Course Introduction

EPD 30.114 ADVANCED FEEDBACK & CONTROL

Advanced Feedback & Control

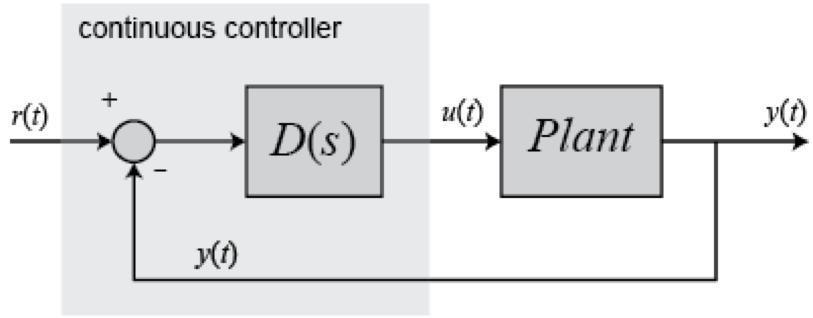
- Analysis and understanding of **multi-state dynamic systems** with possibly **unknown or unobservable states** with the goal of stabilizing and/or improving performance using **modern digital controllers** and components.
  - Majority of controllers are implemented using digital systems today.

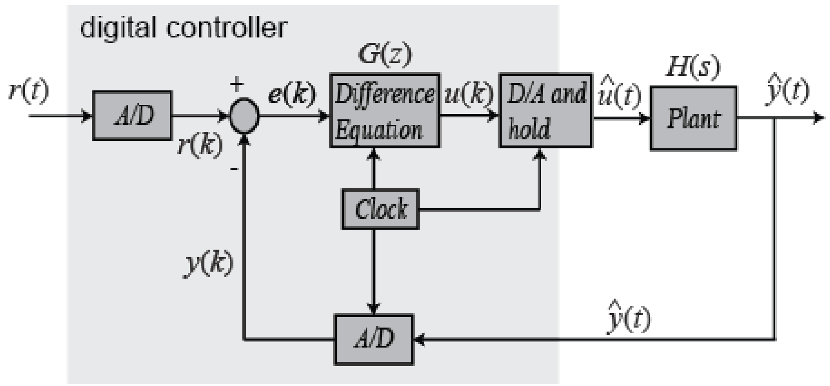
<u>What you learnt in 30.101</u>

- All states are known and can be 'observed'
- Focused on SISO (Transfer Functions)
- Analog/Continuous-time Systems
- Systems described by **differential** equations

<u>Extending your knowledge in 30.114</u>

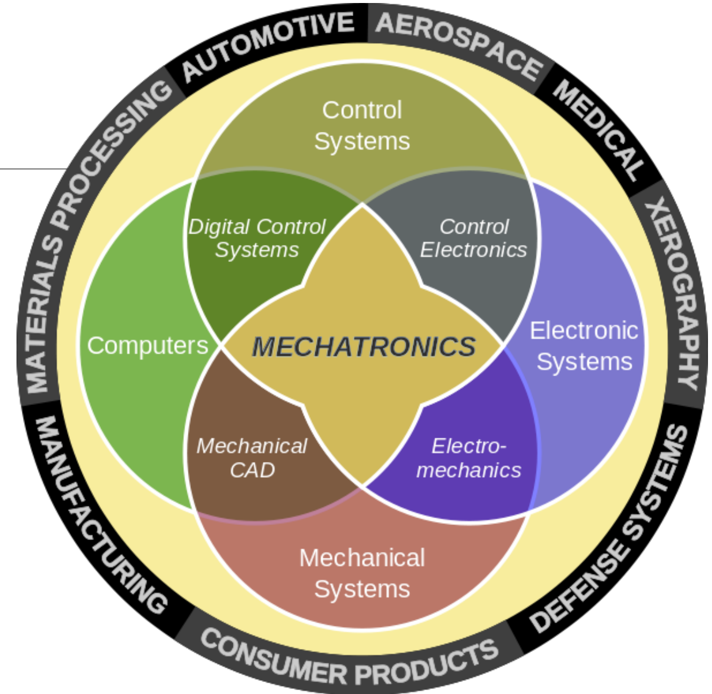
- Not all states are known or 'observed'
- Extension to MIMO (State-Space)
- Optimal controllers
- Digital/Discrete-time Systems
- Systems described by **difference** equations





Class Context

Control Theory
- Classical (SISO)
- Modern (MIMO)



Control Strategies & Approaches
- **Linear Systems**
- Non-linear Systems

- **Digital/Discrete-Time Control**
- Adaptive Control
- Robust Control
- Optimal Control
- Stochastic Control
- **Intelligent Control**
- Distributed Control

Course Information

- Extending control theory and applications to include periodic signals and discrete-time systems. Mathematical modelling and analysis of discrete time systems in various disciplines using state-space, pulse transfer function and z-transform. Relating controllability and observability and their canonical forms to synthesize and design advanced continuous and discrete-time controllers. Introduction of pole-placement based controller design and formulation of state observers.
- Class structure **(DSIS 2.313/2.314)**
  - Monday (2.5 hr): Active Learning + Design Experience (1D/3D)
  - Tuesday (2.5 hr): Active Learning + Design Experience (1D/3D)

All handouts and supplements will be available on eDimension.

All assignments (homework, labs) will be submitted electronically via eDimension.

- Software integration
  - **MATLAB** and Control System Toolbox
  - **LabVIEW** and Control Design Toolkit plus Quanser QNETs
  - **C Programming** and Ubuntu (Virtual Machine)

Applications

Raffaello D'Andrea (2016): Meet the dazzling flying machines of the future
https://www.ted.com/talks/raffaello_d_andrea_meet_the_dazzling_flying_machines_of_the_future

Design & Control Research @ SUTD

- Nature-Inspired Aerial Crafts
  - Derived from Maple Seed (Singapore: Angsana Seed) – Nature's Helicopters
    - Mechanically simple, robust and energy efficient platforms for achieving sustained flight
    - Capable of VTOL operations but operate on the same efficient principles of fixed wing flight
    - Inherently stable due to rotary dynamics
    - Motor failure is not catastrophic as it can perform autorotation
    - Realized using rapid digital fabrication

Dual Wing Transformable Prototype

J. E. Low, L. S. T. Win, C. H. Tan, D. S. B. Shaiful, G. S. Soh, S. Foong, "Design and Dynamic Analysis of a Transformable HOvering Rotorcraft (THOR)", 2017 IEEE International Conference on Robotics and Automation (ICRA), Singapore, 2017, pp. 6389-6396. doi: 10.1109/ICRA.2017.7989755

Controlled Autorotation

S. K. H. Win, T. H. Goh, J. E. Low, D. S. B. Shaiful, L. T. S. Win, G. S. Soh and S. Foong, "Direction Controlled Descent of Samara Autorotating Wings (SAW) with n-Wings," 2018 IEEE International Conference on Robotics and Automation (ICRA), Brisbane, QLD, 2018, pp. 6553-6559. doi: 10.1109/ICRA.2018.8463145

Advanced Controllers via Learning

D. S. B. Shaiful, L. T. S. Win, S. K. H. Win, G. S. Soh and S. Foong, "A Reinforcement Learning Approach for Control of a Nature-Inspired Aerial Vehicle," To be presented at *2019 IEEE International Conference on Robotics and Automation (ICRA)*, Montreal, Canada, 2019.

Course Map

LINEAR SYSTEMS THEORY & STATE SPACE APPROACH

- Vector-Matrix Algebra
- State Space Method
- Canonical Forms
- Linear Transformation
- State Non-uniqueness
- Solving LTI State-Space Systems
- State Transition Matrix
- Eigenvalues & Eigenvectors

ADVANCED CONTROL SYSTEMS DESIGN IN <u>CONTINOUS-TIME DOMAIN</u>

- Laplace Transform (Differential Equations)
- Controllability
- Observability
- State Observers & Reduced Order Observers
- Pole Placement & State Feedback
- Servoing and Integral Control
- LQR Controller
- Estimation + Kalman Filter
- Intelligent Control

ADVANCED CONTROL SYSTEMS DESIGN IN <u>DISCRETE-TIME DOMAIN</u>

- Quantization & Digital Systems
- z – Transform (Difference Equations)
- Pulse Transfer Function & its Matrix
- Mapping between z-plane and s-plane
- Discretization of Continuous-time Systems
- Controllability & Observability
- Pole Placement and Observer Design

CONTROL DESIGN APPLICATIONS

Advanced Vehicular Suspension

Launch & Recovery of Rockets

Micro-UAV Swarming

1-D **DESIGN** Experience (State Space Control for Magnetic Suspension, Digital Control of Inverted Pendulum)

3-D Immersive **DESIGN** Experience (State-Space Modelling, Control Design and Scenario Implementation on Mini-UAV)

Projected Detailed Schedule (Subject to Change)

LESSON	TOPIC	VENUE	LESSON	TOPIC	VENUE
1 11 Sep 23	Course Introduction & Map Controls Recap State-Space Method Canonical Forms	DSIS 2.313	**13** 30 Oct 23	Discrete-Time & Digital Systems z Transform Inverse z Transform	DSIS 2.313
2 12 Sep 23	Canonical Forms Vector-Matrix Algebra	DSIS 2.313	**14** 31 Oct 23	Inverse z Transform Solving Difference Equations	DSIS 2.313
3 18 Sep 23	Solution of Homogenous State Equations Computing Matrix Exponentials	DSIS 2.313	**15** 6 Nov 23	Mapping Between s & z Planes Stability in z Plane Impulse Sampling & Data Hold	DSIS 2.313
4 19 Sep 23	Computing Matrix Exponentials Solution of Nonhomogenous State Equations	DSIS 2.313	**16** 7 Nov 23	Pulse Transfer Function Discrete-Time Control System Design	DSIS 2.313
5 25 Sep 23	Controllability & Observability Pole-Placement Controller Design	DSIS 2.313	**-** 13 Nov 23	Deepavali	
6 26 Sep 23	Pole-Placement Controller Design State-Space System Stability	DSIS 2.313	**17** 14 Nov 23	State-Space in the Discrete Domain Solving Discrete State Equations	DSIS 2.313
7 2 Oct 23	Servo Systems & Integral Control State Observers	DSIS 2.313	**18** 20 Nov 23	Controllability & Observability in Discrete Systems Discrete-Time Pole Placement State Observers for Discrete Systems	DSIS 2.313
8 3 Oct 23	State Observers Observed State Feedback Control	DSIS 2.313	**19** 21 Nov 23	Discretization of Continuous-Time State Equations Estimation, Kalman Filter	DSIS 2.313
9 9 Oct 23	Linear Quadratic Regulator	DSIS 2.313	**20** 27 Nov 23	*Controller Design Experience #2A* (3D) Digital Control of Inverted Pendulum	DSIS 2.313
10 10 Oct 23	Reduced-Order Observers	DSIS 2.313	**21** 28 Nov 23	Kalman Filter Intelligent Control	DSIS 2.313
11 16 Oct 23	*Controller Design Experience #1* (1D) Intermediary MATLAB for Control System Design [Magnetic Suspension]	DSIS 2.313	**22** 4 Dec 23	*Controller Design Experience #2B* (3D) Control of Multirotor UAV	DSIS 2.313
12 17 Oct 23	*Controller Design Experience #1* (1D) Intermediary MATLAB for Control System Design [Magnetic Suspension]	DSIS 2.313	**23** 5 Dec 23	*Controller Design Experience #2B* (3D) Control of Multirotor UAV	DSIS 2.313
Mid-Term 18 Oct 23	**Mid-Term (Wednesday)** **2:30 pm – 4:30 pm**	TBC	**Finals** 15 Dec 23	**Finals (Friday)** **1:00 pm – 3:00 pm**	TBC

Grading Policy

- Finals (15 December 2023, Friday, 2 hours) - **25%**
- Mid-term (18 October 2023, Wednesday, 2 hours) - **25%**
- 1D / 3D Design Experience Projects - **23%**
- In-class Assignments & Homework - **17%**
- Instructor Prerogative - **10%**

Late submissions will be penalized

Course Team

- Instructor:
  - Associate Professor **Foong Shaohui**, foongshaohui@sutd.edu.sg
    https://t.me/SUTD_controls
- Graduate TA:
  - PhD Student **Cai Xinyu**, xinyu_cai@mymail.sutd.edu.sg
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Join Course Telegram Group

https://t.me/+pJpdG7Bsi6ZiYjUx