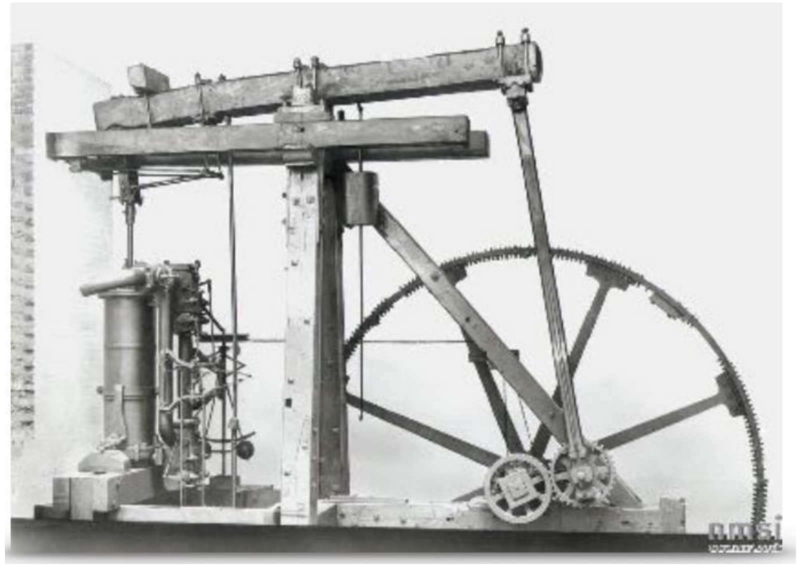
6.3100 Dynamical System Modeling and Control Design

Spring 2023 – Lecture 1

History of control

- Control engineering was first developed in the industrial revolution for controlling the steam engine (1788)



- “Centrifugal governor” controls the speed of the engine

History of control

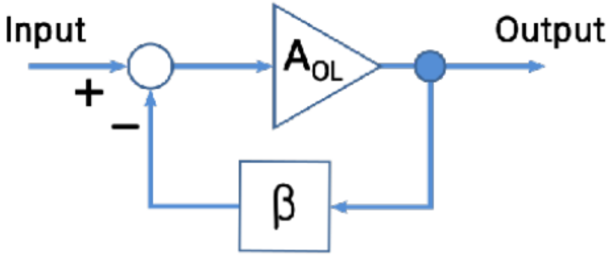
- Signals through telephone wires (1888)

Manhattan

Problem: signal attenuation / noise over a long distance

The Bell Telephone Company

Solution: feedback control



Engineering projects involving control

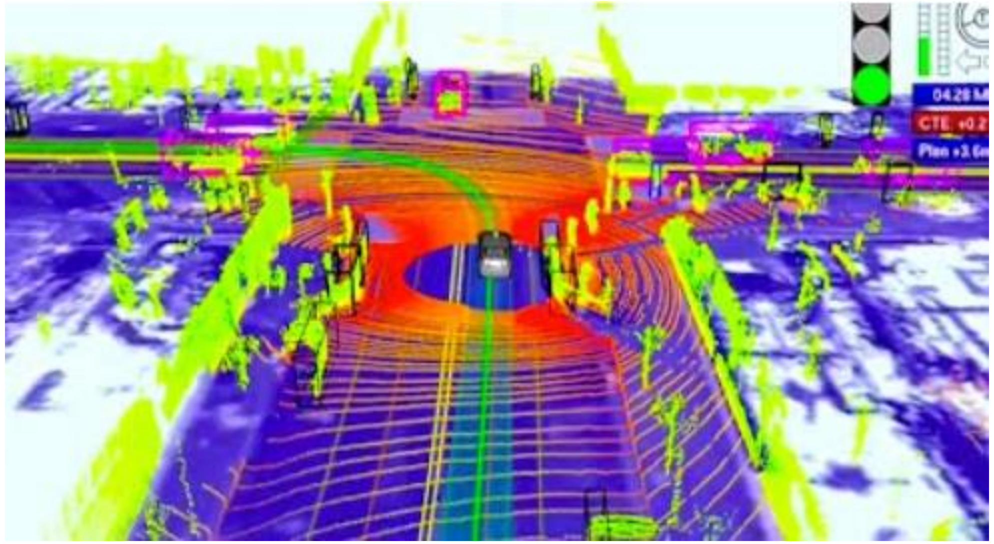
Perseverance Rover (2020)

Ingenuity (2020)

Engineering projects involving control

Self-driving car

Sensing and planning

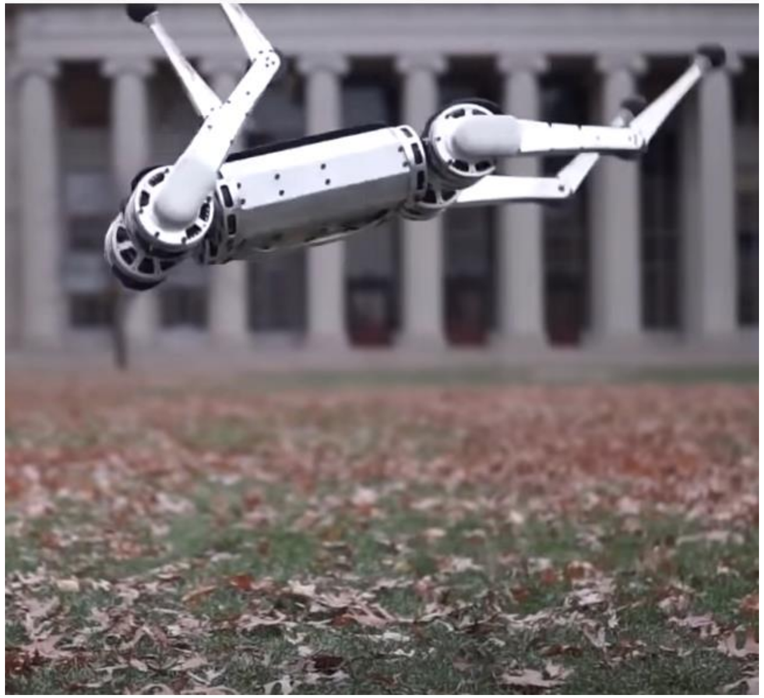


Control research at MIT

MIT Cheetah Mini

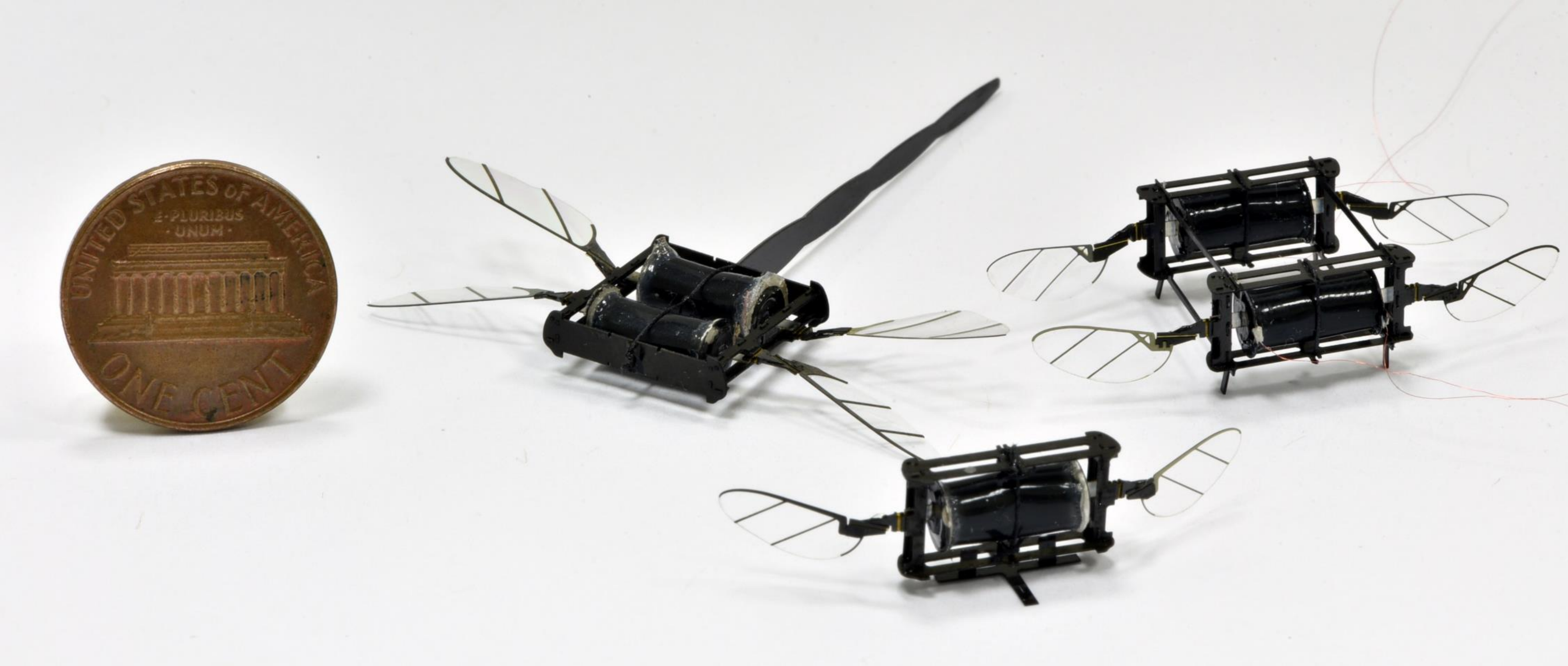
Collision recovery

Body flip



Control research at MIT

MIT SoftFly

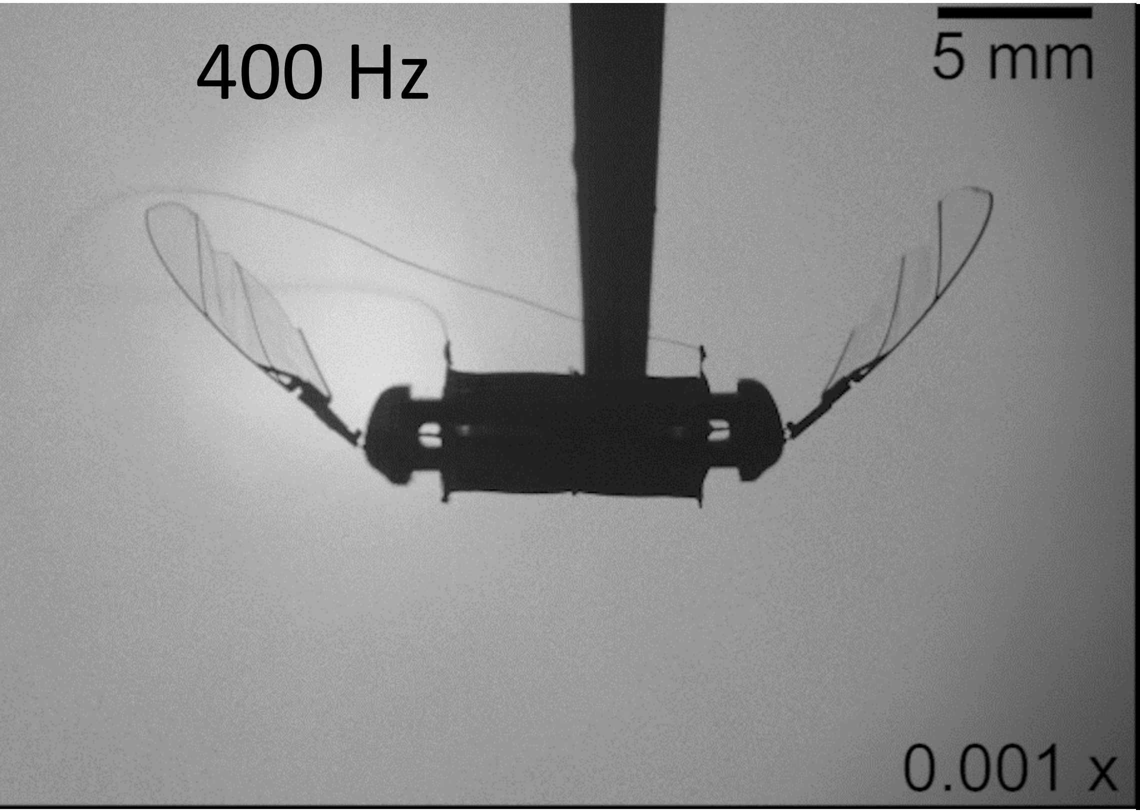


Control research at MIT

MIT SoftFly

High frequency actuation

400 Hz



Feedback controlled flight

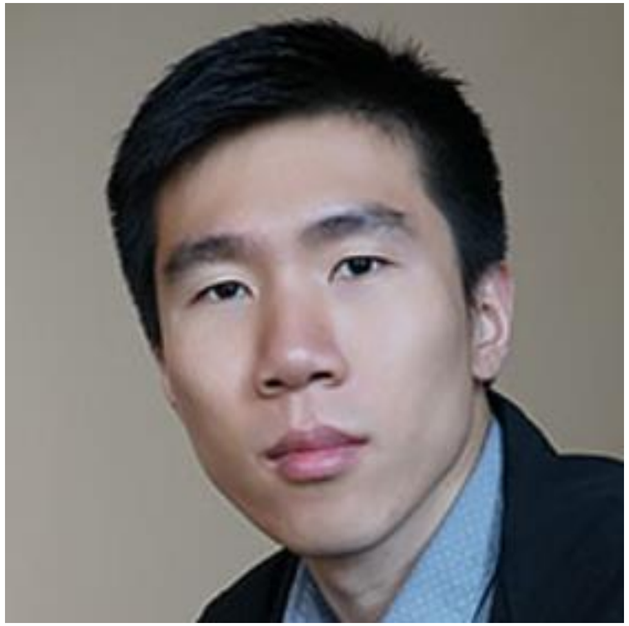
Course logistics

Lecture staff

Lecturers

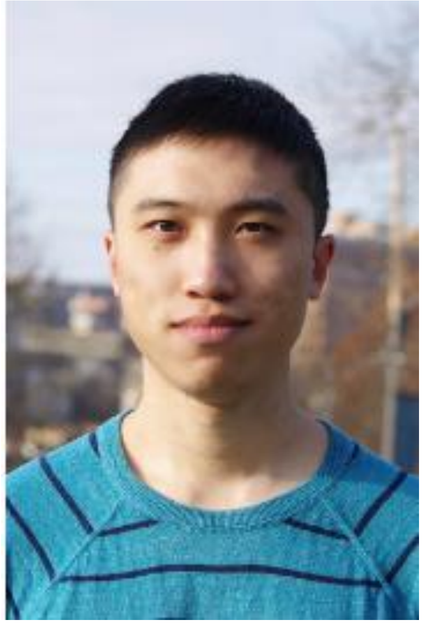
Prof. Dennis Freeman

Prof. Kevin Chen



Teaching assistants

Zhijian Ren



Nemo Hsiao

Course logistics

Meeting time

Lectures: MW 3:00 – 4:00 pm, 4-163

Labs: Friday 10 – 1pm or 2 – 5pm, 38-545

Office hours: all in 38-545 (starting next week)

Monday: 7-10 pm

Thursday: 7-10 pm

Sunday: 2-5 pm, 7-10 pm

Please sign up on piazza

Course logistics

https://introcontrol.mit.edu/spring23

Course content:

Part 1: classical control

- Discrete time (steady state error, stability)
- Continuous time (sinusoidal steady state)

Part 2: introduction to modern control

- State space representation
- Pole placement, LQR
- Observers

Pre-requisite:

18.03 or 18.06:

Differential equation,

Linear algebra,

Complex numbers

Course logistics

Course components:

6 labs (2 weeks per lab) 70%

- Based on in-person checkoffs
- Need to complete a lab before the next lab (Friday midnight)
- Must complete late labs in OH (except cases supported by S^3)

Written postlab problems 20% -- graded by the TAs

- Solution is posted immediately after the deadline
- Please contact the teaching staff for each late submission

Online prelab problems 10% -- no late penalty

February 6, 2023

6.3100 Lecture 1 Notes – Spring 2023

Introduction to control, first-order discrete time system

Dennis Freeman and Kevin Chen

Outline:

1. Feedforward and feedback control
2. Discrete time and continuous time control
3. Block-diagram and key control questions
4. First order system and proportional control

1. Feedforward and feedback control

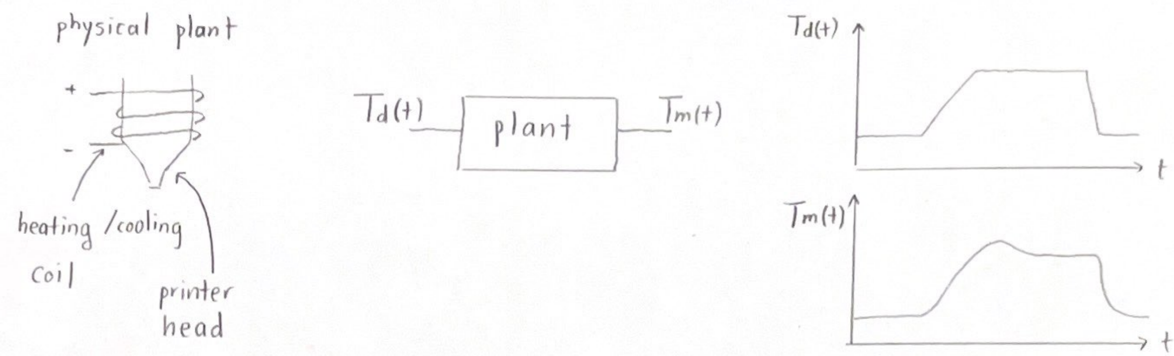
We classify control designs into two broad classes: feedforward and feedback control. Feedforward control corresponds to systems where the control action is not dependent on sensor information. For example, kicking a soccer ball is an example of feedforward control. As soon as the soccer ball is kicked, we can no longer influence the ball's trajectory. In control systems, simple systems can be controlled "open loop" or "feed forwardly". For example, sometimes (not always) a quadrotor does flips without needing sensor information. That's because the motion is too quick and the sensor update is too slow. The controller turns on full thrust in 2 propellors and turns off the other two. The control signal is based on prior simulation results or human designs, and it does not depend on sensor information.

In this class, we will mostly focus on feedback control. It means the control action we take depends on real-time sensor feedback. Most complex systems involve feedback control. For example, driving a car requires us to observe our surroundings and estimate the car's location and speed. Flying a drone requires estimation of drone position, attitude, and altitude. A core question of feedback control design is given sensor information, how do we determine the control action? We will learn many feedback control methods throughout the course.

2. Discrete time and continuous time control

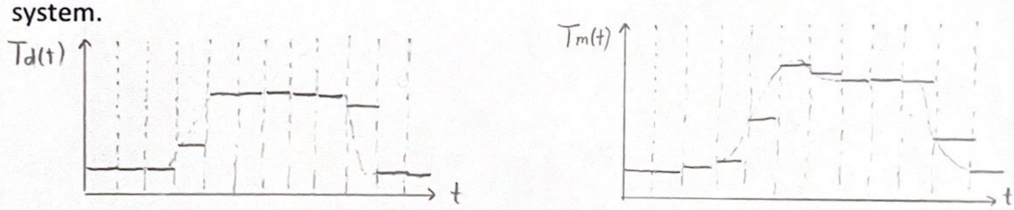
In the first half of this course, we will study both discrete time (DT) and continuous time (CT) control. Both are important in modern control systems.

Continuous time (CT) control: Most physical systems are governed by the Newton Second law, which is in continuous time and described by differential equations. We use an example of 3D-printing to illustrate this idea. In this example, we want to control the temperature of the 3D-printer nozzle. When the temperature is high, the material melts and when the temperature is low, printing stops. Consider the simplest block diagram below. The "system" block can be seen as a black box, as it includes the printing head, the controller, and the sensors. For a user, we have some desired temperature profile to achieve, and we can measure the output temperature at the printing head. This system has input Td(t) and output Tm(t).

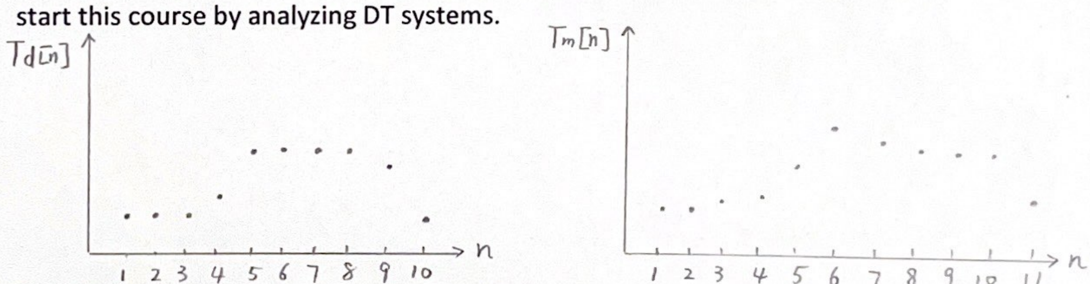


Note that the reference signal and the measured output signals are both functions of time, which is a continuous variable. This type of problem is called continuous time (CT) control problem. We need to solve differential equations, which we will learn starting in the 5th week of class.

Most physical systems are controlled by micro-controllers, which sample and command the system at a fixed rate (kHz to GHz). Due to this discretization, input and output signals become "step-wise constant", as shown below. This type of discrete time (DT) system approximates a CT system.

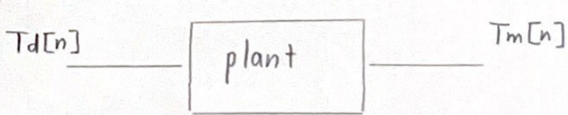


For the ease of analysis, we can change the continuous time variable "t" to a discrete index "n". The system equation will change from "differential equation" to "difference equation". We will start this course by analyzing DT systems.



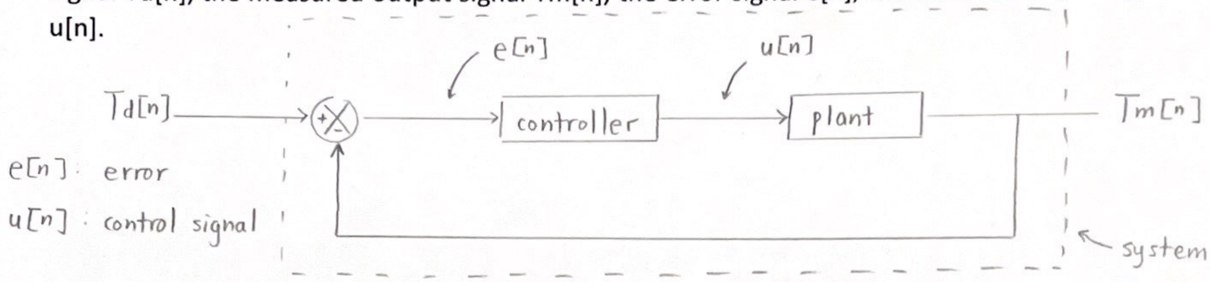
3. Block-diagram and key control questions

An important tool in analyzing control is to use the block diagram. It consists of blocks and connecting paths, which illustrate the control logic. First, let's draw the simplest open-loop control diagram:



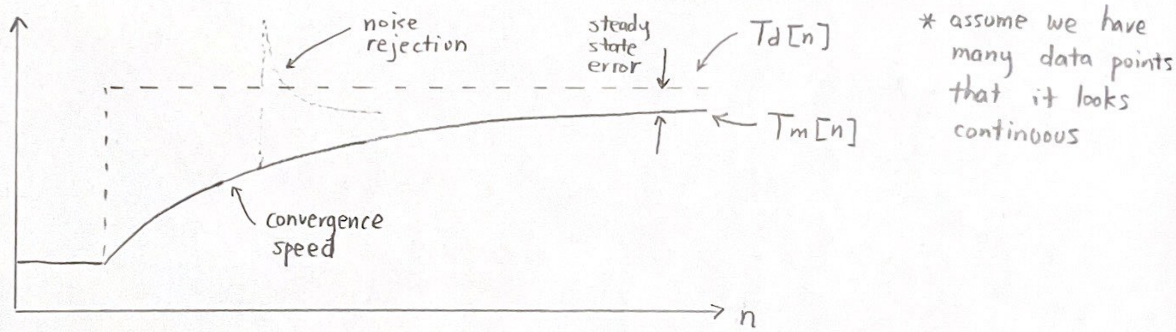
This is an open-loop system because the input goes into the plant (robot, car, etc) and we measure the output, but the output is not used to update our control.

Now let's draw a closed-loop control diagram. There are many components here: the reference signal Td[n], the measured output signal Tm[n], the error signal e[n], the controller input signal u[n].



This diagram is very important, and we will spend a lot of time studying it. In most cases, we will design the controller block with the goal of making the output similar to (or equal to) the desired input. We will always ask a few key questions when designing a controller:

1. Stability: Will the control input be finite?
2. What is the steady-state error? $\lim_{n\to\infty} |T_m[n] - T_d[n]|$
3. Convergence rate: How fast does $T_m[n]$ approach $T_d[n]$?
4. Noise rejection: How well does the controller deal with unexpected disturbance?



We will investigate these problems many times in this course.

4. <u>First order system and proportional control</u>

When we discuss first order system, we mean the equation describing the "system", which is the sum of plant and controller, is first order. Let's again consider the 3D-printing example. The equation that describes the heating nozzle is

$$\frac{dT_m(t)}{dt} = \gamma u(t)$$

This is a continuous time, first order differential equation. It means the rate of change of temperature is proportional to the input control signal. Since we are using a microcontroller, we need to discretize the equation:

$$\frac{T_m[n] - T_m[n-1]}{\Delta T} = \gamma u[n-1]$$

This equation only involves the indices n and n-1, and it is called a first order difference equation.

In most cases, we cannot modify the plant, but we can design the controller. So the design question we have is how to set $u[n]$. A simple type of controller is called proportional control, which simply states that

$$u[n] = K_p e[n] = K_p(T_d[n] - T_m[n])$$

The basic idea is that we find an operating point. Around that operating point, our input is proportional to the error. If there is a non-zero error, then hopefully our control input causes the system to correct the error. If the error is 0, then our corrective input is also 0. Hopefully the system stays around the equilibrium operating point. We will investigate how to choose the gain parameter K_p next lecture.