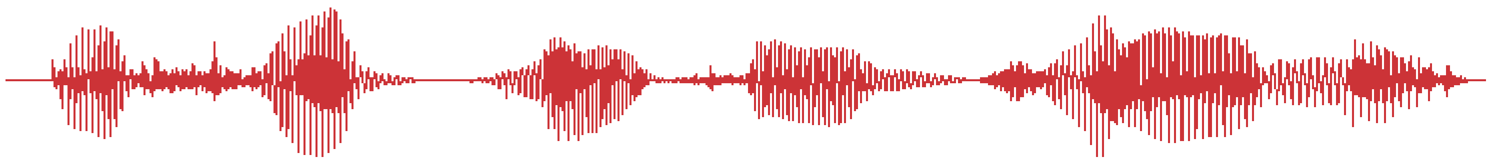
Digital Control Systems

EEME E4601



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: 1127 Mudd Building
- Class Time: Wednesdays ***4:10*** PM – ***6:40*** PM
- Instructor: ***Homayoon Beigi*** *<hb87@columbia.edu>*
- TA: *Do-Gon Kim <dk3322@columbia.edu>*
- Website: ***https://www.RecoTechnologies.com/beigi***

Office Hours

1. Homayoon Beigi (Prof.)

   Email: *hb87@columbia.edu*

   Days: Mondays and Wednesdays Time: 11AM to 12 Noon on zoom:

   Link: https://columbiauniversity.zoom.us/j/93321040837?pwd=fipJs4JkAXh50aPwTXBqDLHI0Ry2iQ.1

   And Thursdays: 4PM-5PM by appointment only

2. Do-Gon Kim (TA)

   Email: *dk3322@columbia.edu*

   Days: Tuesdays: Time 10AM to 11AM and Fridays Time: 11AM to 12Noon

   Link: https://meet.jit.si/ColumbiaEEME00YpsEAJajhm

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Background

- **Recognition Technologies, Inc.** - *President* – since 2003
- **Internet Server Connections, Inc.** - *Vice President* – since 2001
- **Columbia University** – *Adjunct Professor* – since 1995
  Courses: Fundamentals of Speech Recognition, Signal Recognition,
  Speaker Recognition, Handwriting Recognition, and Digital Control
  Depts: CS, ME, EE, and CE
- **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**

Academic Activities

Textbook Publication:

Fundamentals of Speaker Recognition *– 2007 - 2011*
Springer-Verlag 2011

Columbia University – *SEAS*
Adjunct Professor – since 2003
Adjunct Associate Professor: 1997 – 2003
Adjunct Assistant Professor: 1995 – 1997

Spring 2012 – 2023
Fundamentals of Speaker/Speech Recognition – *Computer Science Dept.*

Other Courses:

Speech Recognition (1995 & 1996) – *Electrical Engineering. Dept.*

Applied Signal Recognition (2004, 2005, 2019, 2020) – *Mechanical Engineering Dept.*

Digital Control Systems (1998, 2004, 2013, 2019) – *Mechanical & Electrical Engineering*

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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

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

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

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

Grading

Homework – 30%

Small Problems and/or Coding Assignments

Midterm – 20% – Mar. 12, 2025

Problems and/or Coding Assignments

Project Proposal – 10% – Mar. 26, 2025

2-page proposal, including state of the art and proposed methodology

Final Project – 40% – May 14, 2025

15% – Code – Dec. 15, 2024
25% – 6-page IEEE Style Report of the methodology and result +
3 minute Video Presentation

Grading *(Continued)*

Proposal (10%)

Two-page extended abstract – as you would submit to a conference for publication

- Description of the problem + Data
- Quick review of the State of the Art
- Roadmap of the research
- Description of the intended experiments
- Expectations – Expected results and problems

Project -- 40% (25% written Paper and 3 minute Video Presentation & 15% Code)

Six-page conference-style paper

- Abstract
- Introduction – problem description and the State of the Art
- Problem Formulation – Mathematical formulation, etc.
- Experiment – Description and Setup + Data
- Results – Presentation and Analysis
- Conclusion – including Future Direction

Source code and documentation for running the experiment

Input and Output Data

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Tools

Matlab

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

- Student license should be available through Columbia.

Audacity

Audio Manipulation Application

Google Cloud

We will use Google cloud for access to GPUs for training Neural Nets.

GPU

Installing a GPU card such as the Nvidia GTX 1080Ti or better would be advantageous.

- Google cloud is temperamental and credits can be easily depleted.

Books

Textbooks:

Required:

Charles L. Phillips, Digital Control System Analysis & Design, Pearson Prentice Hall, 2015.

Reference:

Homayoon Beigi, “Fundamentals of Speaker Recognition, Springer-Verlag, New York, 2011.

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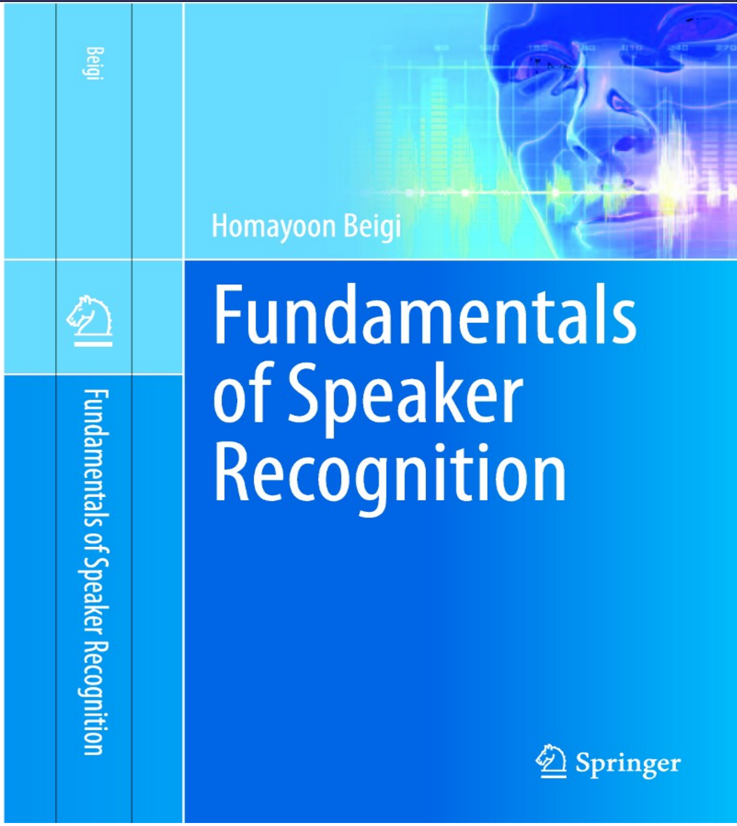
Textbook

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

100,000+ downloads of online version

www.FundamentalsOfSpeakerRecognition.org



ISBN: 978-0-387-77591-3

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Control Problem Components

Goals

- Transient Response
- Disturbance Rejection
- Steady-State Error Correction
- Plant Parameter-Change Sensitivity

Approach

- Sensor Selection
- Actuator Selection
- System Modeling – Developing Equations for the Plant Dynamics, Sensor Response, and Actuator Dynamics
- Controller Design
- Evaluation – analytic evaluation, simulation, hardware test
- Repetition of the tests to achieve repeatable and acceptable results

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)

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Controllers

- Adaptive Control Systems
  - Self-tuning Regulators
  - Model-Reference Control
  - Fuzzy Control Systems

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

Nonlinear Control Systems

$$
\begin{aligned}
\dot{\mathbf{x}}(t) &= \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t), t) \\
\mathbf{y}(t) &= \mathbf{h}(\mathbf{x}(t), t)
\end{aligned}
$$

Linear Time-Invariant (LTI)
Single-Input Single Output (SISO)

$$
\begin{aligned}
\frac{d^{(n)}y(t)}{dt^{(n)}} &+ p_{n-1}\frac{d^{(n-1)}y(t)}{dt^{(n-1)}} + p_{n-2}\frac{d^{(n-2)}y(t)}{dt^{(n-2)}} + \cdots + p_0 y(t) \\
&= q_{n-1}\frac{d^{(n-1)}u(t)}{dt^{(n-1)}} + q_{n-2}\frac{d^{(n-2)}u(t)}{dt^{(n-2)}} + \cdots + q_0 u(t)
\end{aligned}
$$

Linear Time-Invariant (LTI) State-Space Representation (SISO & MIMO)

$$
\begin{aligned}
\dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \\
\mathbf{y}(t) &= \mathbf{C}\mathbf{x}(t) + \mathbf{D}\mathbf{u}(t)
\end{aligned}
$$

A is the System Matrix
B is the Control Matrix
C is the Observation Control
D is the Direct Input Observation

Time-Variant System

$$
\begin{aligned}
\dot{\mathbf{x}}(t) &= \mathbf{A}(t)\mathbf{x}(t) + \mathbf{B}(t)\mathbf{u}(t) \\
\mathbf{y}(t) &= \mathbf{C}(t)\mathbf{x}(t) + \mathbf{D}(t)\mathbf{u}(t)
\end{aligned}
$$

$\mathbf{A}(t)$ is the time-dependent System Matrix
$\mathbf{B}(t)$ is the time-dependent Control Matrix
$\mathbf{C}(t)$ is the time-dependent Observation Control
$\mathbf{D}(t)$ is the time-dependent Direct Input Observation

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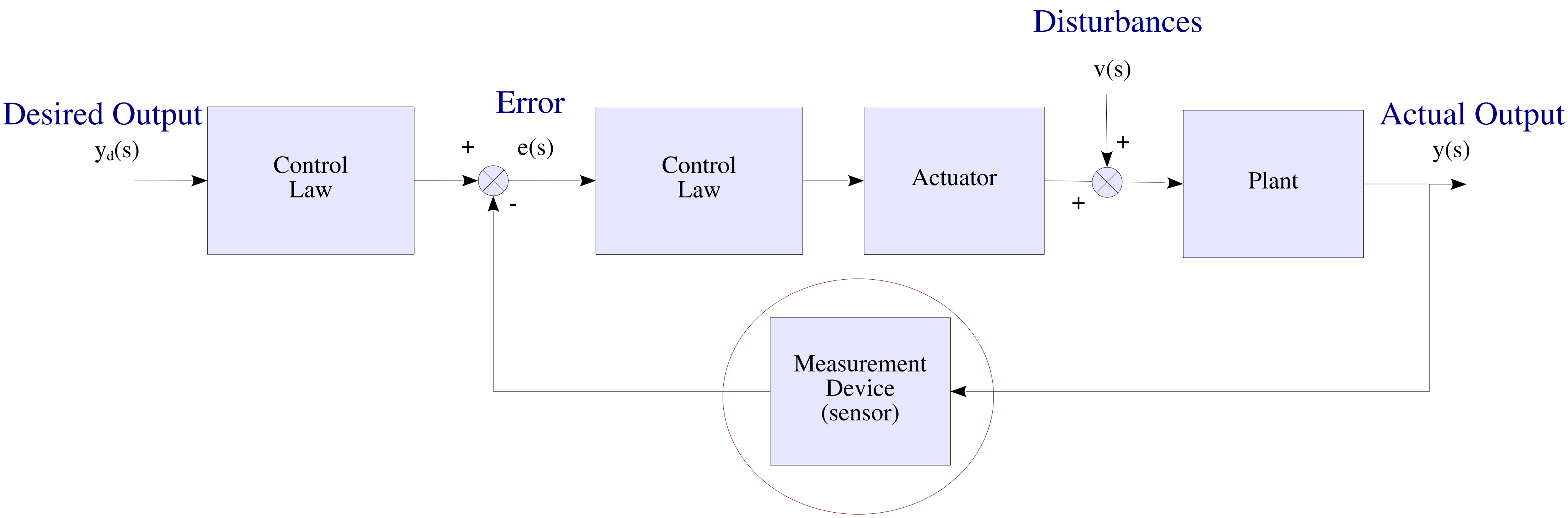
Generic Control System



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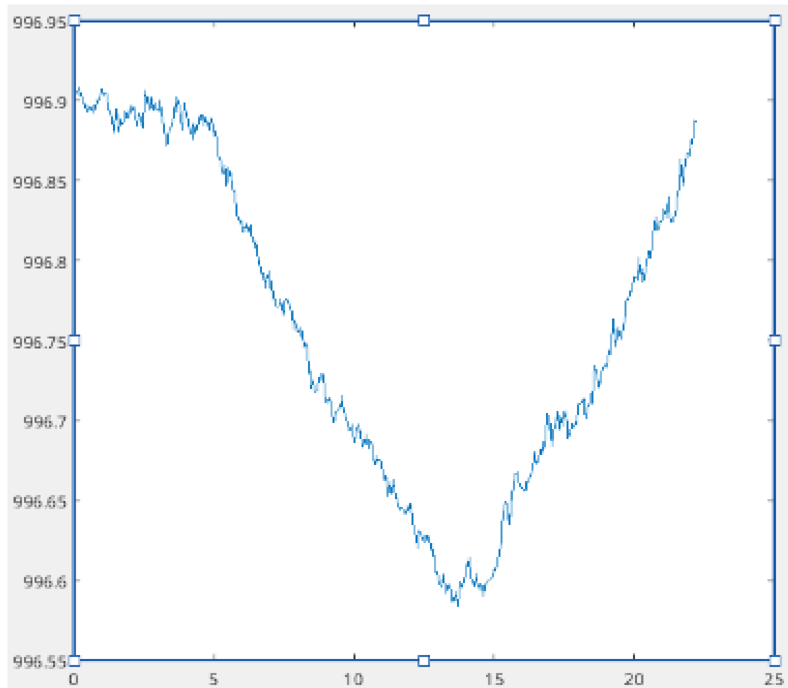
Sensor Data

137.14 m

139.68 m

Pressure(Hecto Pa)



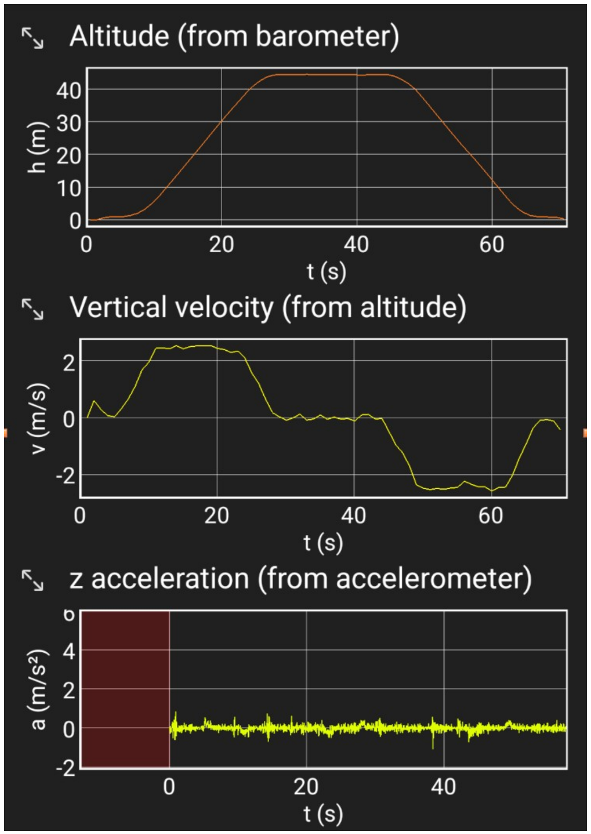
Time (s)

Walked up and down stairs at home

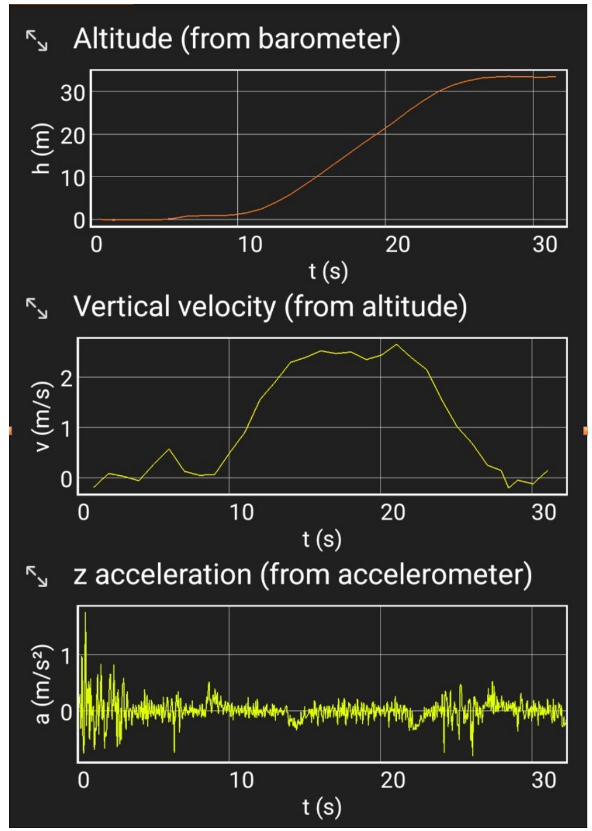
Based on the ideal gas law: $h = \frac{RT}{g} \ln(\frac{P_0}{P})$

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

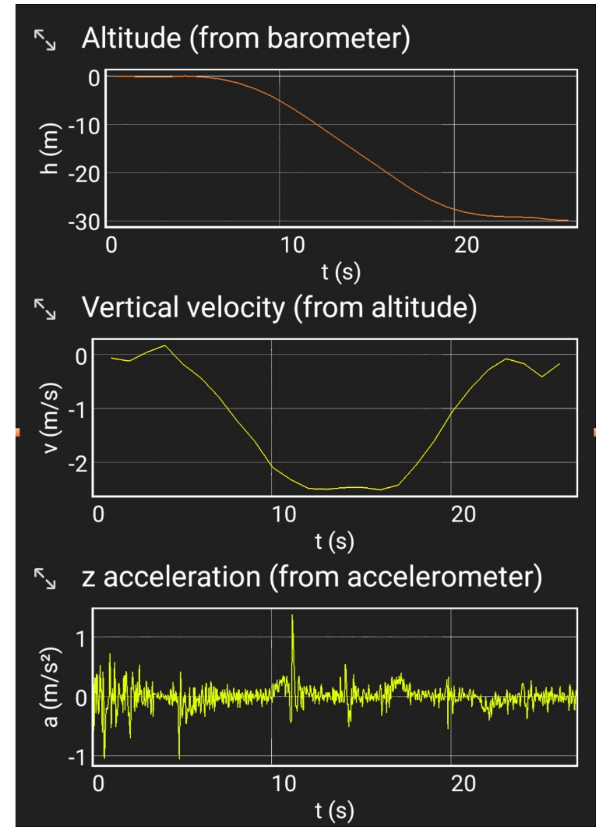
Sensor Data



Mudd Building
1^{st} floor to 13^{th} floor and back



Mudd Building
1^{st} floor to 10^{th} floor



Mudd Building
10^{th} floor to 2^{nd} floor

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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 Pressure and Elevator options

Send yourself the raw data using CSV format

Record the pressure going from the lowest floor to the highest and back – Do two trials

From the Pressure sensor data compute speed and acceleration using Matlab

Repeat experiment with Elevator option two times

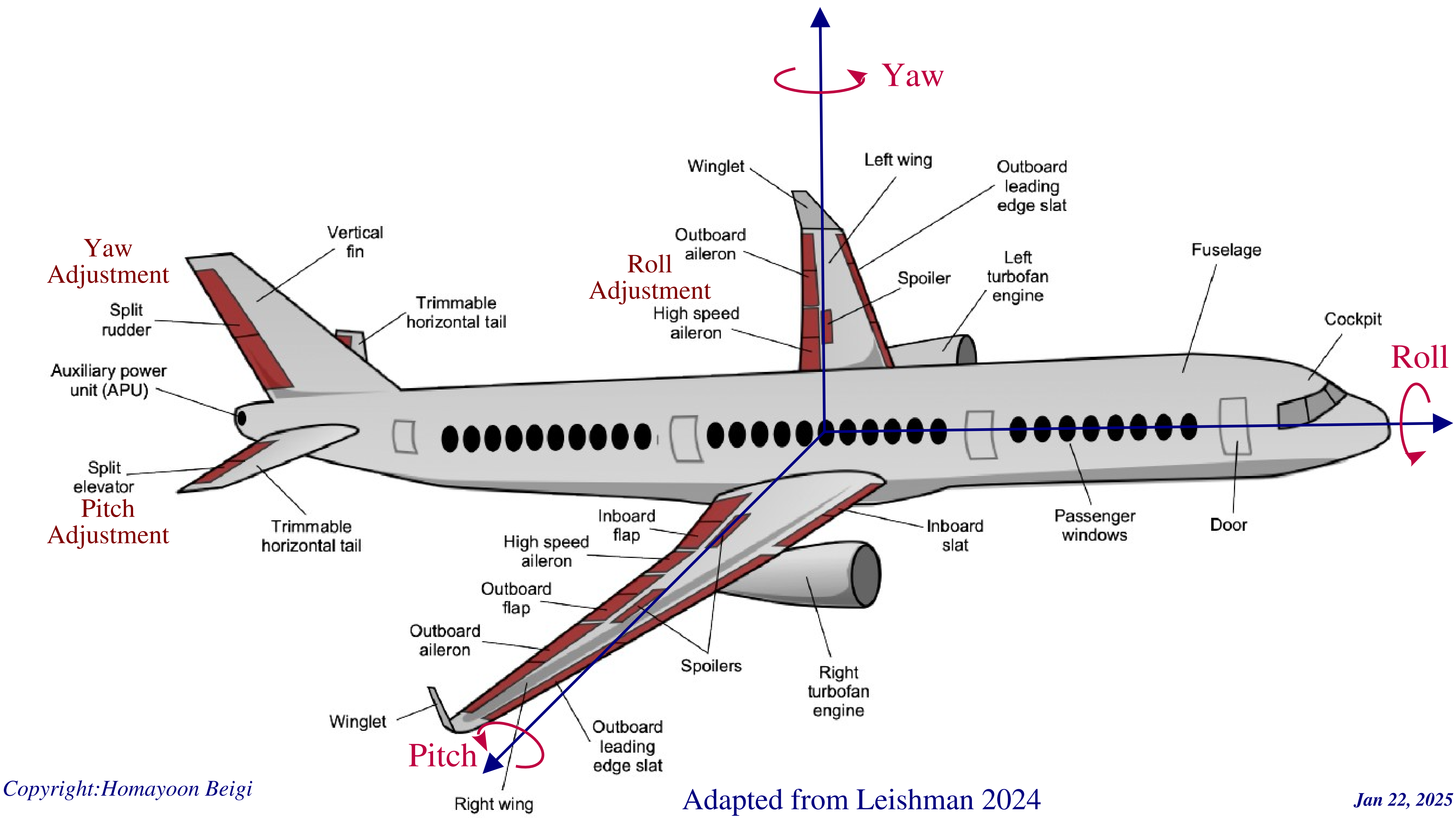
Compare the 4 results by finding the sum of squares of errors

Save the plot screenshots from Phyphox as well

In one page, present the results and make any discussions that you note

Talk about the control strategy and profile of the speed

Sample Plant (Commercial Airplane)



Adapted from Leishman 2024

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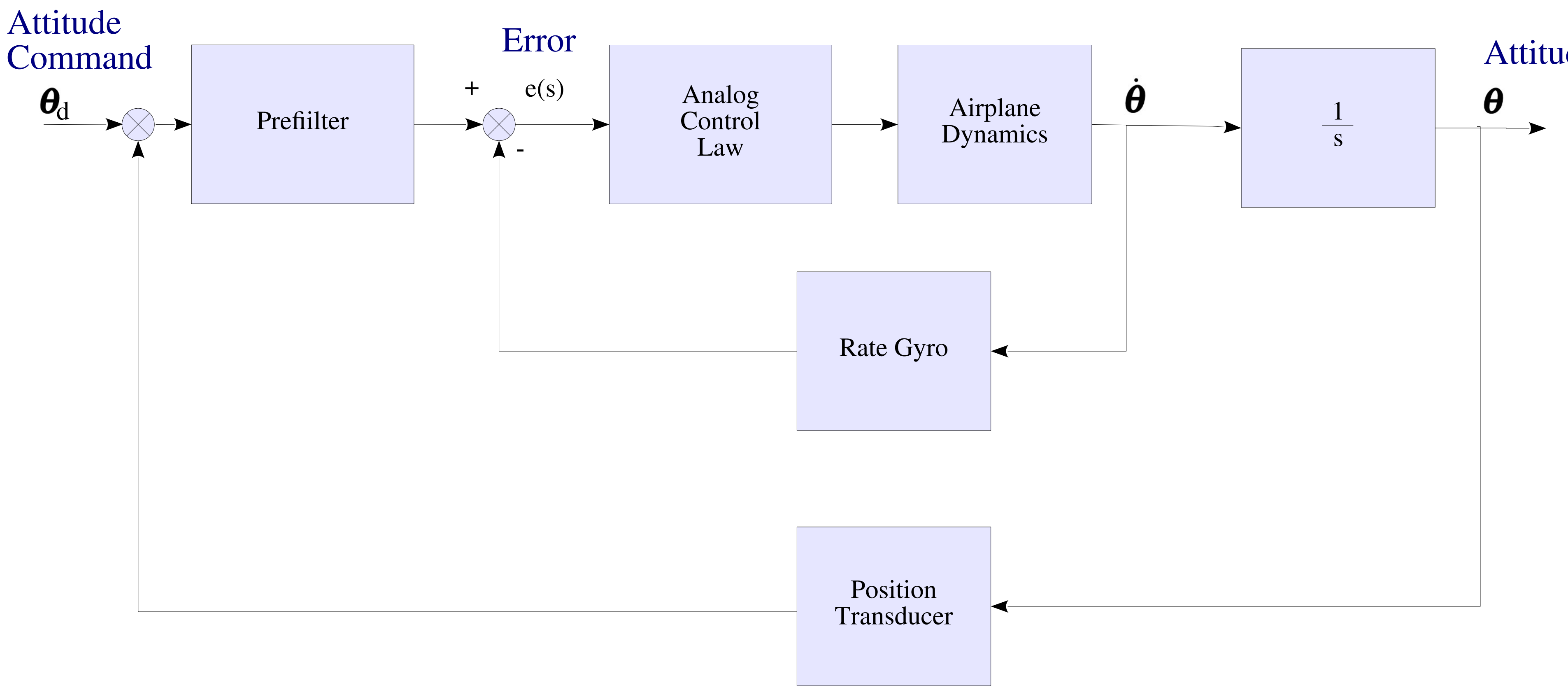
Single Axis Analog Attitude Control Systems

Attitude: Combination of Pitch and Bank



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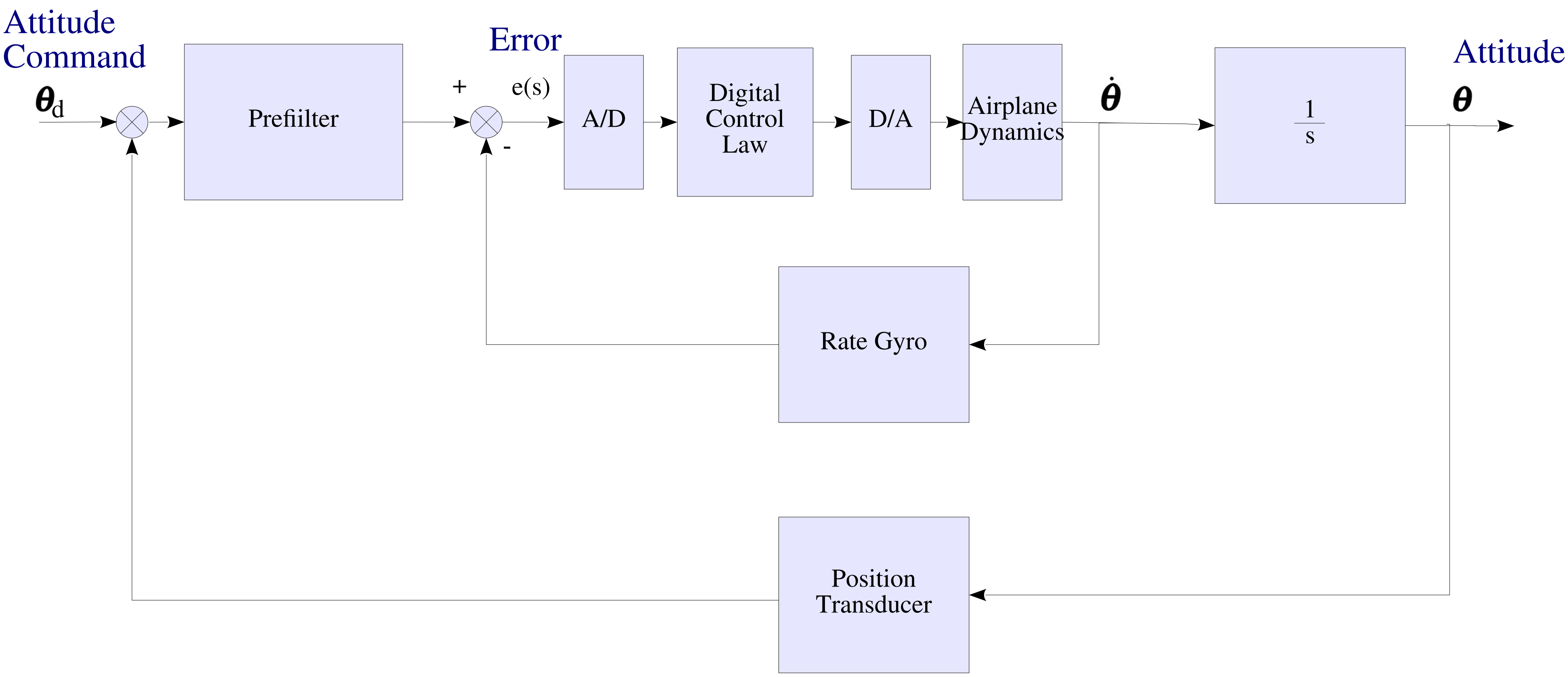
Single Axis Discrete Attitude Control Systems

Attitude: Combination of Pitch and Bank



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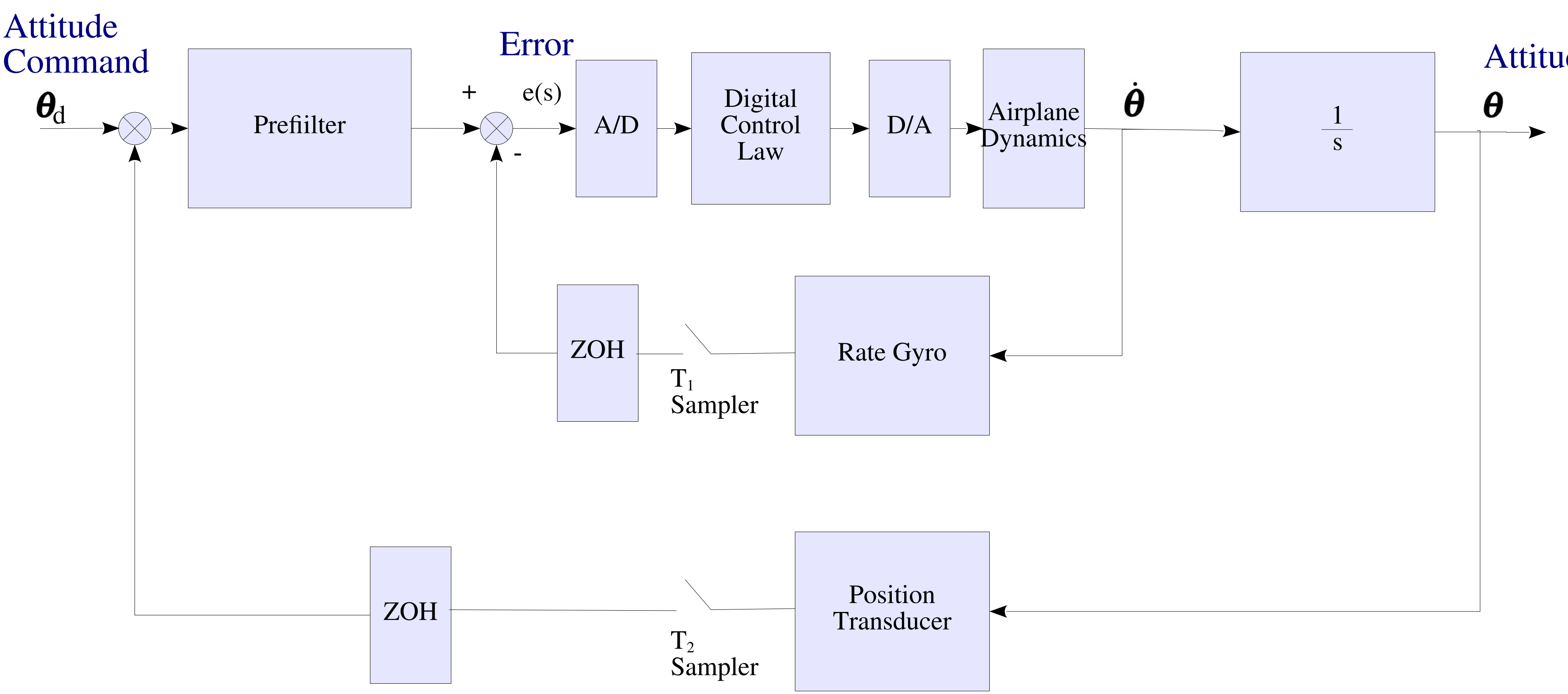
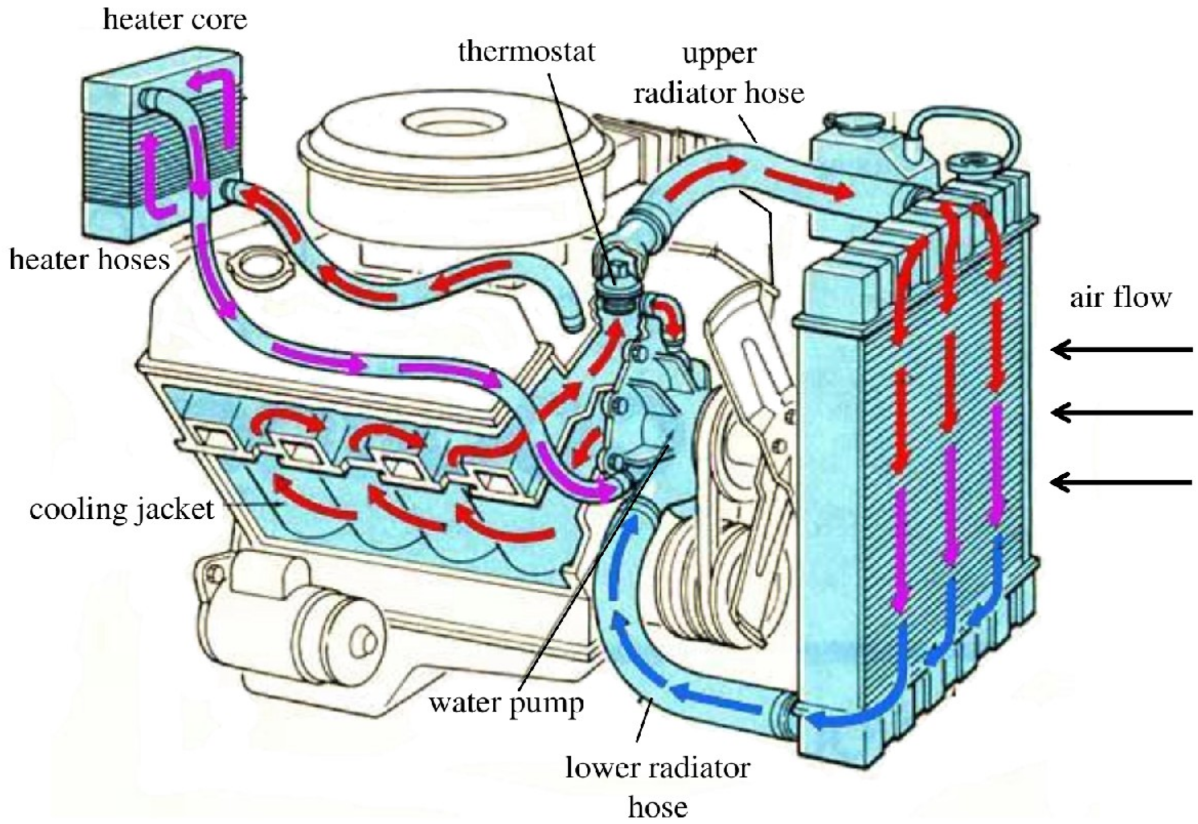
Single Axis Discrete Attitude Control Systems with Multirate Sampling

Attitude: Combination of Pitch and Bank

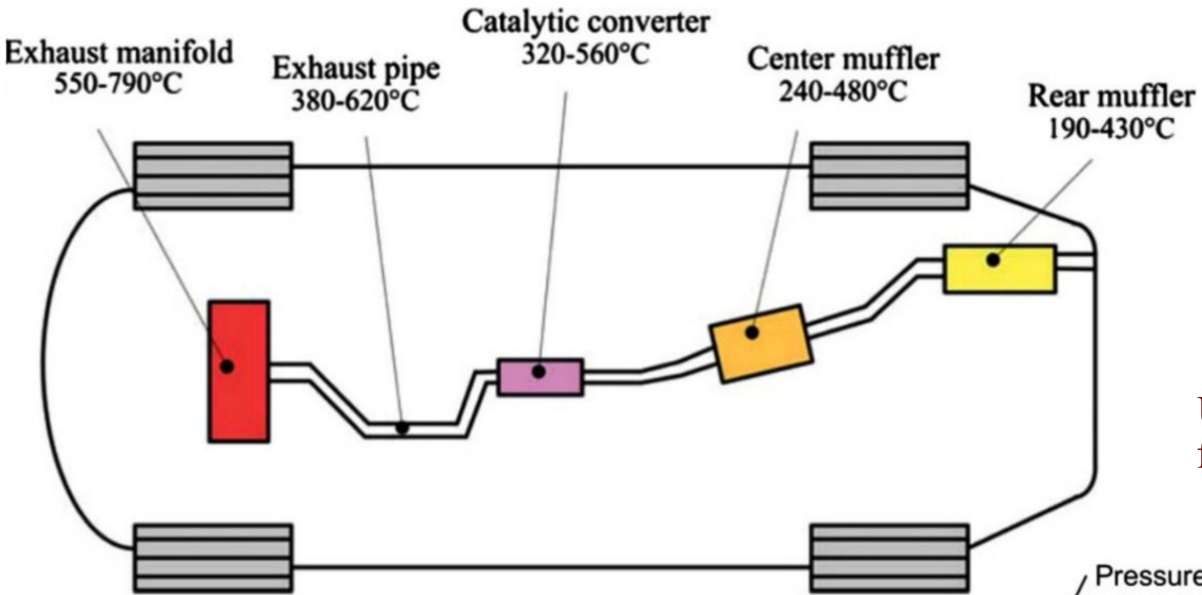


Sample Plant
(Engine Cooling System)



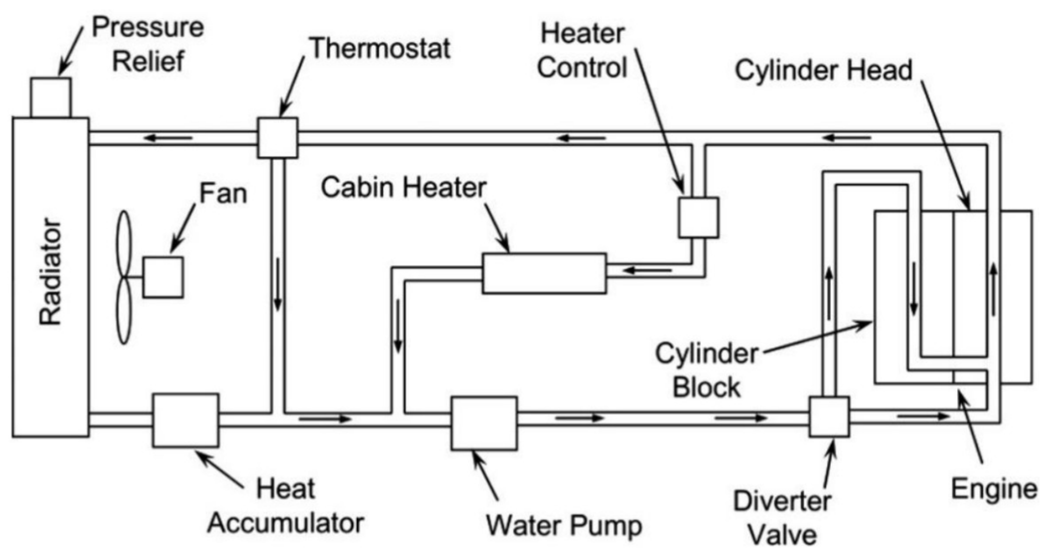
Source: Bencs 2021

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

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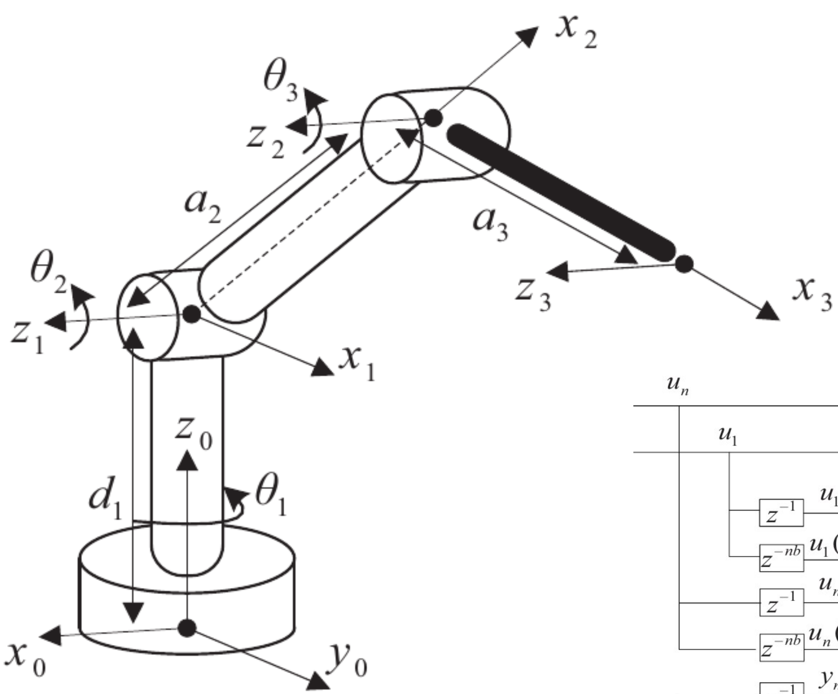
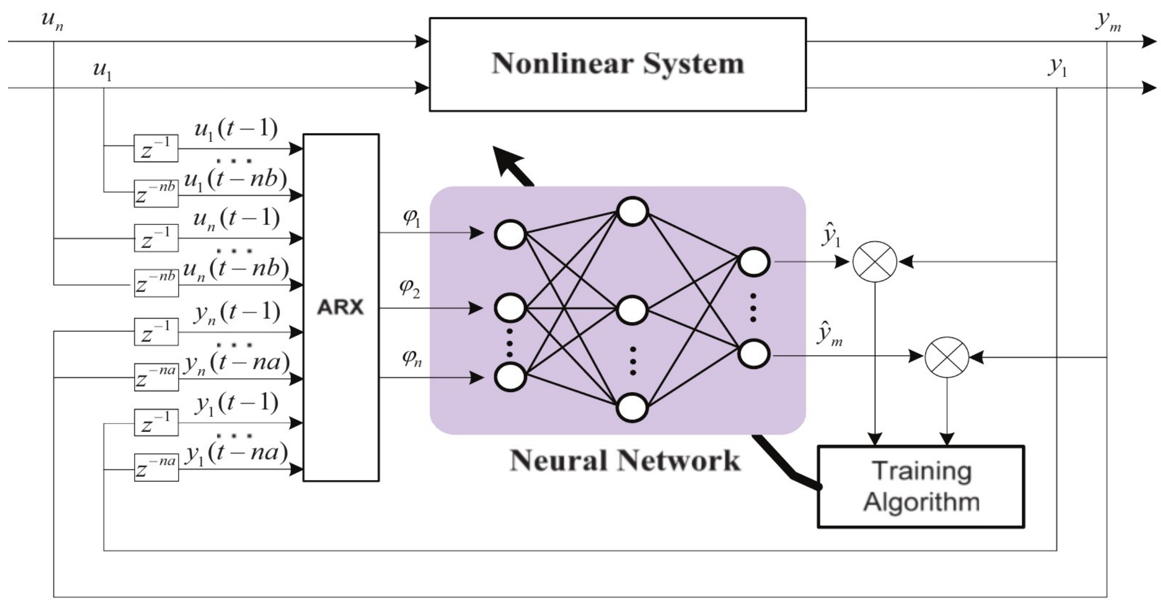
Robot Manipulator Control



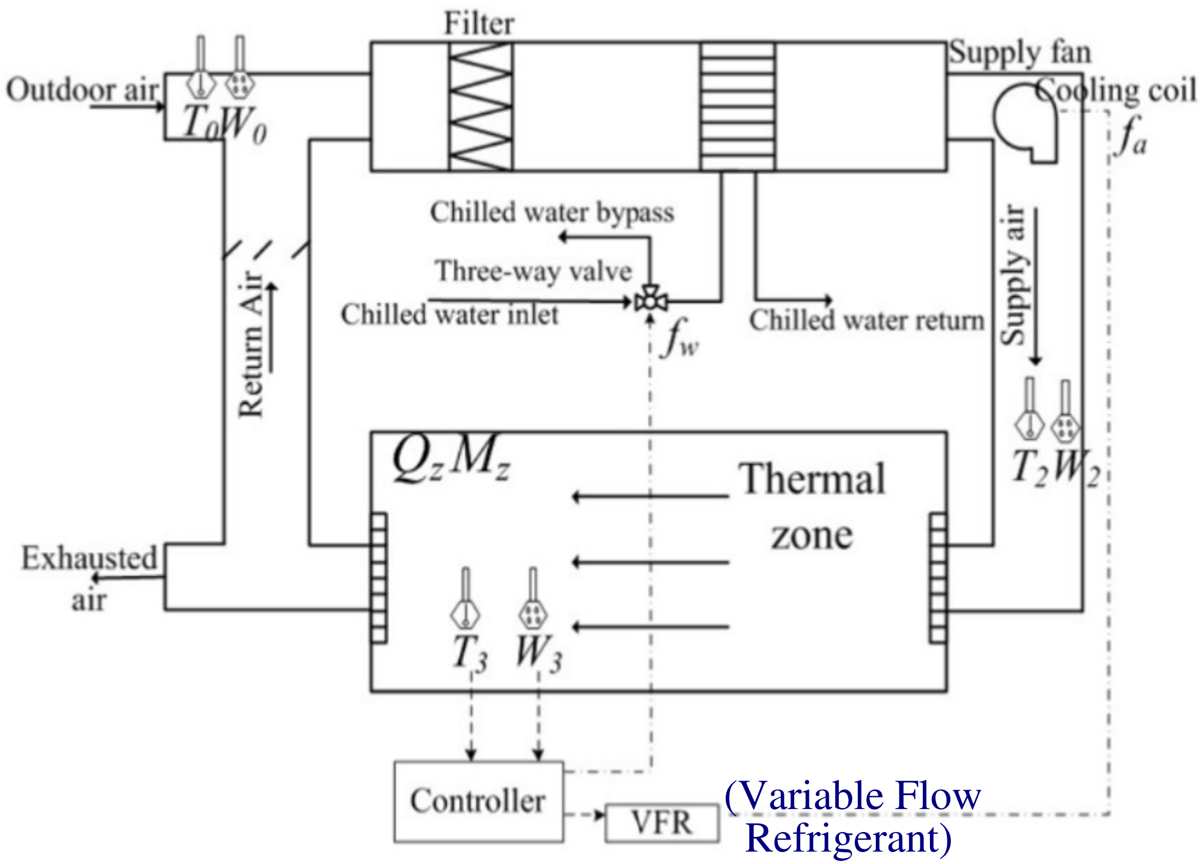
3-DOF Industrial Robot



Nonlinear System ID using Neural Networks for Robot Control

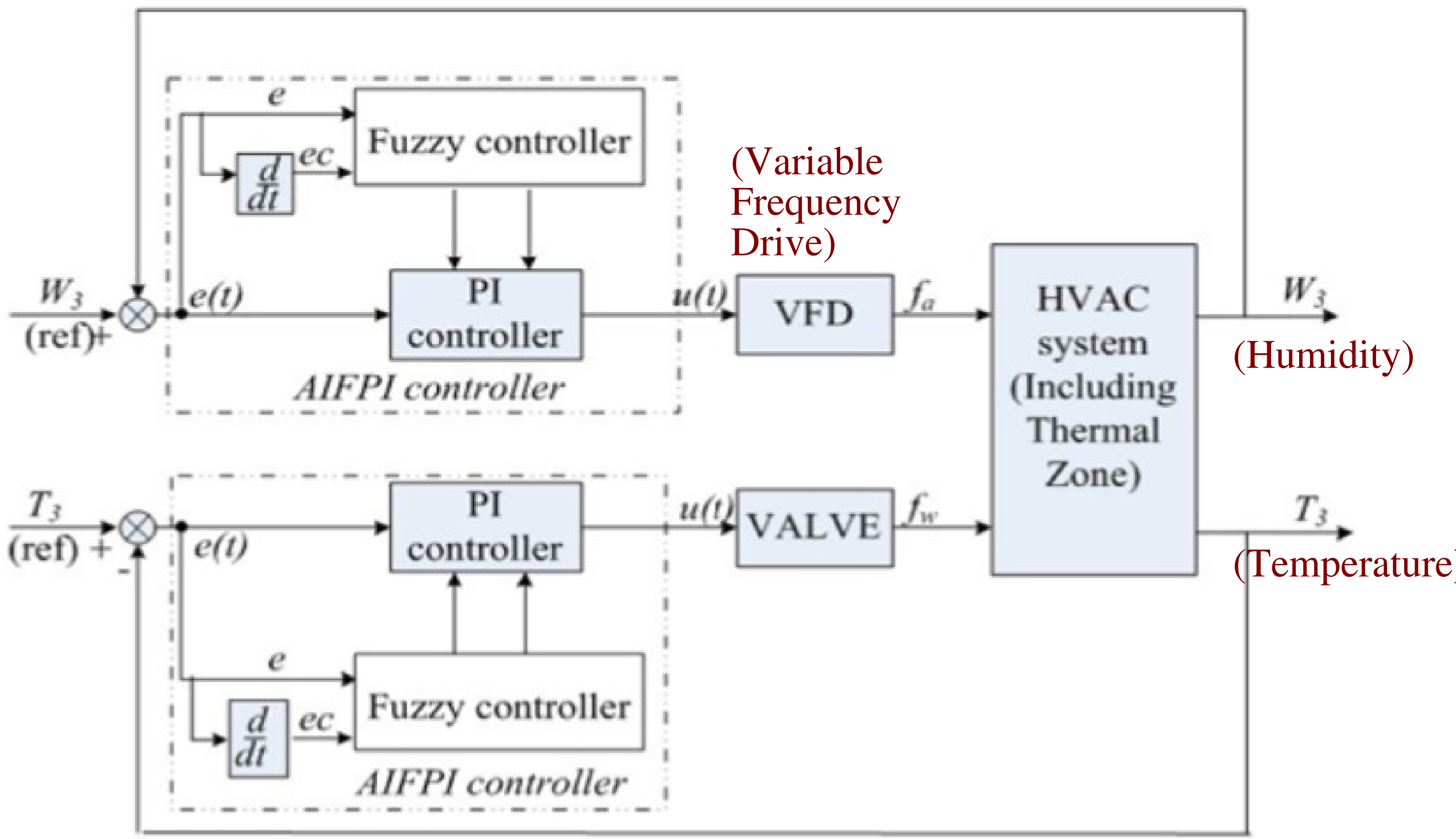
Source: Son 2017

Sample Plant
(Home HVAC System)



Bai-2013

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



Bai-2013

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

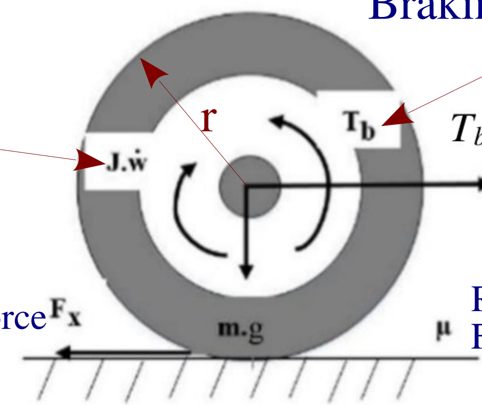
Quarter Vehicle Model (one wheel)

Braking Torque

Wheel
Inertia

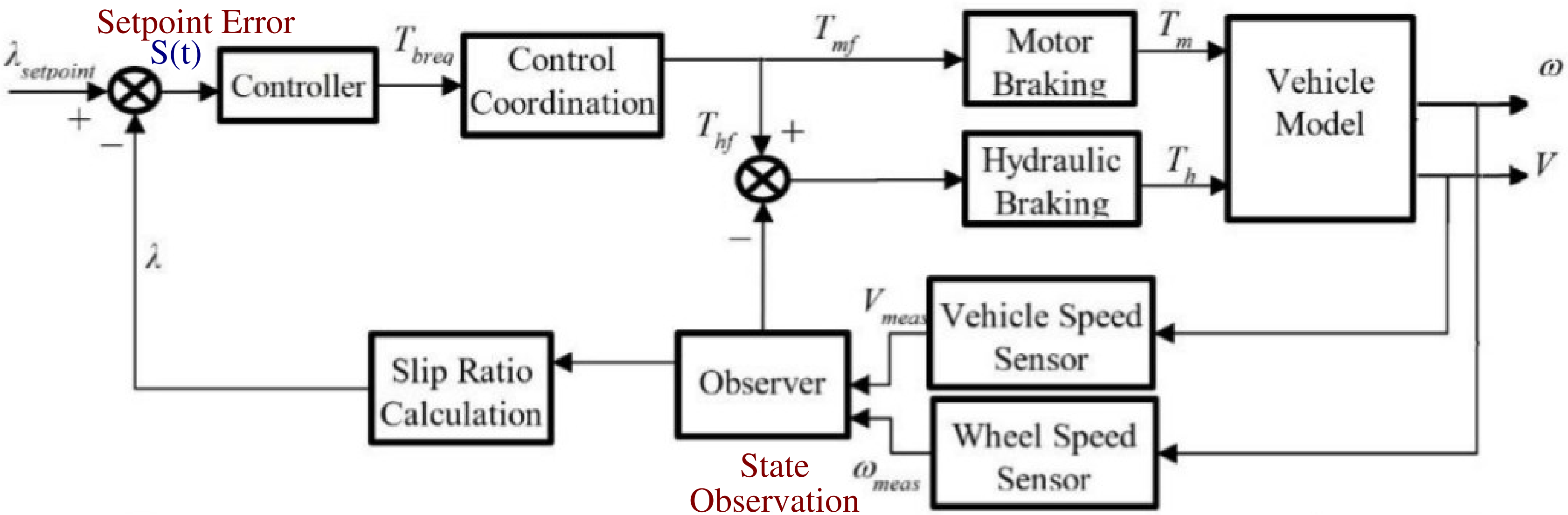
$J = \frac{1}{2} m r^2$

$T_b = T_m + T_h$



Braking Force

Road Surface
Friction Coeff.



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

Source: Widjiantoro 2020
Uses Sliding Mode Control

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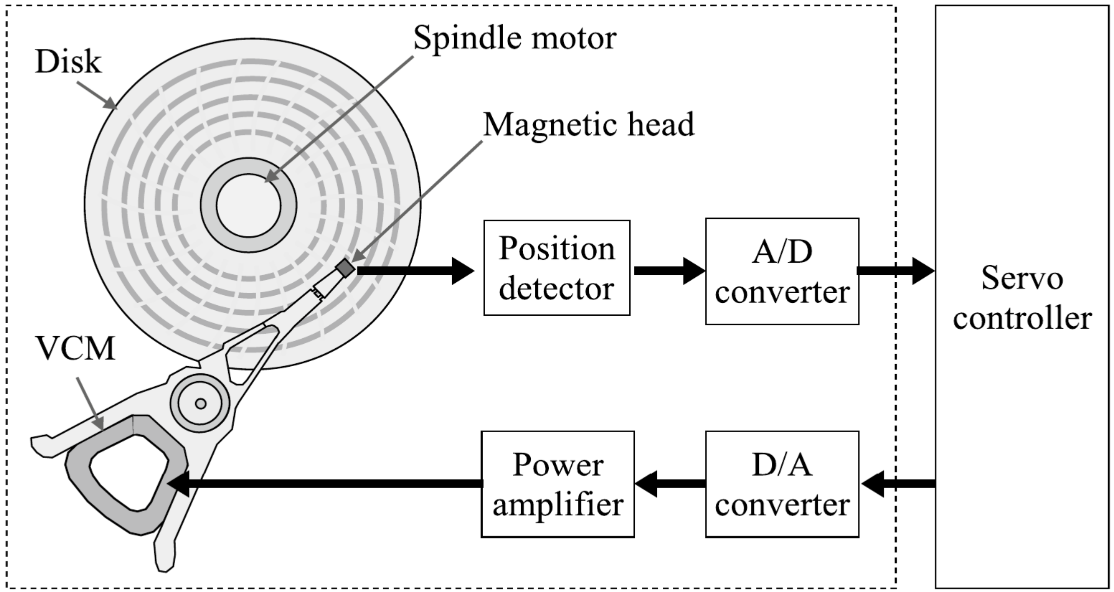
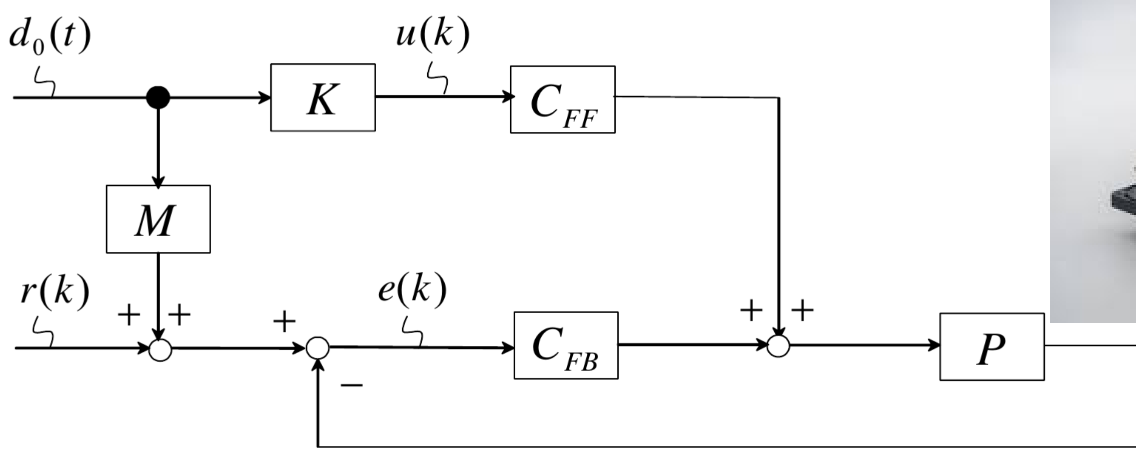
Disk Drive Control



Disk Drive System



Position Control

Source: Yabui 2016

Uses Adaptive Feedforward Control

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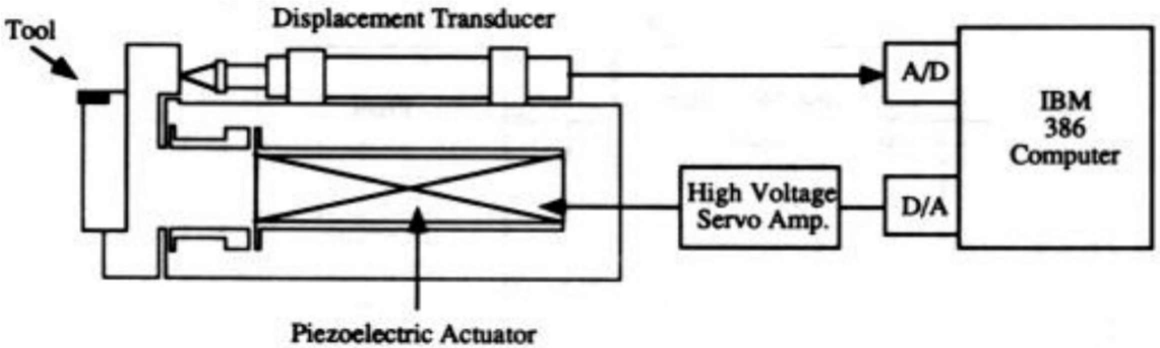
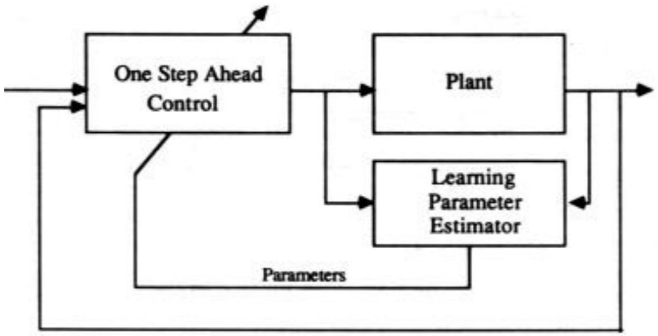
Iterative Learning Control



Diamond Cutting Lathe

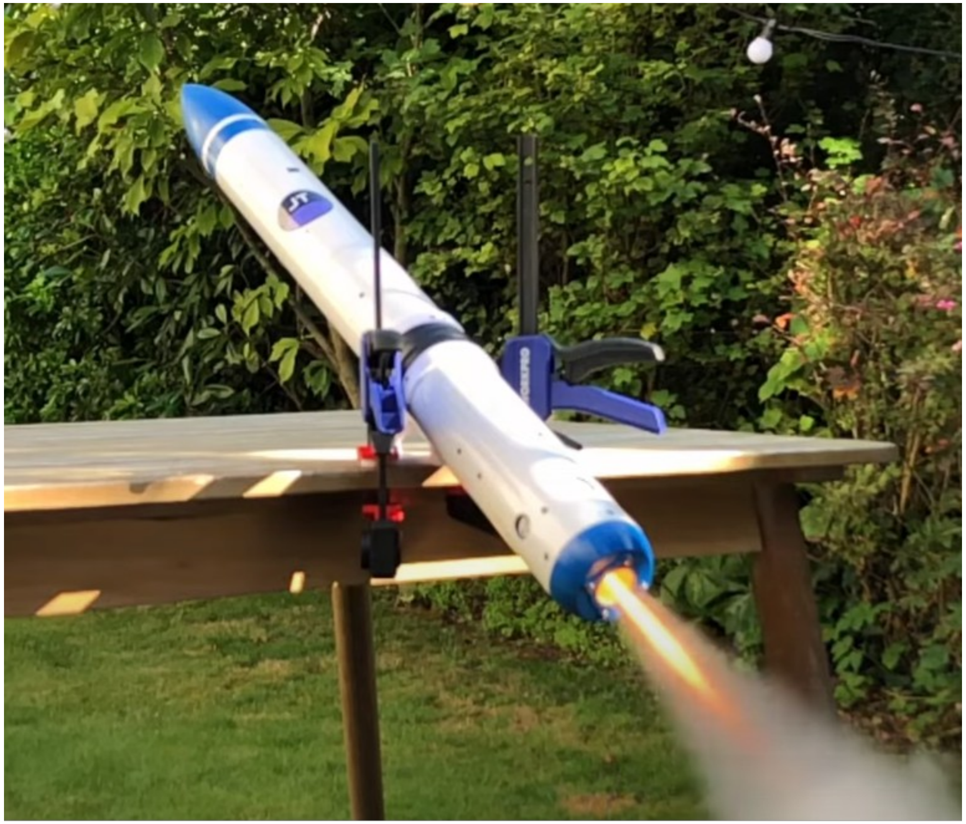


Learning Self-Tuning Regulator

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)

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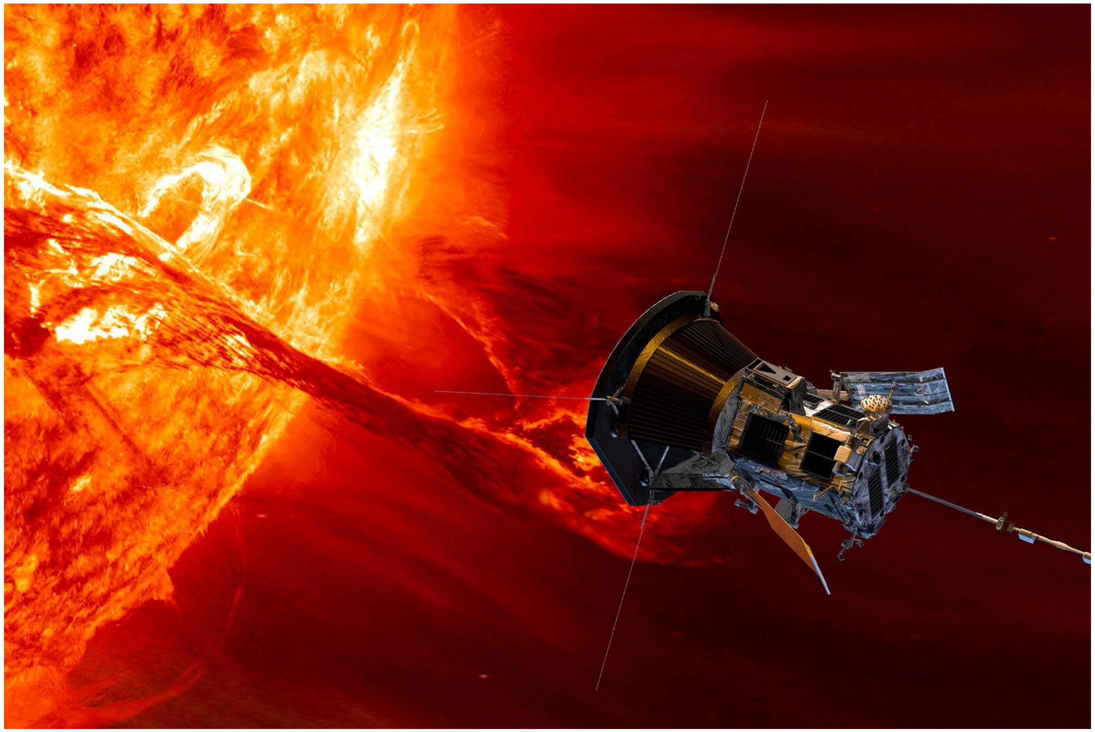
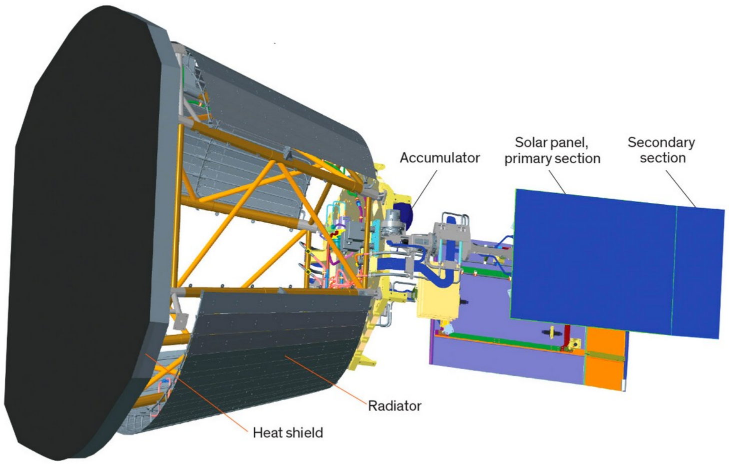
The Parker Solar Probe



Source: Johns Hopkins Applied Physics Department

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



Source: IEEE Spectrum

Source: Jacob Thornhill (Youtube)

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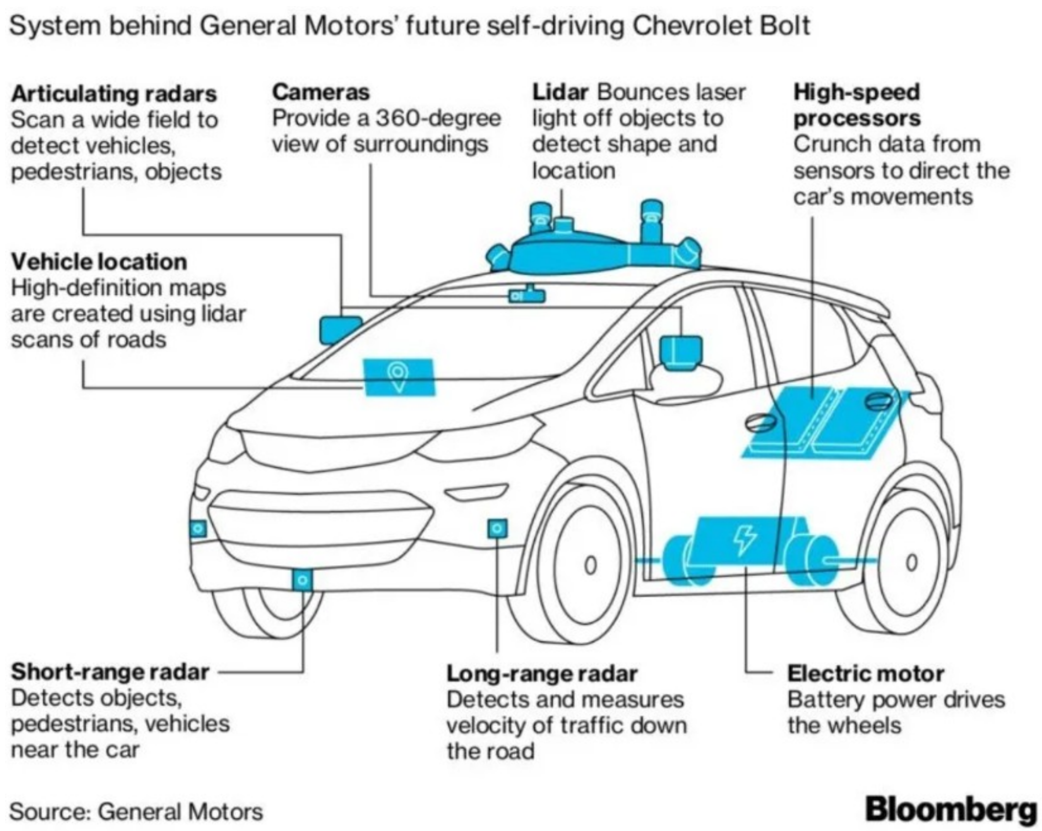
Autonomous Vehicle Sensors



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

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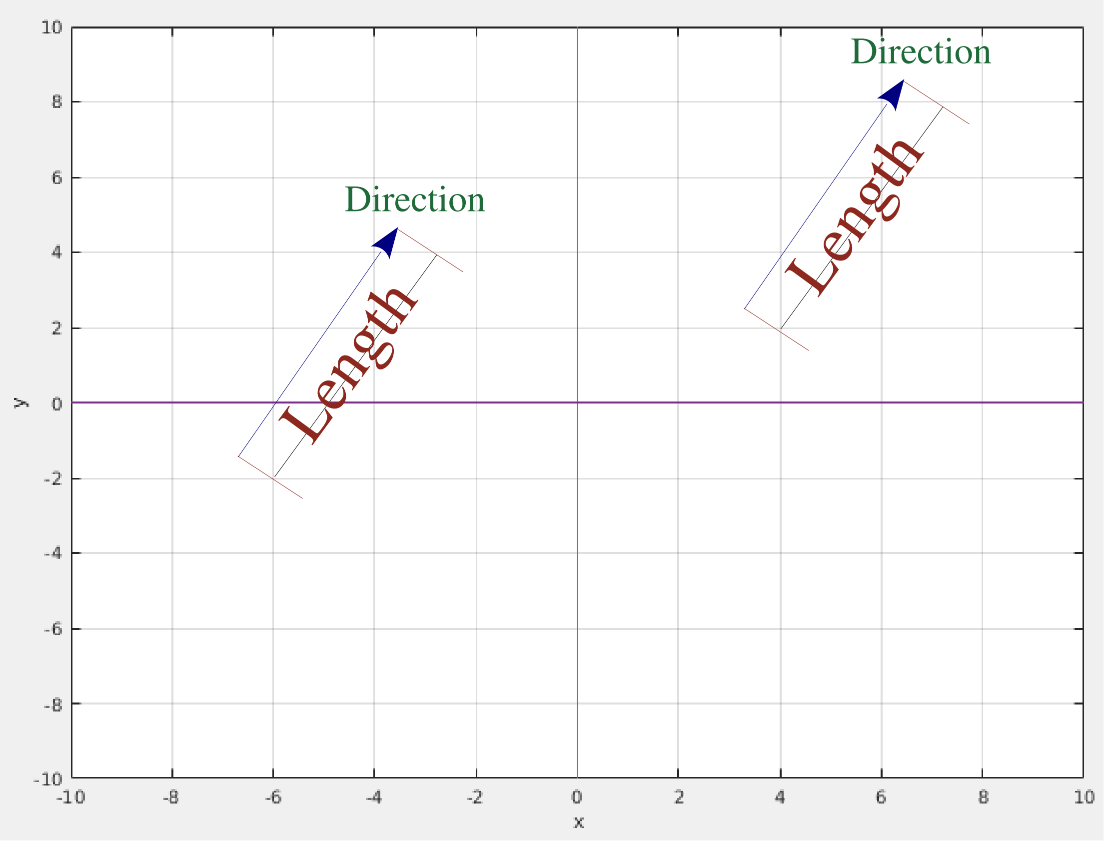
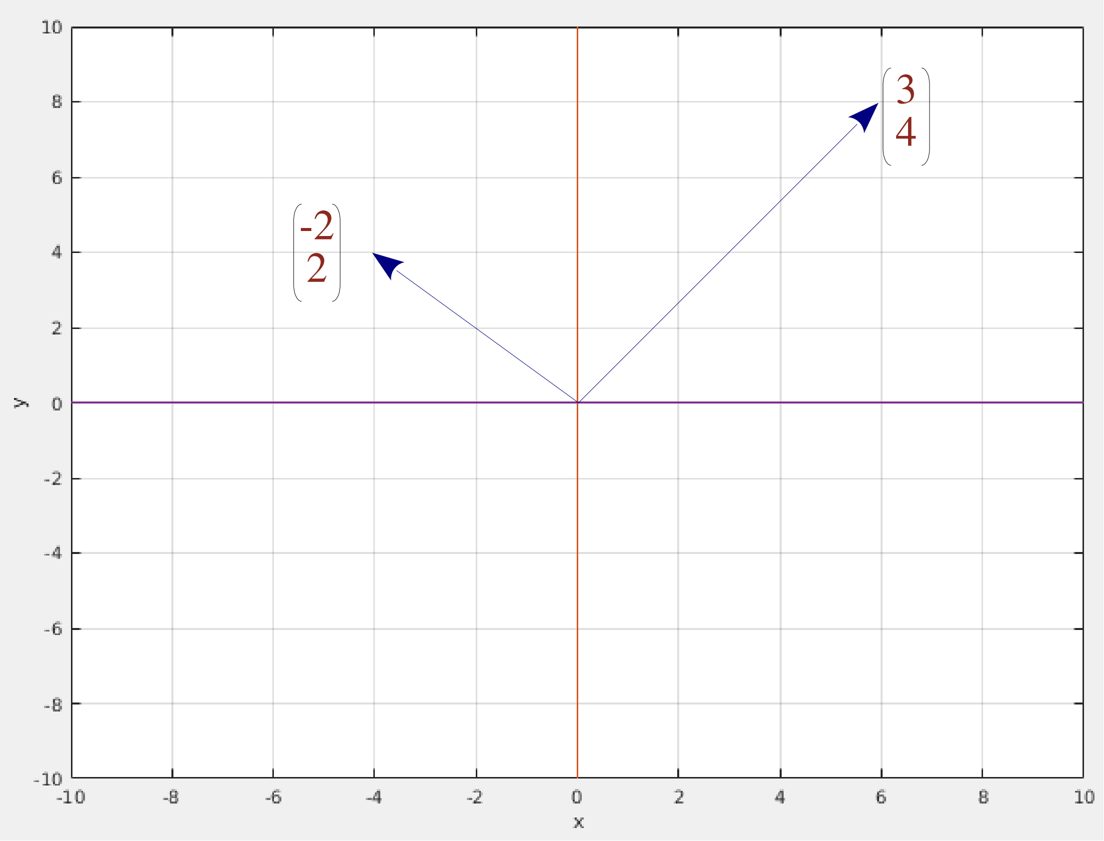
Vector



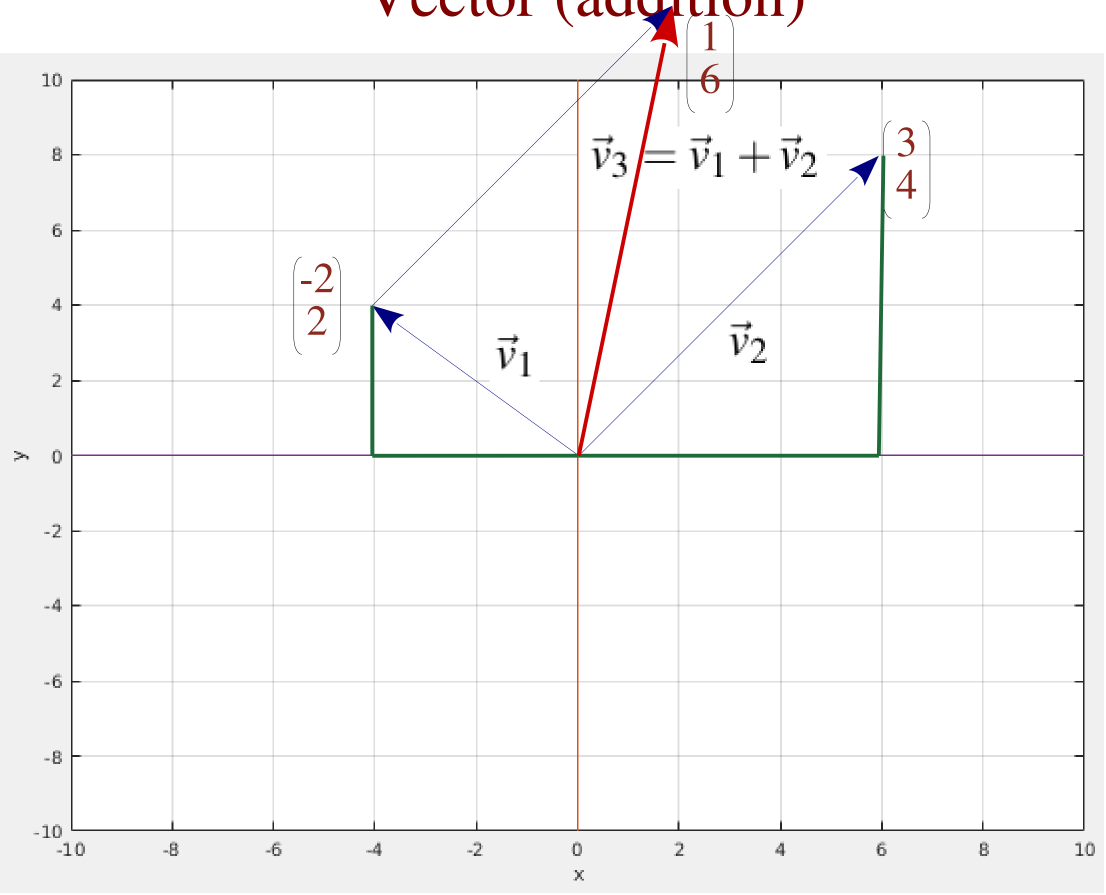
In Engineering and physics
the location does not matter

Vector

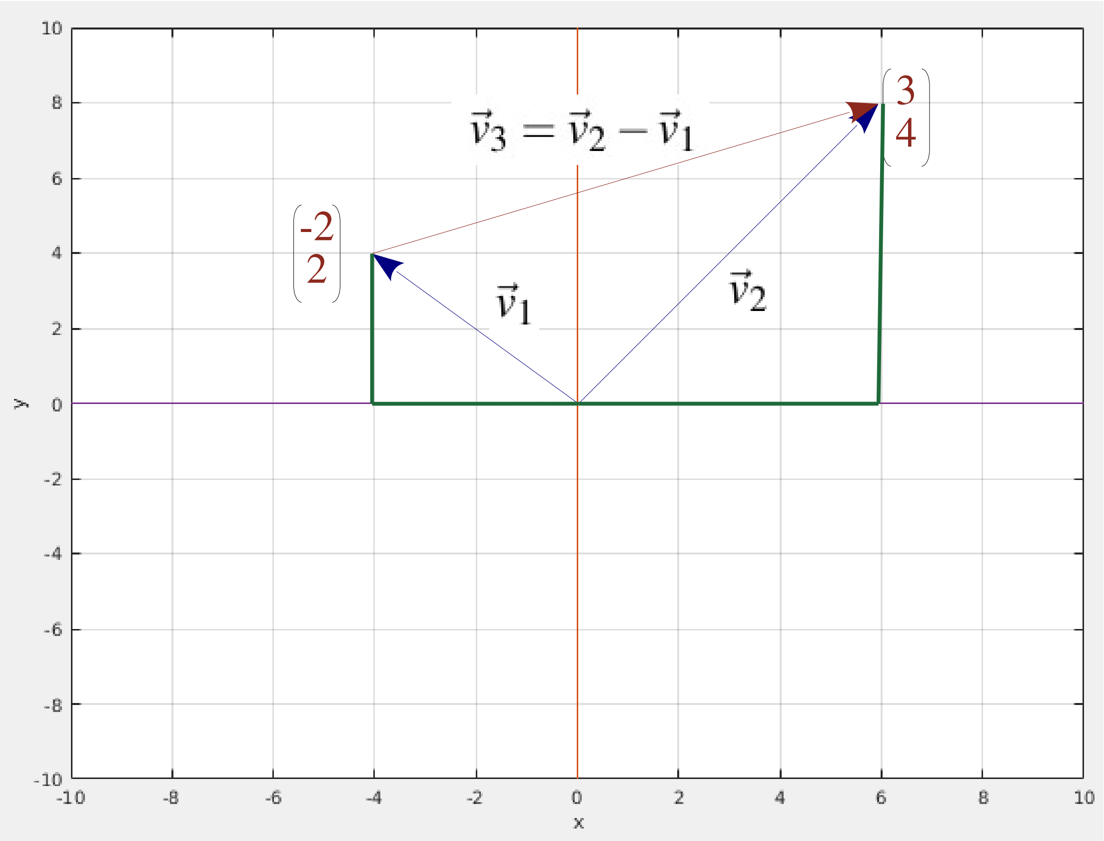


In Mathematics, we define a
vector about the origin

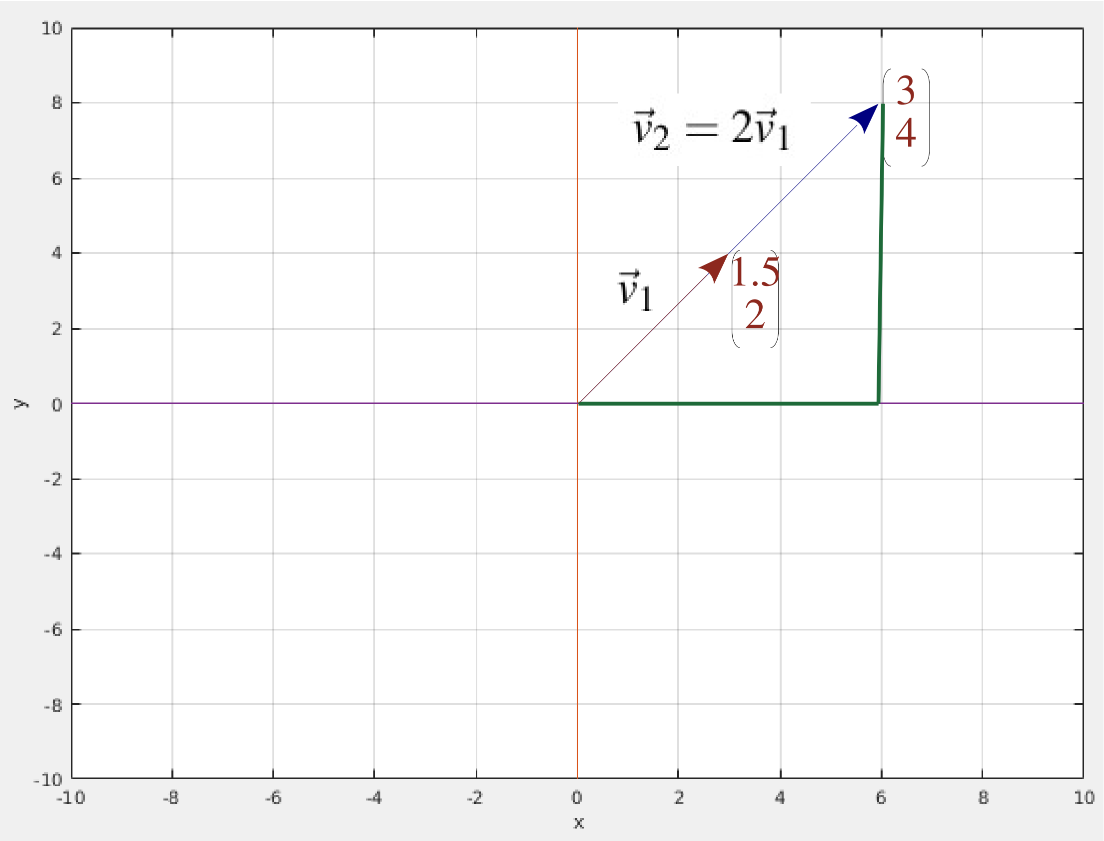
Vector (addition)



Vector (subtraction)



Vector (scaling)



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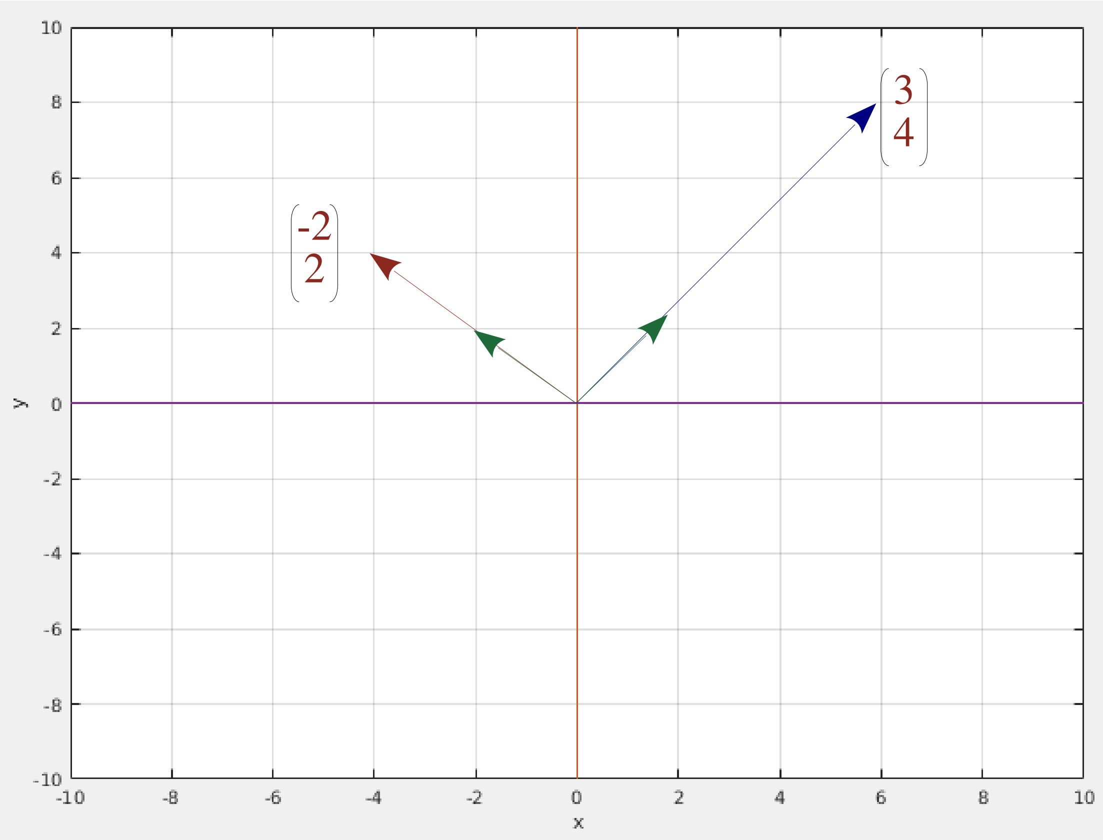
Vector (span of multiple vectors)

Take two 2-D vectors. The Span of two vectors is given by,

$$\vec{s} = \alpha \vec{v}_1 + \beta \vec{v}_2$$

If the two basis vectors are colinear, then only one dimension can be spanned. Otherwise, they will span the whole two-dimensional space. The scaling factors are used to allow access to any point on the spanned plane.



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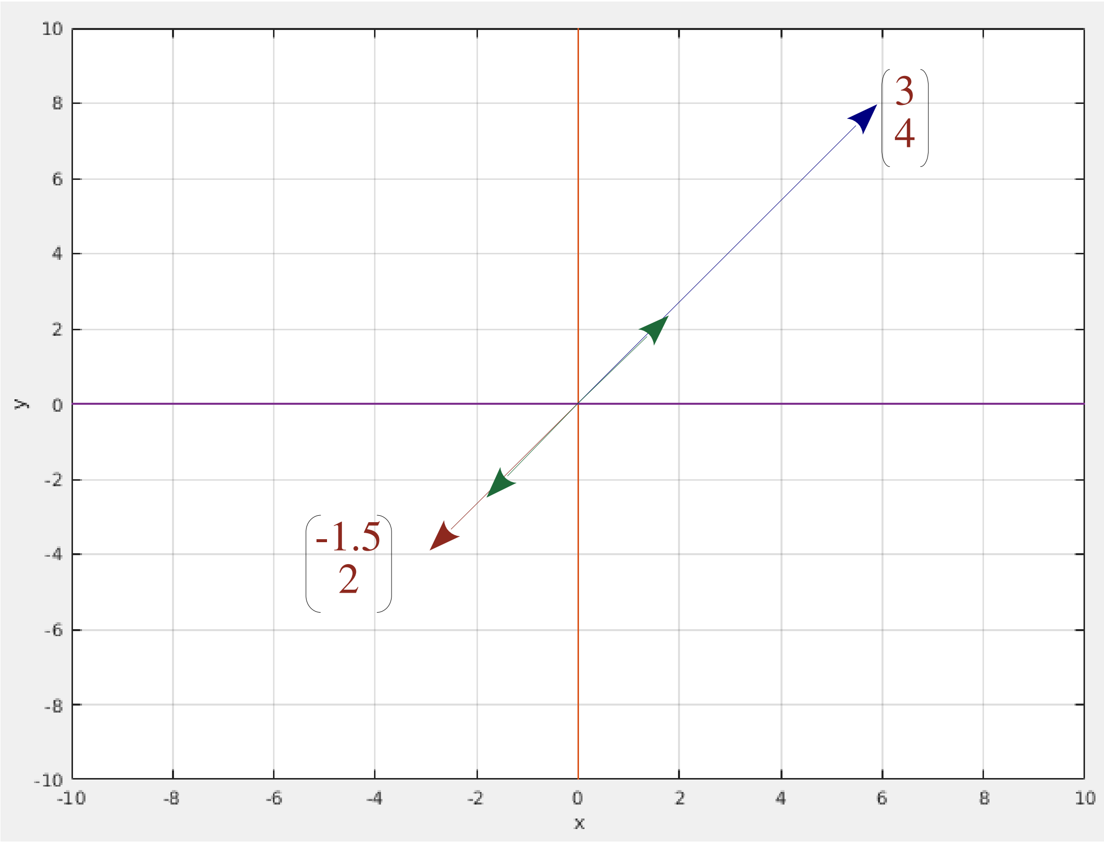

Identity Matrix

Definition 23.1 (Identity Matrix). *The N dimensional identity matrix is denoted by $\mathbf{I}_N$ (or sometimes $\mathbf{I}$) and is defined as follows,*

$\mathbf{I}_N : \mathscr{R}^N \mapsto \mathscr{R}^N$ *is the matrix such that*

$$\mathbf{I}_{ij} = \begin{cases} 1 & \forall \quad i = j \\ 0 & \forall \quad i \neq j \end{cases} \tag{23.1}$$

where $i, j \in \{1, 2, \ldots, N\}$ are the row number and column number of the corresponding element of matrix $\mathbf{I}_N$.

Matrix Transpose

Definition 23.2 (Transpose of a Matrix). *The transpose of a matrix* $\mathbf{A} : \mathscr{R}^N \mapsto \mathscr{R}^M$ *is given by* $\mathbf{A}^T : \mathscr{R}^M \mapsto \mathscr{R}^N$ *such that,*

$$\mathbf{A}^T_{ji} = \mathbf{A}_{ij} \tag{23.2}$$

where indices $i \in \{1, 2, \ldots, M\}$ *and* $j \in \{1, 2, \ldots, N\}$ *denote the location of elements of the matrix such that the first index corresponds to the row and the second index corresponds to the column number.*

Hermitian Transpose

Definition 23.3 (Hermitian Transpose). *The Hermitian transpose of a matrix* $\mathbf{A} : \mathscr{C}^N \mapsto \mathscr{C}^M$ *is given by* $\mathbf{A}^H : \mathscr{C}^M \mapsto \mathscr{C}^N$ *such that,*

$$\begin{aligned} \mathbf{A} &= \mathbf{A}_R + i\mathbf{A}_I \\ &\mathbf{A}_R, \mathbf{A}_I : \mathscr{R}^N \mapsto \mathscr{R}^M \end{aligned} \tag{23.3}$$

and

$$\mathbf{A}^H = \mathbf{A}_R^T - i\mathbf{A}_I^T \tag{23.4}$$

Matrix $\mathbf{A}^H$ *is also known as the adjoint matrix of matrix* $\mathbf{A}$.

Hermitian Matrix

Definition 23.4 (Hermitian Matrix). *A Hermitian matrix* $\mathbf{A} : \mathscr{C}^N \mapsto \mathscr{C}^N$ *is the matrix for which,*

$$\mathbf{A} = \mathbf{A}^H \tag{23.5}$$

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Inverse of a Square Matrix

Definition 23.5 (Inverse of a Square Matrix). *The Inverse of a Square Matrix* $\mathbf{A} : \mathscr{R}^N \mapsto \mathscr{R}^N$ *(if it exists) is denoted by* $\mathbf{A}^{-1} : \mathscr{R}^N \mapsto \mathscr{R}^N$ *and is that unique matrix such that,*

$$\mathbf{A}^{-1}\mathbf{A} = \mathbf{A}\mathbf{A}^{-1} = \mathbf{I}_N \tag{23.6}$$