GRASP Laboratory
General Robotics & Autonomous Systems and Processes

Mechatronic Modeling and Design with Applications in Robotics

Course Outline and Introduction

Instructor

Course Website:

http://grasplab.ca/modeling.html

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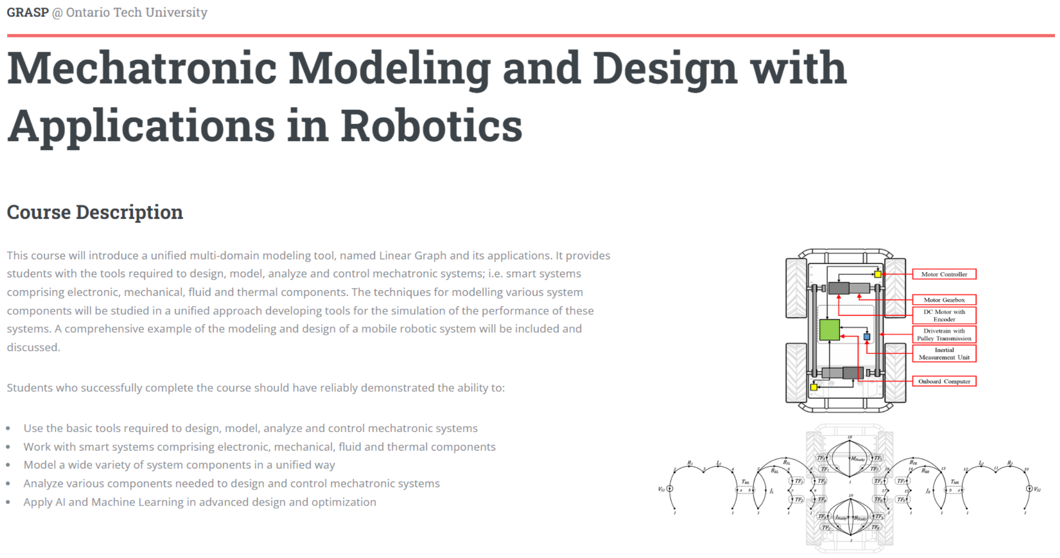


GRASP @ Ontario Tech University

Mechatronic Modeling and Design with Applications in Robotics

Course Description

This course will introduce a unified multi-domain modeling tool, named Linear Graph and its applications. It provides students with the tools required to design, model, analyze and control mechatronic systems; i.e. smart systems comprising electronic, mechanical, fluid and thermal components. The techniques for modelling various system components will be studied in a unified approach developing tools for the simulation of the performance of these systems. A comprehensive example of the modeling and design of a mobile robotic system will be included and discussed.

Students who successfully complete the course should have reliably demonstrated the ability to:

- Use the basic tools required to design, model, analyze and control mechatronic systems
- Work with smart systems comprising electronic, mechanical, fluid and thermal components
- Model a wide variety of system components in a unified way
- Analyze various components needed to design and control mechatronic systems
- Apply AI and Machine Learning in advanced design and optimization

A snapshot of the course website

Director of the GRASP Lab @ OntarioTech

Design, development and application of advanced technologies for autonomous systems and processes

- Mechatronics
- Robotics
- Machine vision
- Advanced Control
- Artificial intelligence

GRASP Laboratory
General Robotics & Autonomous Systems and Processes

OntarioTech UNIVERSITY

Selected Projects in GRASP Lab

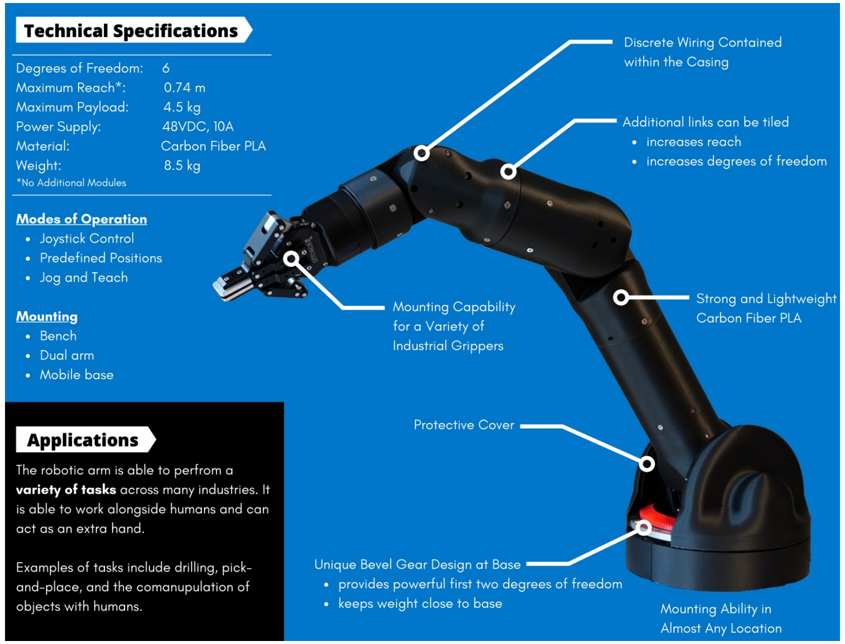
Real-time object identification and segmentation

Object tracking and post estimation

3D scanning and mapping

Autonomous Navigation

Vision-based Motion Control



Technical Specifications

Degrees of Freedom:	6
Maximum Reach*:	0.74 m
Maximum Payload:	4.5 kg
Power Supply:	48VDC, 10A
Material:	Carbon Fiber PLA
Weight:	8.5 kg

*No Additional Modules

Modes of Operation

- Joystick Control
- Predefined Positions
- Jog and Teach

Mounting

- Bench
- Dual arm
- Mobile base

Applications

The robotic arm is able to perfrom a **variety of tasks** across many industries. It is able to work alongside humans and can act as an extra hand.

Examples of tasks include drilling, pick-and-place, and the comanupulation of objects with humans.

Discrete Wiring Contained within the Casing

Additional links can be tiled
- increases reach
- increases degrees of freedom

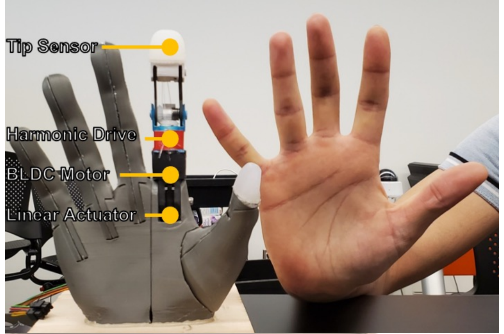
Mounting Capability for a Variety of Industrial Grippers

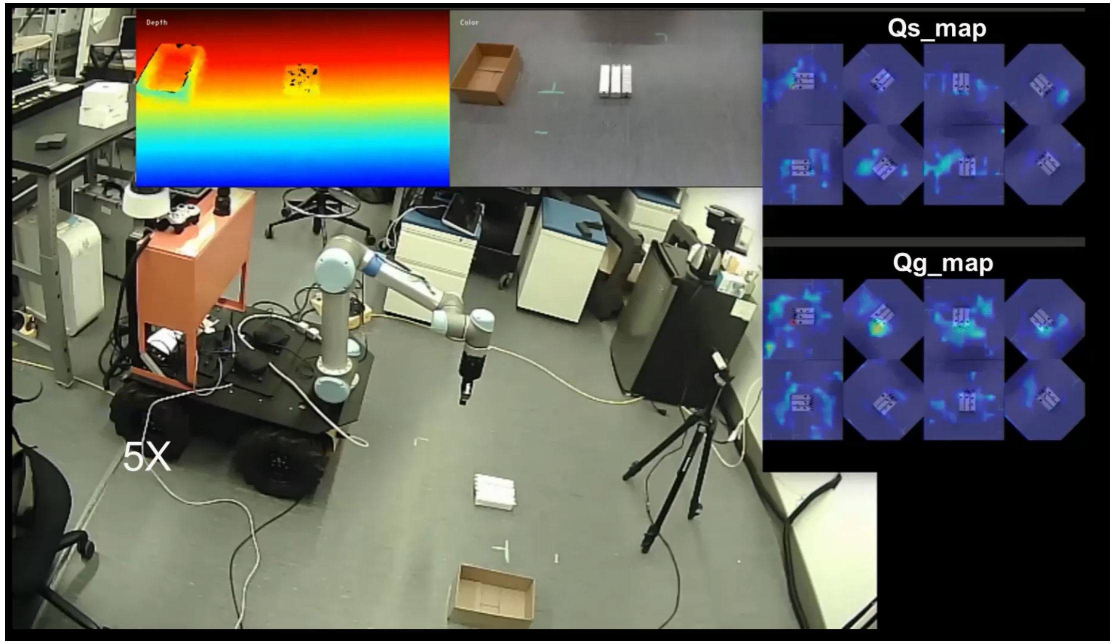
Strong and Lightweight Carbon Fiber PLA

Protective Cover

Unique Bevel Gear Design at Base
- provides powerful first two degrees of freedom
- keeps weight close to base

Mounting Ability in Almost Any Location





Course Outline

- Course Overview and Introduction
- Introduction to Modeling
- Basic Model Elements
- Analytical Modeling
- Graphical Models
- Linear Graph
- Linear Graph Examples
- Frequency Domain Models
- Transfer-Function Linear Graph
- Examples in Applications

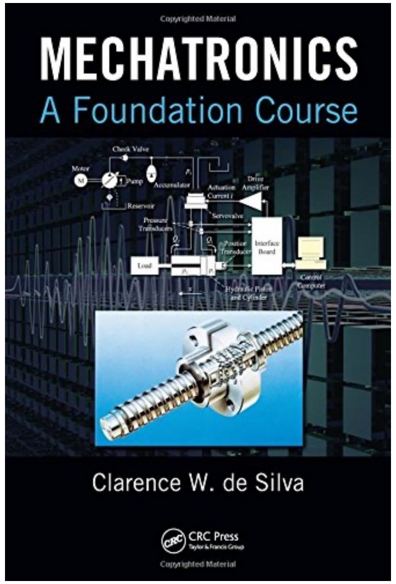
dot o → line

Learning Outcomes

- Understand the formal meanings of a dynamic system of multi-physics systems (e.g., mechatronic systems).
- Recognize different types of models (e.g., physical, analytical, computer, experimental) and their importance, usage, comparative advantages and disadvantages.
- Under analytical models, recognize the general and specific pairs of model categories.
- Understand the concepts of ① through-variables and ② across-variables and their physical significance, and relationship to state variables.

  2 categories
- Recognize similarities or analogies among the four physical domains: mechanical, electrical, fluid, and thermal ~~(this is the basis of the "unified" approach to modeling~~).
- In each physical domain, recognize the lumped elements that store energy and that dissipate energy, based on the analogy among different physical domains.
- Model a wide variety of system components in a unified way
- Apply AI and Machine Learning in system modeling and design optimization

Reference Books and Articles



Clarence W. de Silva, *Mechatronics: A Foundation Course*, CRC Press, 2010.

Haoxiang Lang, Eric McCormick and Clarence W. de Silva, Appendix B of *Modeling of Dynamic Systems with Engineering Applications*

Matlab Toolbox: GitHub Link
https://github.com/GRASP-ONTechU/Linear_Graph

Three Reference Articles: (downloadable on the course website)

- Research and Development of a Linear Graph-based Matlab Toolbox.
- Automated Multi-domain Engineering Design through Linear Graphs and Genetic Programming.
- Dynamic Modeling and Simulation of a Four-wheel Skid-Steer Mobile Robot using Linear Graphs.

Course Evaluation

Take-home exam / assignment.

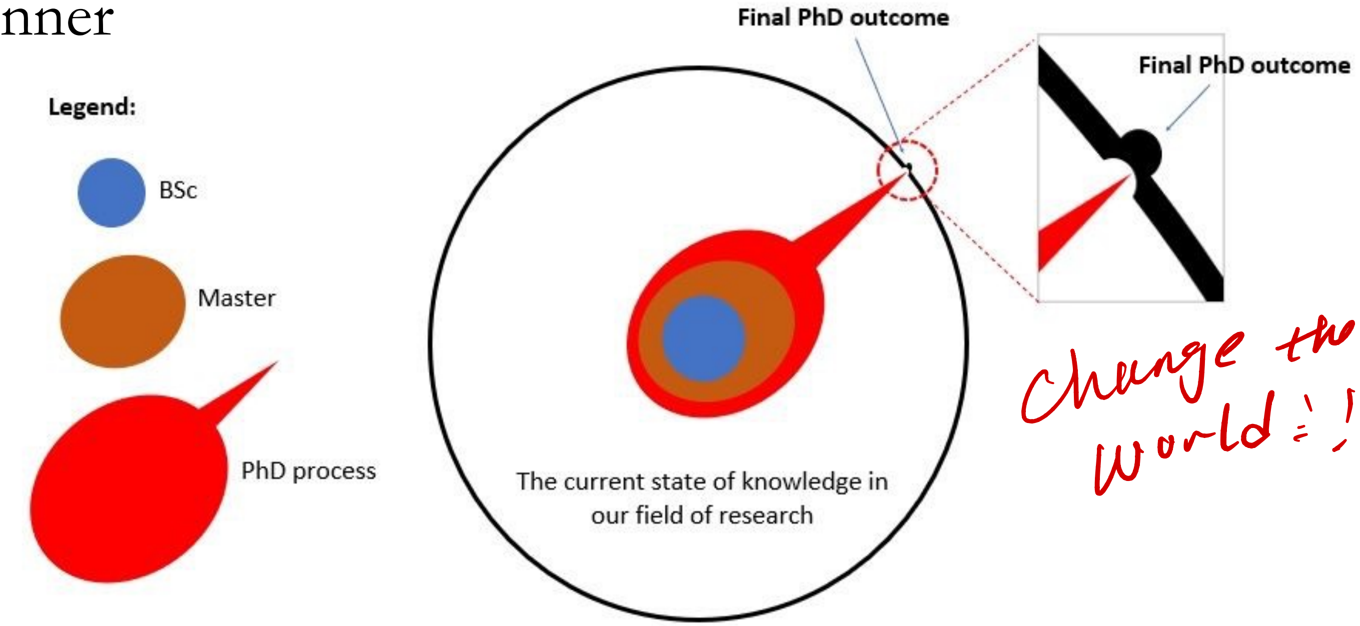
Goals:

- To understand basic modeling of dynamic systems and its procedure
- To formulate realistic modeling/design and possible control problems
- To do analysis and design for the problem using the course material
- To design and analyze of the multi-physics systems in Matlab, and implementation if possible

Ultimate Goals

Broaden your vision

- Cutting-edge insight into system dynamics
- Foundation to develop expertise in design prototyping, control, instrumentation, experimentation and performance analysis
- Discussion of system dynamics
- Systematic, unified and integrated manner
- Introduce tools of modeling



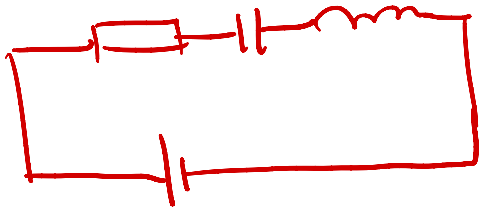
Change the world!!!

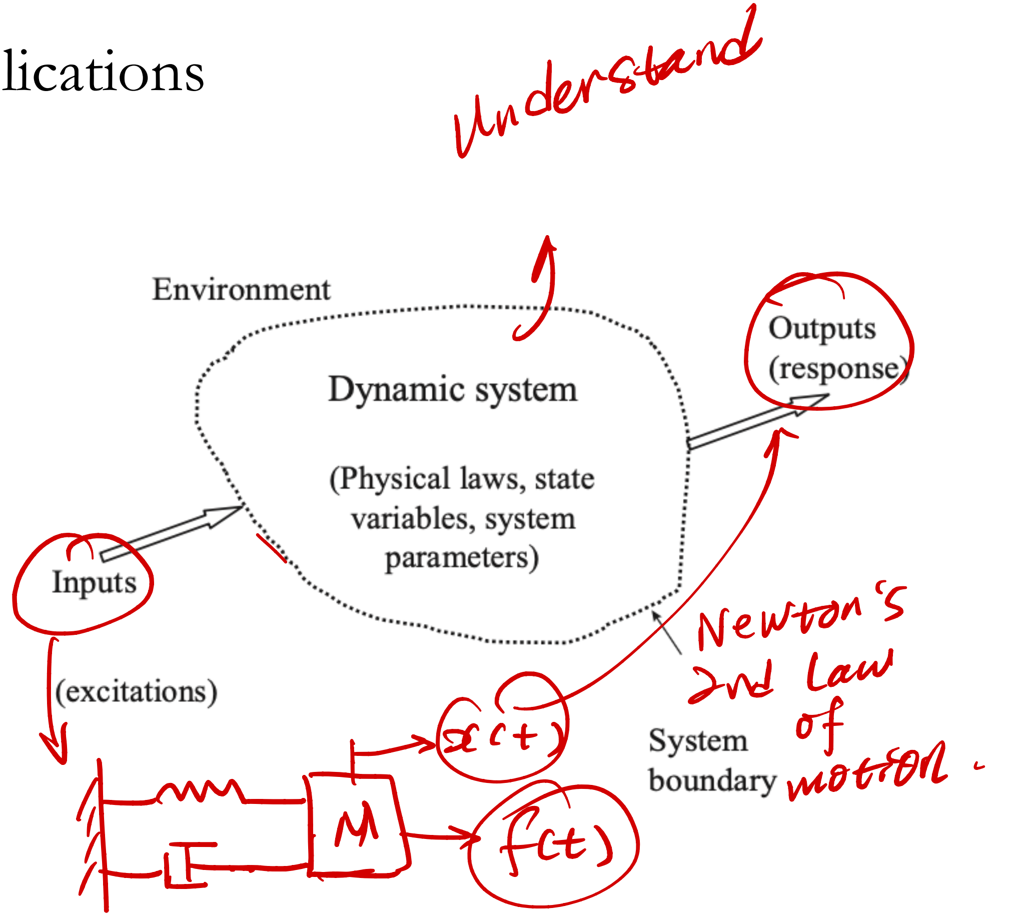
Introduction

Introduction to Modeling

- Introduce the subject of modeling, with focus on multi-physics engineering dynamic systems.
- The importance of dynamic modeling in various applications
- The use of models in the design and control
- Common types of models and modeling techniques and their advantages and disadvantages
- The idea of integrated, unified, systematic mechatronic modeling

1P ← { Mechanical system
1P. { electrical system





Basic Model Elements

- Re-visit basic elements in mechanical, electrical, ~~fluid and thermal domain~~
- Introduce two new concepts: across-variables and through-variables
- Discuss similarities across domains
- Re-define basic elements with new categories for energy storage elements, energy dissipation elements and sources.
- Identification of proper and physically meaningful state variable across multiple physics domains.

state-space model (time domain model)

TF Transfer function (TF) Frequency domain model.

Analytical Modeling

– state-space model

- Formally introduces analytical modeling of dynamic systems – TF (input-output) -
- Systematic development of state-space models of engineering systems in fours physical domains (2 physical domain: Mechanical electrical)
- Frequency domain models: Transfer Function (TF) $\frac{\text{Output}}{\text{Input}}$ → s domain) ↘ s domain
- A general methods of converting a state-space model into an input-output model
- Indicate the advantages and limitations state space model. ⇒ TF
- Examples will be discussed

of system ⇐

Graphical Modeling Tools

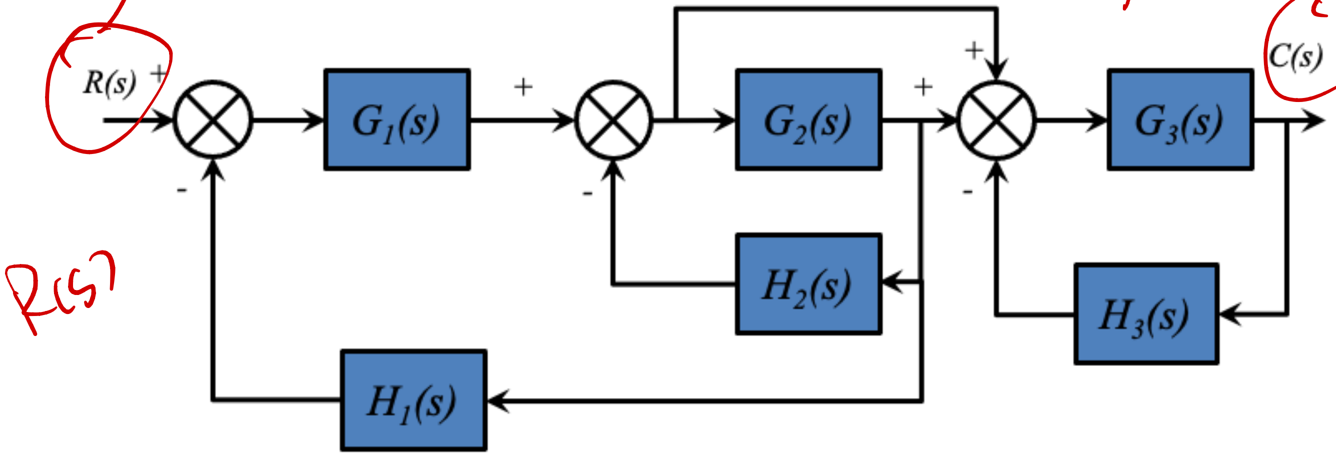
- System block diagram: formulation, simplification and generation of input-output model.
- Signal Flow Graph: formulation and calculation

classic control

$TF: \; G(s) = \frac{output}{input} = \frac{C(s)}{R(s)}$

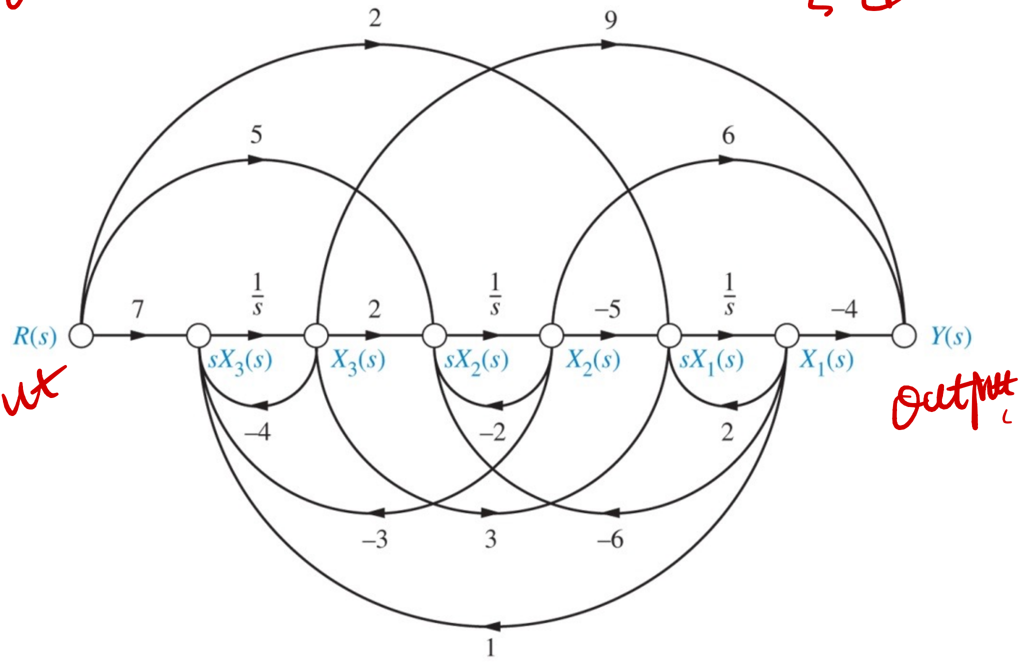
input

R(s)



output

s-domain

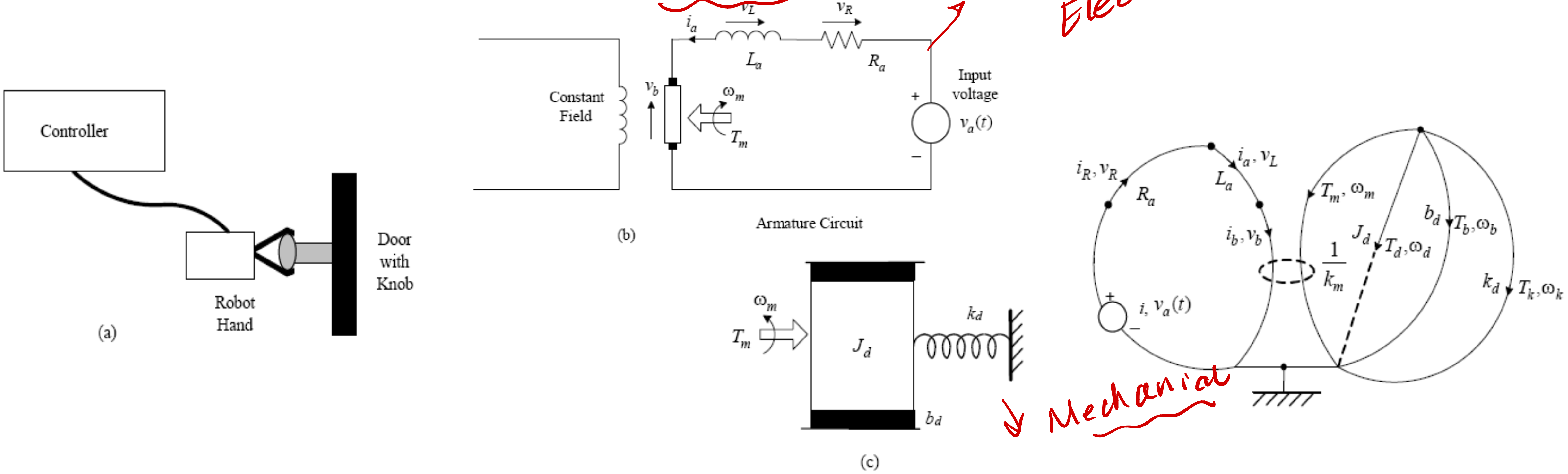


input

output

Linear Graph

- Introduce the graphical tool for developing models of dynamic systems
- State-space model formulation of any physics (mechanical, electrical, fluid and thermal) or multi-domain (mixed) systems
- Discuss more advanced method in Linear Graph



DC Motor

Electrical

Mechanical

Frequency-Domain Models

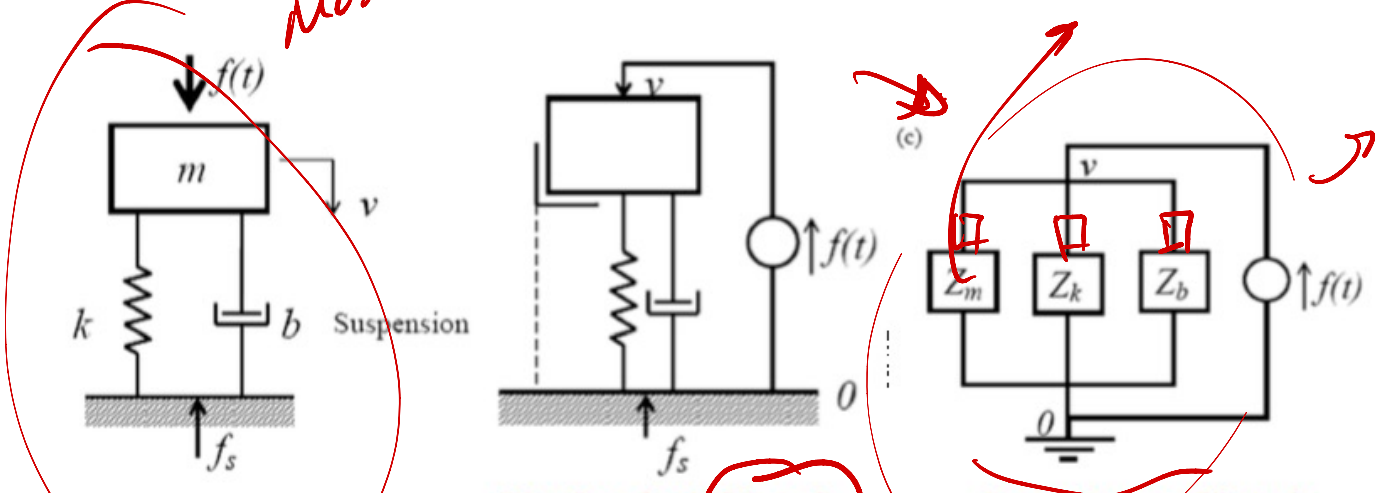
electrical circuit

- Mechanical Circuit
- Mechanical and electrical impedance
- Mechanical mobility and its interconnection laws
- Practical applications

mechanical

Impedance. { electrical.

Mass-spring-damper



Mechanical Circuit **Impedance Circuit**

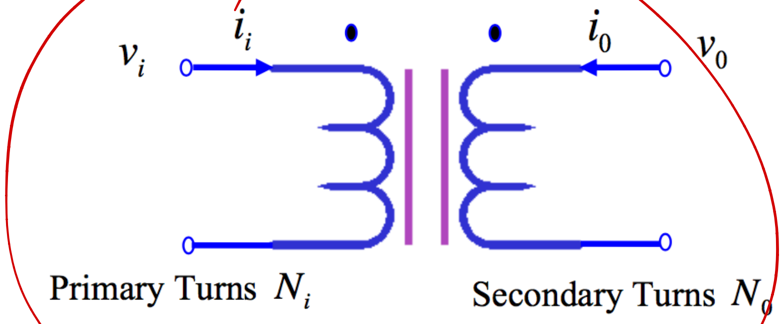
Electrical circuit ?

Transfer-Function Linear Graph

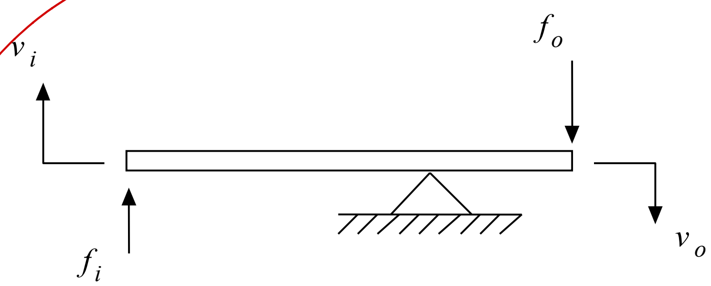
- Extension of the equivalent circuits (commonly in electrical domain) to other physical domain such as mechanical and fluid domains

electrical

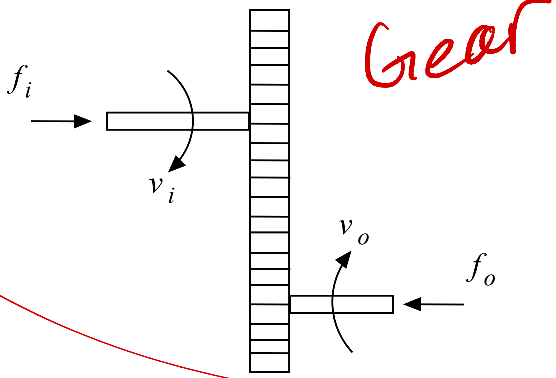
- Reduction of linear graph using Thevenin and Norton equivalence
- Two port linear graph elements



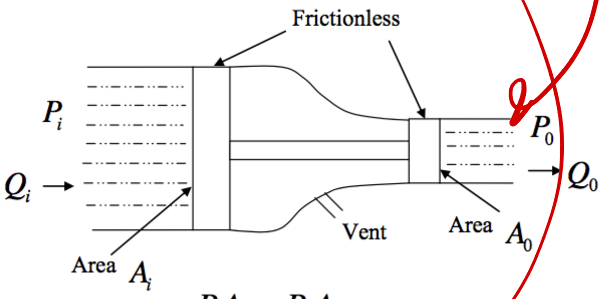
$$r = \frac{N_0}{N_i} = \frac{v_0}{v_i}$$



lever



Gear



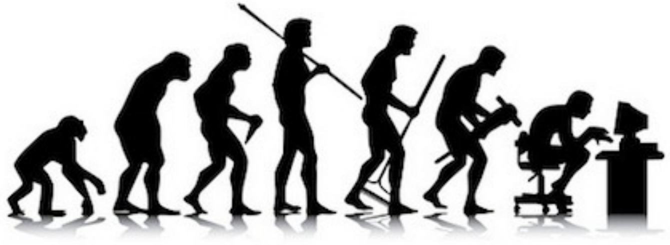
Fluid.

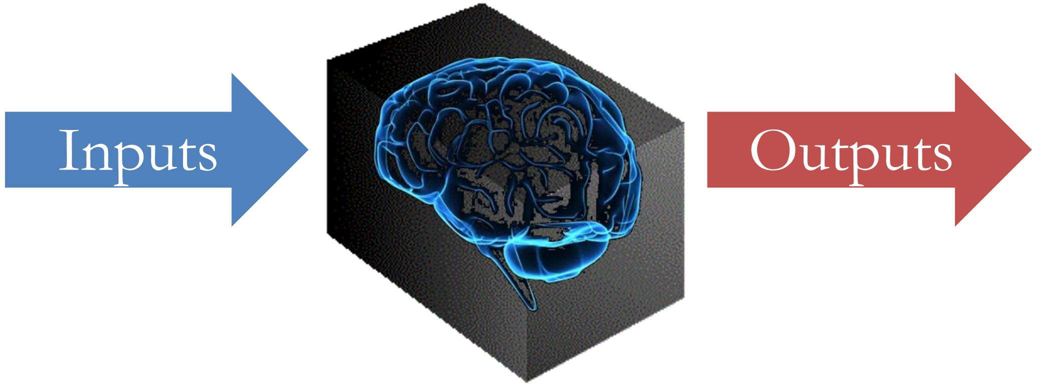
$$P_iA_i = P_0A_0$$

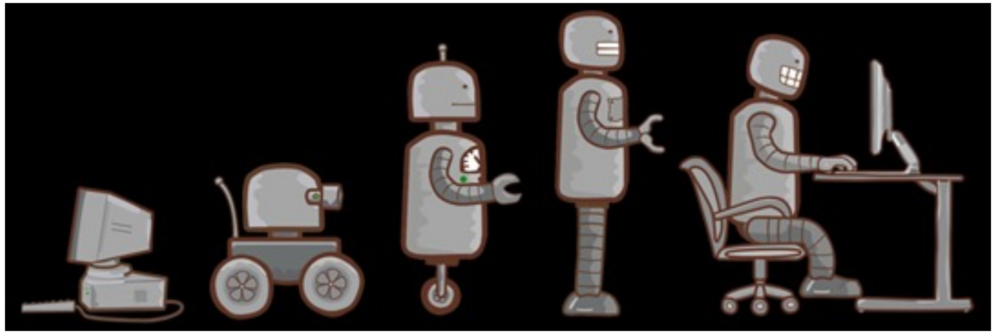
$$r = \frac{A_i}{A_0} = \frac{P_0}{P_i}$$

AI in Modeling and Design

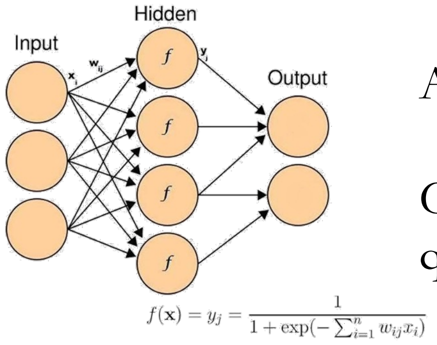
- Introduce general AI algorithms including NNs, GA and Machine Learning
- Discuss possible integration of AI in modeling and desig
- Introduce examples







Reverse
Engineering



$$f(\mathbf{x}) = y_j = \frac{1}{1+\exp(-\sum_{i=1}^{n} w_{ij}x_i)}$$

Artificial Intelligence:

Capable of human-like
qualities

Understanding the system (e.g., human brain)

! The driving force behind the creation/evolution

Modeling and Design Example 1

linear Graph model.

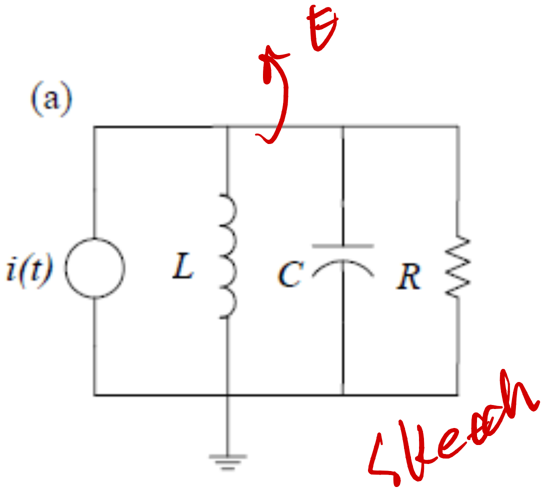
State space model

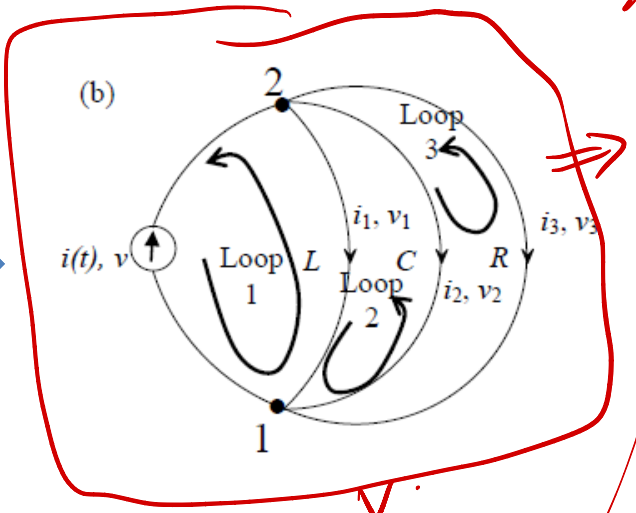
$$\begin{cases}\dot{x} = Ax + Bu \\ y = Cx + Du.\end{cases}$$

u: inputs

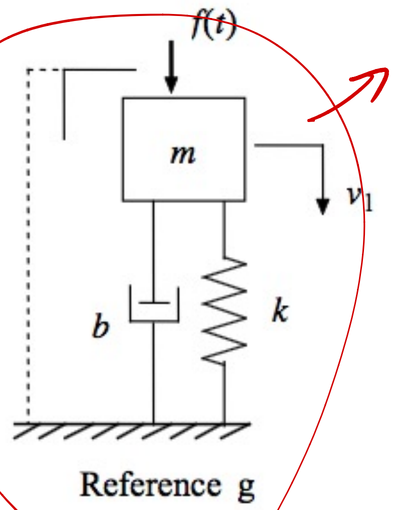
y: outputs.

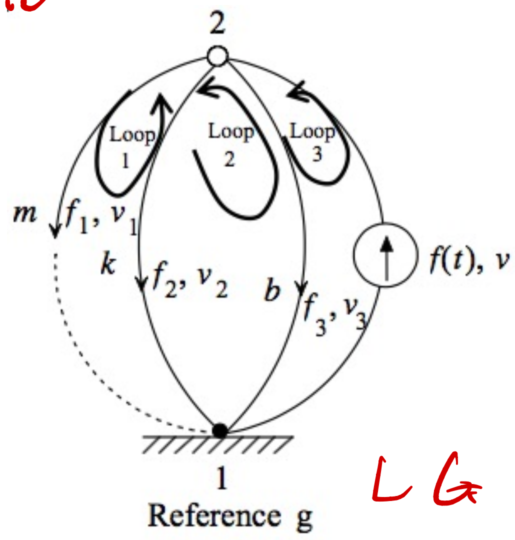
x: states.





Mechanical





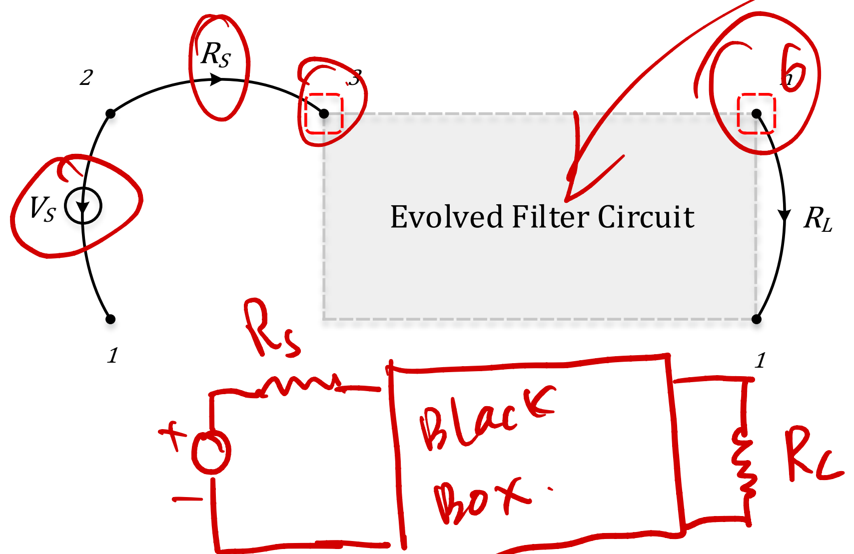
LG

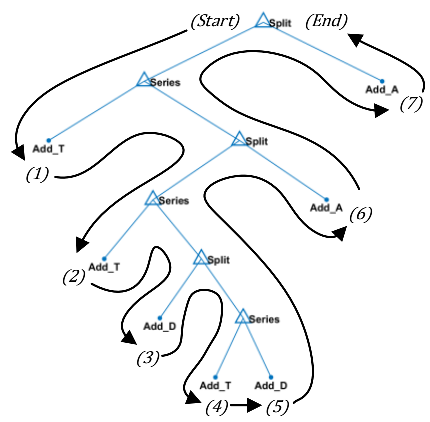
$$A = \begin{bmatrix} -b/m & -1/m \\ k & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 1/m \\ 0 \end{bmatrix}$$

$$u = f(t) \qquad x = [x_1 \quad x_2]^T = [v_1 \quad f_2]^T$$

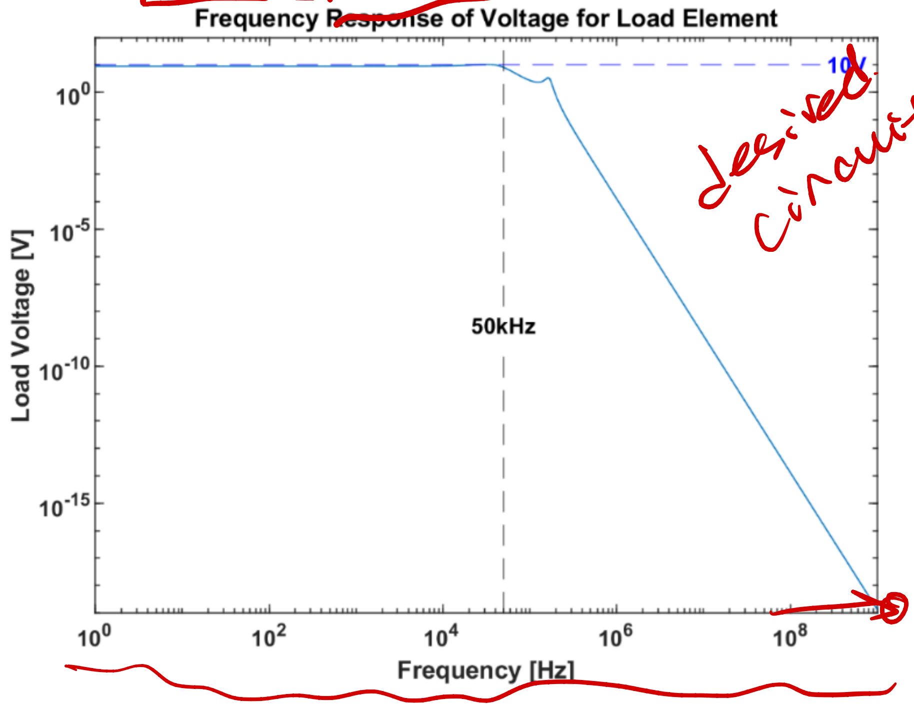
Modeling and Design Example 2

Automated Design





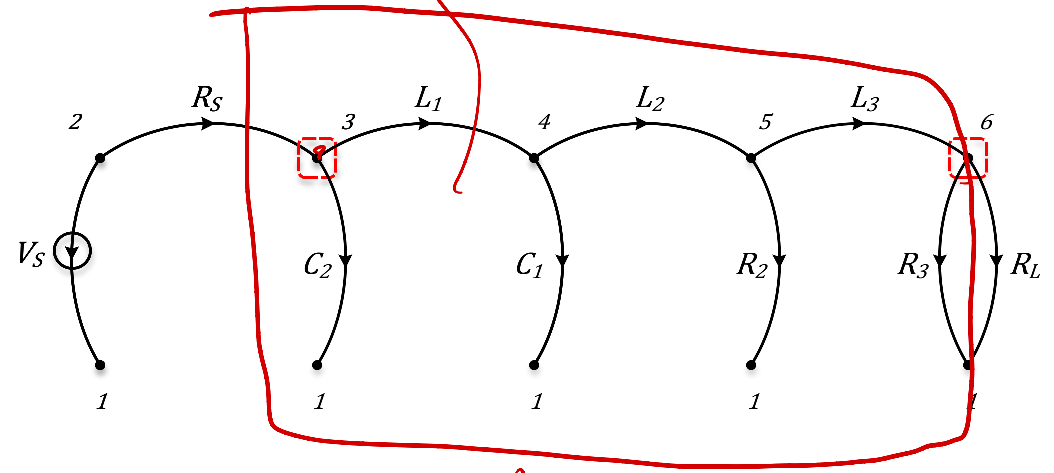
Genetic Programming

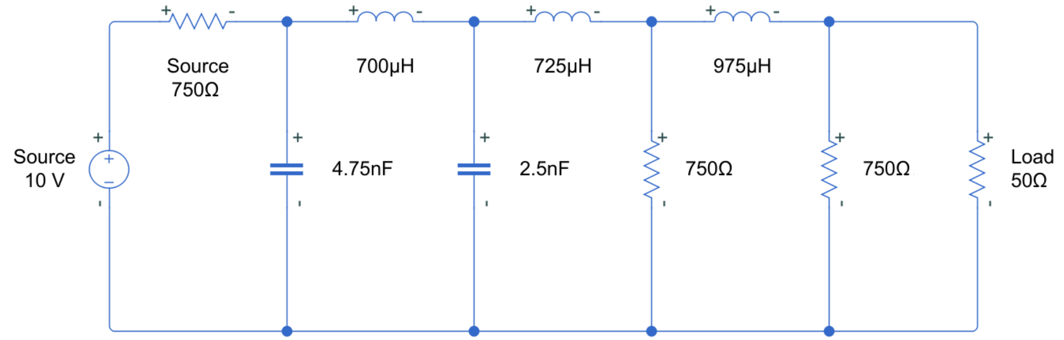


desired circuit.

low-pass filter.

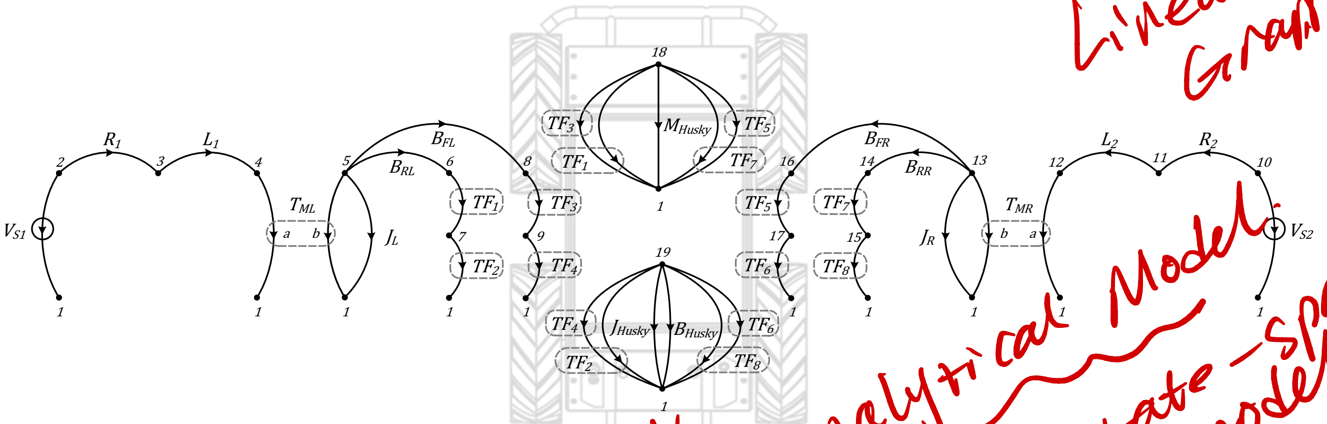
High frequency





Remove high frequency signal.
conserving low frequency signal.

Modeling and Design Example 3



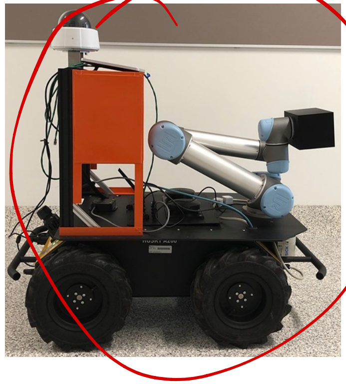
Linear Graph

⇓. Analytical Model

State-space model.

$$A = \begin{bmatrix} \frac{-B_{FL}-B_{RL}}{J_L} & 0 & \frac{B_{FL}TF_3+B_{RL}TF_1}{J_L} & \frac{B_{FL}TF_4+B_{RL}TF_2}{J_L} & \frac{T_{ML}}{J_L} & 0 \\ 0 & \frac{-B_{FR}-B_{RR}}{J_R} & \frac{B_{FR}TF_5+B_{RR}TF_7}{J_R} & \frac{B_{FR}TF_6+B_{RR}TF_8}{J_R} & 0 & \frac{T_{MR}}{J_R} \\ \frac{B_{FL}TF_3+B_{RL}TF_1}{M_H} & \frac{B_{FR}TF_5+B_{RR}TF_7}{M_H} & \frac{-B_{RL}TF_1^2-B_{FL}TF_3^2-B_{FR}TF_5^2-B_{RR}TF_7^2}{M_H} & \frac{-B_{FL}TF_3TF_4-B_{FR}TF_5TF_6-B_{RL}TF_1TF_2-B_{RR}TF_7TF_8}{M_H} & 0 & 0 \\ \frac{B_{FL}TF_4+B_{RL}TF_2}{J_H} & \frac{B_{FR}TF_6+B_{RR}TF_8}{J_H} & \frac{-B_{FL}TF_3TF_4-B_{FR}TF_5TF_6-B_{RL}TF_1TF_2-B_{RR}TF_7TF_8}{J_H} & \frac{-B_{RL}TF_2^2-B_{FL}TF_4^2-B_{FR}TF_6^2-B_{RR}TF_8^2-B_H}{J_H} & 0 & 0 \\ -\frac{T_{ML}}{L_1} & 0 & 0 & 0 & -\frac{R_1}{L_1} & 0 \\ 0 & -\frac{T_{MR}}{L_2} & 0 & 0 & 0 & -\frac{R_2}{L_2} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{L_1} & 0 \\ 0 & \frac{1}{L_2} \end{bmatrix} \quad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \quad D = [0]_{4\times2}$$



Description	Parameter	Value	Units
Voltage Inputs	V_{s1} , V_{s2}	±24	V
Internal Motor Resistance	R_1 , R_2	0.46	Ω
Internal Motor Inductance	L_1 , L_2	0.22	mH
Motor Torque Constant	k_t	0.044488	$N \cdot m/A$
Gear Ratio	GR	78.71 : 1	Gear Ratio
Motor Transformer Ratio	T_{ML} , T_{MR}	$k_t \times GR$	$N \cdot m/A$
Drivetrain Inertia	J_{LW} , J_{RW}	0.08	$kg \cdot m^2$
Drivetrain Damping	$B_{RL,FL,FR,RR}$	Unknown	$rad/(N \cdot m \cdot s)$
Power Conversion Transformer Ratios	TF_{odd}	Equation (7)	
	TF_{even}	Equation (8)	
Husky Mass	M_{Husky}	48.39	kg
Husky Rotational Damping	B_{Husky}	Unknown	$rad/(N \cdot m \cdot s)$
Husky Inertia	J_{Husky}	3.0556	$kg \cdot m^2$

The End!!