GRASP Laboratory
General Robotics & Autonomous Systems and Processes

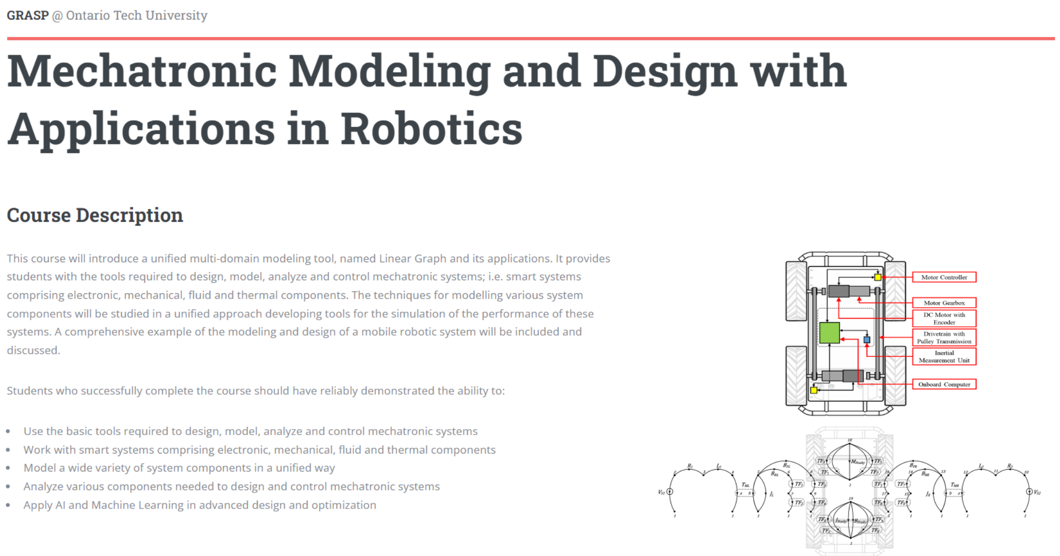
# Mechatronic Modeling and Design with Applications in Robotics

## Course Outline and Introduction

# Instructor

## Course Website:

https://faculty.ontariotechu.ca/lang/modeling.html




A snapshot of the course website

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Director of the GRASP Lab @ OntarioTech

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

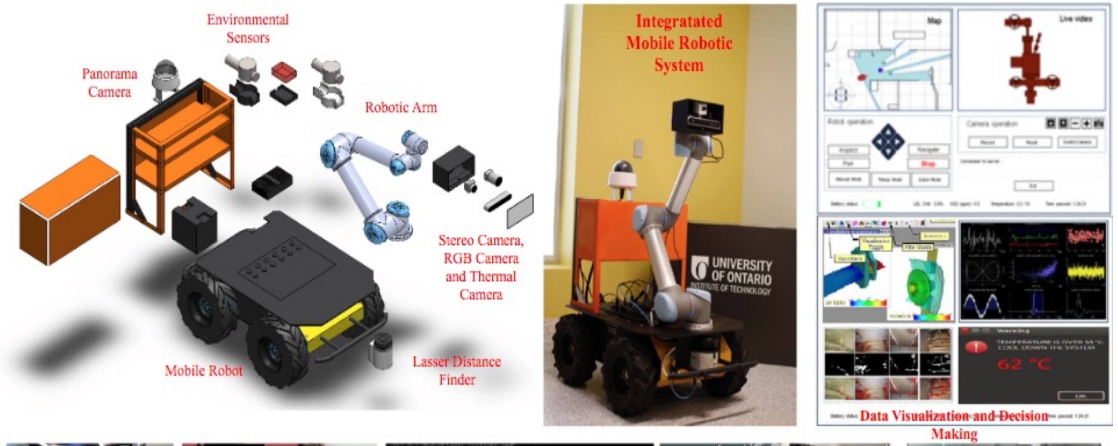
- Mechatronics
- Robotics
- Machine vision
- Advanced Control
- Artificial intelligence

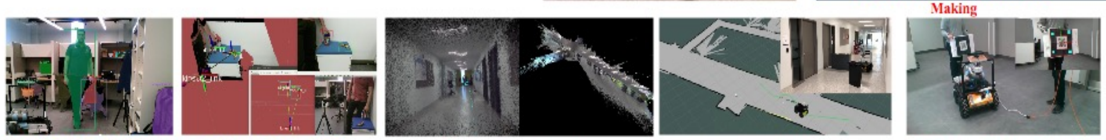
GRASP Laboratory
General Robotics & Autonomous Systems and Processes

OntarioTech UNIVERSITY

# Selected Projects in GRASP Lab



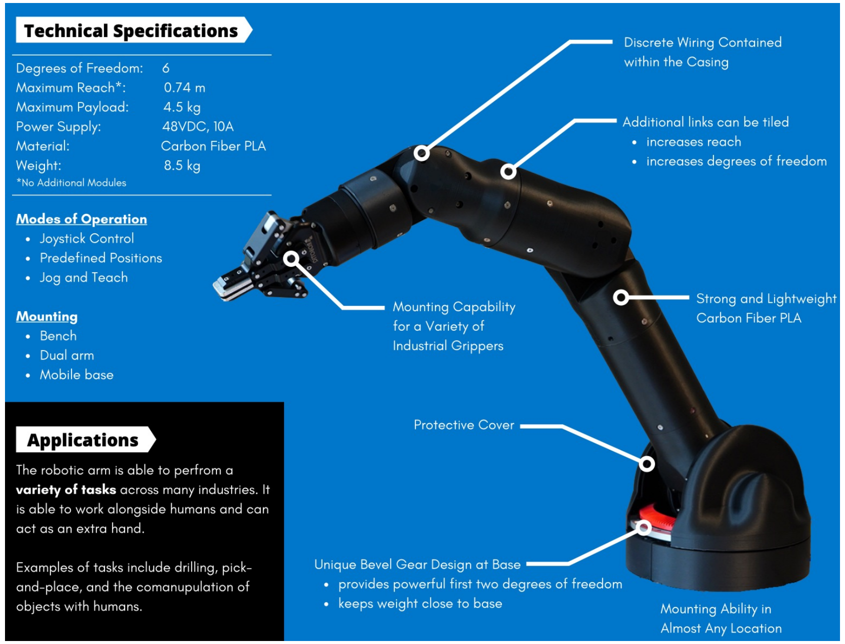
Real-time object identification and segmentation

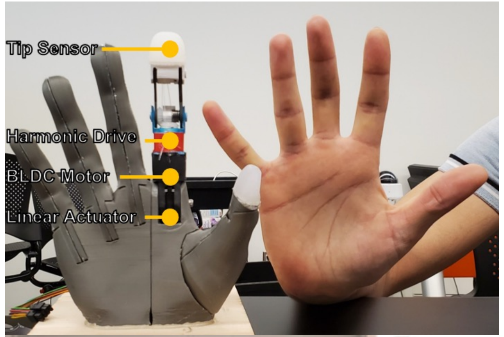
Object tracking and post estimation

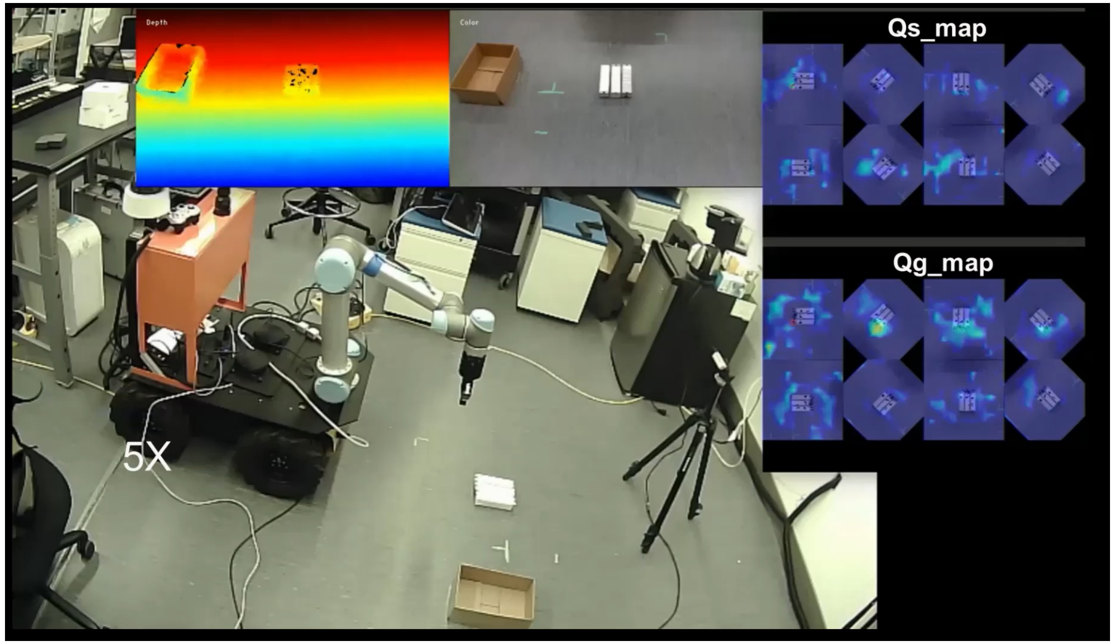
3D scanning and mapping

Autonomous Navigation

Vision-based Motion Control



# 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

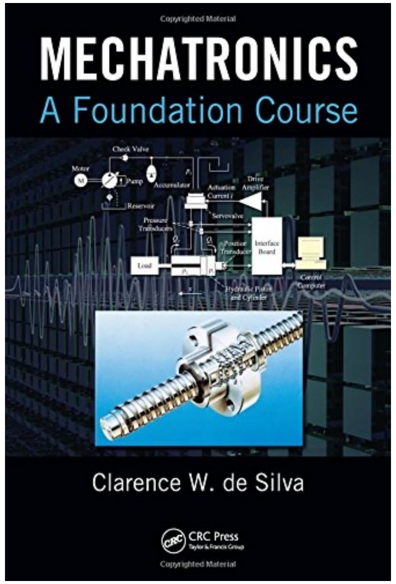
# Learning Outcomes



- 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 through-variables and across-variables and their physical significance, and relationship to state variables.
- 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



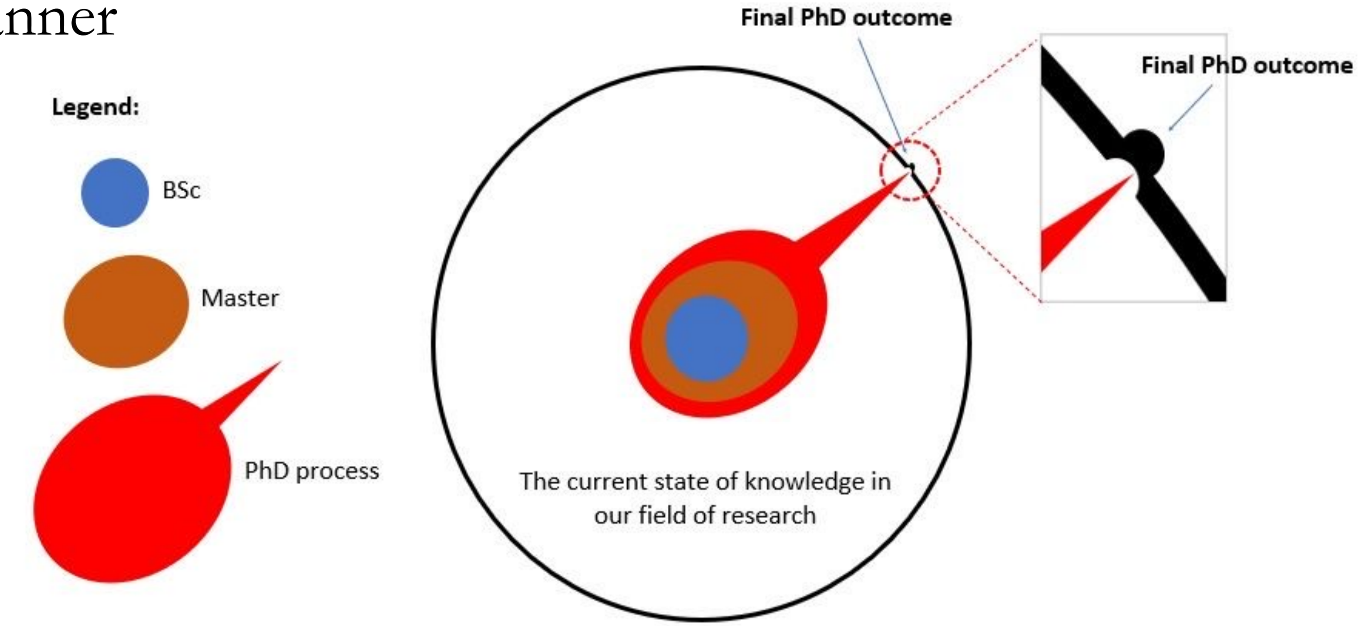
**Goals:**

- 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



- 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

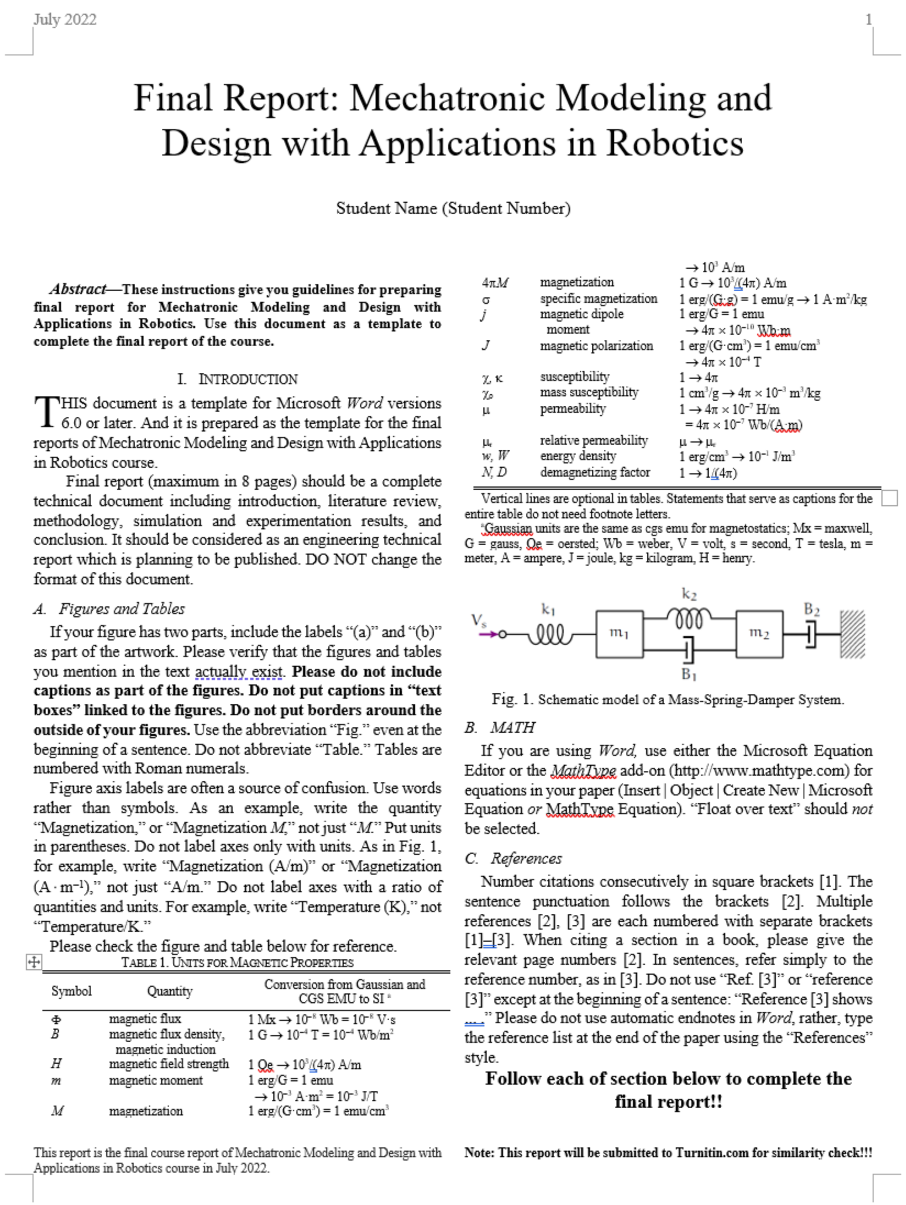


A Course Final Report: Template is downloadable from the course website.

**Note:**

- DO NOT change the format of the template
- The current introduction part is an explanation of how you are expecting to complete the report. You can remove all the text and rewrite the introduction section using the given section titles after the text “**Follow each of section below to complete the final report!**”
- You need to use your own word to write the report, copying and pasting from online or other reference is not acceptable.

**Warning:** Your final report will be submitted to Turnitin.com for similarity check.



July 2022 1

# Final Report: Mechatronic Modeling and Design with Applications in Robotics

Student Name (Student Number)

***Abstract*—These instructions give you guidelines for preparing final report for Mechatronic Modeling and Design with Applications in Robotics. Use this document as a template to complete the final report of the course.**

## I. Introduction

THIS document is a template for Microsoft *Word* versions 6.0 or later. And it is prepared as the template for the final reports of Mechatronic Modeling and Design with Applications in Robotics course.

Final report (maximum in 8 pages) should be a complete technical document including introduction, literature review, methodology, simulation and experimentation results, and conclusion. It should be considered as an engineering technical report which is planning to be published. DO NOT change the format of this document.

### A. Figures and Tables

If your figure has two parts, include the labels “(a)” and “(b)” as part of the artwork. Please verify that the figures and tables you mention in the text actually exist. **Please do not include captions as part of the figures. Do not put captions in “text boxes” linked to the figures. Do not put borders around the outside of your figures.** Use the abbreviation “Fig.” even at the beginning of a sentence. Do not abbreviate “Table.” Tables are numbered with Roman numerals.

Figure axis labels are often a source of confusion. Use words rather than symbols. As an example, write the quantity “Magnetization,” or “Magnetization *M*,” not just “*M*.” Put units in parentheses. Do not label axes only with units. As in Fig. 1, for example, write “Magnetization (A/m)” or “Magnetization (A $\cdot$ m$^{-1}$),” not just “A/m.” Do not label axes with a ratio of quantities and units. For example, write “Temperature (K),” not “Temperature/K.”

Please check the figure and table below for reference.

TABLE 1. UNITS FOR MAGNETIC PROPERTIES

| Symbol | Quantity | Conversion from Gaussian and CGS EMU to SI [a] |
|---|---|---|
| $\Phi$ | magnetic flux | 1 Mx $\rightarrow 10^{-8}$ Wb $= 10^{-8}$ V·s |
| $B$ | magnetic flux density, magnetic induction | 1 G $\rightarrow 10^{-4}$ T $= 10^{-4}$ Wb/m$^2$ |
| $H$ | magnetic field strength | 1 Oe $\rightarrow 10^3/(4\pi)$ A/m |
| $m$ | magnetic moment | 1 erg/G = 1 emu $\rightarrow 10^{-3}$ A·m$^2 = 10^{-3}$ J/T |
| $M$ | magnetization | 1 erg/(G·cm$^3$) = 1 emu/cm$^3$ $\rightarrow 10^3$ A/m |
| $4\pi M$ | magnetization | 1 G $\rightarrow 10^3/(4\pi)$ A/m |
| $\sigma$ | specific magnetization | 1 erg/(G·g) = 1 emu/g $\rightarrow$ 1 A·m$^2$/kg |
| $j$ | magnetic dipole moment | 1 erg/G = 1 emu $\rightarrow 4\pi \times 10^{-10}$ Wb·m |
| $J$ | magnetic polarization | 1 erg/(G·cm$^3$) = 1 emu/cm$^3$ $\rightarrow 4\pi \times 10^{-4}$ T |
| $\chi$, $\kappa$ | susceptibility | $1 \rightarrow 4\pi$ |
| $\chi_\rho$ | mass susceptibility | 1 cm$^3$/g $\rightarrow 4\pi \times 10^{-3}$ m$^3$/kg |
| $\mu$ | permeability | $1 \rightarrow 4\pi \times 10^{-7}$ H/m $= 4\pi \times 10^{-7}$ Wb/(A·m) |
| $\mu_r$ | relative permeability | $\mu \rightarrow \mu_r$ |
| $w$, $W$ | energy density | 1 erg/cm$^3$ $\rightarrow 10^{-1}$ J/m$^3$ |
| $N$, $D$ | demagnetizing factor | $1 \rightarrow 1/(4\pi)$ |

Vertical lines are optional in tables. Statements that serve as captions for the entire table do not need footnote letters.

[a] Gaussian units are the same as cgs emu for magnetostatics; Mx = maxwell, G = gauss, Oe = oersted; Wb = weber, V = volt, s = second, T = tesla, m = meter, A = ampere, J = joule, kg = kilogram, H = henry.



Fig. 1. Schematic model of a Mass-Spring-Damper System.

### B. MATH

If you are using *Word,* use either the Microsoft Equation Editor or the *MathType* add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation *or* MathType Equation). “Float over text” should *not* be selected.

### C. References

Number citations consecutively in square brackets [1]. The sentence punctuation follows the brackets [2]. Multiple references [2], [3] are each numbered with separate brackets [1]–[3]. When citing a section in a book, please give the relevant page numbers [2]. In sentences, refer simply to the reference number, as in [3]. Do not use “Ref. [3]” or “reference [3]” except at the beginning of a sentence: “Reference [3] shows ... .” Please do not use automatic endnotes in *Word*, rather, type the reference list at the end of the paper using the “References” style.

**Follow each of section below to complete the final report!!**

This report is the final course report of Mechatronic Modeling and Design with Applications in Robotics course in July 2022.

**Note: This report will be submitted to Turnitin.com for similarity check!!!**

# Requirement of the Final Report

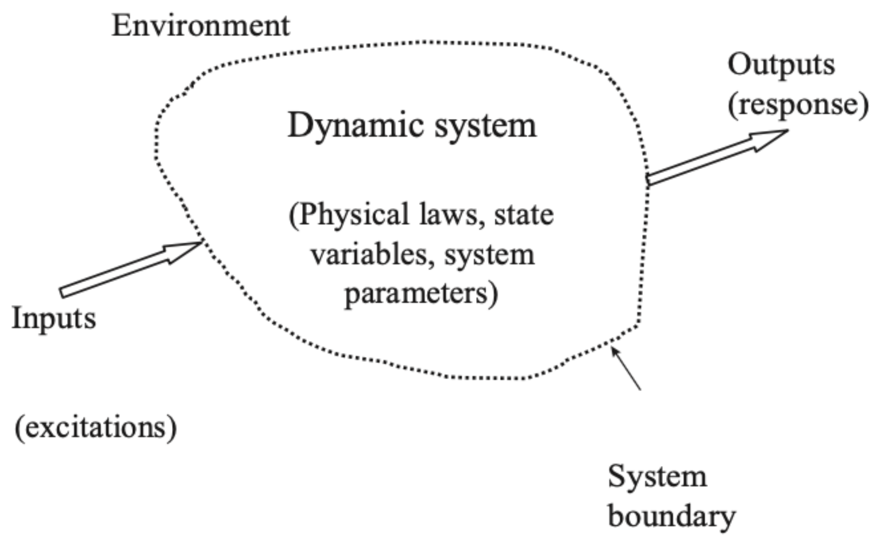


1. Download three reference work from the course website
2. Read the first and second reference papers and try to understand them during the course.
3. Repeat the implementation of the circuit design in the second reference paper using Matlab, and report your results in the final report. Compare your results and discuss your findings and your understanding in the final report
4. Or complete the take home exam in the end of the course

The maximum page number of your final report is 6. Please put the most important information in your report. Codes or other figures can be submitted as appendices if necessary ( will not be counted as a part of the main report).

# Introduction

- 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



# 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.

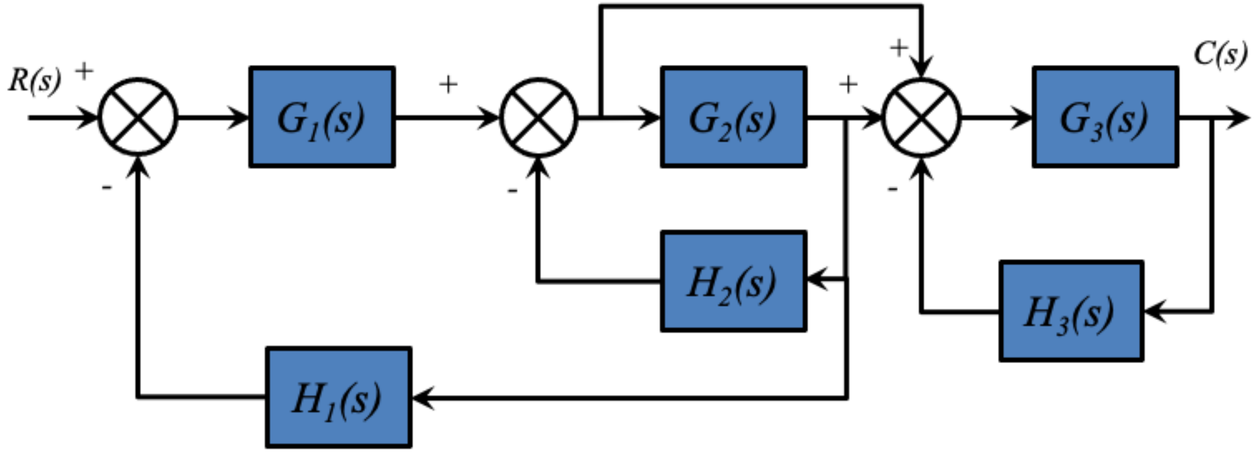
# Analytical Modeling

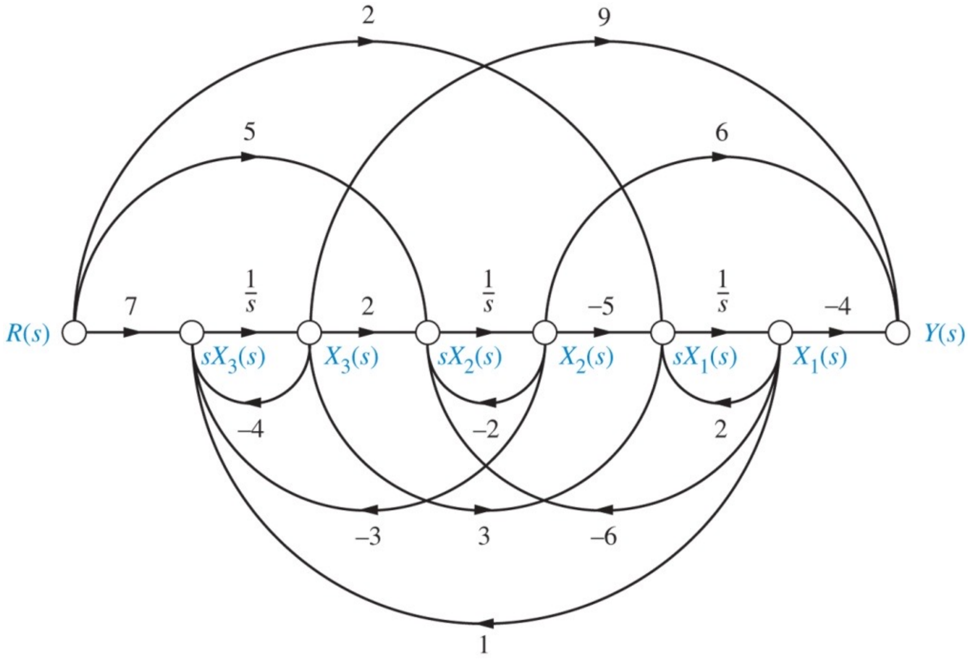


- Formally introduces analytical modeling of dynamic systems
- Systematic development of state-space models of engineering systems in fours physical domains
- Frequency domain models: Transfer Function
- A general methods of converting a state-space model into an input-output model
- Indicate the advantages and limitations
- Examples will be discussed

# Graphical Modeling Tools

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

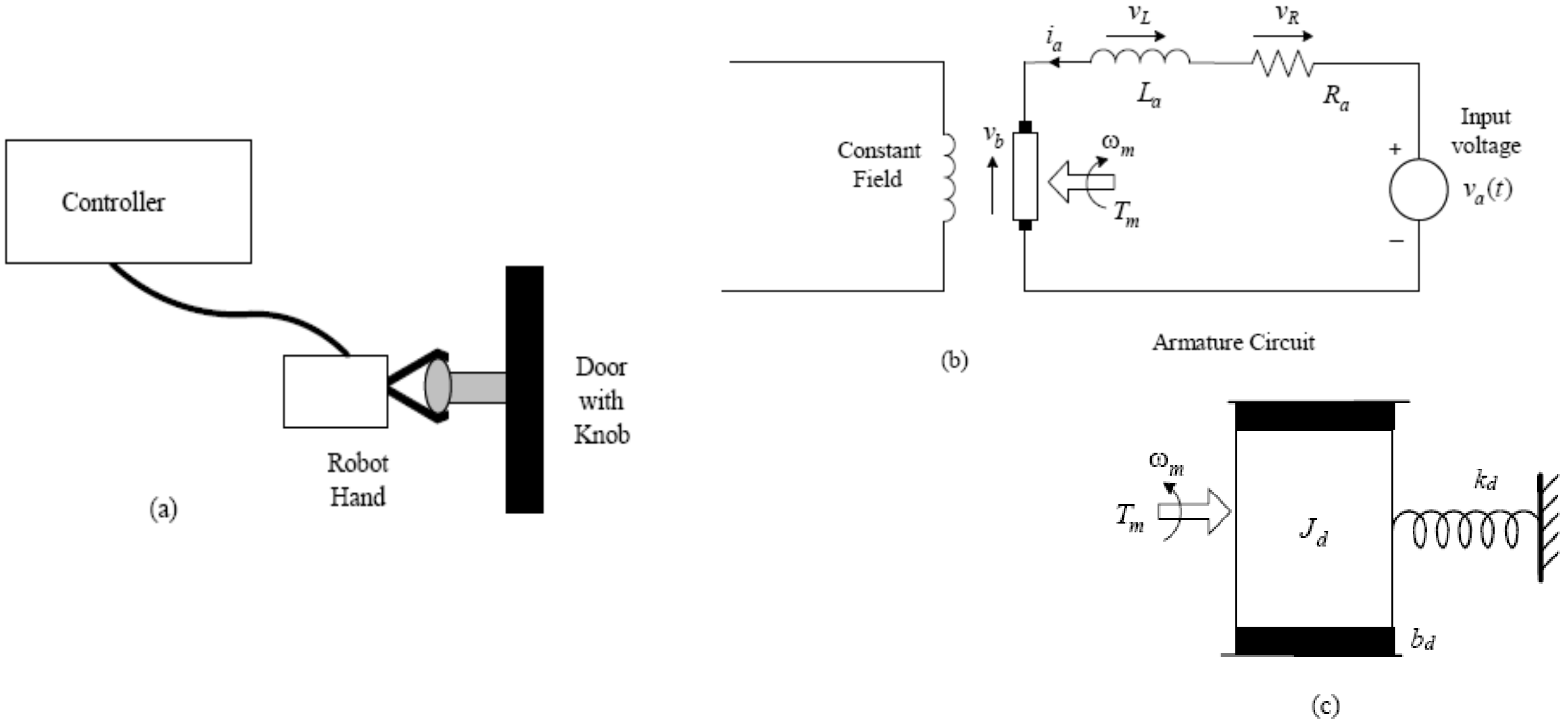


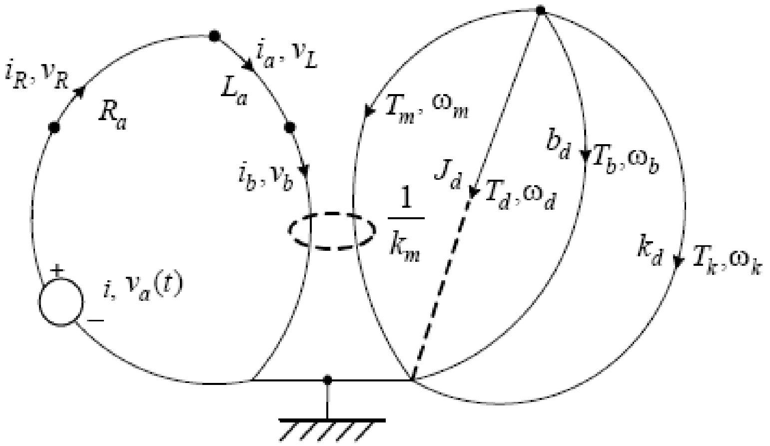



# Linear Graph



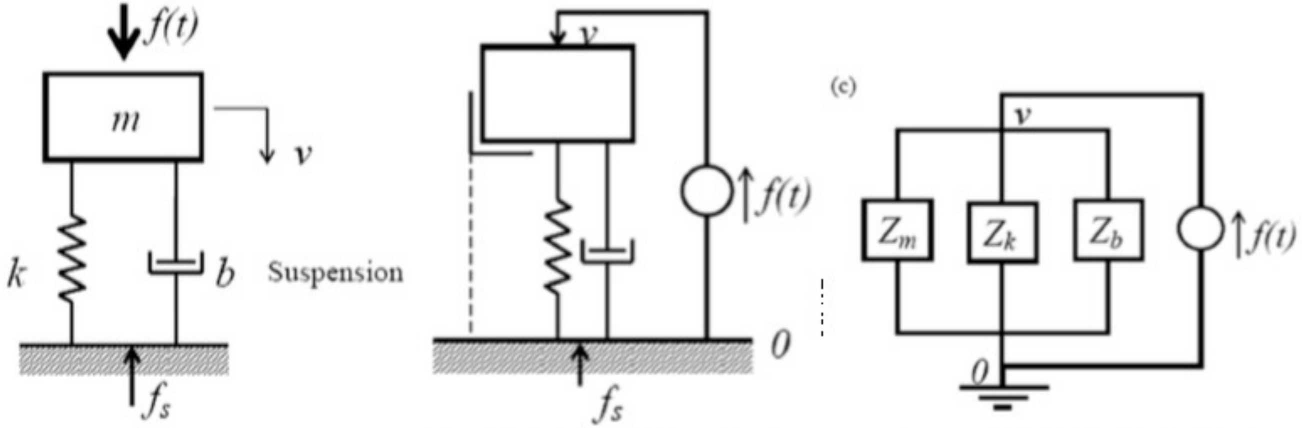
- Introduce the graphical tool for developing models of dynamic systems
- State-space model formulation of any physics (mechanical, electrical, fluid and thermal) or multi-domain (mixed) systems
- Discuss more advanced method in Linear Graph



# Frequency-Domain Models

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

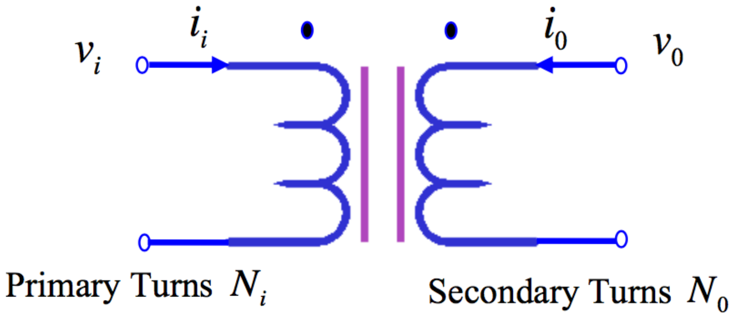



**Mechanical Circuit** **Impedance Circuit**

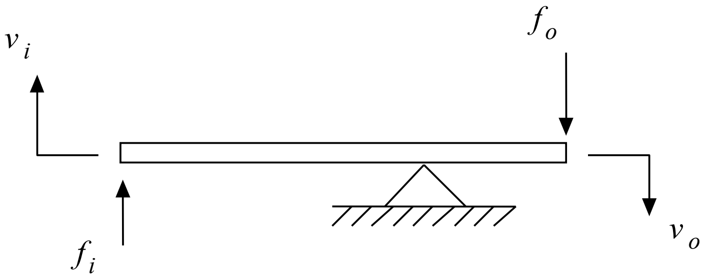
# Transfer-Function Linear Graph

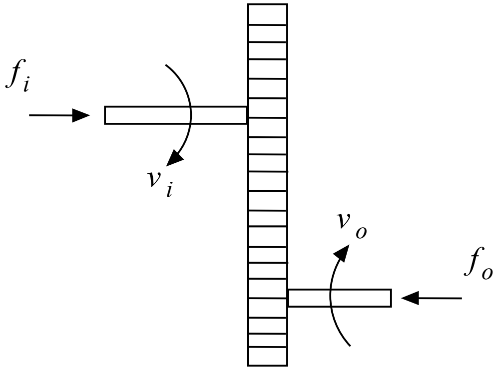


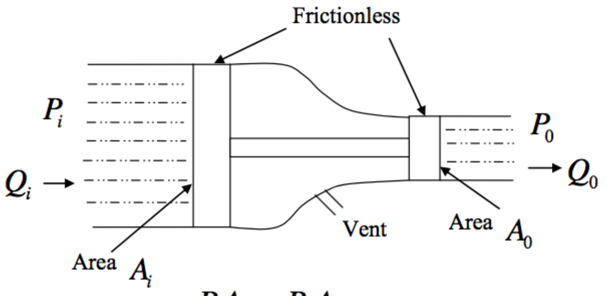
- Extension of the equivalent circuits (commonly in electrical domain) to other physical domain such as mechanical and fluid domains
- Reduction of linear graph using Thevenin and Norton equivalence
- Two port linear graph elements




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



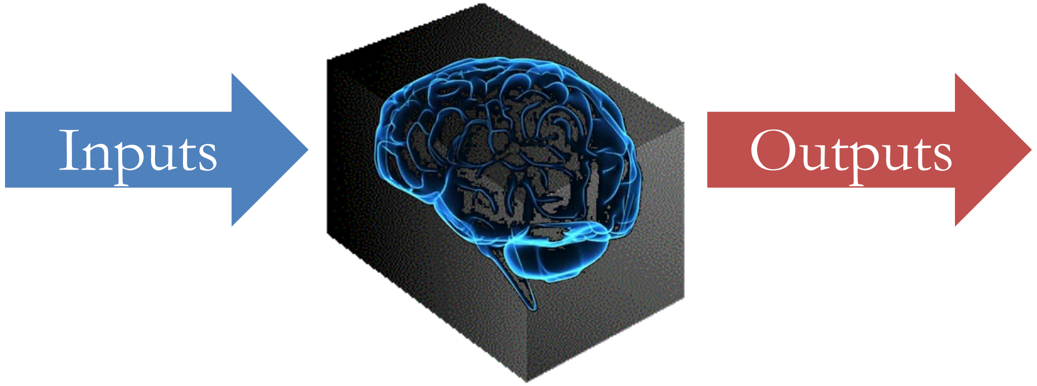

$$P_i A_i = P_0 A_0$$

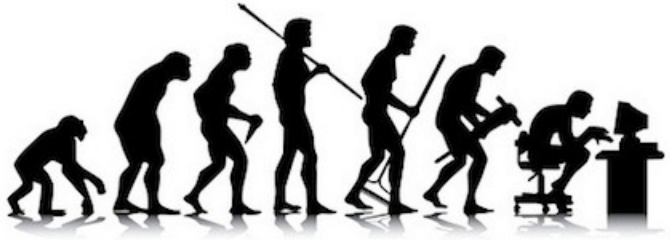
$$r = \frac{A_i}{A_0} = \frac{P_0}{P_i}$$

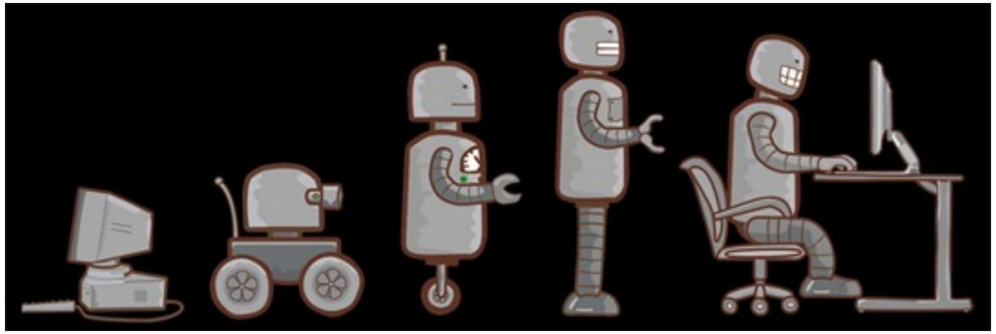
# AI in Modeling and Design



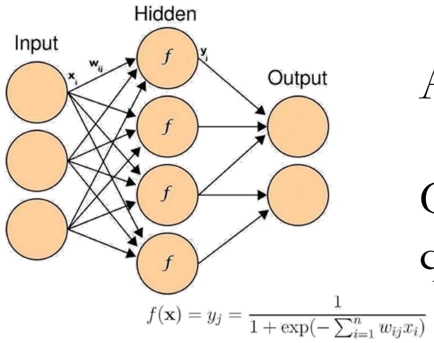
- Introduce general AI algorithms including NNs, GA and Machine Learning
- Discuss possible integration of AI in modeling and design
- Introduce examples





Reverse Engineering



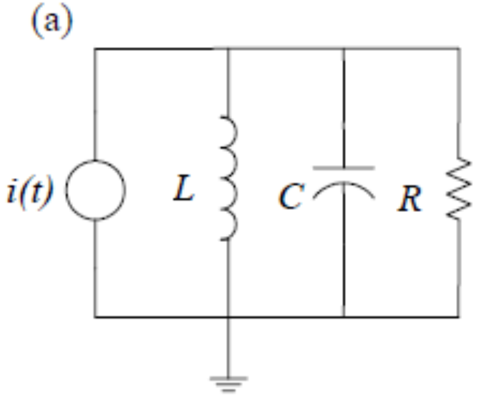

Artificial Intelligence:

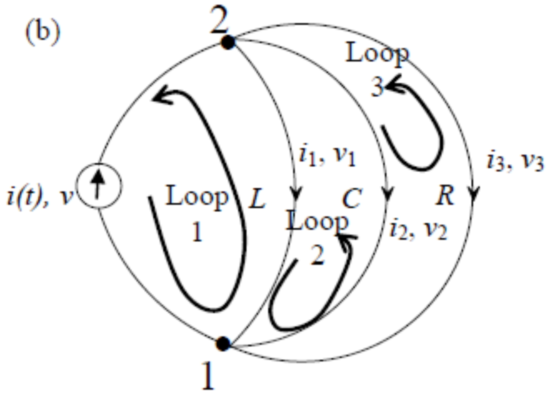
Capable of human-like qualities

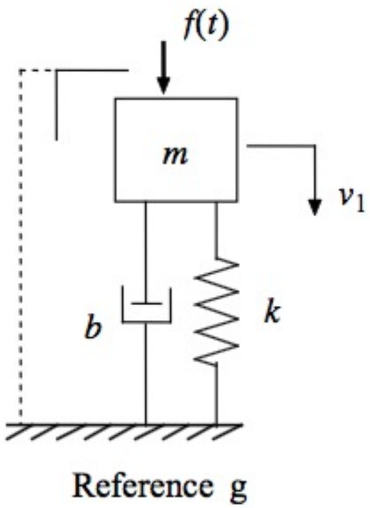
Understanding the system (e.g., human brain)

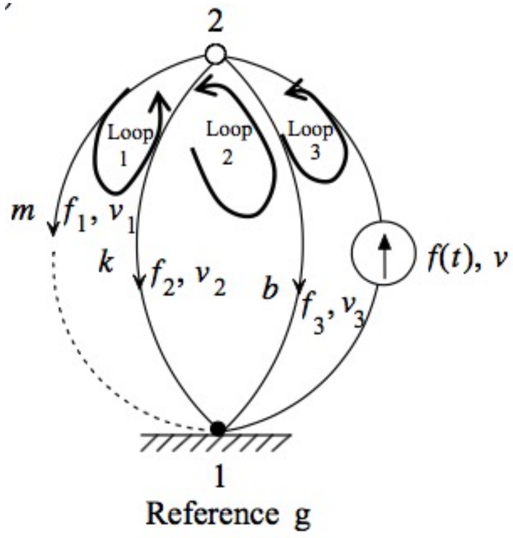
The driving force behind the creation/evolution

# Modeling and Design Example 1



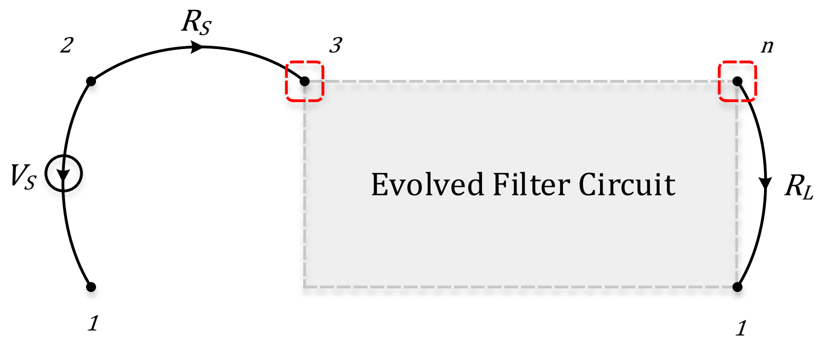



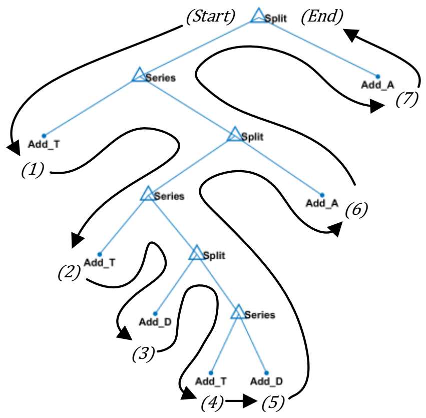

$$A = \begin{bmatrix} -b/m & -1/m \\ k & 0 \end{bmatrix} \qquad B = \begin{bmatrix} 1/m \\ 0 \end{bmatrix}$$

$$u = f(t) \qquad x = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T = \begin{bmatrix} v_1 & f_2 \end{bmatrix}^T$$

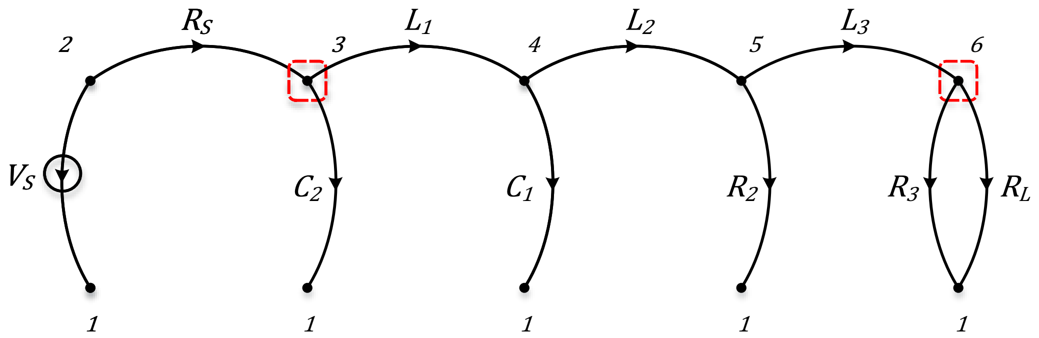
# Modeling and Design Example 2

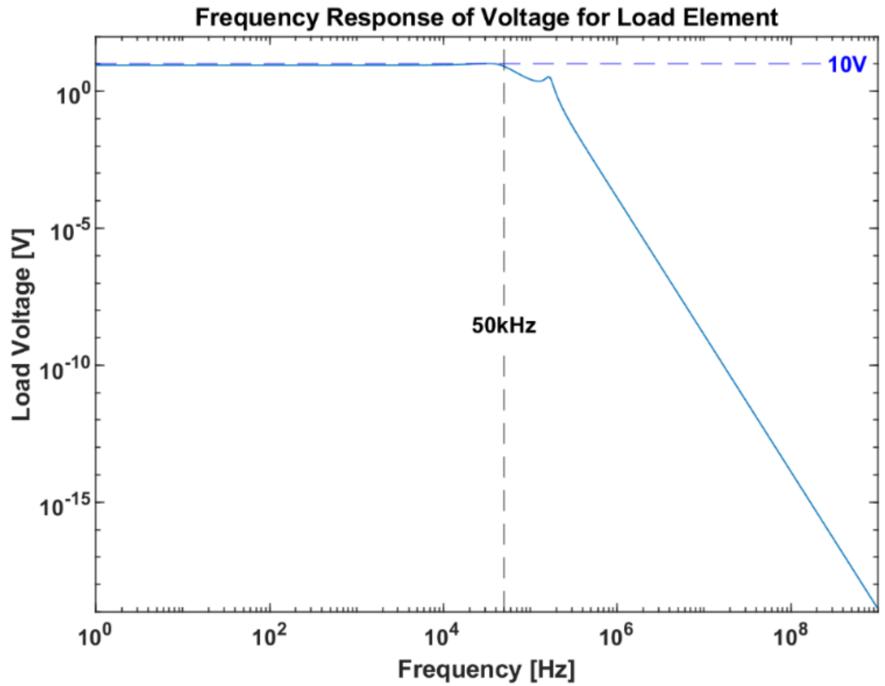


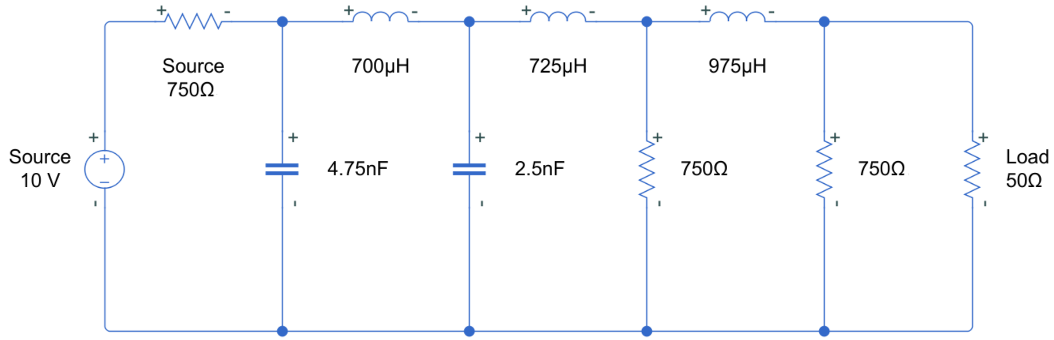


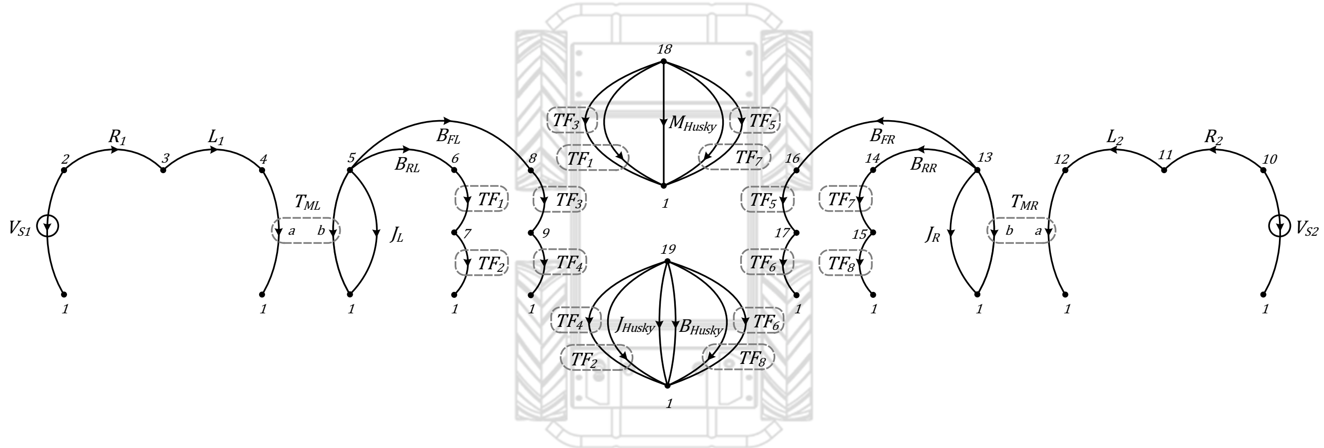

Genetic Programming



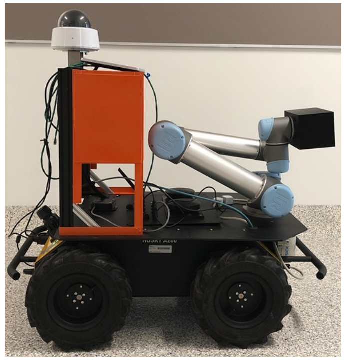



# Modeling and Design Example 3




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

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



| Description | Parameter | Value | Units |
|---|---|---|---|
| Voltage Inputs | $V_{s1}, V_{s2}$ | $\pm 24$ | $V$ |
| Internal Motor Resistance | $R_1, R_2$ | 0.46 | $\Omega$ |
| 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!!