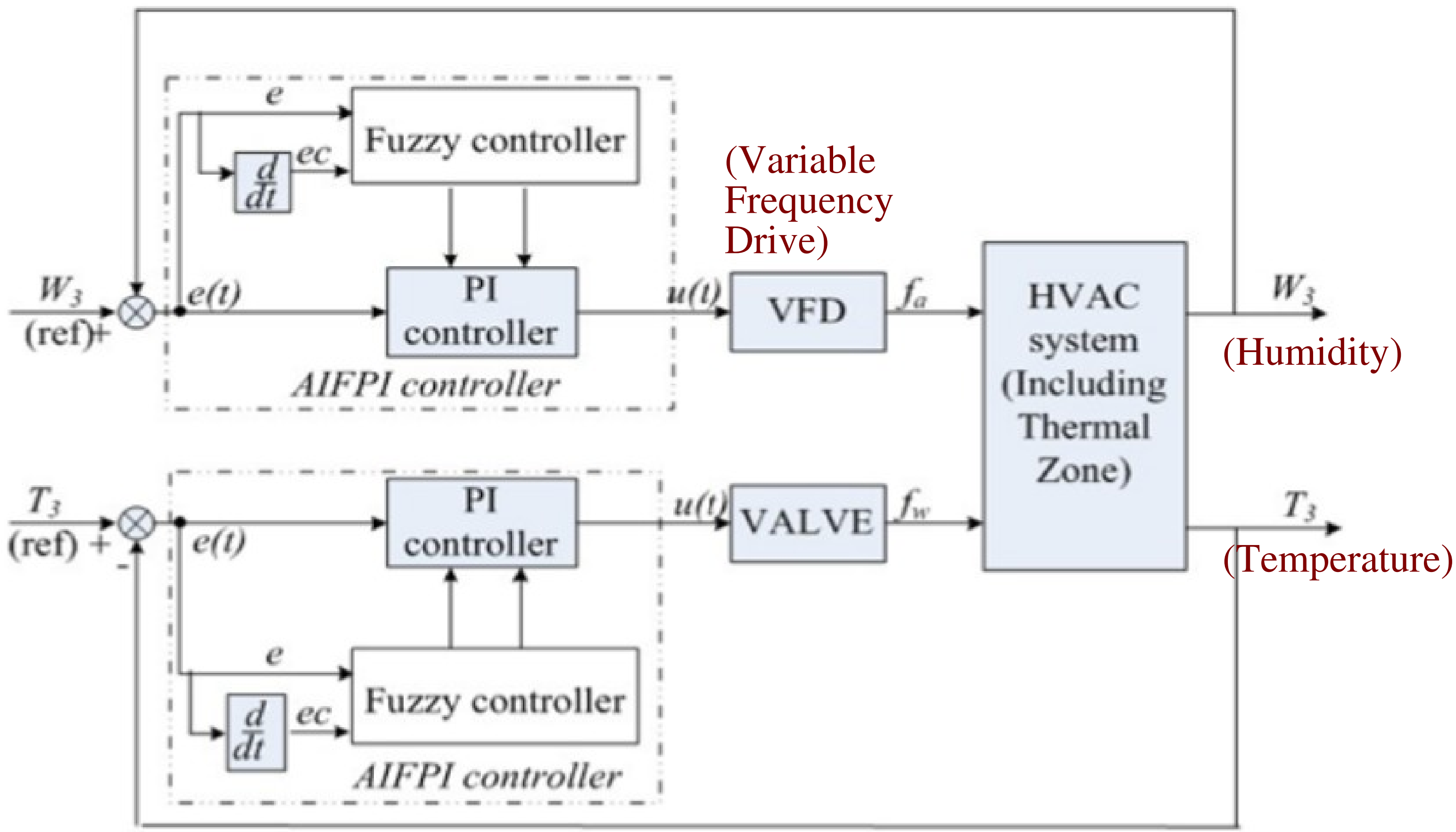
*Source: Son 2017*

# Sample Plant
# (Home HVAC System)




*Bai-2013*

# Sample Control System (HVAC)
# (Adaptive Incremental Fuzzy Proportional Integrator Controller)




*Bai-2013*

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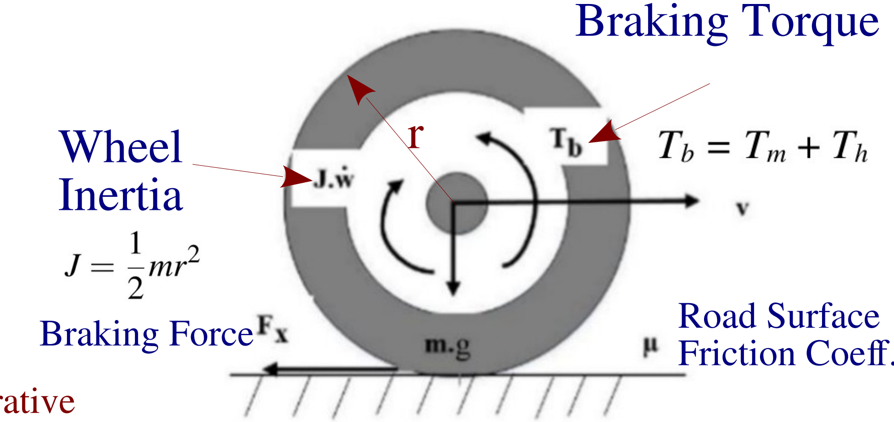
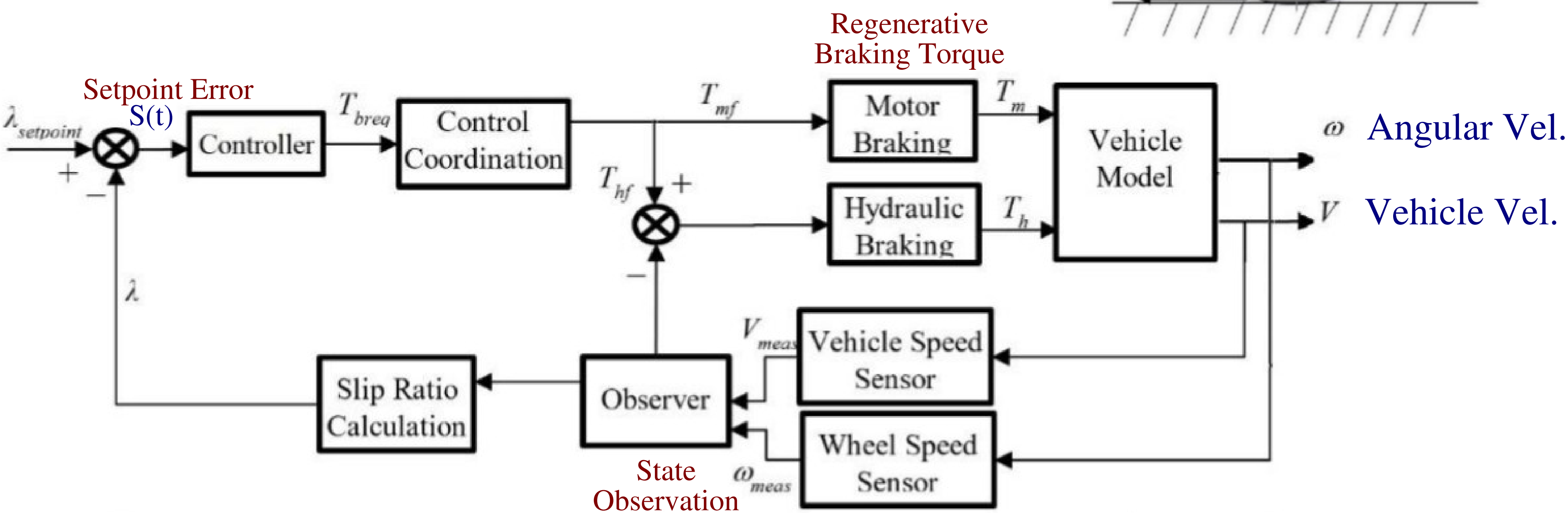
Quarter Vehicle Model (one wheel)

# Electric Vehicle Antilock Braking System (ABS) using Sliding Mode Control



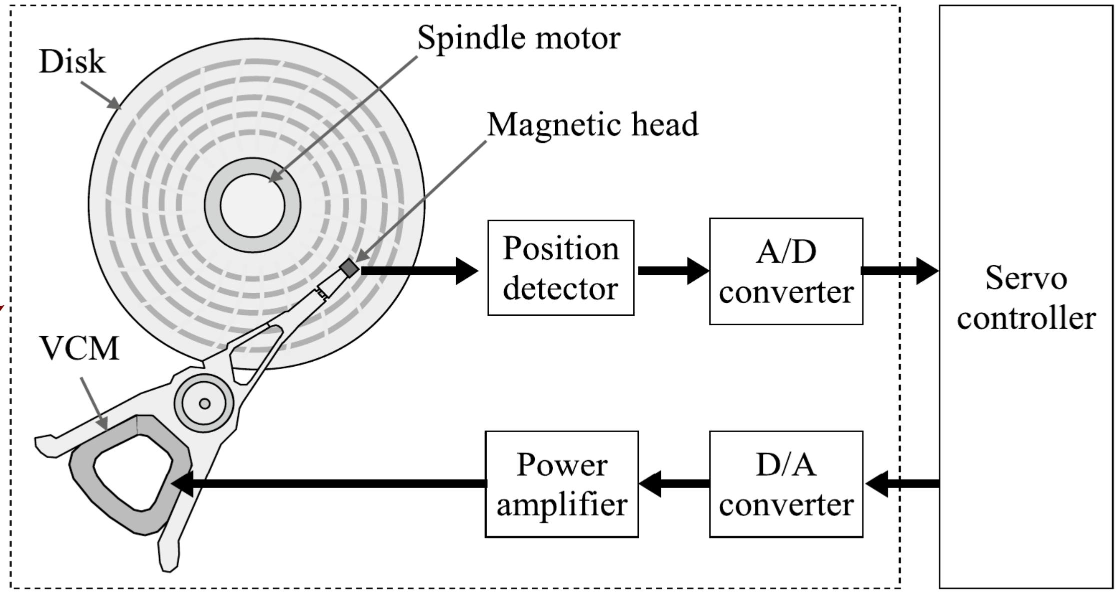




Use a sliding mode schedule to control $T_b$, the braking torque

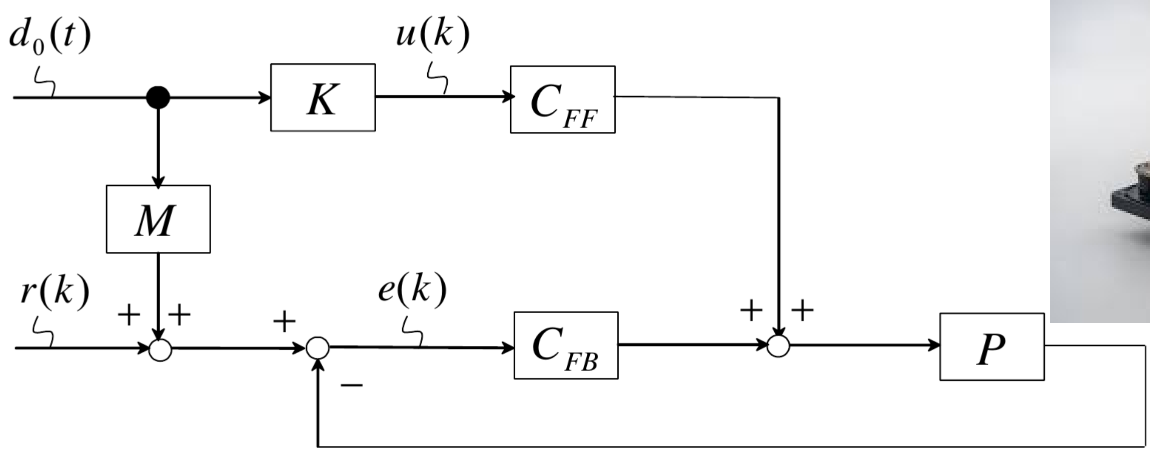
*Source: Widjiantoro 2020*
*Uses Sliding Mode Control*

# Disk Drive Control

Voice Coil Motor




Disk Drive System




Position Control

*Source: Yabui 2016*

*Uses Adaptive Feedforward Control*

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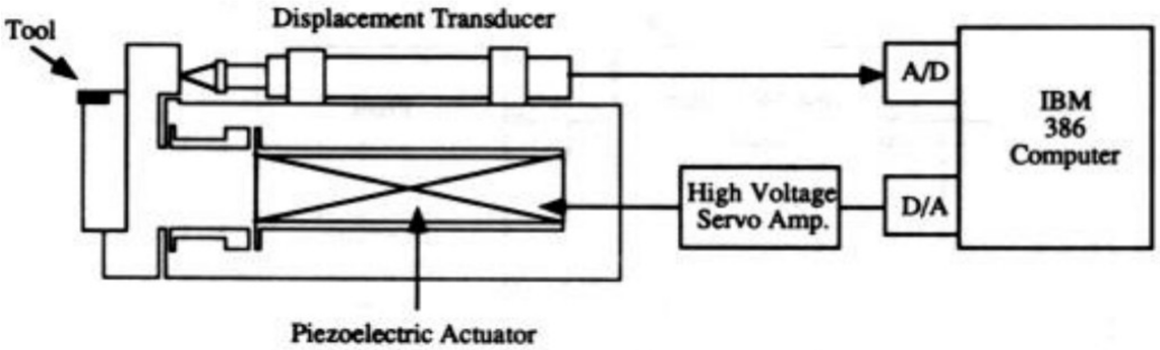
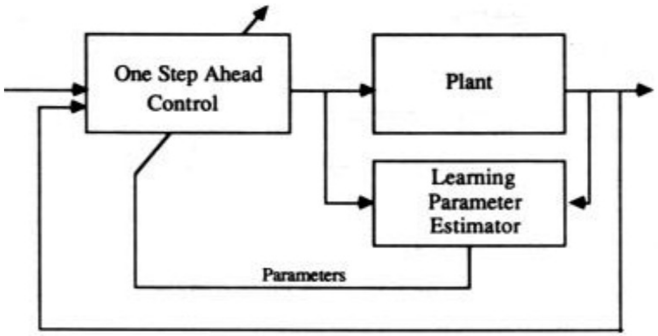
# Iterative Learning Control




Diamond Cutting Lathe

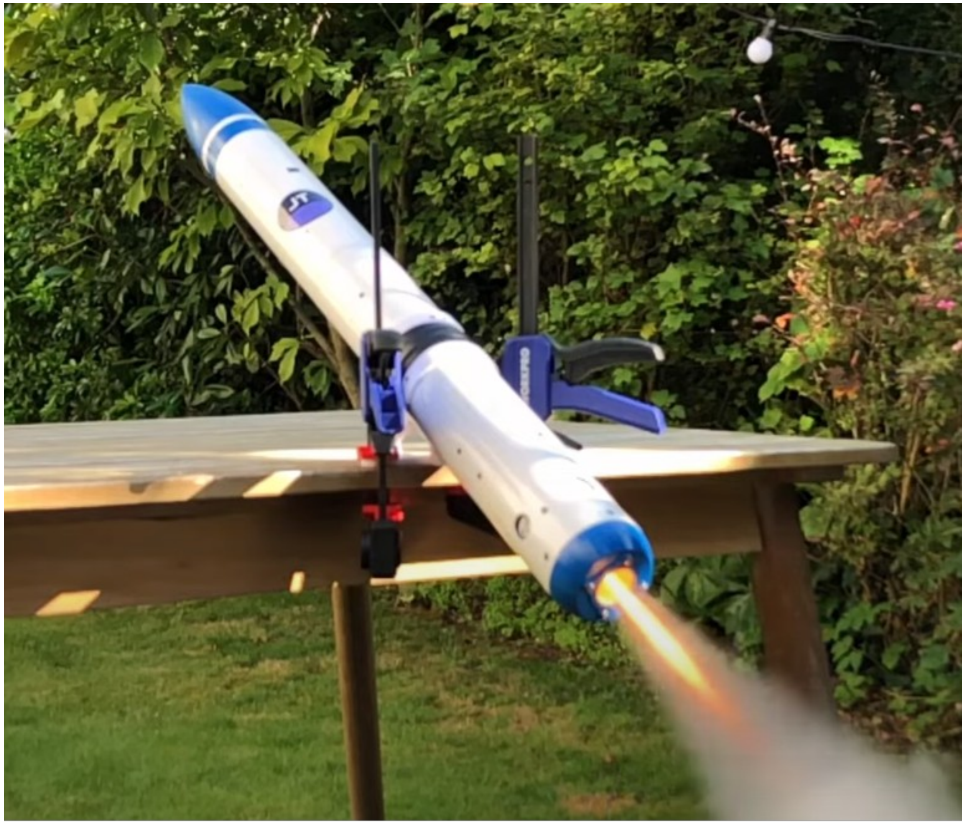



Learning Self-Tuning Regulator

*Source: C. James Li, H. Beigi 1993*

*Uses a Learning Self-Tuning Regulator (Adaptive Control)*

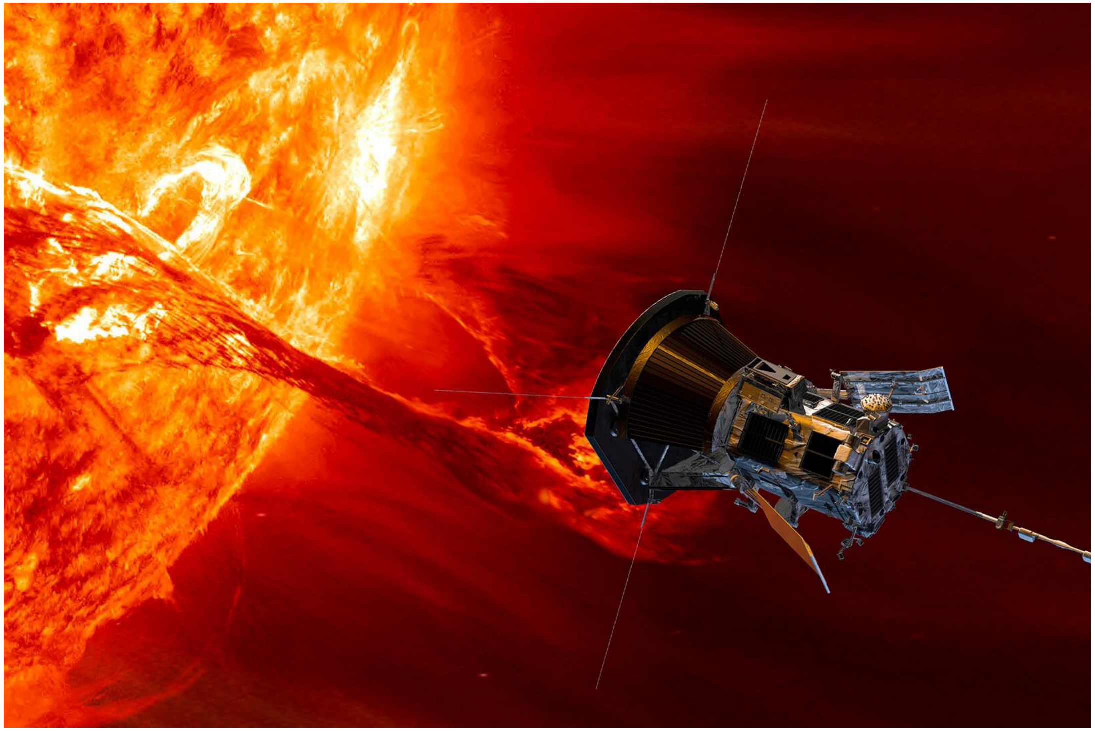
# Fin-Controlled Rocket



Flight Computer And Navigation Software
Fin-Controlled Rocket

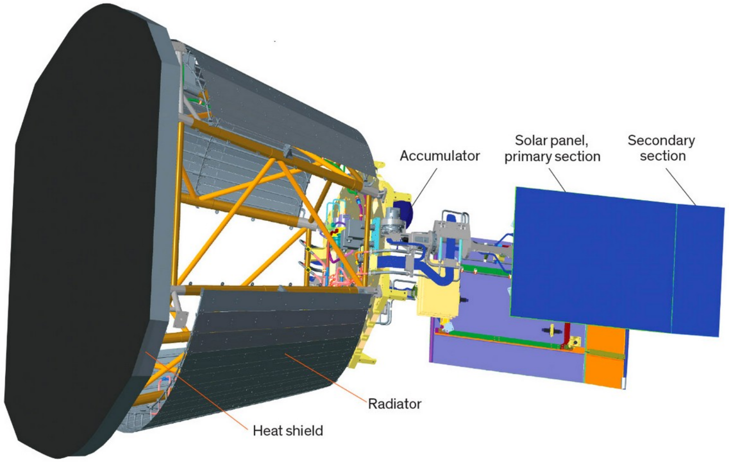
*Source: Jacob Thornhill (Youtube)*

# The Parker Solar Probe



*Source: Johns Hopkins Applied Physics Department*

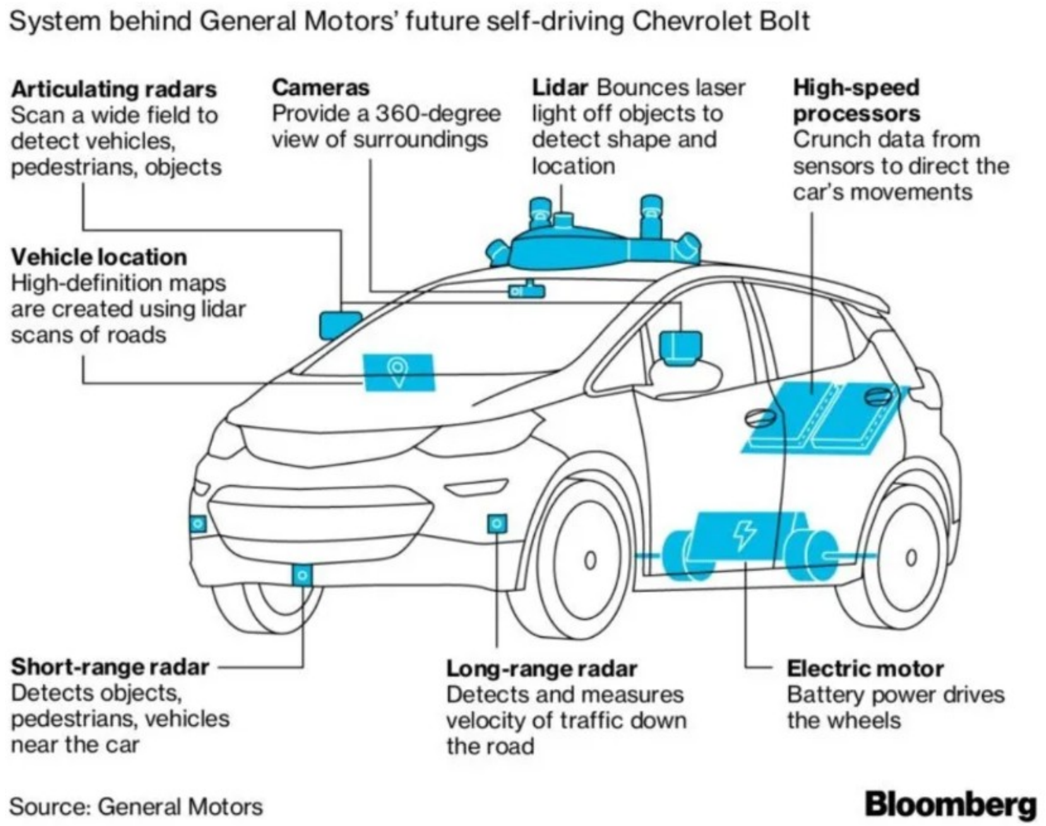
*Maximum Speed: 691,870 km/h = 192 km/s*




*Source: IEEE Spectrum*

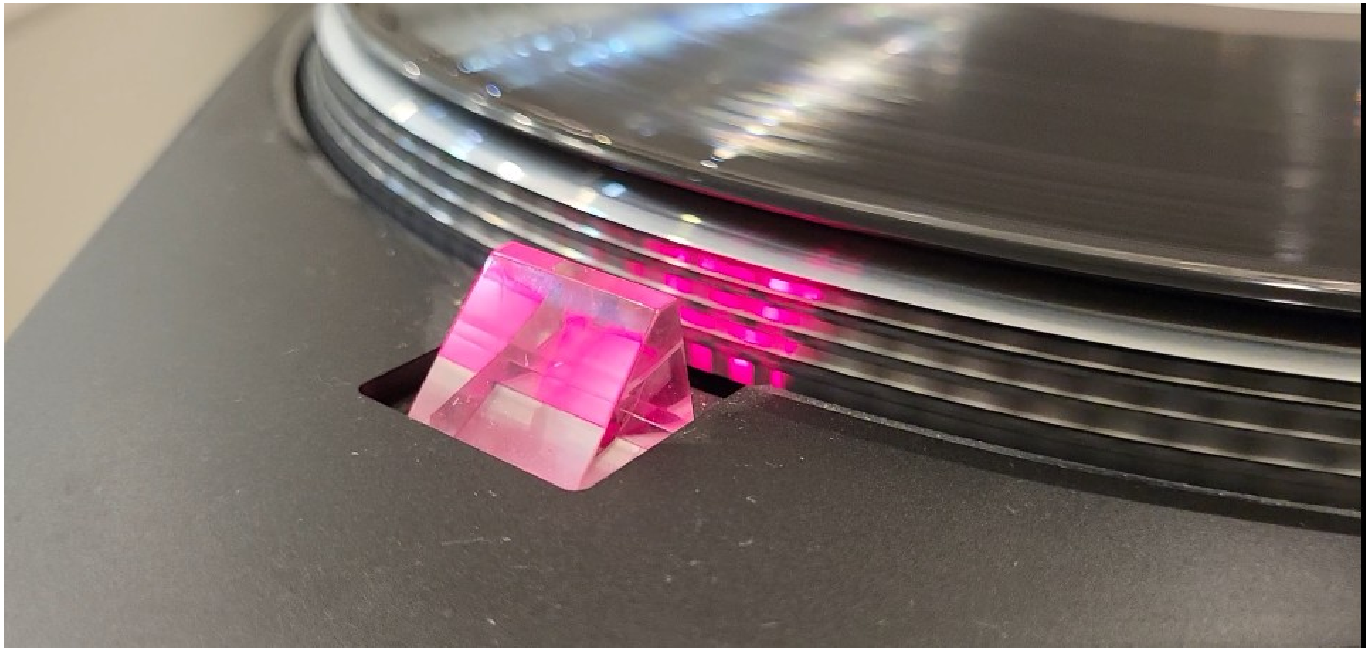
*Source: Jacob Thornhill (Youtube)*

# Autonomous Vehicle Sensors



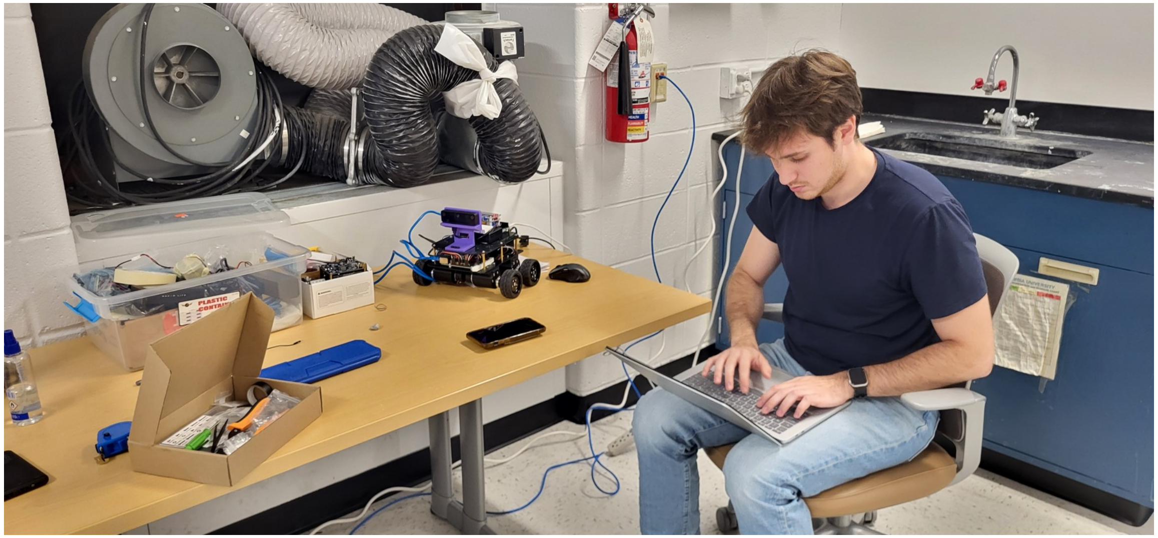

*Source: Using Machine Learning for Autonomous Control (Medium Article)*

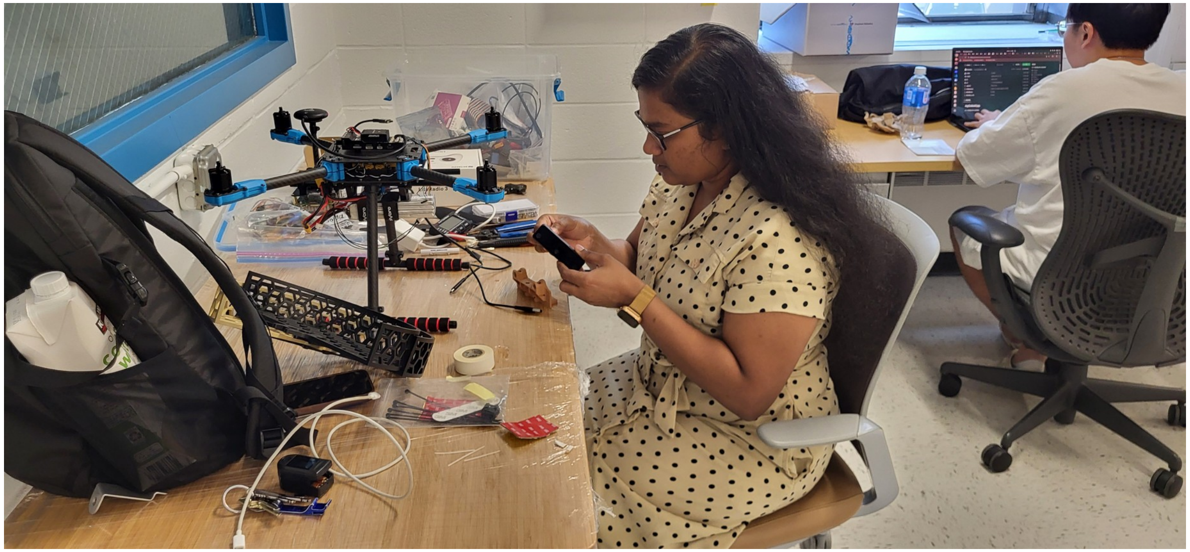
# Sample Plant
# Phonograph (Record Player)



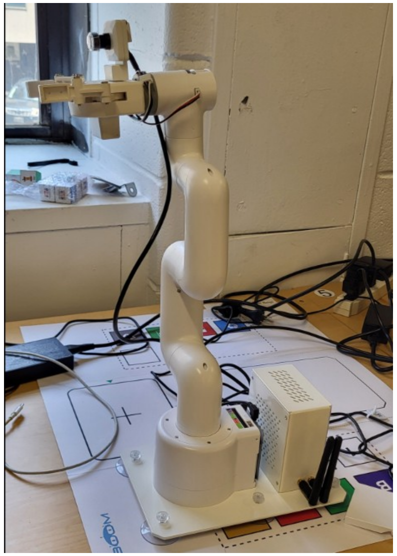
Phonograph speed control – Open-Loop vs Closed-Loop

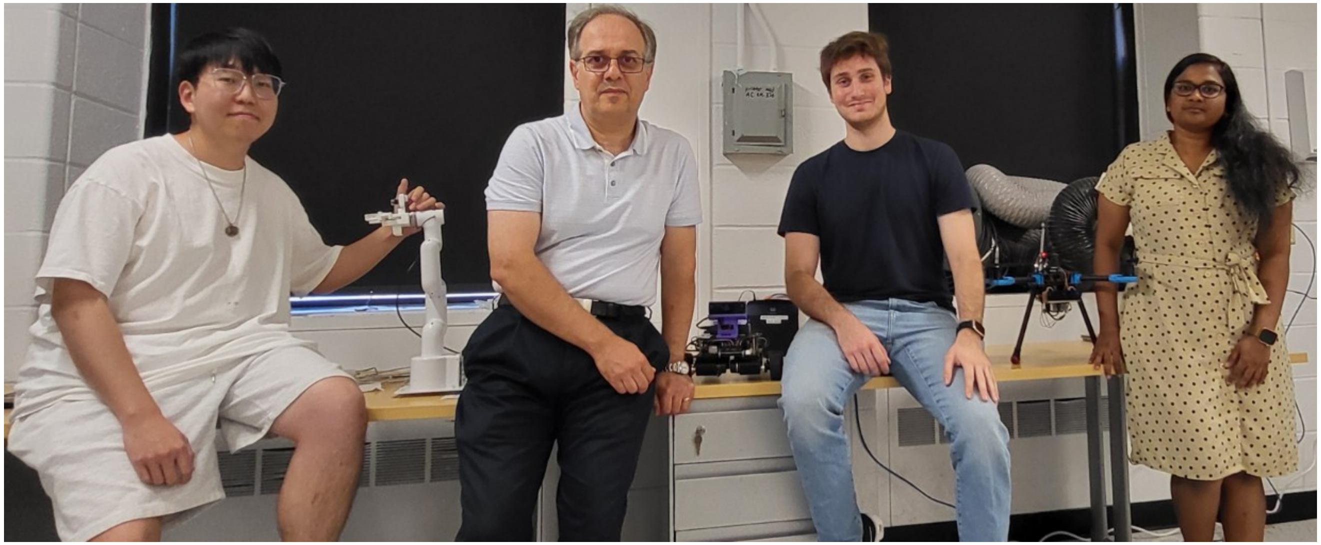
# Nonlinear Control Lab



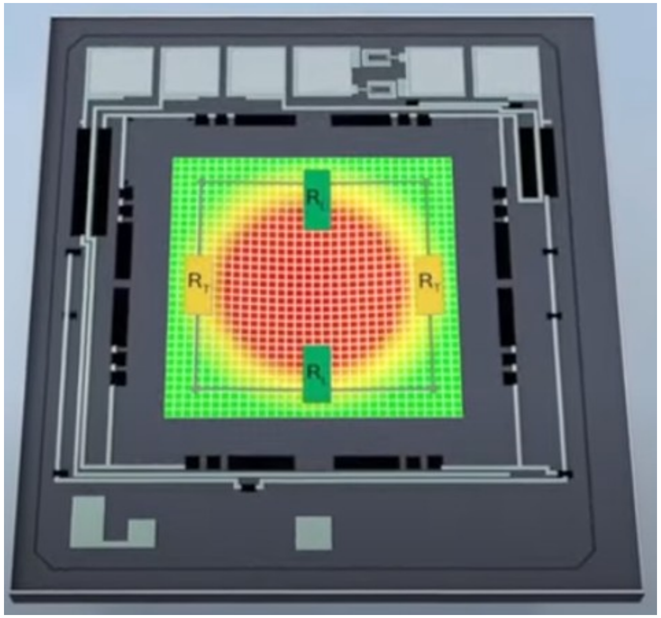


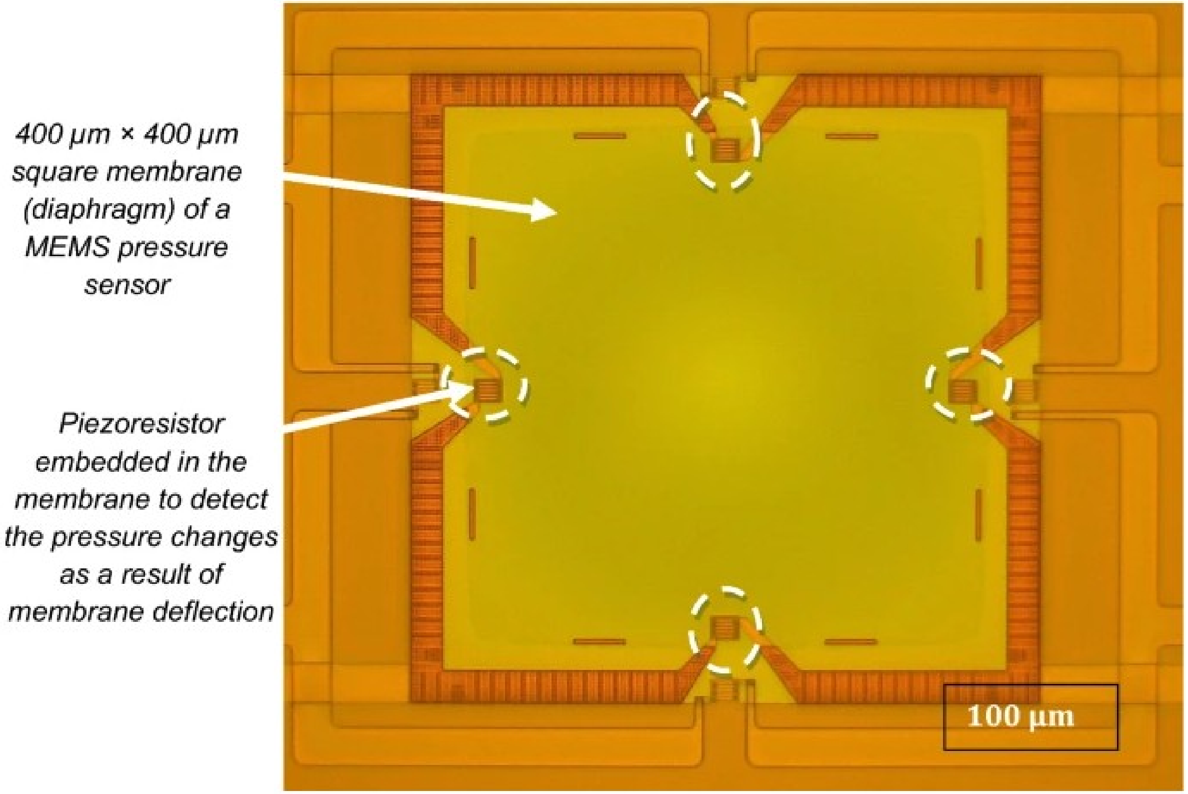
# Nonlinear Control Lab





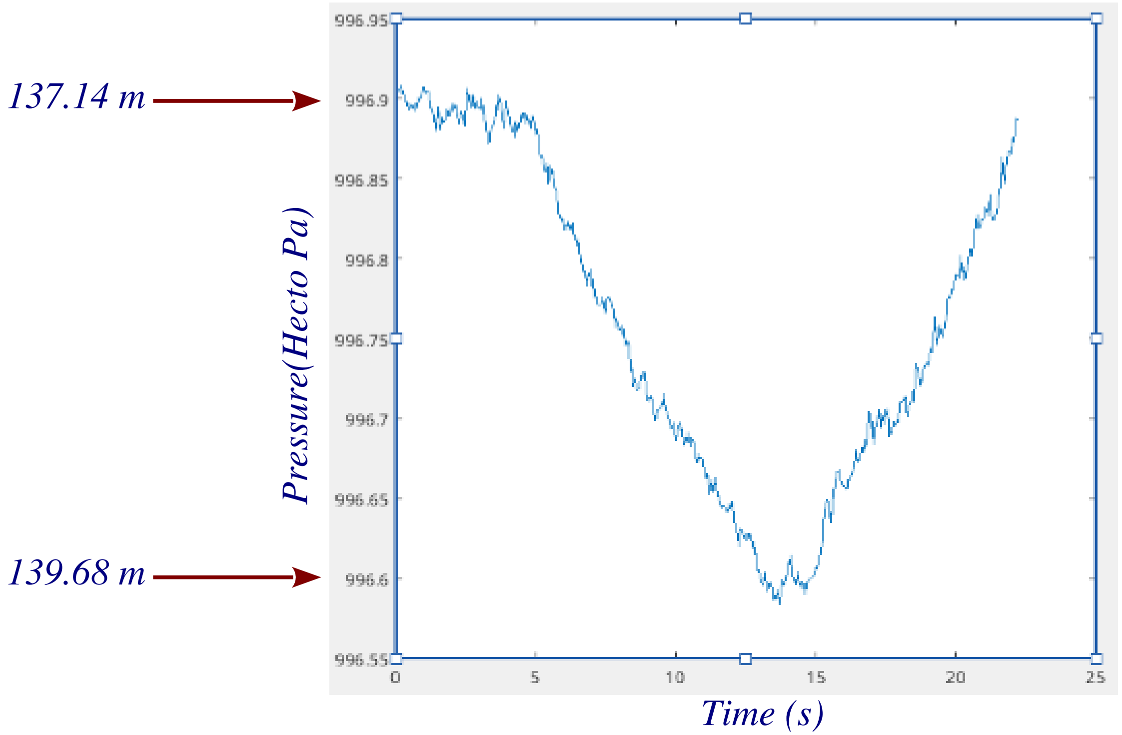
# Pressure Sensor






Z. Mehmood, et al, "Material selection for optimum design of MEMS pressure sensors," Microsystem Technologies, 2020, 26:2751-2766

# Sensor Data

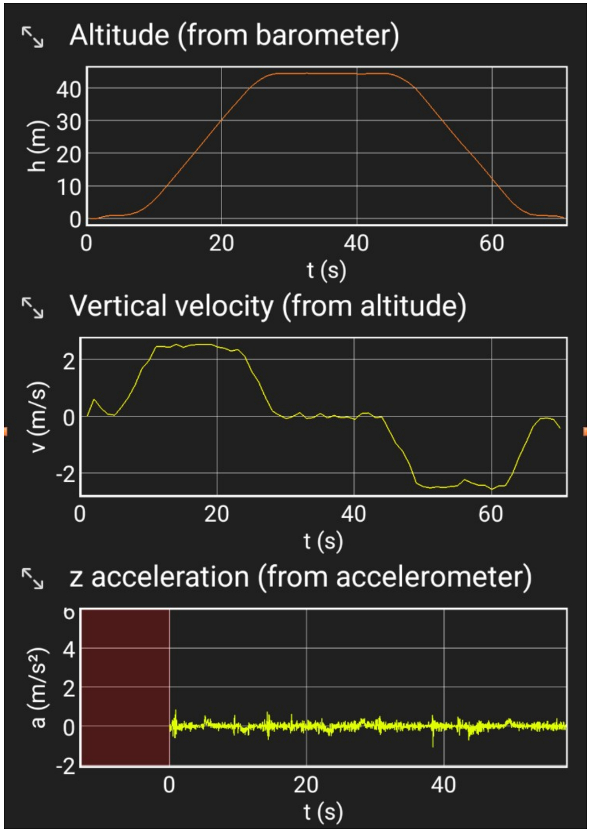



Walked up and down stairs at home

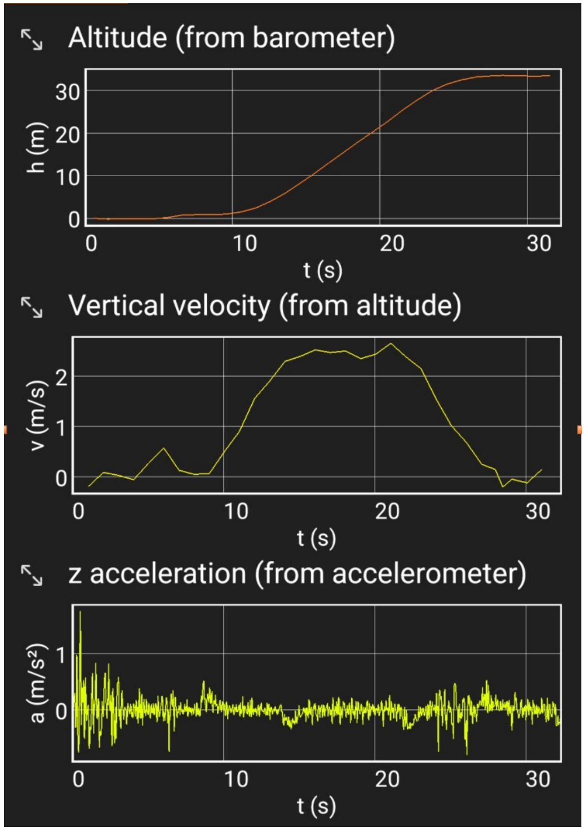
*Based on the ideal gas law:* $h = \frac{RT}{g} \ln(\frac{P_0}{P})$

$$\begin{aligned} R &= 287 \ \frac{J}{kg \times^\circ K} \\ g &= 9.81 \ \ m/s^2 \\ T &= 273.15 + 15 = 288.15 \ \ ^\circ K \\ P_0 &= 1013.25 \ \ hPa \end{aligned}$$

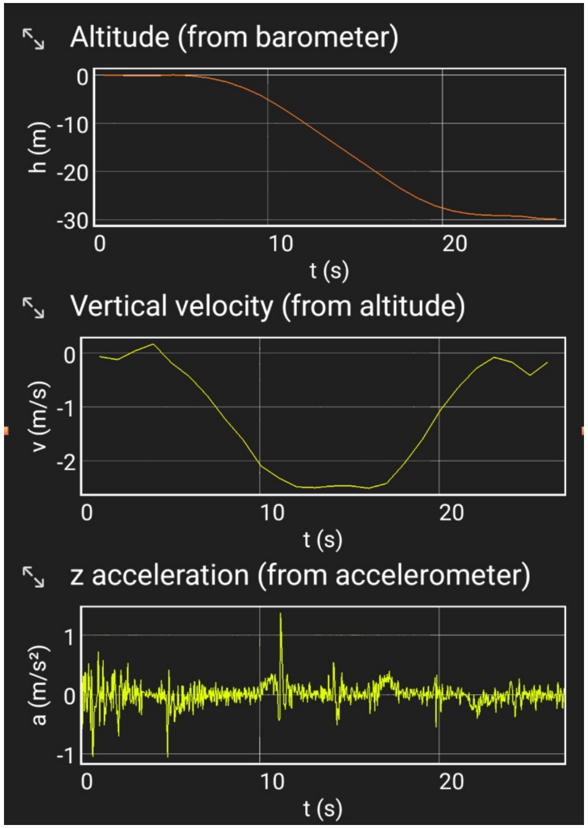
# Sensor Data




Mudd Building
1st floor to 13th floor and back




Mudd Building
1st floor to 10th floor




Mudd Building
10th floor to 2nd floor

# Homework – Due in two weeks (See Courseworks for details)

Download and Install Phyphox (by Univ. of Aachen) on a smartphone

Choose two buildings – the taller the better

Examples: Mudd, CEPSR, your dorm, etc.

Use the Elevator and Pressure options of the app as follows

For each trial described below, send the CSV formatted raw data and the plots as screenshots from the Phyphox menu

Using the Elevator option of the app, record data from the lowest floor to the highest and back -- perform two trials

Using the Pressure option of the app, record data from the lowest floor to the highest and back -- perform two trials

From the Pressure sensor data compute the height, the speed, and the acceleration using the ideal gas law and derivative approximations in Matlab

Compare the 4 trials for each building by finding the sum of squares of errors across different trials

describe your findings in text, with graphs for support. Use about 1 page of text. Present the results and make any discussions that you observe

Make sure you about the control strategy and the speed profile and its repeatability

Include your Matlab code in the uploaded package