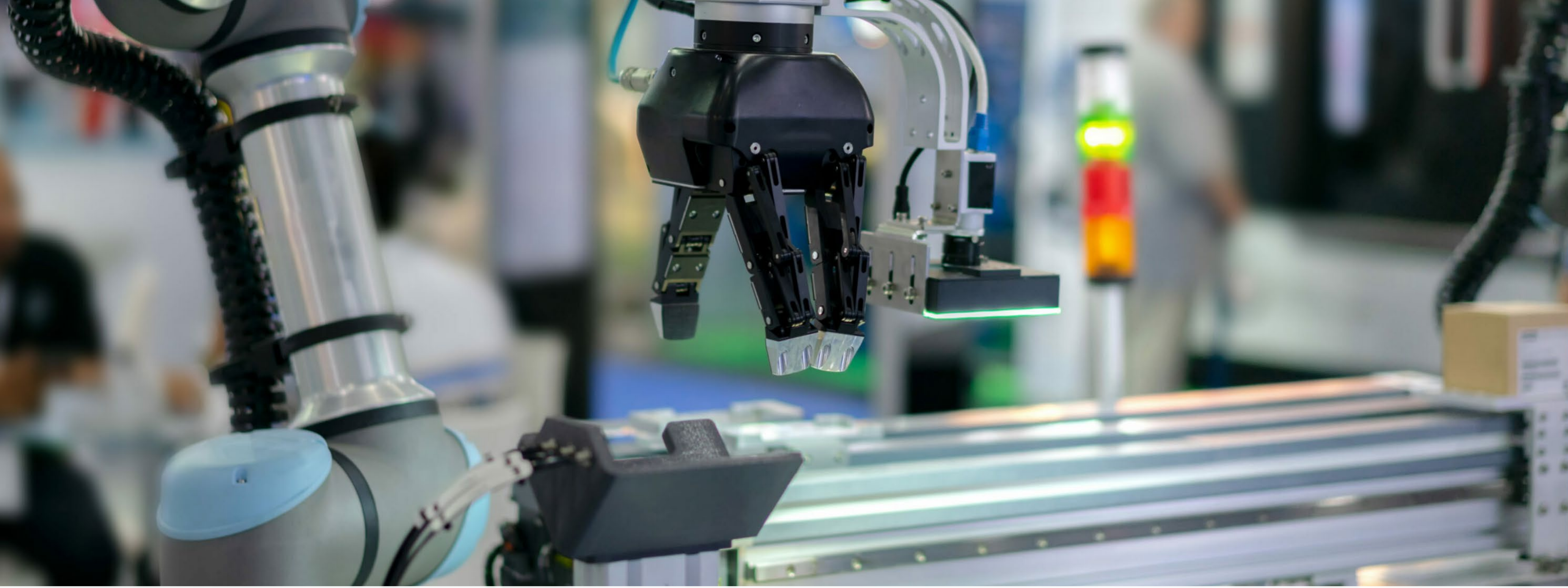
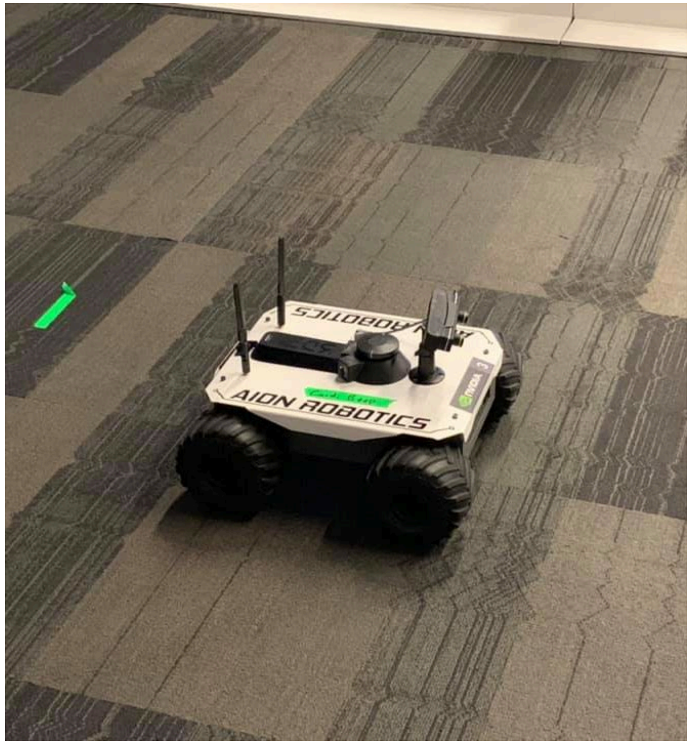


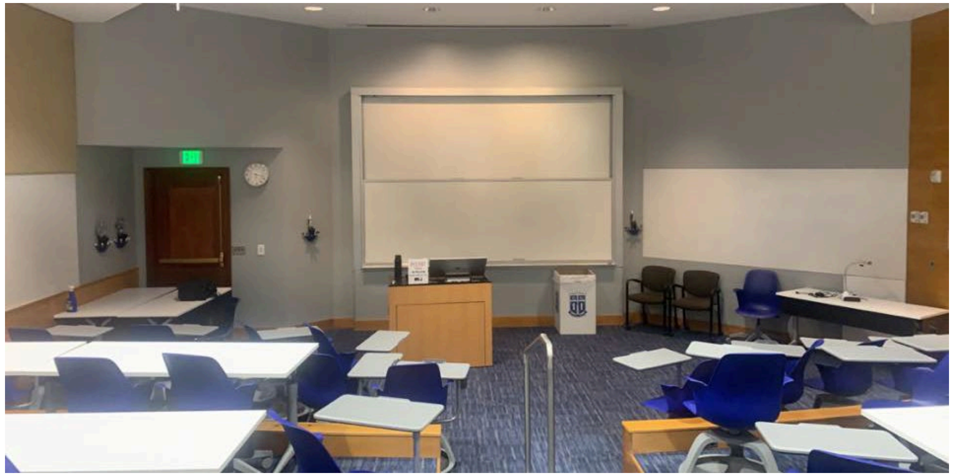
ISE 589-006: INTRODUCTION TO MODERN INDUSTRIAL AUTOMATION

LECTURE 001
Fred Livingston, PhD

LECTURE 1: INTRODUCTION 001

- Introduction
- Course Info
- Concepts of Automation
- Performance Terminology





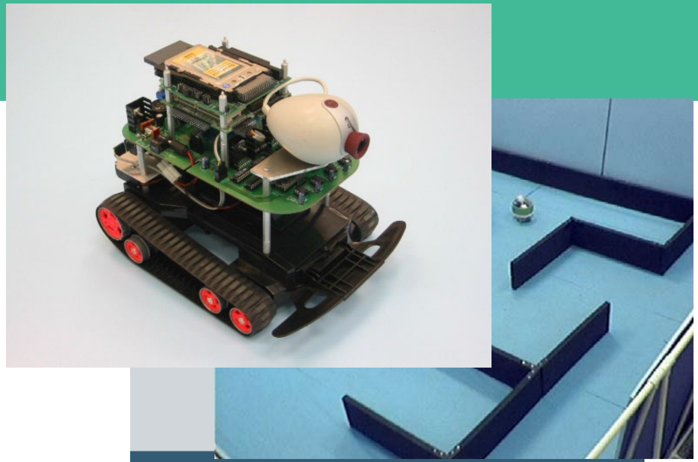
Fred Livingston, Ph.D.

Principle Robotics Engineer (Secmation LLC)

Vice Chair: IEEE ENCS Robotics and Automation Society

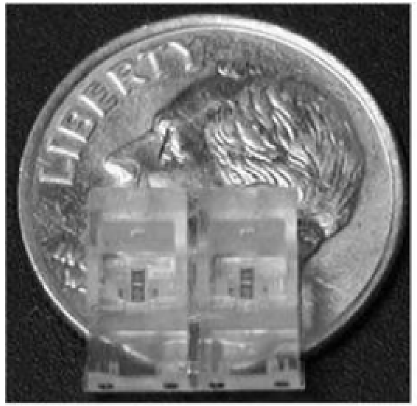
Dr. Livingston is actively involved in robotics for the last 20 years. As a graduate of the Center for Robotics and Intelligent Machines, North Carolina State University. His main research goal is communication, command, and control of unmanned vehicles. This work laid the foundation for machine-learning control models developed from Human-Machine Interactions. Livingston led the mechanical, electrical, and firmware/software components system design and manufacturing for a fleet of unmanned aerial systems as a post-doctoral fellow. This post-doctoral resulted in the development of Olaris AEVA, a remotely operated aircraft. In 2018, Livingston joined MechaSpin to developed perception systems using 3D Lidar. This research aid the result of an autonomous ship-to-ship mooring for the Office of Naval Research. Since 2021, under Secmation, Livingston has focused on developing security solutions for unmanned systems. Livingston is currently developing a platform for the rapid design and development of secure modular unmanned systems.

ABOUT ME

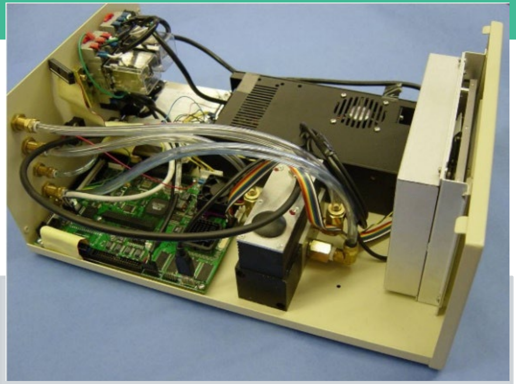


2000 — Undergrad Research – Robot Colony, Human Machine Interaction

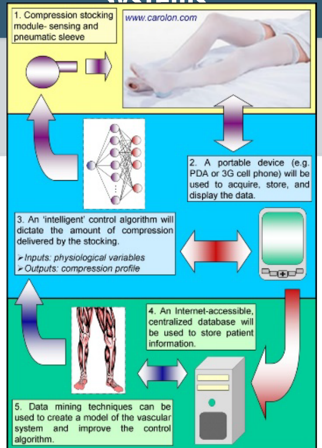
2004 — Advance Manufacturing



2006 — Internet Addressable Pneumatic Control System

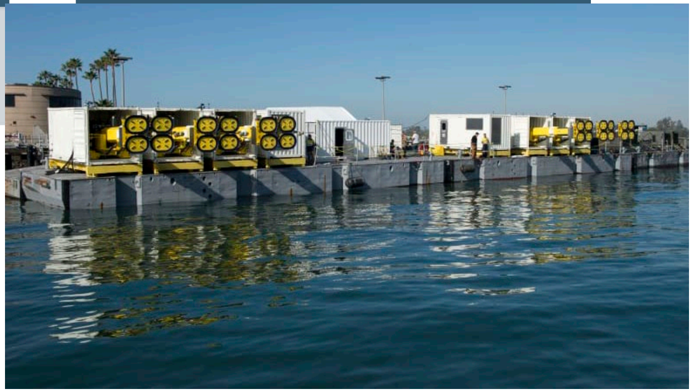


2014 — Ambulatory Health-Monitoring Systems

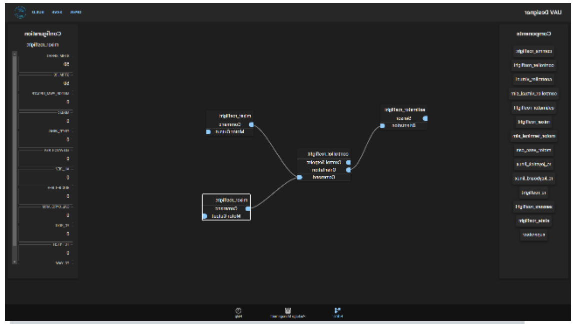


2017 — AEVA

2020 — Autonomous Ship-to-Ship Mooring

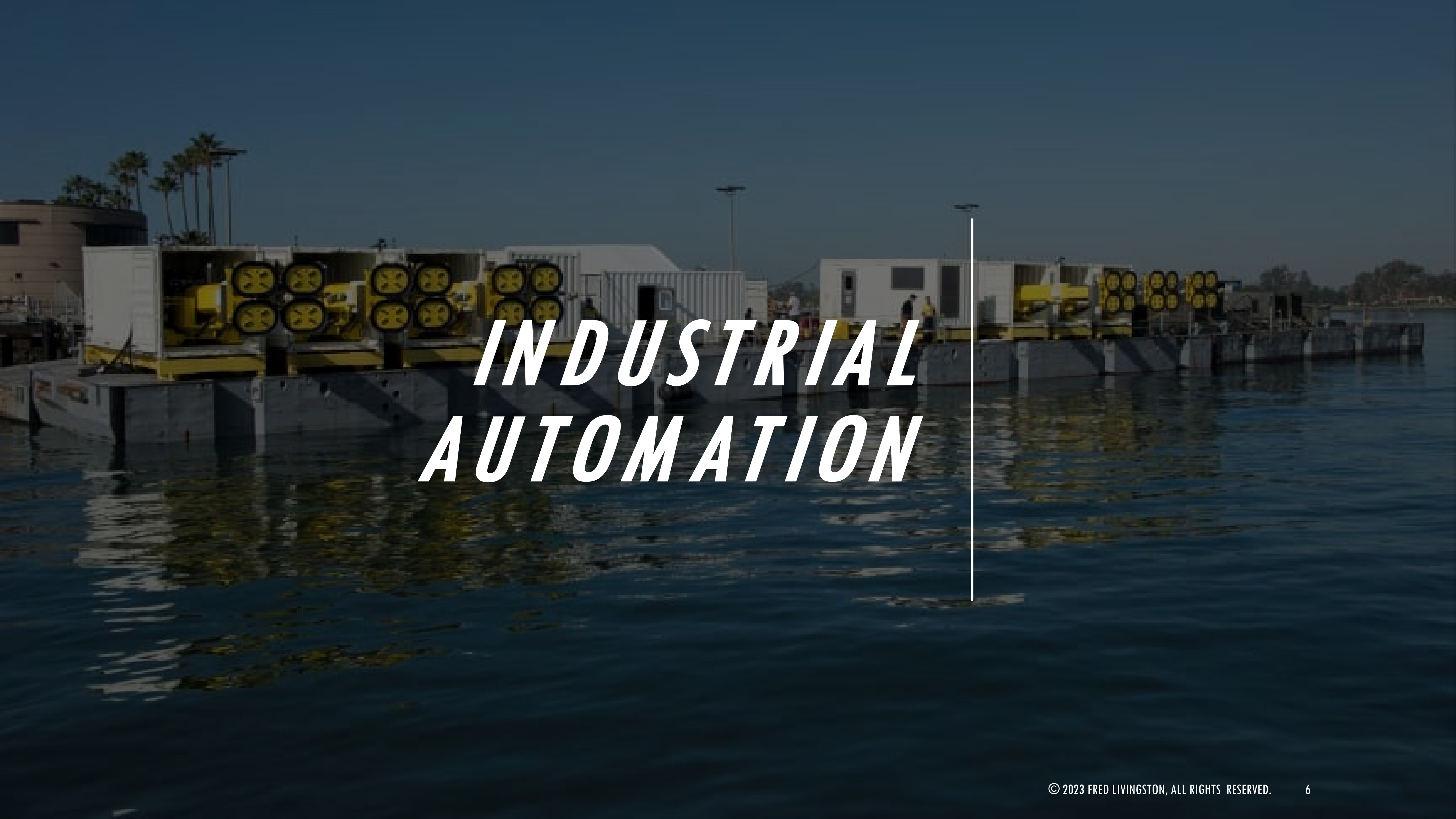


2022 — Secured Open-Source Architectures



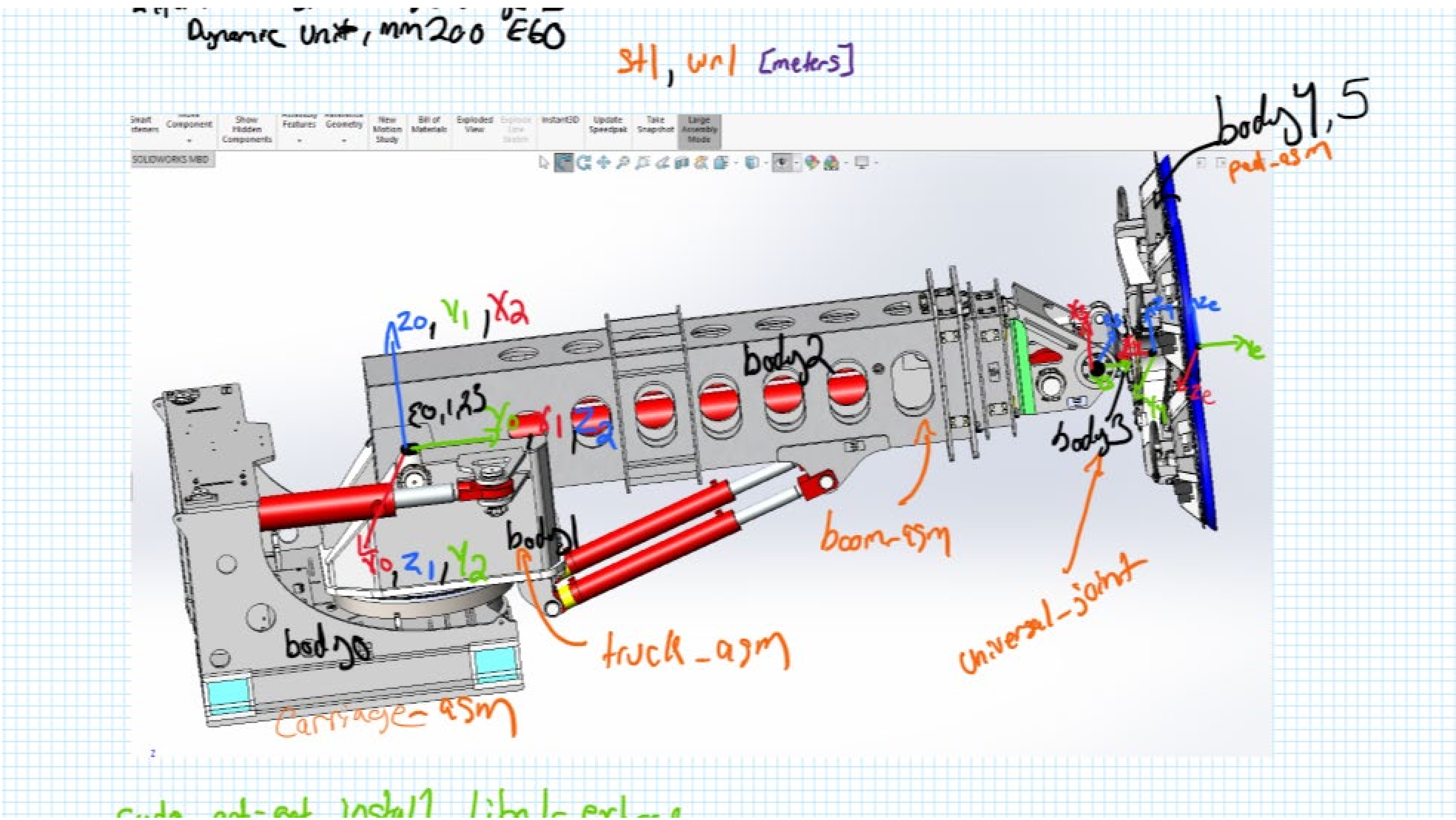
CONTACT INFO

- Fred Livingston, PhD
  - fjliving@ncsu.edu
  - 919.795.4710 (Feel free to call or text)
  - Office Hours: TBA

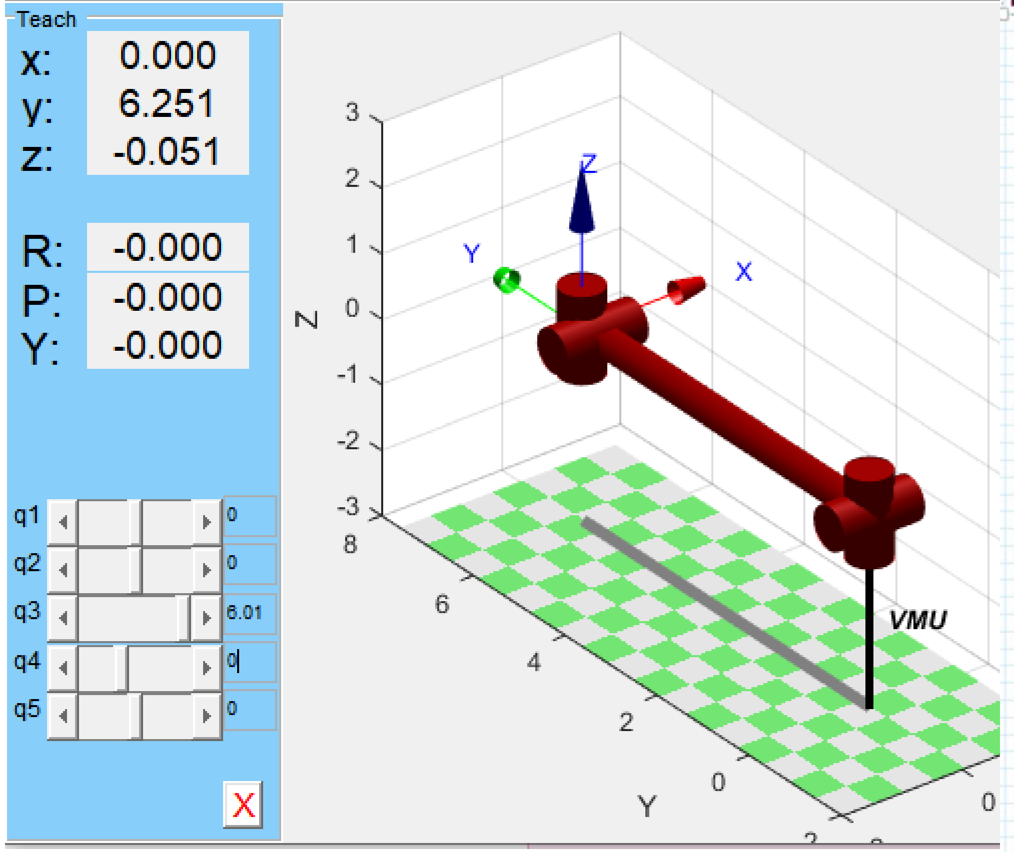


INDUSTRIAL AUTOMATION

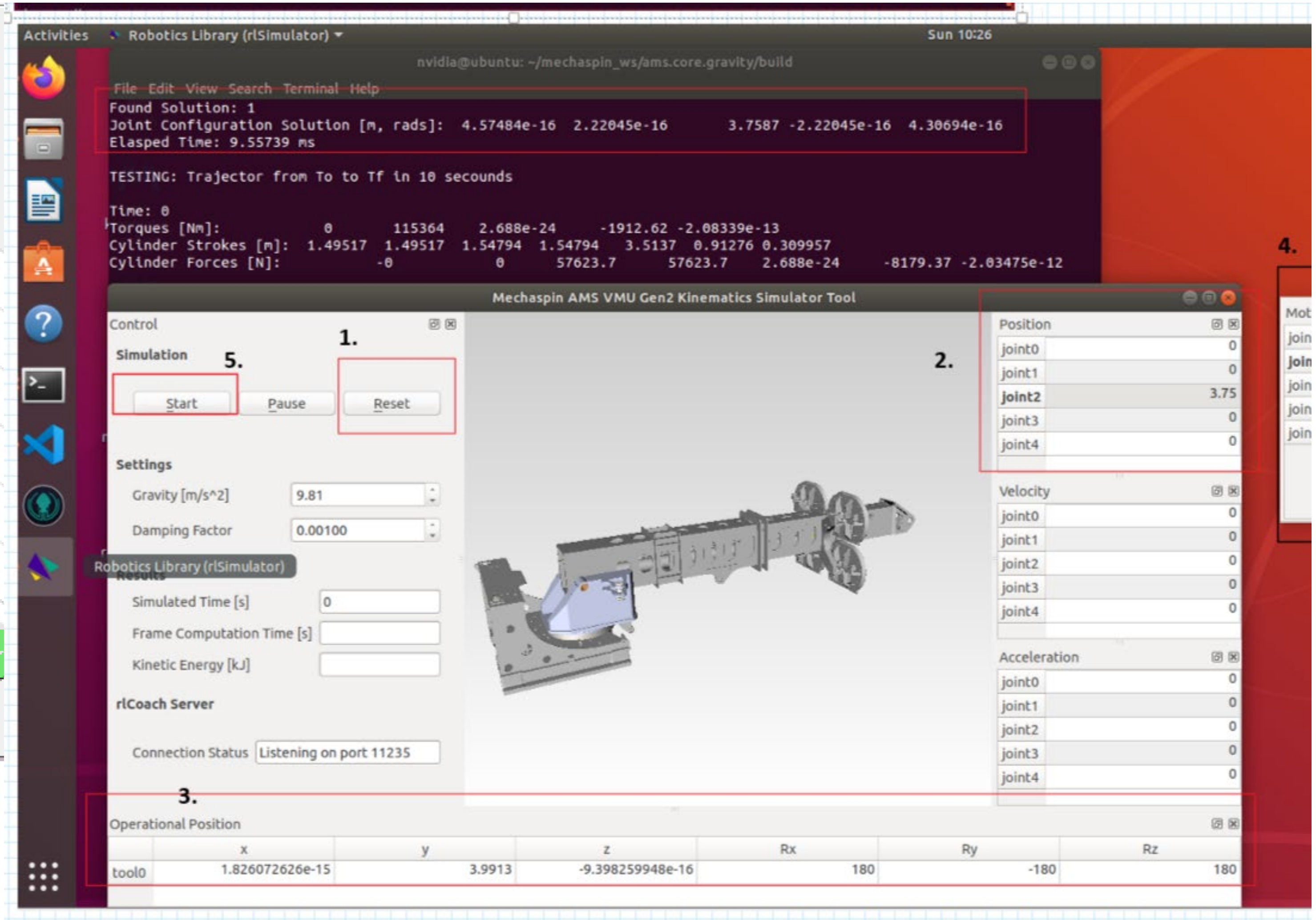
MODELING AND SIMULATION



MODELING

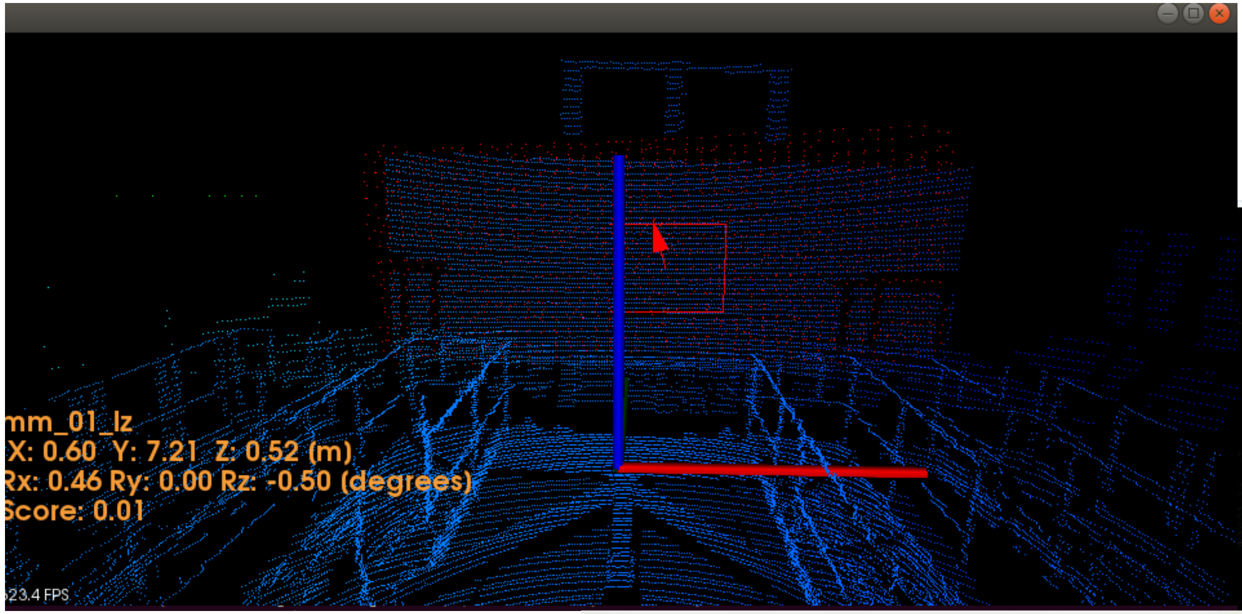


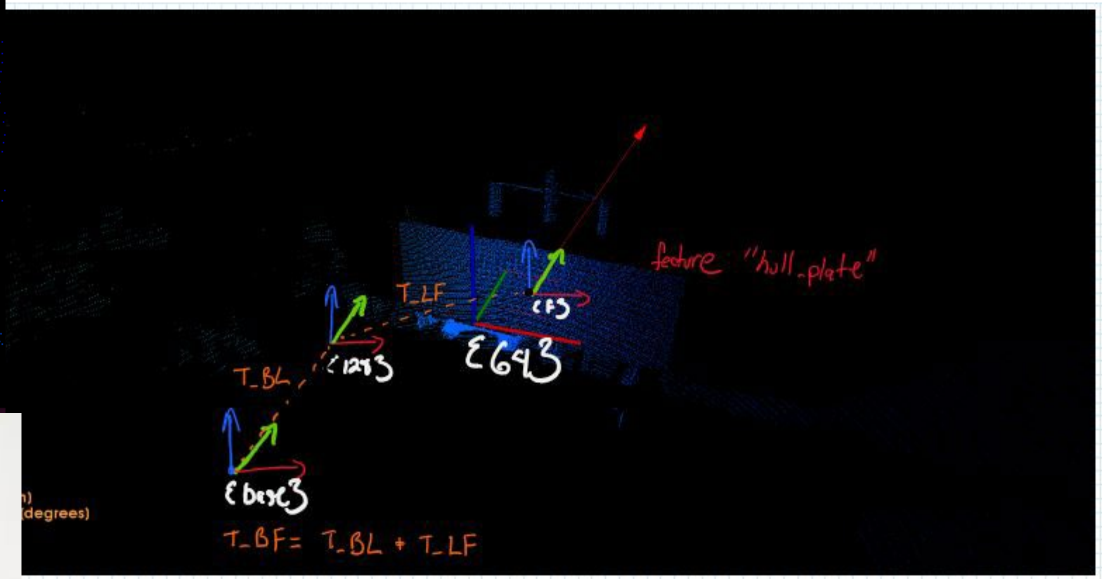
- MATLAB / SIMULINK



- C++, QT (Simulation-In-Loop)

REAL-TIME 3D POSE DETECTION





COMMAND AND CONTROL

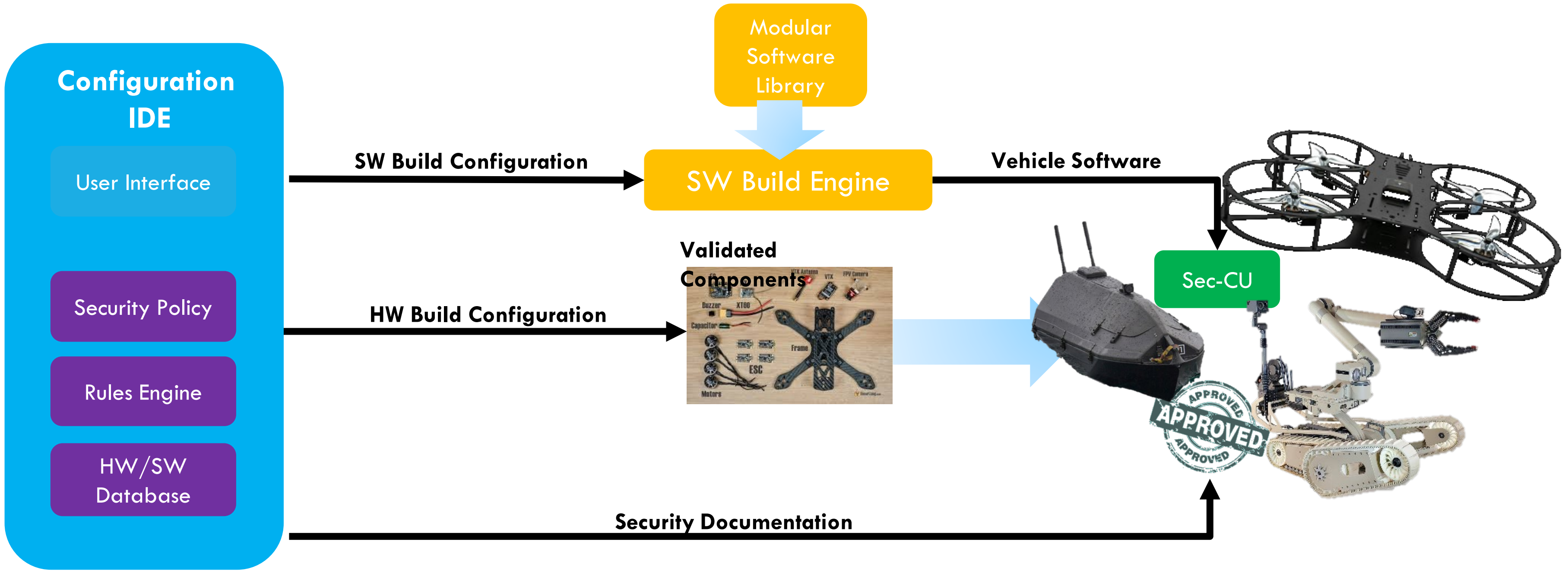
- SICK Flexi Soft Controller
- Modular & Configurable
- Controller
- Ethernet/IP
- Digital IO
- Relay Module

- Hydraulic System
- Output: 4-20 mA Proportional Valves
- Inputs: Pressure Transducers
  - Time of Flight Sensors
  - IMU
  - LiDAR
  - LVDTS

- Processing Units
  - SICK Safety PLC (E-stops, Heartbeats, Loss of Signals, DOS) – ETHERNET/IP
  - Allen-Bradley (Hydraulic) -ETHERNET/IP
  - Xavier (Machine Control, Scanning Tracking) - ETHERNET/IP

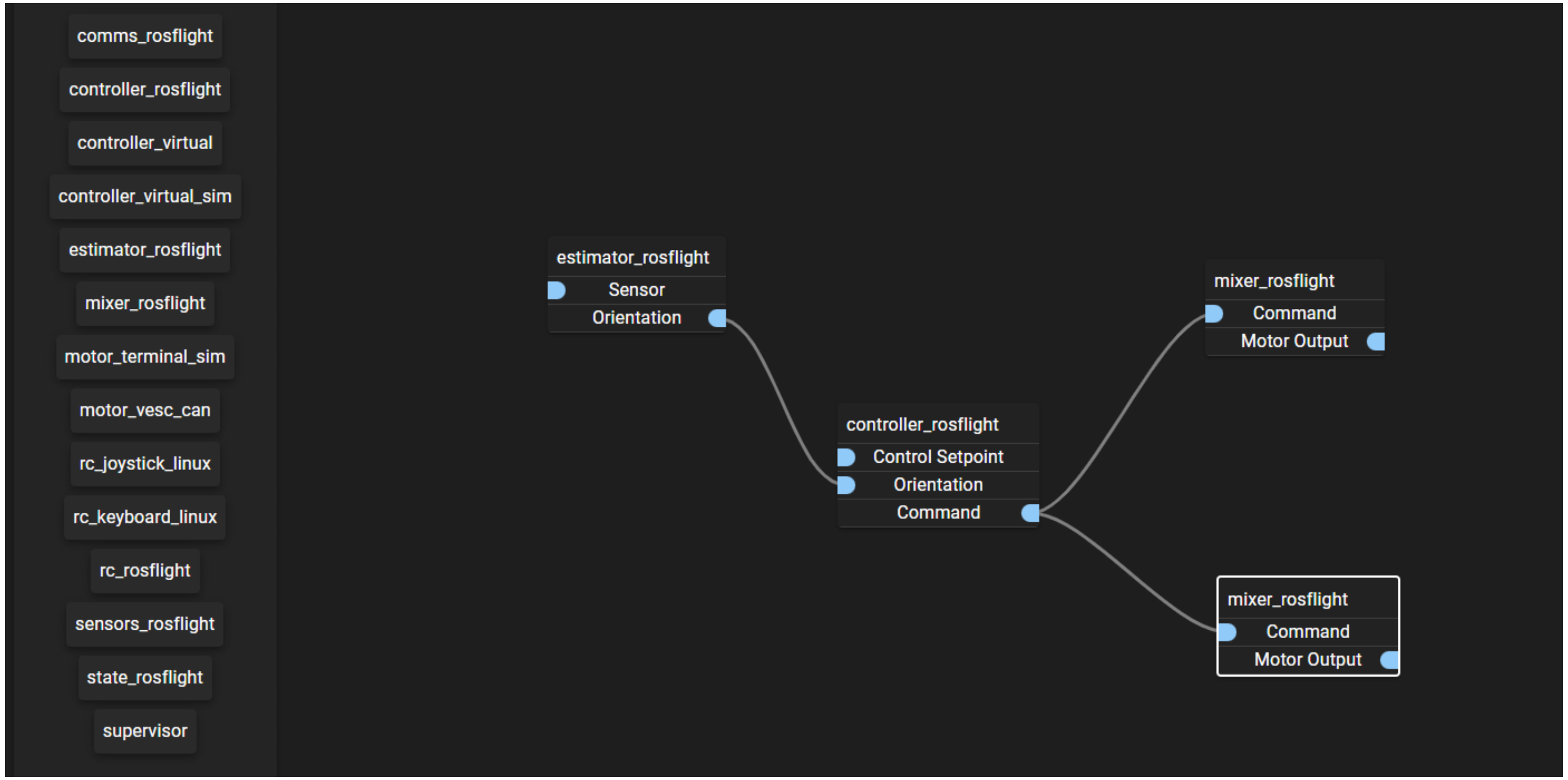
SHIP MOTION TRACKING

RAPID DEVELOPMENT OF UXS



SecMUAS technology can be used to create secure control systems for all domains of unmanned systems

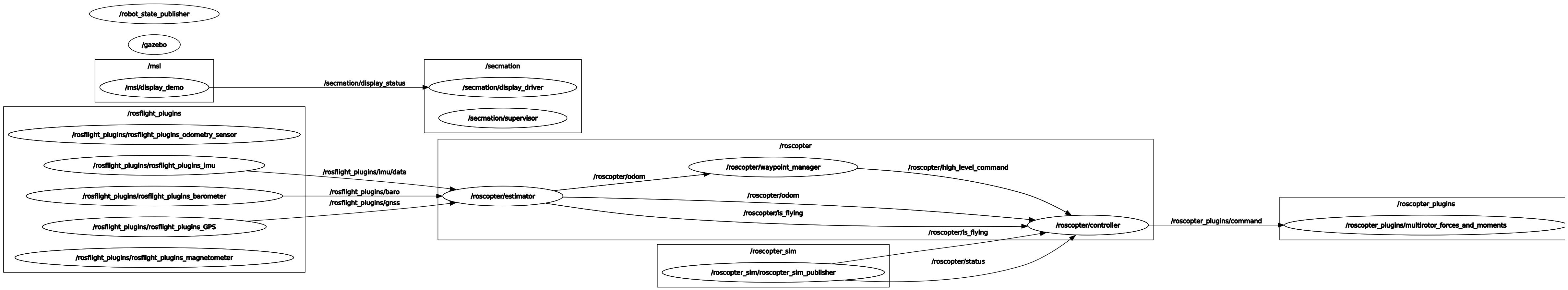
CONFIGURATION IDE



IDE provides an easy to use, drag and drop interface for creating control systems and allows the user to build control software with security in mind by only allowing access to system resources that are configured by the user

FIELD-UNITS/EDGE-COMPUTING

MODULAR SOFTWARE COMPONENTS



Features:

ROS2 (Mixed C++/Python) Nodes

Real-Time Control System

Hardware/Software Isolation

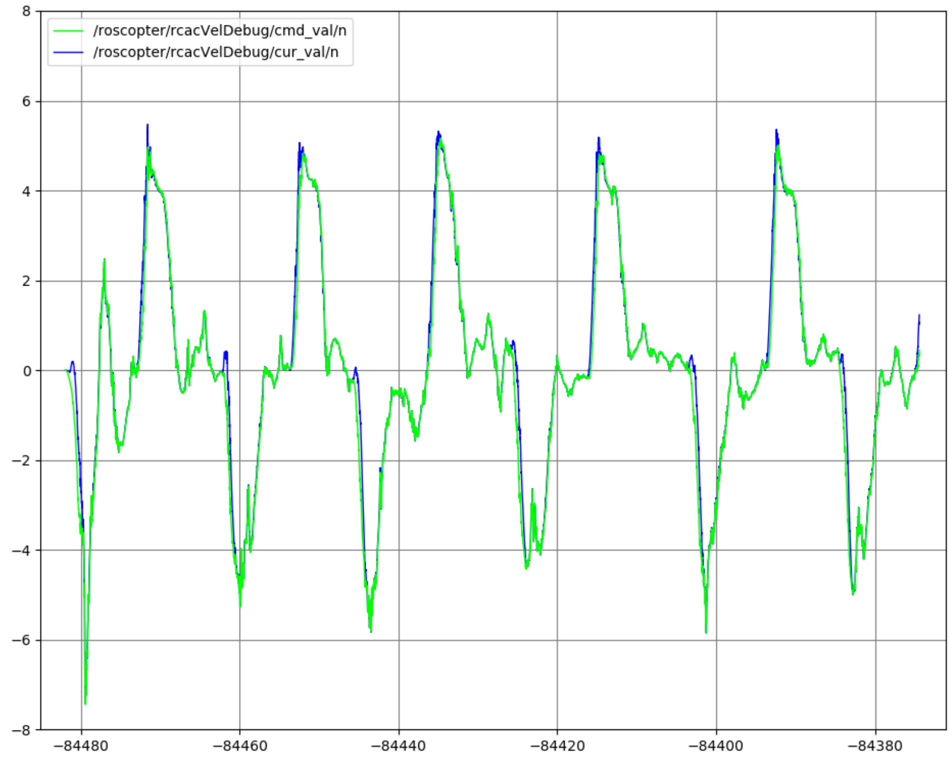
Data Encryptions using hardware and software security

Dockers

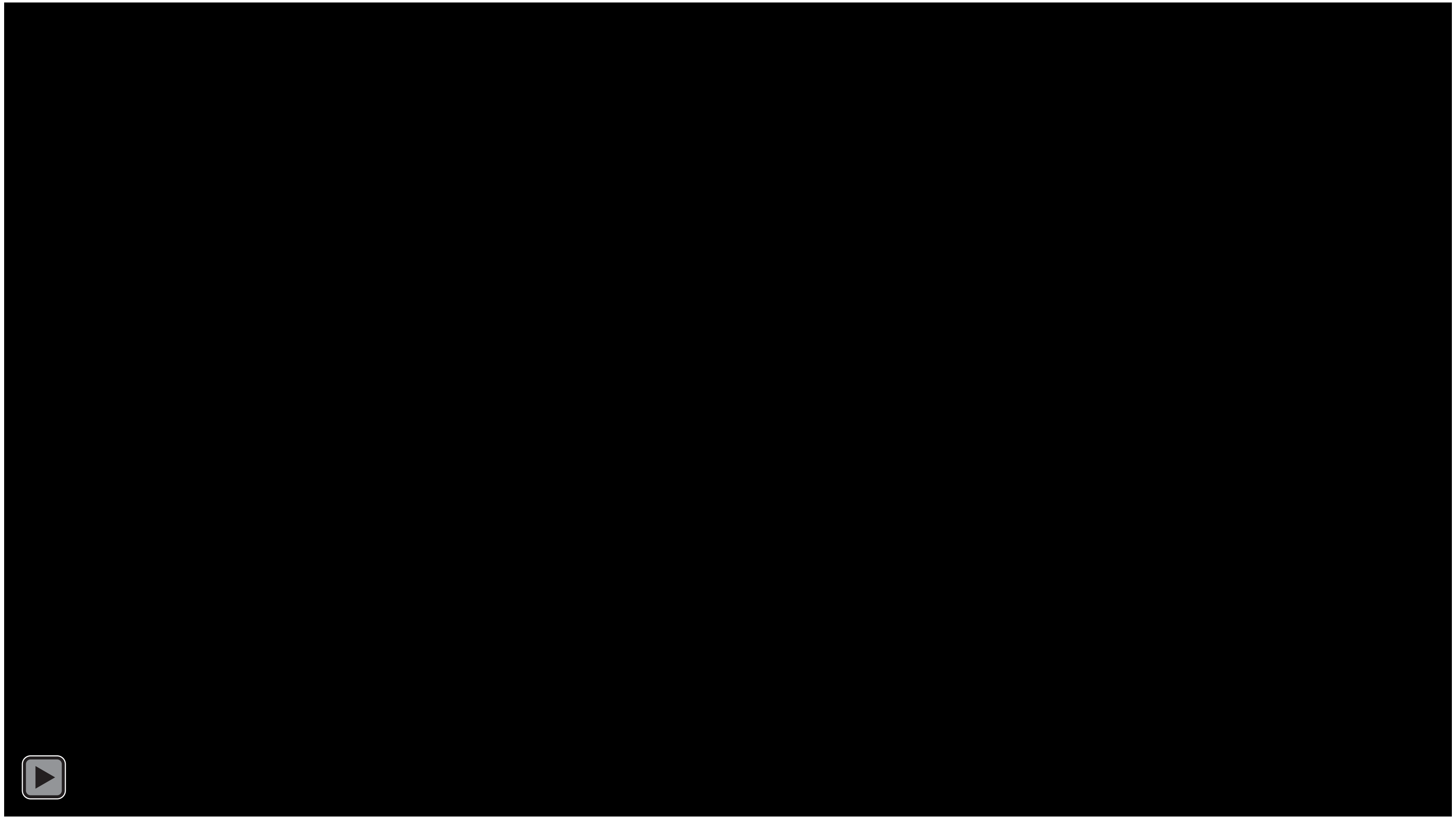
MATLAB/Simulink Integration

SIMULATION

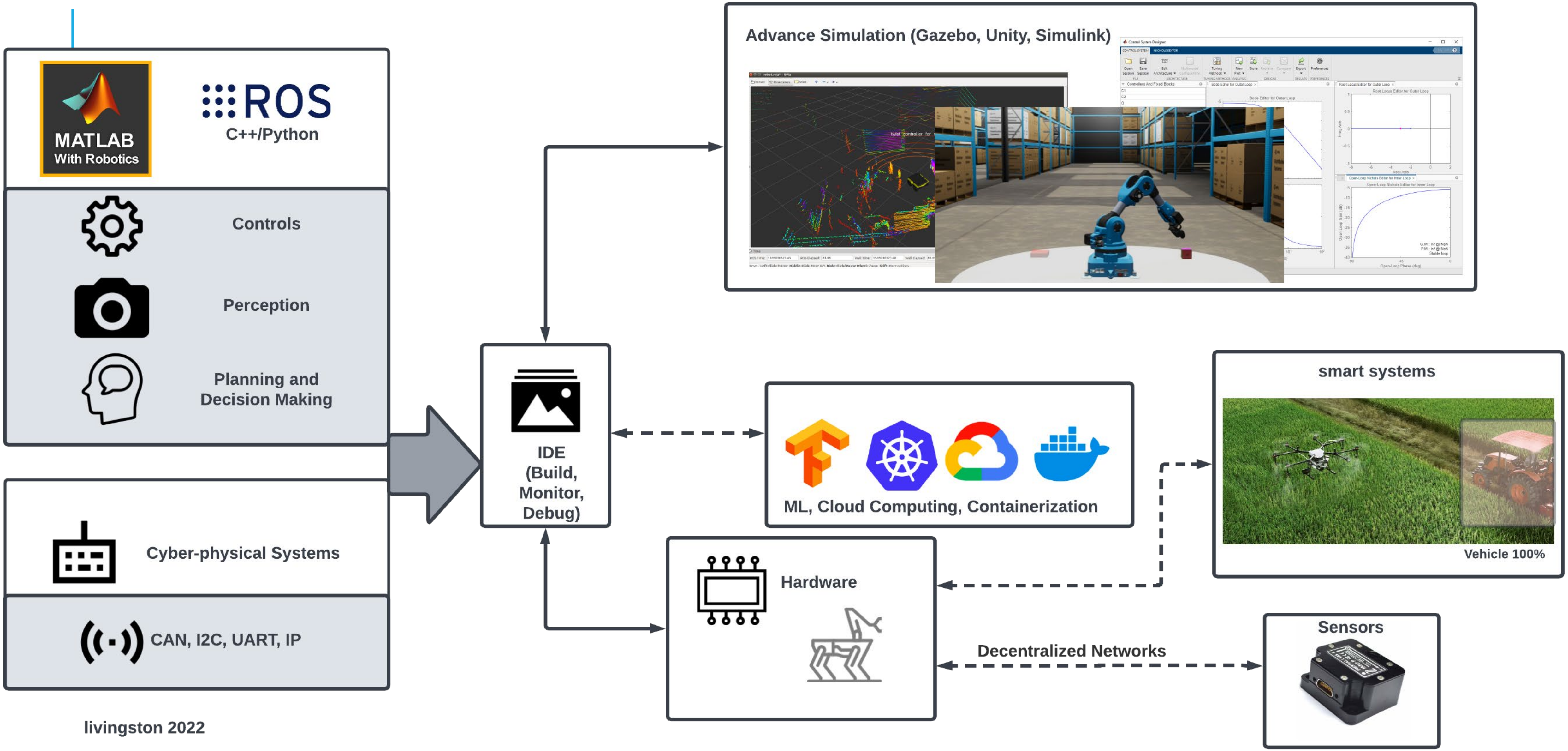
RCAC (Adaptive Control) Attitude, Navigation Coupled N,E,D



PRATICAL EXPERIMENTS

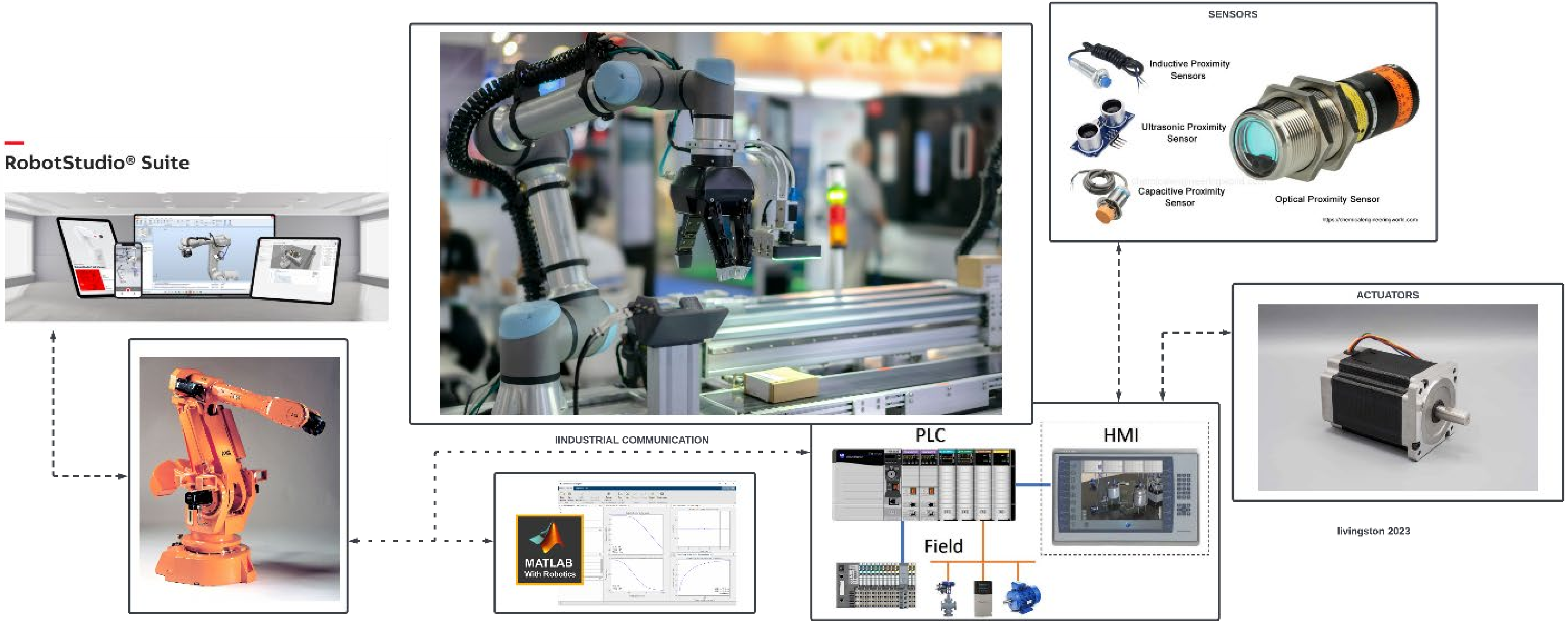


CURRENT RESEARCH OBJECTIVE



livingston 2022

ISE 589-006 COURSE OBJECTIVE



COURSE DESCRIPTION

This course covers industrial automation theory and practice in the modern industrial environment. It is designed to give students a thorough understanding of industrial automation control systems, including programmable logic controllers (PLCs), robot manipulators, sensors, motor drives, and industrial networks to achieve Industrial 4.0. Industrial Automation applications must be developed and demonstrated with modern, data-driven manufacturing systems that collaborate in real time. For instance, a PLC-controlled assembly, combined with data acquisition industrial communication, such as via OPC UA technology, and robotics, such as a robot manipulator properly integrated into the IoT (Internet of Things). Through this collaboration, data can be released in the Core data model exchanged between systems and machines in different locations to provide new opportunities to increase productivity efficiently and cost-effectively. This course will provide the fundamental theory of modern industrial automation, including hands-on laboratory experience and a final course project.

IN-CLASS STUDENT SURVEY

1. Identity Industrial Engineering Students
2. Identity other Departments (EE, CPE, CS, MAE)
3. PCL Experience
4. Robot Manipulators
5. Edge-Computing
6. Machine Learning
7. Computer Vision
8. MATLAB/Simulink
9. Programing Languages
10. Why taking this class?

LEARNING OBJECTIVES

Module 1: Introduction

Module 2: Measurement Systems

- Sensors
- Data Acquisition
- Actuators
- System Modeling

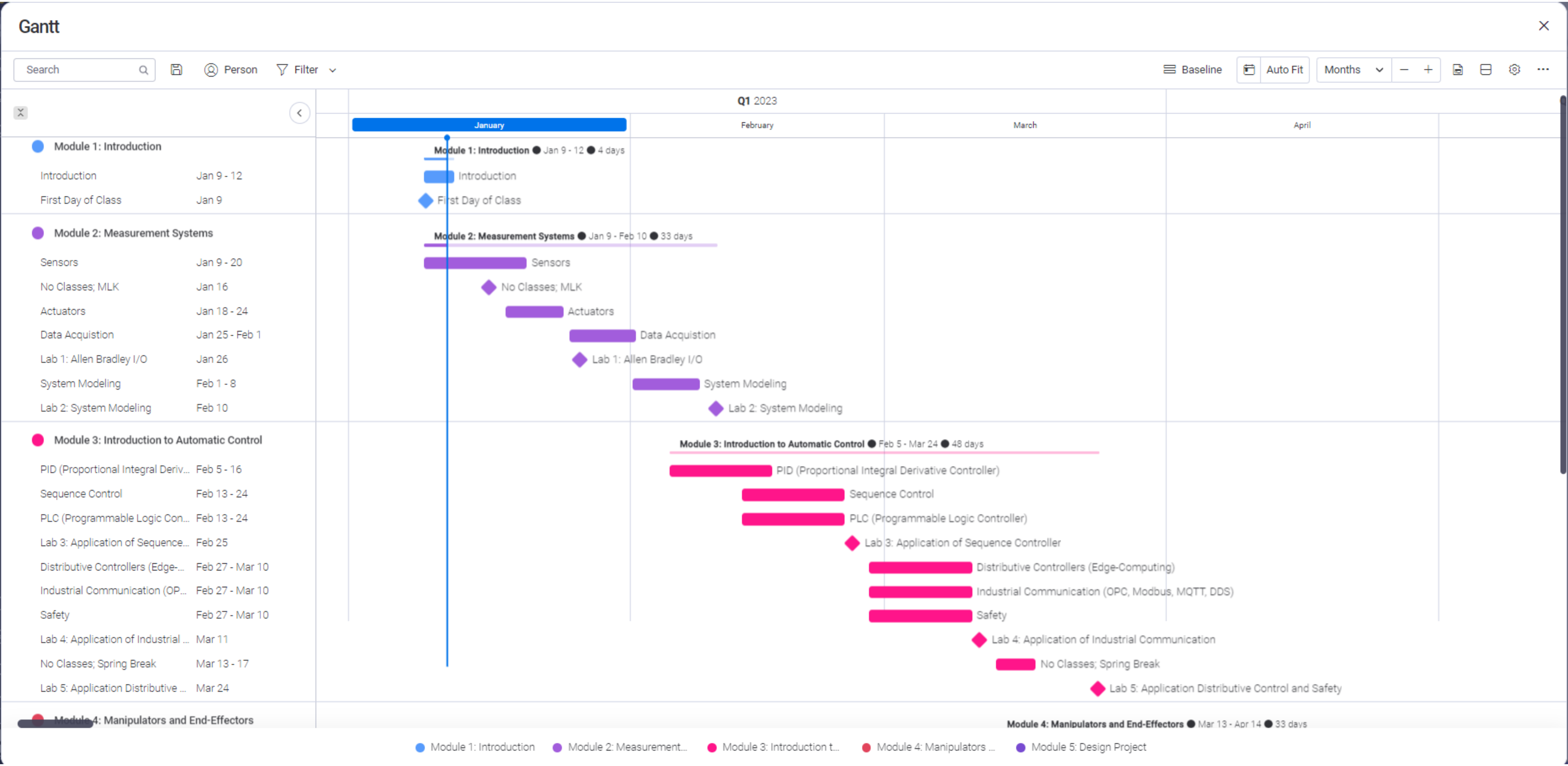
Module 3: Introduction to Automatic Control

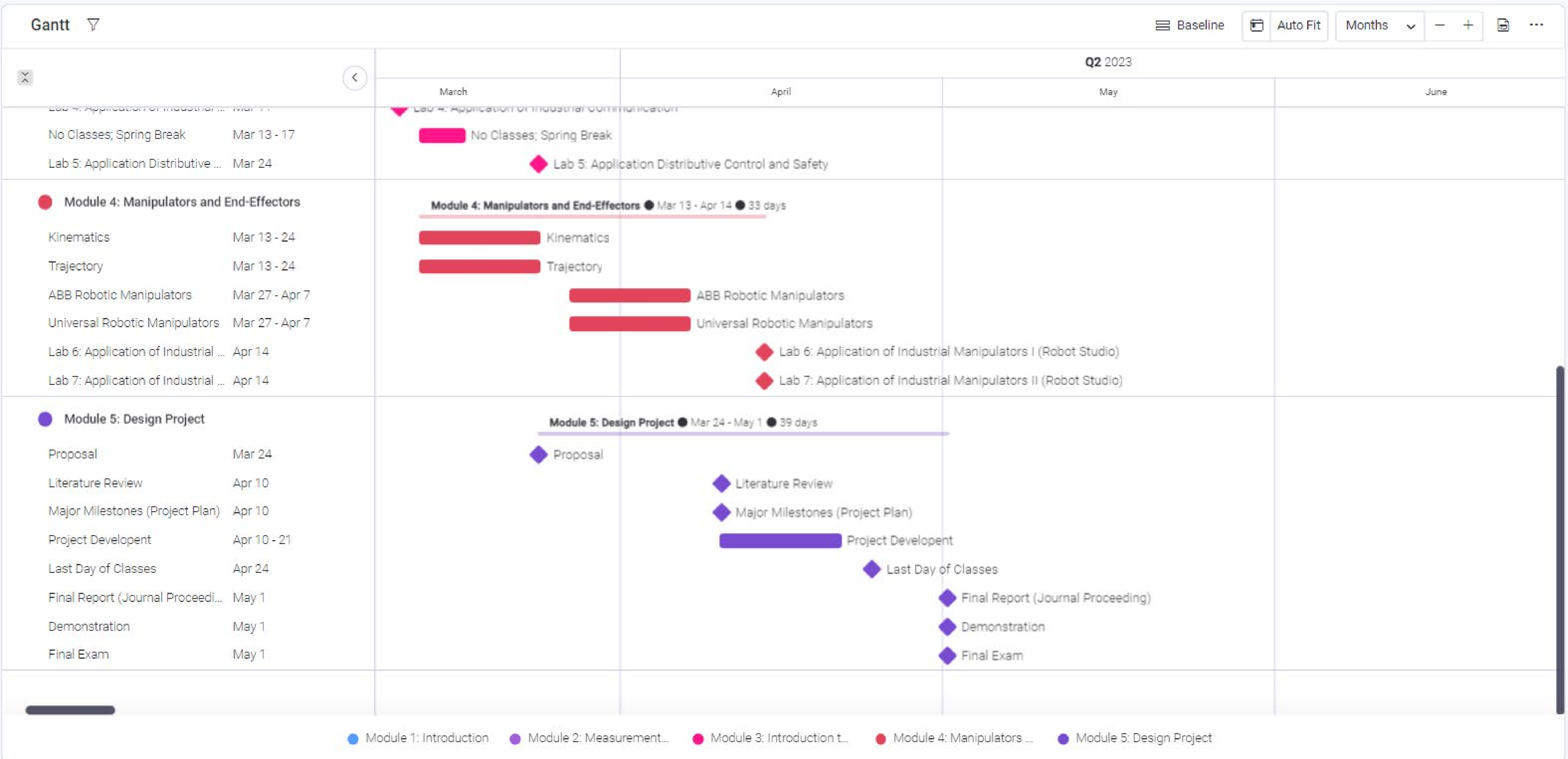
- PID (Proportional Integral Derivative Controller)
- Sequence Control
- PLC (Programmable Logic Controller)
- Distributive Controllers (Edge-Computing)
- Industrial Communication
- Safety

Module 4: Manipulators and End-Effectors

- Kinematics
- Trajectory
- ABB Robotic Manipulators
- Universal Robotic Manipulators

Module 5: Design Project


Gantt
Search
Person
Filter
Baseline
Auto Fit
Months
Q1 2023
January
February
March
April
Module 1: Introduction
Introduction Jan 9 - 12
First Day of Class Jan 9
Module 2: Measurement Systems
Sensors Jan 9 - 20
No Classes; MLK Jan 16
Actuators Jan 18 - 24
Data Acquistion Jan 25 - Feb 1
Lab 1: Allen Bradley I/O Jan 26
System Modeling Feb 1 - 8
Lab 2: System Modeling Feb 10
Module 3: Introduction to Automatic Control
PID (Proportional Integral Deriv... Feb 5 - 16
Sequence Control Feb 13 - 24
PLC (Programmable Logic Con... Feb 13 - 24
Lab 3: Application of Sequence... Feb 25
Distributive Controllers (Edge-... Feb 27 - Mar 10
Industrial Communication (OP... Feb 27 - Mar 10
Safety Feb 27 - Mar 10
Lab 4: Application of Industrial ... Mar 11
No Classes; Spring Break Mar 13 - 17
Lab 5: Application Distributive ... Mar 24
Module 4: Manipulators and End-Effectors
Module 1: Introduction ● Jan 9 - 12 ● 4 days
Introduction
First Day of Class
Module 2: Measurement Systems ● Jan 9 - Feb 10 ● 33 days
Sensors
No Classes; MLK
Actuators
Data Acquistion
Lab 1: Allen Bradley I/O
System Modeling
Lab 2: System Modeling
Module 3: Introduction to Automatic Control ● Feb 5 - Mar 24 ● 48 days
PID (Proportional Integral Derivative Controller)
Sequence Control
PLC (Programmable Logic Controller)
Lab 3: Application of Sequence Controller
Distributive Controllers (Edge-Computing)
Industrial Communication (OPC, Modbus, MQTT, DDS)
Safety
Lab 4: Application of Industrial Communication
No Classes; Spring Break
Lab 5: Application Distributive Control and Safety
Module 4: Manipulators and End-Effectors ● Mar 13 - Apr 14 ● 33 days
Module 1: Introduction
Module 2: Measurement...
Module 3: Introduction t...
Module 4: Manipulators ...
Module 5: Design Project


Gantt
Baseline
Auto Fit
Months
Q2 2023
March
April
May
June
No Classes; Spring Break Mar 13 - 17
Lab 5: Application Distributive ... Mar 24
Module 4: Manipulators and End-Effectors
Kinematics Mar 13 - 24
Trajectory Mar 13 - 24
ABB Robotic Manipulators Mar 27 - Apr 7
Universal Robotic Manipulators Mar 27 - Apr 7
Lab 6: Application of Industrial ... Apr 14
Lab 7: Application of Industrial ... Apr 14
Module 5: Design Project
Proposal Mar 24
Literature Review Apr 10
Major Milestones (Project Plan) Apr 10
Project Developent Apr 10 - 21
Last Day of Classes Apr 24
Final Report (Journal Proceedi... May 1
Demonstration May 1
Final Exam May 1
No Classes; Spring Break
Lab 5: Application Distributive Control and Safety
Module 4: Manipulators and End-Effectors Mar 13 - Apr 14 33 days
Kinematics
Trajectory
ABB Robotic Manipulators
Universal Robotic Manipulators
Lab 6: Application of Industrial Manipulators I (Robot Studio)
Lab 7: Application of Industrial Manipulators II (Robot Studio)
Module 5: Design Project Mar 24 - May 1 39 days
Proposal
Literature Review
Major Milestones (Project Plan)
Project Developent
Last Day of Classes
Final Report (Journal Proceeding)
Demonstration
Final Exam
Module 1: Introduction
Module 2: Measurement...
Module 3: Introduction t...
Module 4: Manipulators ...
Module 5: Design Project

COURSE REQUIREMENTS

Pre-requisite

- NONE: This is an introductory course presenting broad topics related to Industrial 4.0, automation, and robotics

Requirements

Willing to work on hands-on assignments and laboratory in a group environment.

Optional
- basic MATLAB/SIMULINK
- basic PLC Knowledge
- Robot manipulators
- Edge-Computing

LABS

Lab1 - Allen Bradley I/O

Lab 2 - System Modeling using Simulink

Lab 3 - Application of Sequence Controller

Lab 4 - Application of Industrial Communication Protocol

Lab 5 - Application of Disruptive Control and Safety

Lab 6 - Application of Industrial Manipulators I

Lab 7 - Application of Industrial Manipulator II

PROJECTS

Semester group project demonstrating interaction with one or more industrial automation process. Example: robot manipulator(s) interacting with PLC or external sensors using an industrial communication protocol.

More to come later!

TOOLS

ABB Robotics

https://new.abb.com/products/robotics/robotstudio

MATLAB/Simulink

https://www.mathworks.com/products/industrial-communication.html

https://www.mathworks.com/products/control.html

Connected Component Workbench

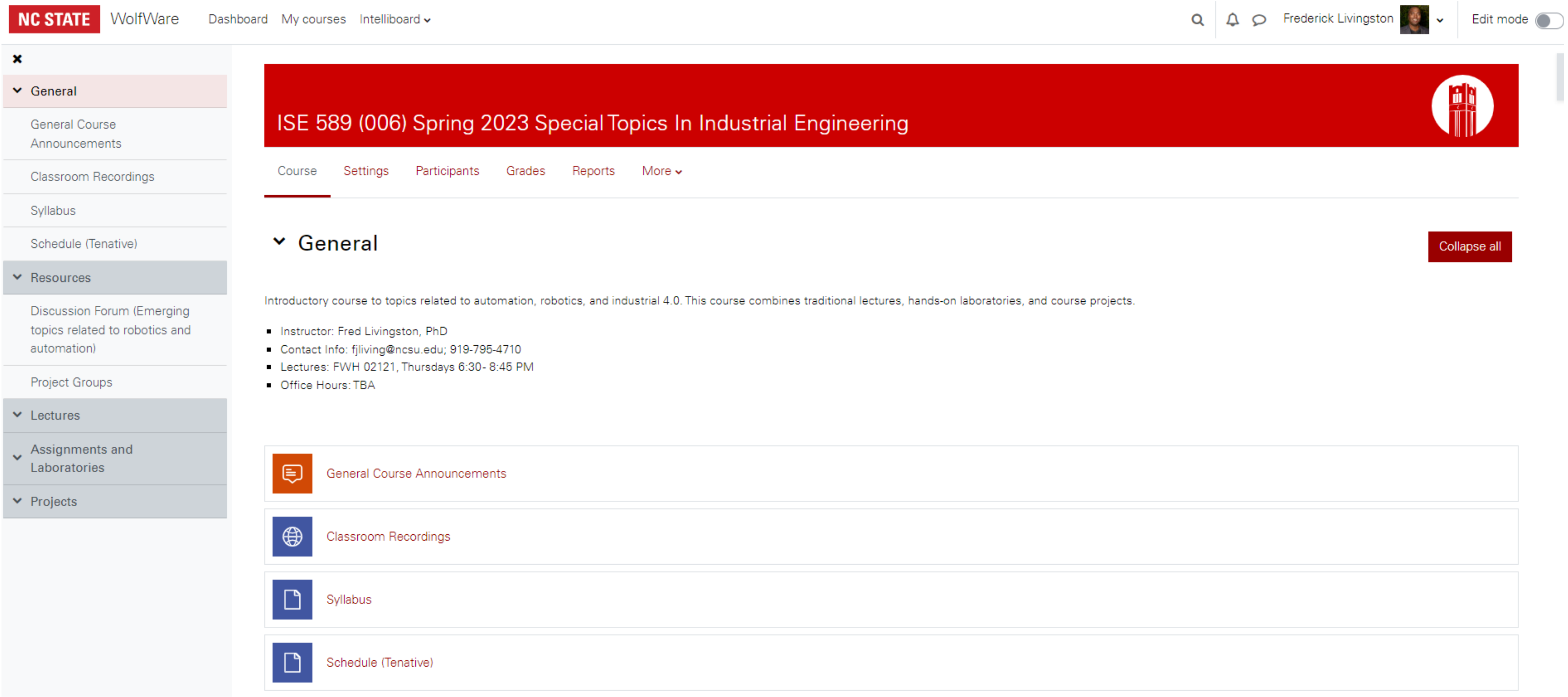
https://www.rockwellautomation.com/en-us/capabilities/industrial-automation-control/design-and-configuration-software.html

GRADING

	Weight
Assignments	10%
Labs	35%
Midterm Exam	10%
Project	
Proposal	5%
Literature Review	5%
Major Milestones (Project Plan)	10%
Final Report (Journal Proceeding)	15%
Demonstration	10%

COURSE SITE

All course materials will be posted on the [ISE 589-006 Moodle site]:



LECTURE STRUCTURE

Weekly 2.5 In class Instructions + additional outside of class activities

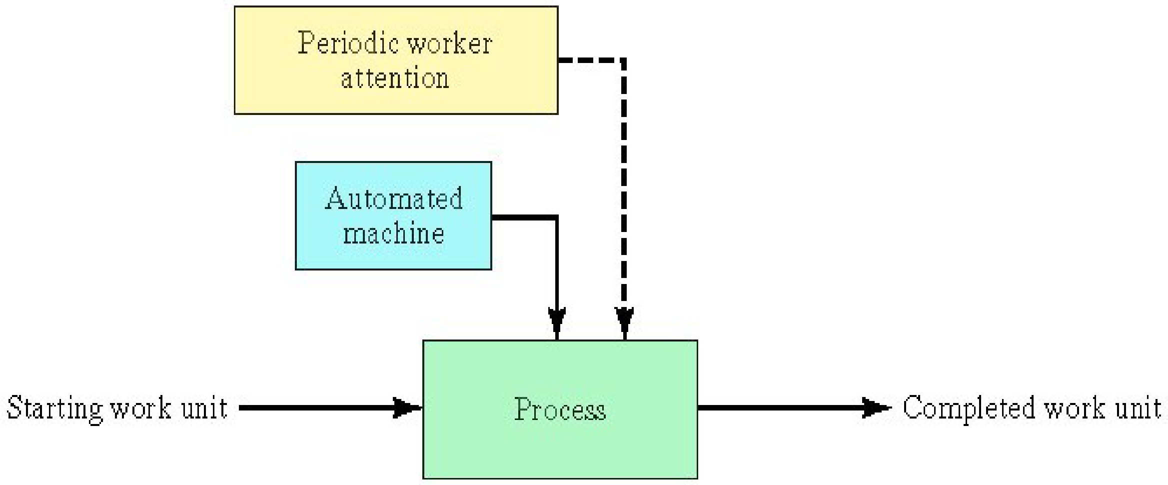
Typical Structure

- Traditional Lecture
- Break
- Laboratory related to lecture or project time

- Weekly Discussion on Emerging Topics related to Automation and Robotics

AUTOMATED SYTEMS

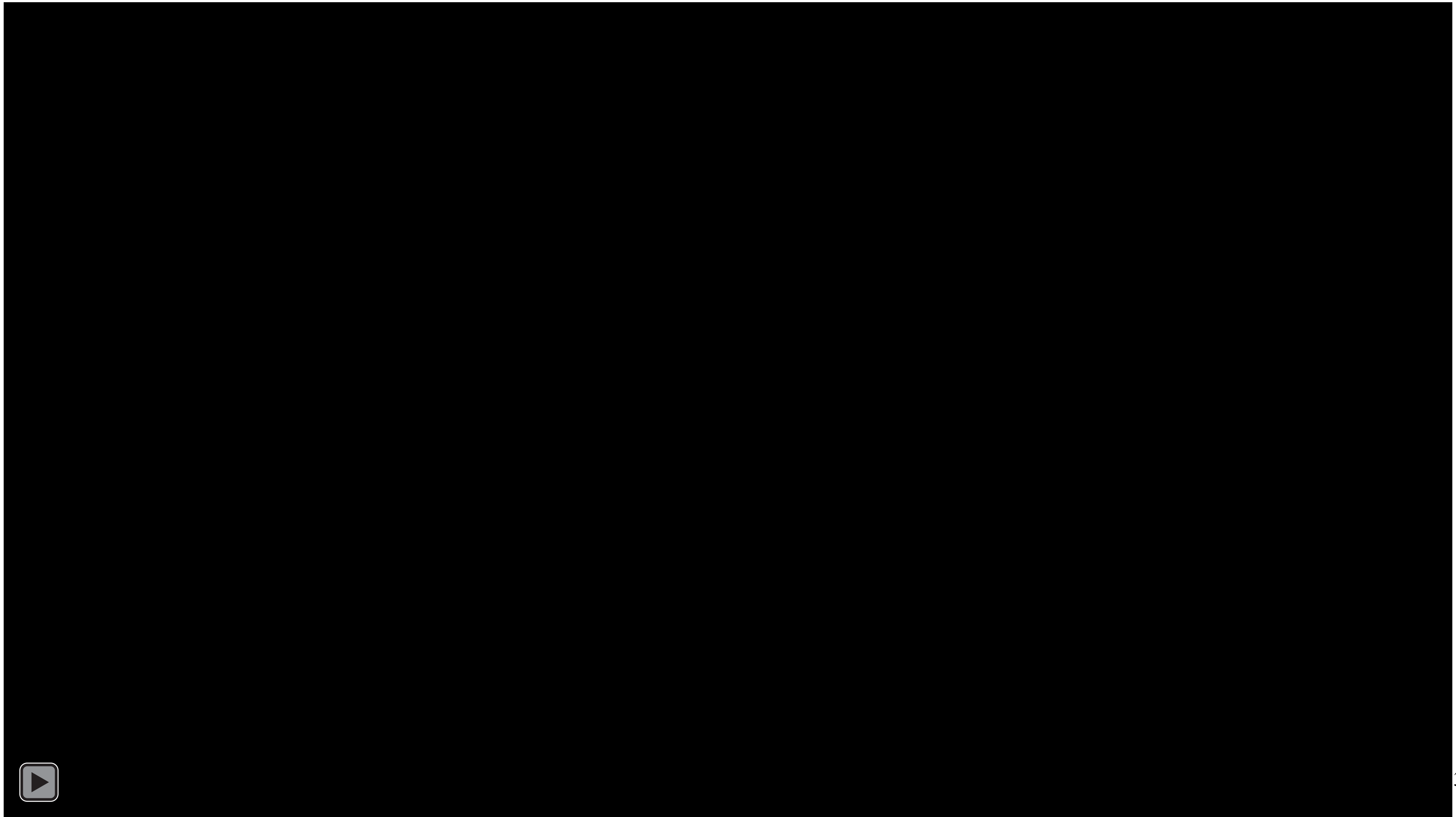
Automated systems - a process performed by a machine without direct participation of a human



Automation example: Automated warehouse

https://www.youtube.com/watch?v=Elaw716w1_0

AUTOMATED WAREHOUSE



DISCRETE VS. CONTINUOUS AUTOMATION

Discrete Automation

- Finite number of discrete steps
- Parts and products are separable entities

Continuous Automation

- Continuous process

INDUSTRIAL AUTOMATION

Uninterrupted automatic process

A collection of mechanical, electrical, and electronic components coupled together to perform one or more task

In general, the process of following a predetermined sequence of operations with little or no human labor, using specialized equipment and devices that perform and control processes

AUTOMATION EXAMPLE

Automated machine tools

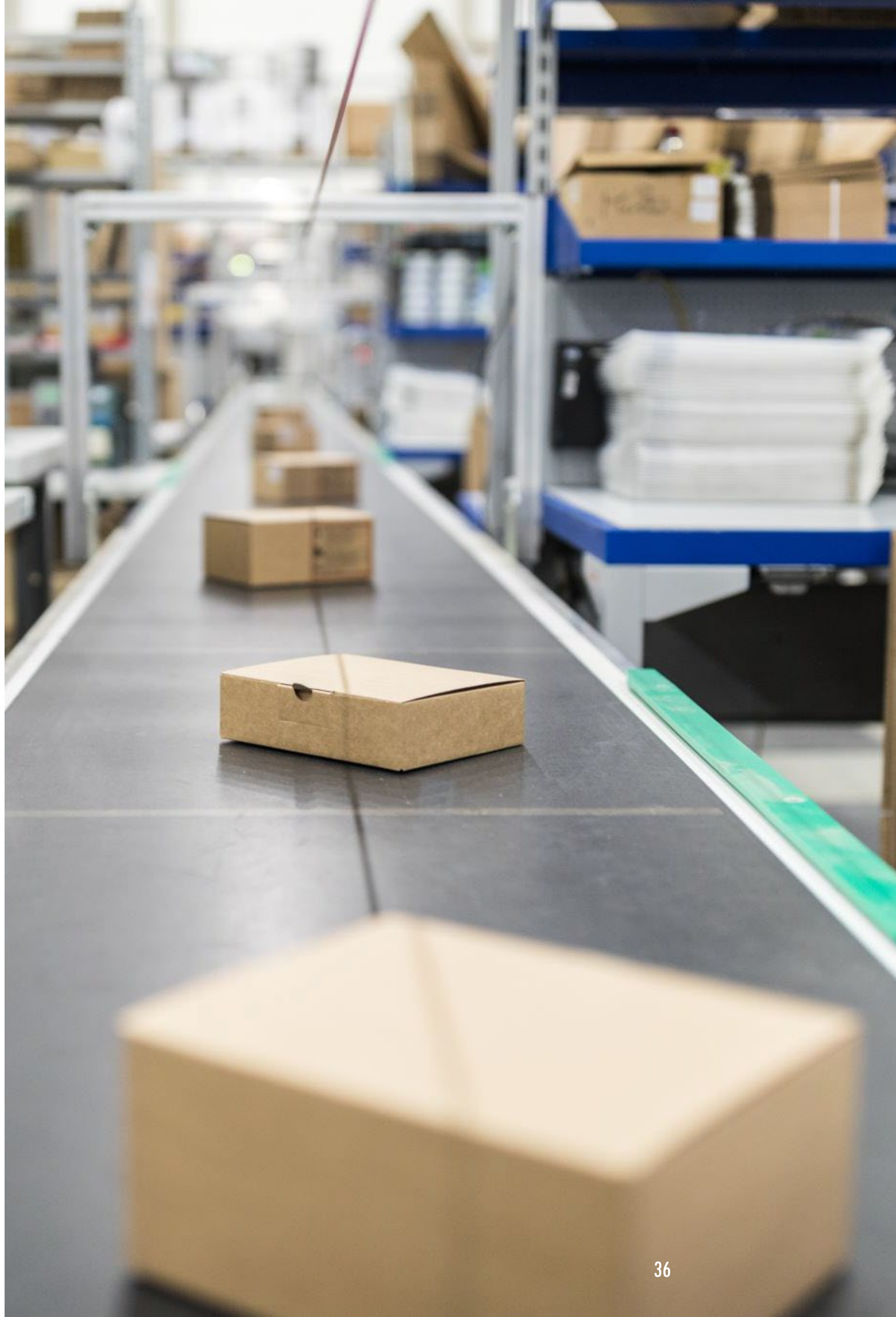
Transfer line

Assembly systems

Industrial robots performing processing or assembly operations

Automated material handling and storage systems

Automatic inspection and quality control



AUTOMATION TYPES

Fixed Automation

Programmable Automation

Flexible Automation

FIXED AUTOMATION

Multiple machines or workstations are linked together by handling devices that transfer parts between stations

Sequence of processing/assembly operation is fixed by the equipment configuration

Typical features:

- High production quantities
- High initial investment for custom-engineered equipment
- High production rates
- Relatively inflexible in accommodating product variety

PROGRAMMABLE AUTOMATION

System designed with the capability to change the sequence of operations to accommodate different configurations

Typical features:

- High investment in general purpose equipment
- Flexibility to deal with variations and changes in configuration
- Most suitable for batch production
- Physical setup and part program must be changed between jobs (batches)
- Lower production rates than fixed automation

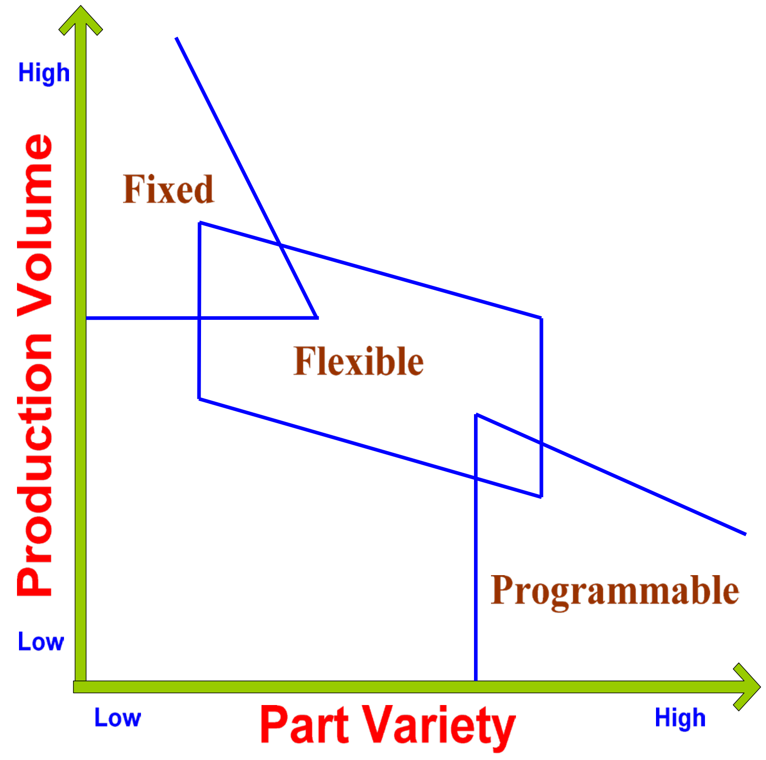
FLEXIBLE AUTOMATION

An extension of programmable automation in which the system is capable of changing over from one job to the next with no lost time between jobs

Typical features:

- High investment for custom-engineered systems
- Continuous production of variable mixes of products
- Most suitable for batch production
- Medium production rates
- Flexibility to deal with soft product variety

TYPES OF AUTOMATION



WHY AUTOMATE?

- Increase labor productivity
- Reduce labor cost
- Alleviate the adverse effects of labor shortage
- Reduce or eliminate routine manual tasks
- Improve safety
- Improve product quality
- Increase production rate
- Reduce in-process inventory
- Reduce manufacturing lead time
- Reduce material handling cost and time
- Overcome the limitation of manual labor

INDUSTRIAL AUTOMATION

END OF THE 18TH CENTURY	START OF THE 20TH CENTURY	START OF THE 1970S	PRESENT
INDUSTRY 1.0 **Mechanization**	**INDUSTRY 2.0** **Electrification**	**INDUSTRY 3.0** **Automatization**	**INDUSTRY 4.0** **Cyber-Physical Systems**
Introduced mechanization of production by using water and steam to increase production capacity and productivity, versus manual craft work	Introduced labor-based mass production (assembly lines) powered by electrical energy	Introduced electronics and computers to replace manual work by stand-alone robotic systems	The convergence of physical, digital, and virtual environments through **Cyber-Physical Systems (CPS)** and the **Internet of Things (IoT)**
1784 First mechanical loom	**1870** First production line, Cincinnati slaughterhouses	**1969** First programmable logic controller (PLC), Modicon 084	

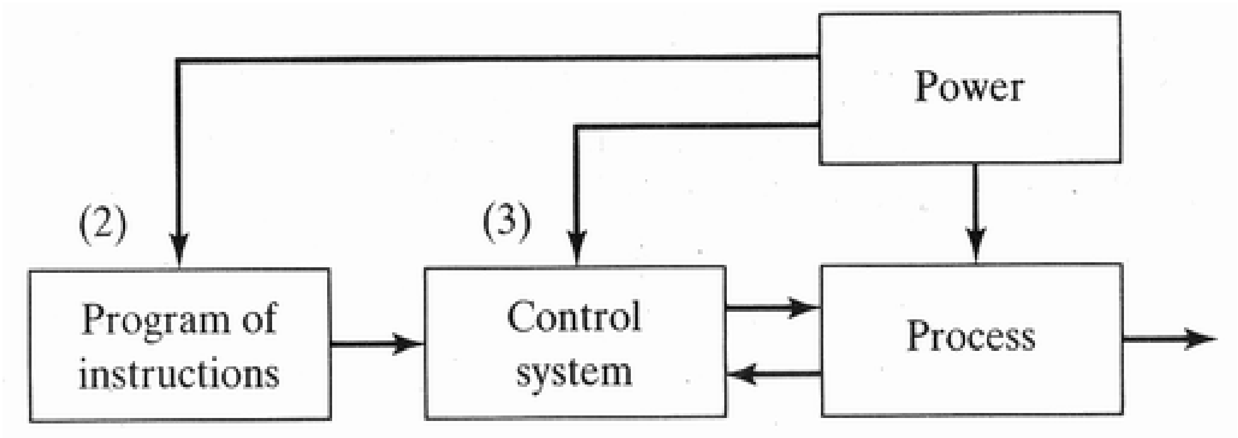
INDUSTRIAL 4.0

INDUSTRIAL AUTOMATION DESIGN PROBLEM

- **Task to design and control a conveyor system to move an object at user-selected velocity:**
- Power?
- Inputs?
- Outputs?
- Controls?
- **Performance Metrics?**

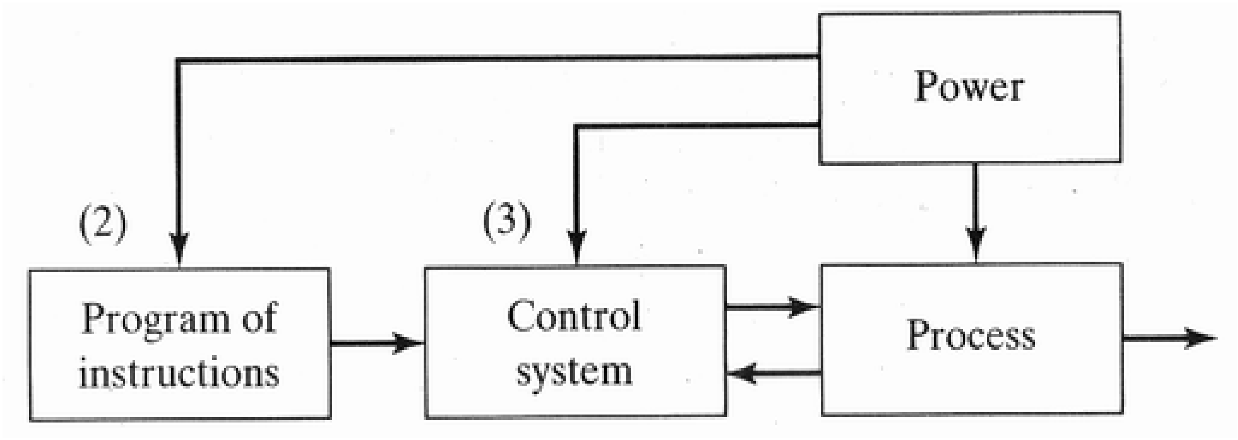
ELEMENTS OF AUTOMATION

- **Power** to accomplish the process and operate the system
- **Program of Instruction** to direct the process
- **Control Systems** to actuate the instructions

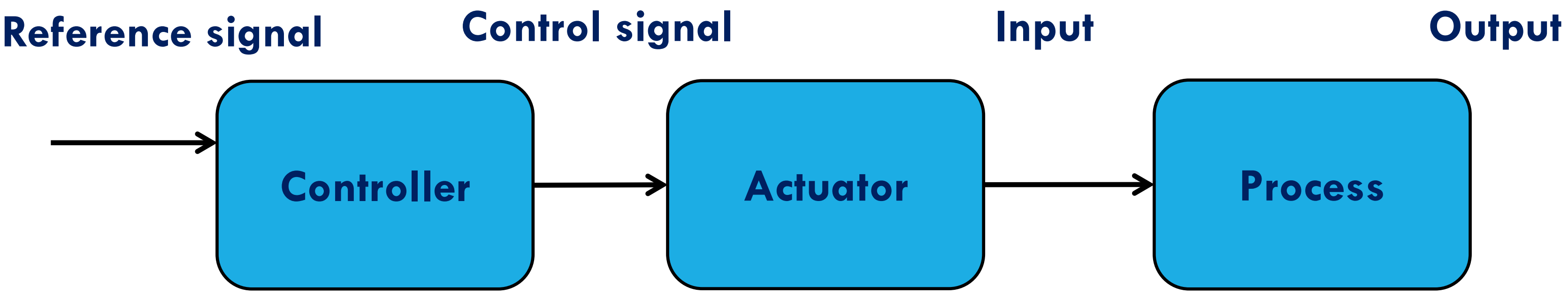


SENSOR, CONTROLLER, AND ACTUATOR

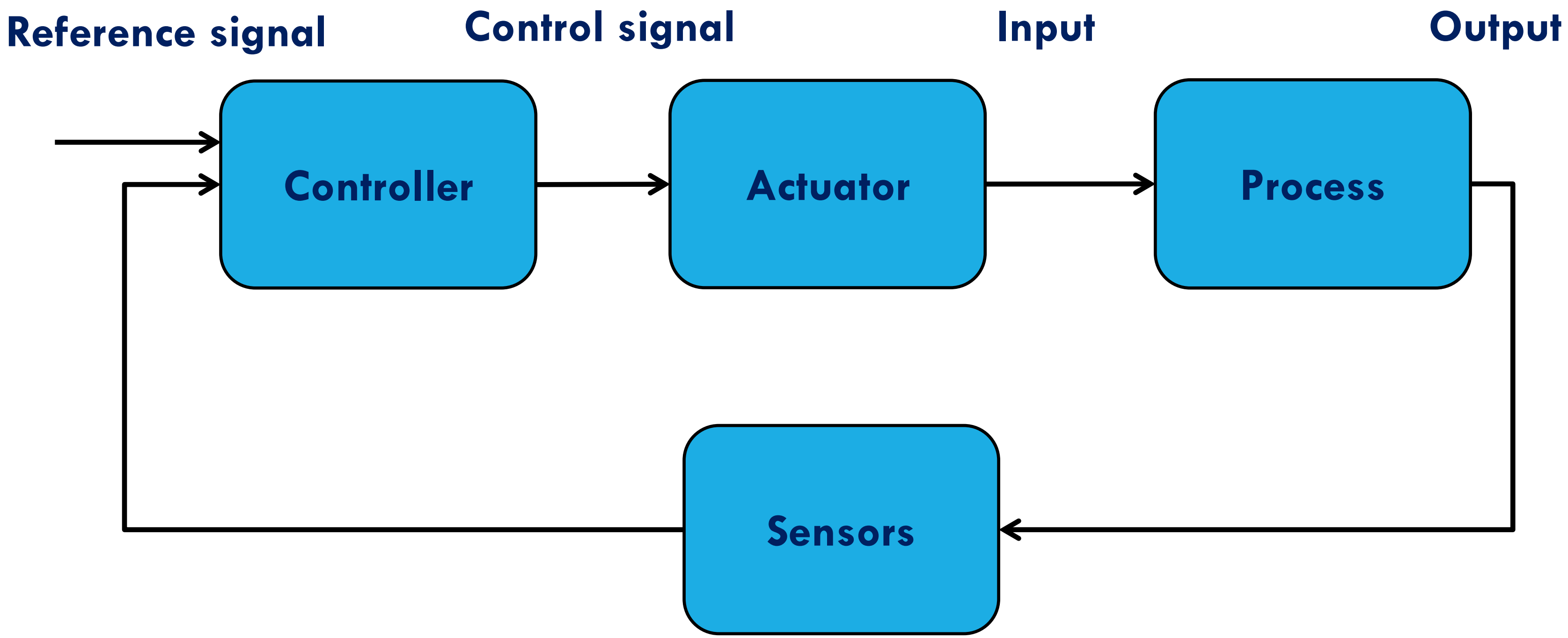
- **Sensor** is used to measure the output variable
- **Controller** compares the output with the input and makes the required adjustments
- **Actuators,** hardware devices that physically carry out the control actions



OPEN-LOOP CONTROL SYSTEMS

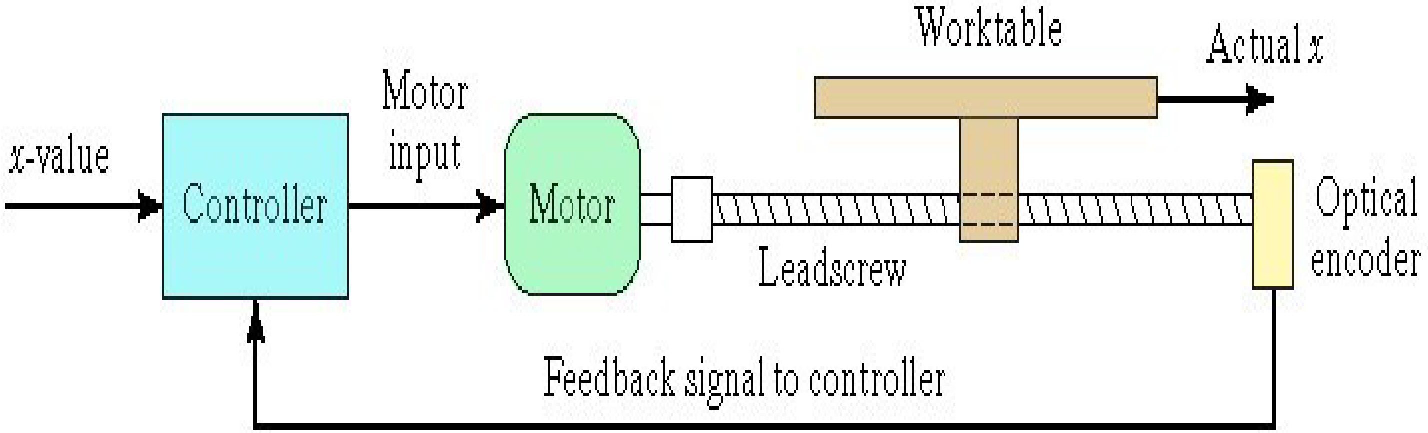


CLOSED-LOOP CONTROL SYSTEMS



EXAMPLE: POSITIONING SYSTEM

- **One-axis position control system consisting of a leadscrew driven by a DC servomotor using an optical encoder as the feedback sensor**



PERFORMANCE TERMINOLOGY FOR AUTOMATION SYSTEMS

1. Range
- The limits between which the input can vary.

2. Error
- The deviation of measurements from actual values

3. Accuracy
- The extent to which the value indicated by a measurement system might be wrong

4. Sensitivity
- The relationship indicating how much output there is per unit input.

5. Non-linearity error
- A non-linear input-output relation deviated from a linear system relation

6. Resolution
- The smallest change in the input value that will produce an observable change in the output

7. Deadband
- The range of input values for which there is no output

RANGE

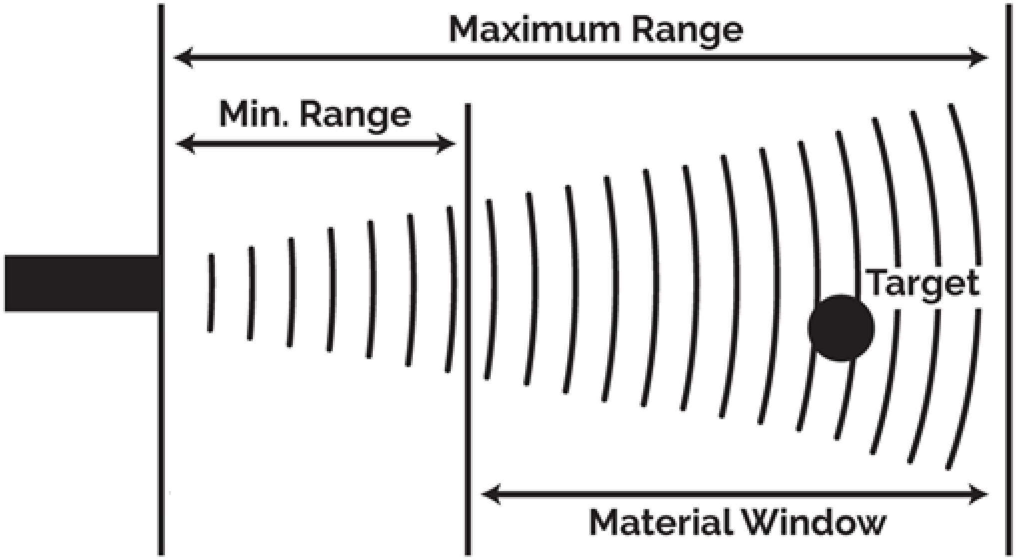
- The limits between which the input can vary.

1. RANGE

The full scale range defines the maximum and minimum values of the measured property

Range of lidar sensor:

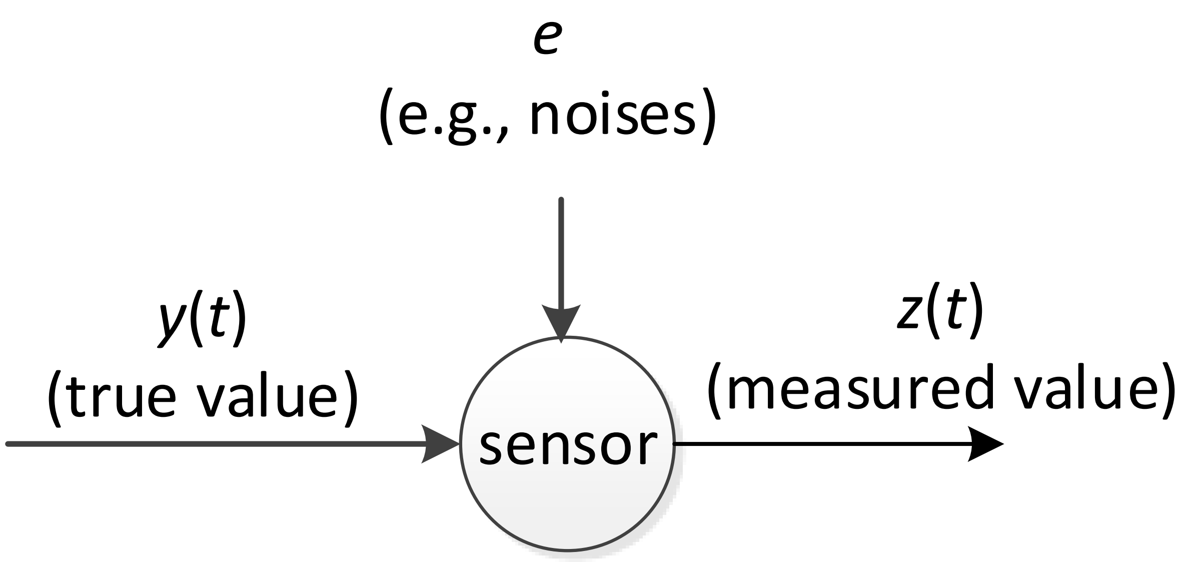
- Minimal range: around 3 cm
- Maximal range: 255 cm



ERROR

The deviation of measurements from actual values

2. ERROR



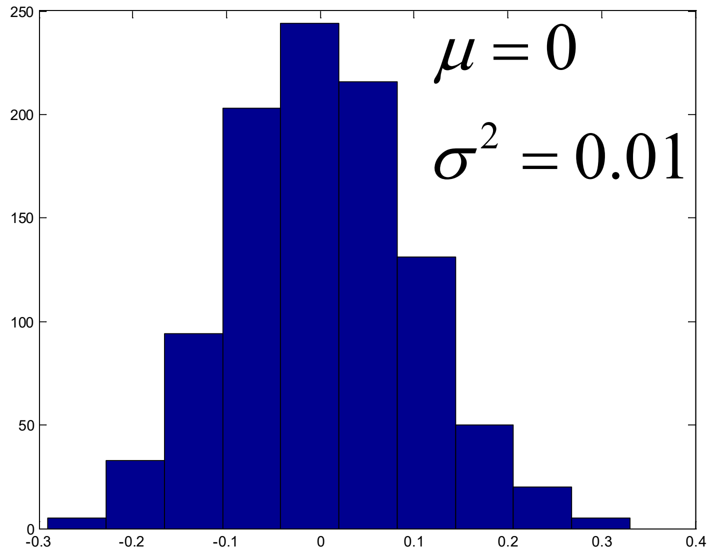
$$\boldsymbol{z} = \boldsymbol{y} + \boldsymbol{e},$$

or $$\boldsymbol{e} = \boldsymbol{z} - \boldsymbol{y}.$$

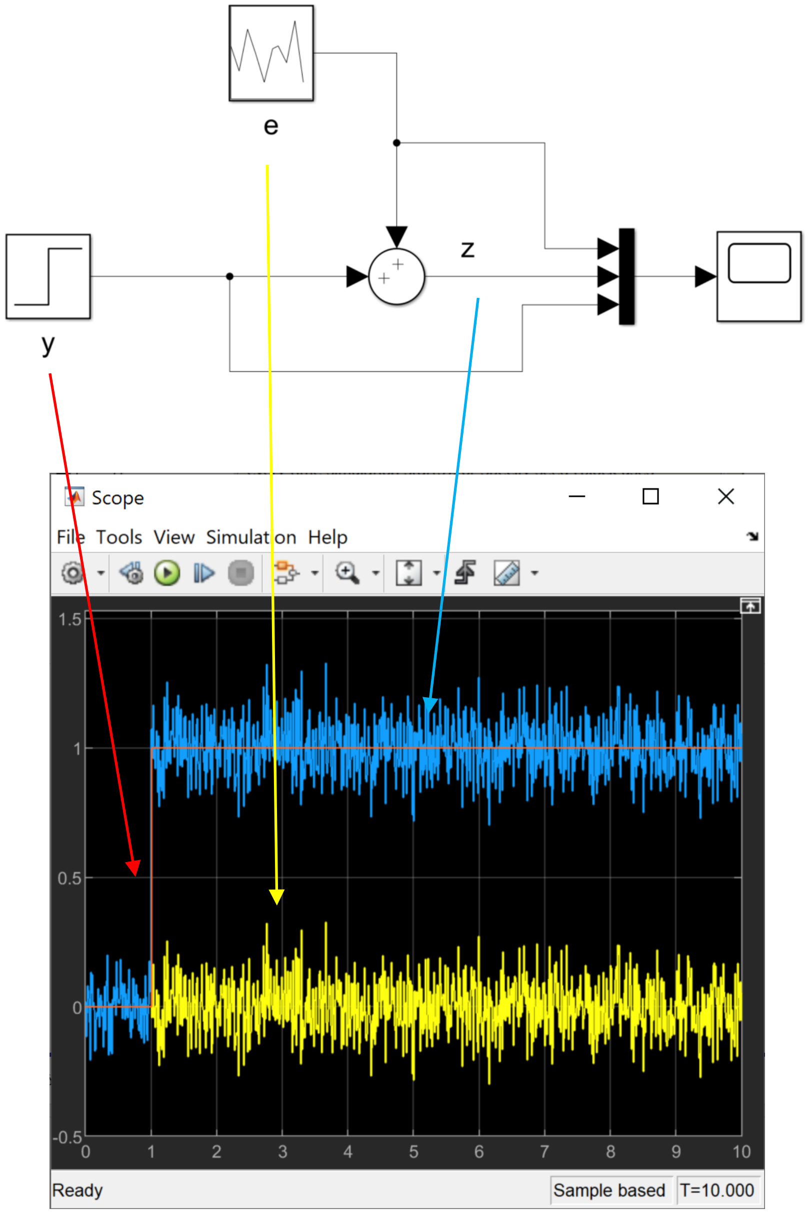
Typical measurement noise assumptions (can vary subjected to applications)

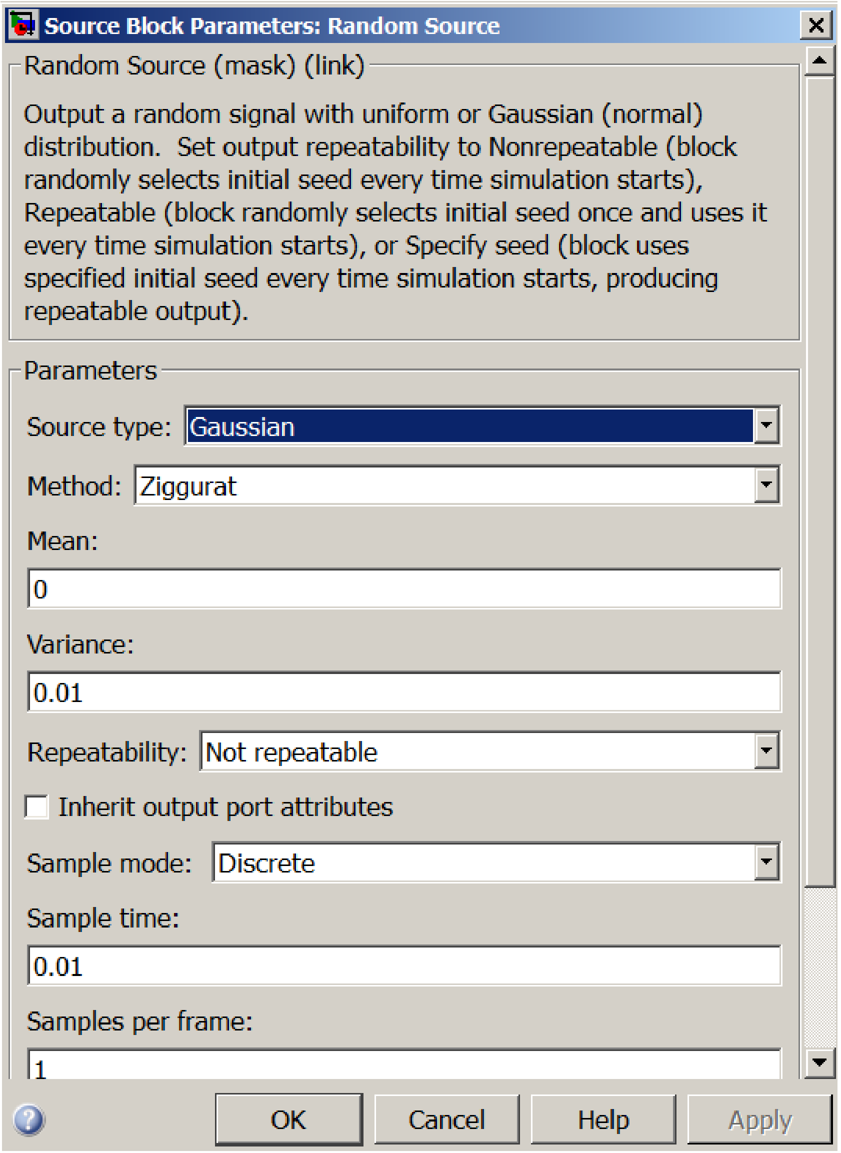
$$e \in G(\mu, \sigma^2)$$

a Gaussian noise with mean μ and variance σ^2

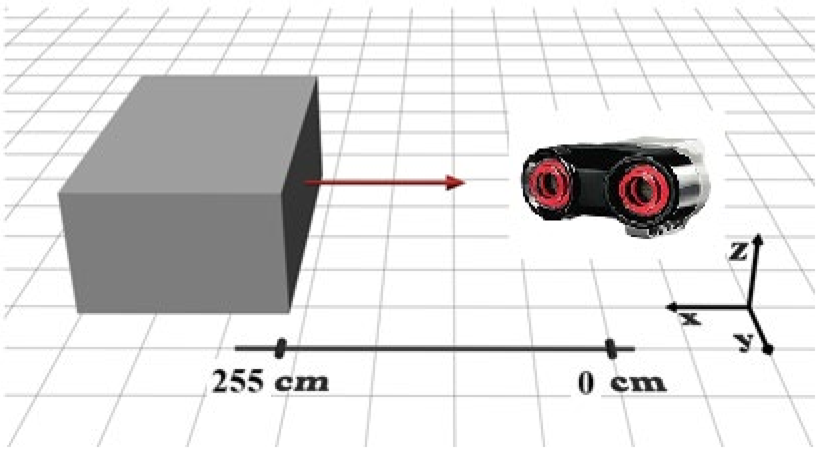


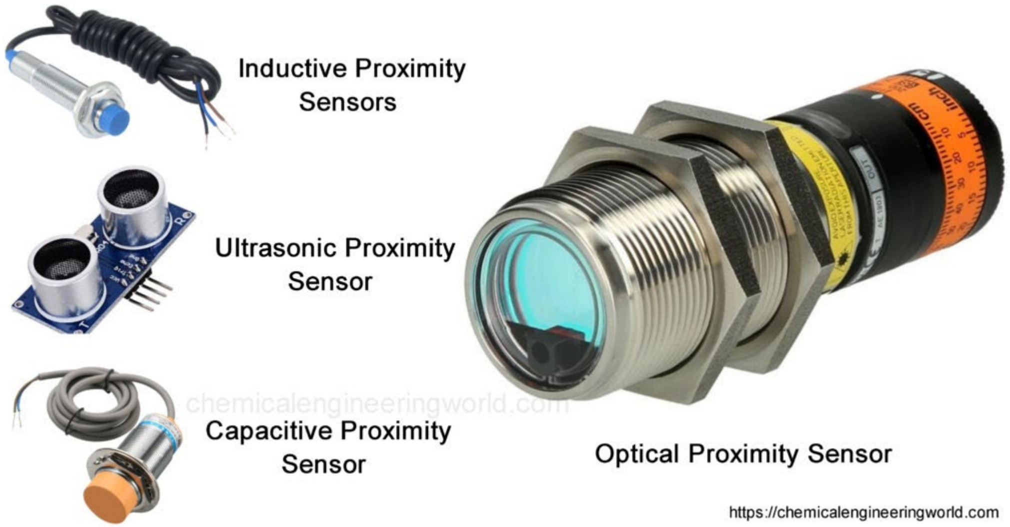
MEASUREMENT NOISE SIMULATION

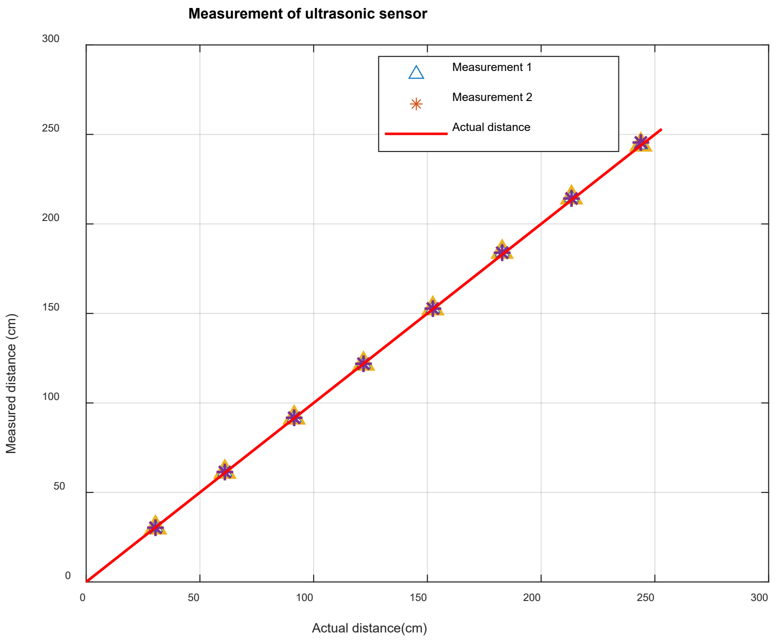




EXAMPLE: PROXIMITY SENSOR MEASUREMENTS







Input (u, feet/cm)	Output (y_1, cm)	Output (y_2, cm)
1 ft (30.48 cm)	30.3	30.3
2 ft (60.96 cm)	61.4	61.4
3 ft (91.44 cm)	91.7	91.7
4 ft (121.92 cm)	121.8	121.9
5 ft (152.40 cm)	152.7	152.7
6 ft (182.88 cm)	184.3	183.9
7 ft (213.36 cm)	214.7	214.2
8 ft (243.84 cm)	244.2	245.5

INCLASS WORKED EXAMPLE: COMPUTE ERROR

Input (u, feet/cm)	Output (y_1, cm)	Output (y_2, cm)
1 ft (30.48 cm)	30.3	30.3
2 ft (60.96 cm)	61.4	61.4
3 ft (91.44 cm)	91.7	91.7
4 ft (121.92 cm)	121.8	121.9
5 ft (152.40 cm)	152.7	152.7
6 ft (182.88 cm)	184.3	183.9
7 ft (213.36 cm)	214.7	214.2
8 ft (243.84 cm)	244.2	245.5

WORKED EXAMPLE: COMPUTE ERROR (ANSWER)

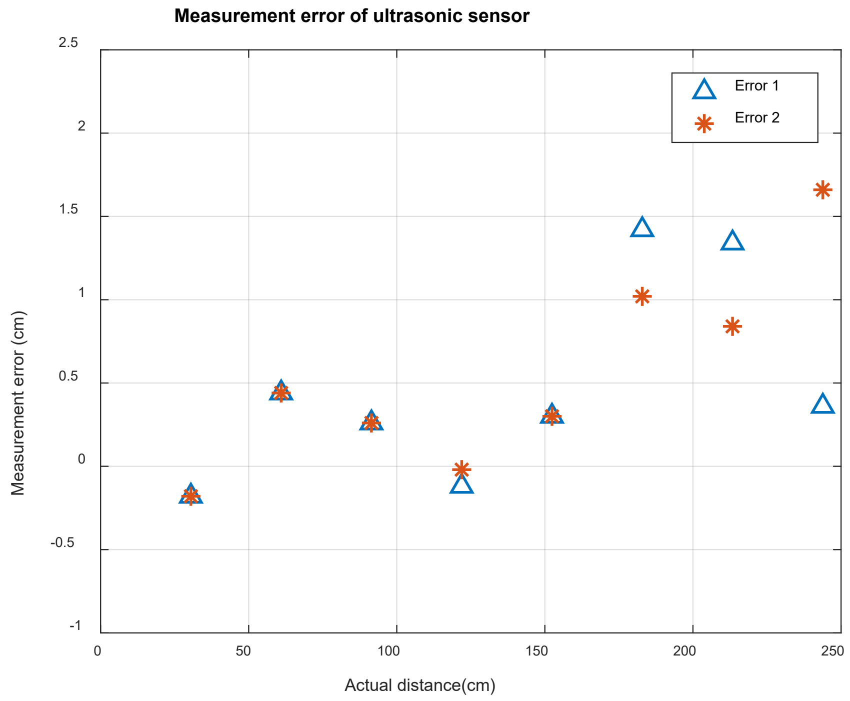
Input (u, feet/cm)	Output (y_1, cm)	Output (y_2, cm)
1 ft (30.48 cm)	30.3	30.3
2 ft (60.96 cm)	61.4	61.4
3 ft (91.44 cm)	91.7	91.7
4 ft (121.92 cm)	121.8	121.9
5 ft (152.40 cm)	152.7	152.7
6 ft (182.88 cm)	184.3	183.9
7 ft (213.36 cm)	214.7	214.2
8 ft (243.84 cm)	244.2	245.5

Input (u, feet/cm)	Error 1 (e_1, cm)	Error 2 (e_2, cm)
1 ft (30.48 cm)	−0.18	−0.18
2 ft (60.96 cm)	0.44	0.44
3 ft (91.44 cm)	0.26	0.26
4 ft (121.92 cm)	−0.12	−0.02
5 ft (152.40 cm)	0.3	0.30
6 ft (182.88 cm)	1.42	1.02
7 ft (213.36 cm)	1.34	0.84
8 ft (243.84 cm)	0.36	1.66

SENSOR MEASUREMENT

Based on the data from the previous slide, calculate the measurement error of the data

Input (u, feet/cm)	Error 1 (e_1, cm)	Error 2 (e_2, cm)
1 ft (30.48 cm)	−0.18	−0.18
2 ft (60.96 cm)	0.44	0.44
3 ft (91.44 cm)	0.26	0.26
4 ft (121.92 cm)	−0.12	−0.02
5 ft (152.40 cm)	0.3	0.30
6 ft (182.88 cm)	1.42	1.02
7 ft (213.36 cm)	1.34	0.84
8 ft (243.84 cm)	0.36	1.66



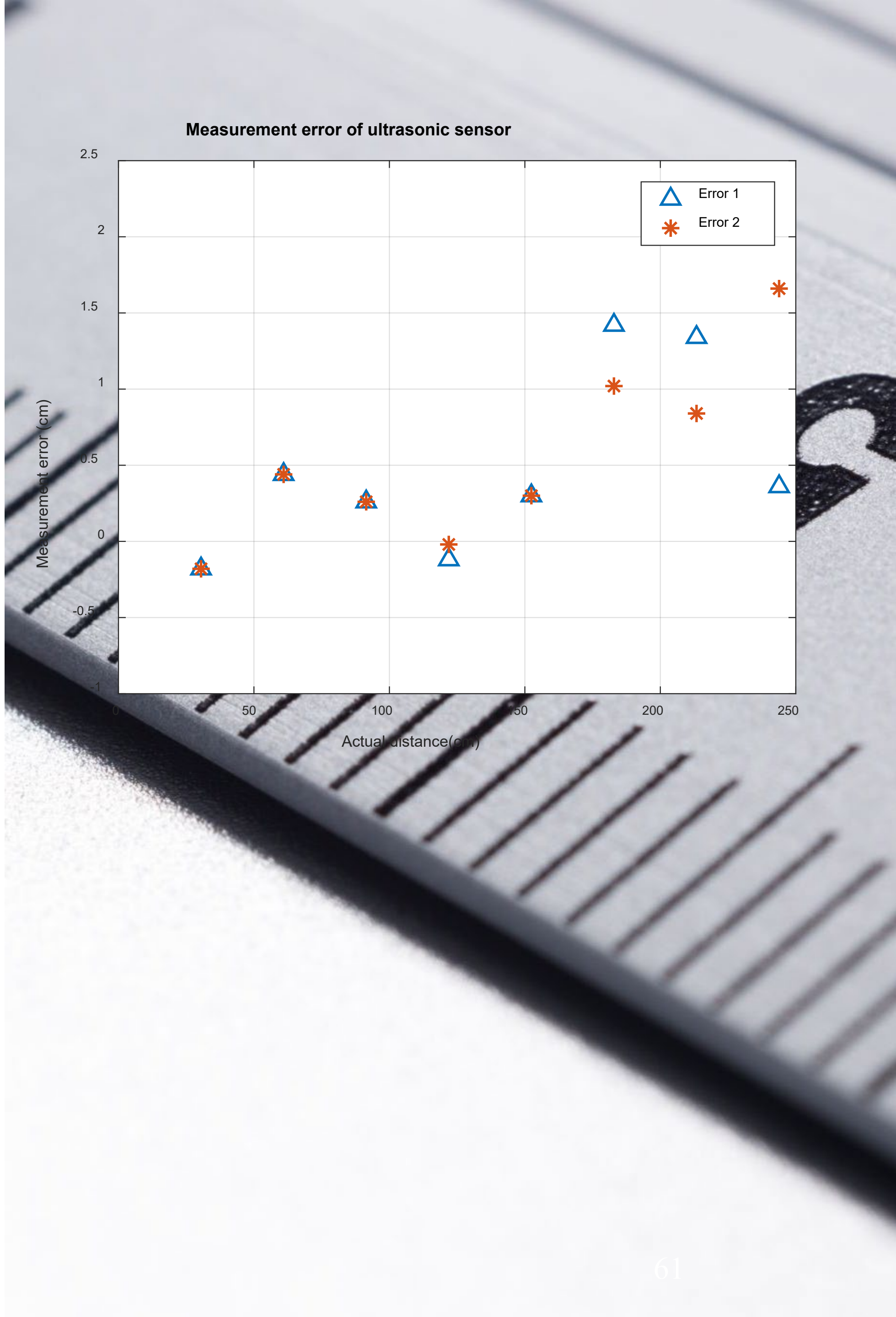
Question: What observations do you have from the data?

3. ACCURACY

Sensor accuracy is a degree of conformity of a measured quantity to its actual value.

Example

- The ultrasonic sensors are specified to have the accuracy of ±1 cm.
- Is the previous measurement example of ultrasonic sensor within the accuracy specification range?



3. ACCURACY

Sensor accuracy is a degree of conformity of a measured quantity to its actual value.

Example

- The ultrasonic sensors are specified to have the accuracy of ± 1 cm.
- Is the previous measurement example of ultrasonic sensor within the accuracy specification range?

Answer: No! (Assuming the measurement is exactly correct)

- The maximal error for y1 is 1.42 cm$\notin$[-1, 1] cm.
- The maximal error for y2 is 1.66 cm$\notin$[-1, 1] cm.

SENSITIVITY

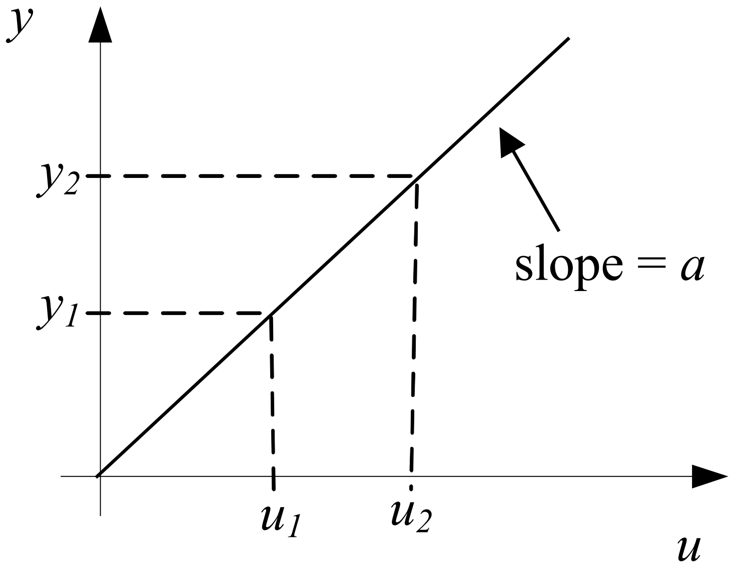
- The relationship indicating how much output there is per unit input.

4. SENSITIVITY

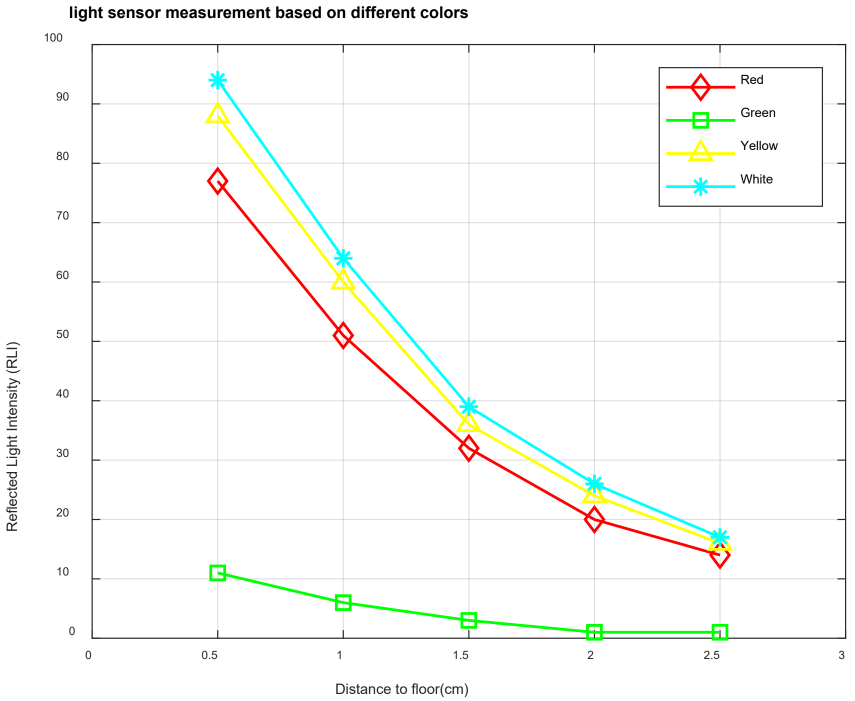
$$S\left(u^n\right) = \left.\frac{\Delta y}{\Delta u}\right|_{u^n}$$

Linear systems $y = au$

$$S = \frac{\Delta y}{\Delta u} = \frac{dy}{du} = a$$



SENSITIVITY – NONLINEAR SYSTEMS



Example – light sensor sensitivity

- Reflected light intensity (RLI) with different colors and changing distance to floor

Distance (cm)	Red	Green	Yellow	White
0.5	77	11	88	94
1.0	51	6	60	64
1.5	32	3	36	39
2.0	20	1	24	26
2.5	14	1	16	17

Calculate the sensitivity of the light sensor at the measurement points

SENSITIVITY – NONLINEAR SYSTEMS

$$S(d_i) = \frac{y(d_{i+1}) - y(d_i)}{d_{i+1} - d_i}$$

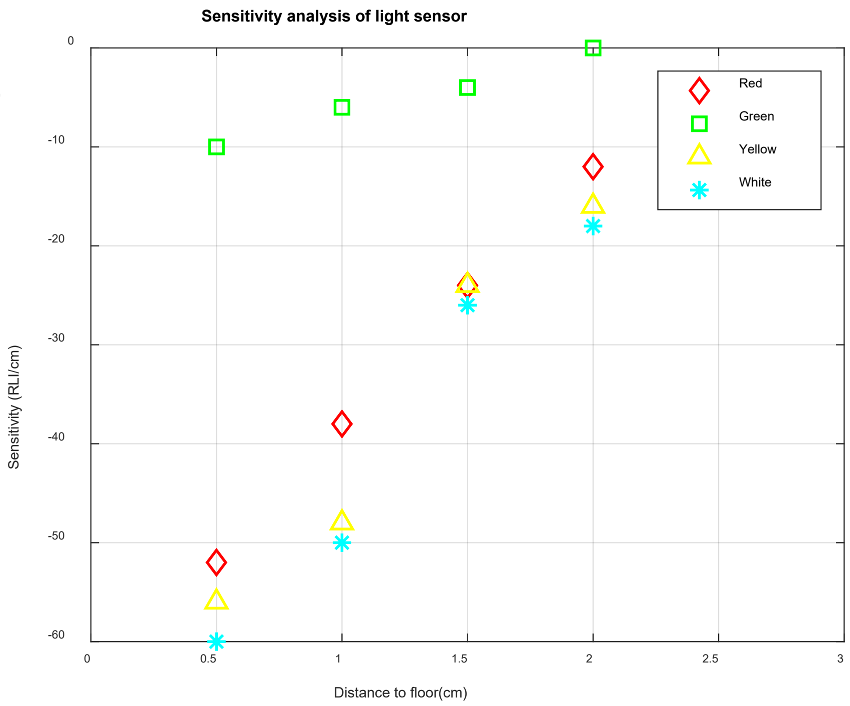
Distance (cm)	Red	Green	Yellow	White
0.5	77	11	88	94
1.0	51	6	60	64
1.5	32	3	36	39
2.0	20	1	24	26
2.5	14	1	16	17

SENSITIVITY – NONLINEAR SYSTEMS – CONT'

Sensitivity of the light sensor

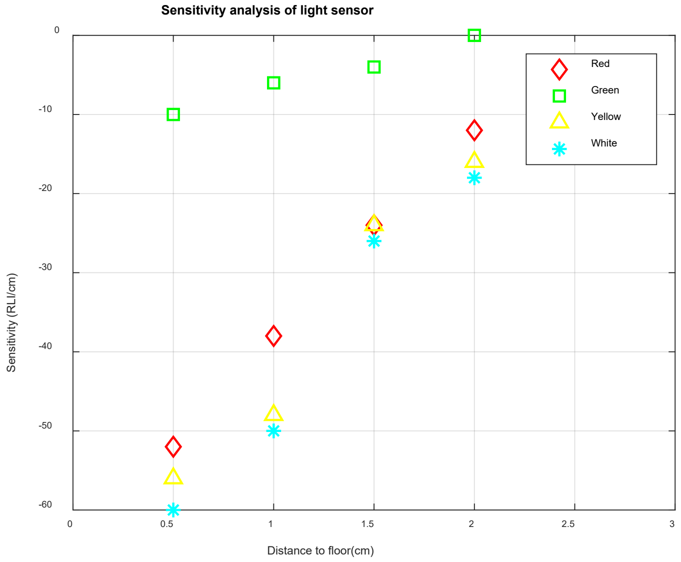
$$S(d_i) = \frac{y(d_{i+1}) - y(d_i)}{d_{i+1} - d_i}$$

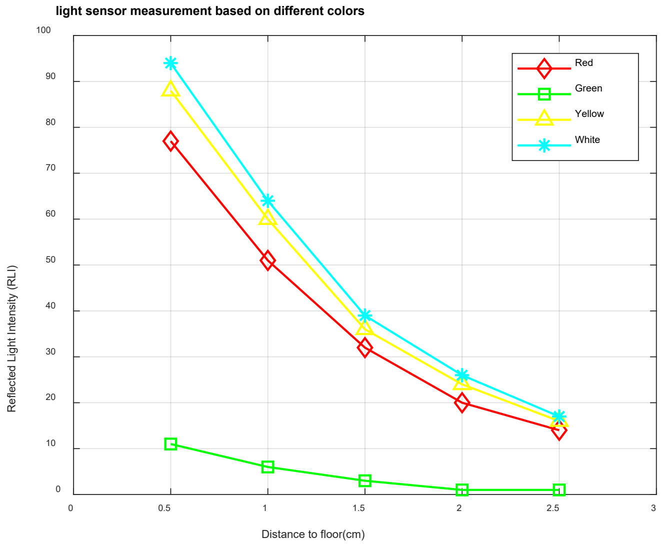
Distance	Red	Green	Yellow	White
0.5	-52	-10	-56	-60
1.0	-38	-6	-48	-50
1.5	-24	-4	-24	-26
2.0	-12	0	-16	-18



What are the observation and potential applications from this sensitivity analysis?

SENSITIVITY – NONLINEAR SYSTEMS - CONT'2





Observations

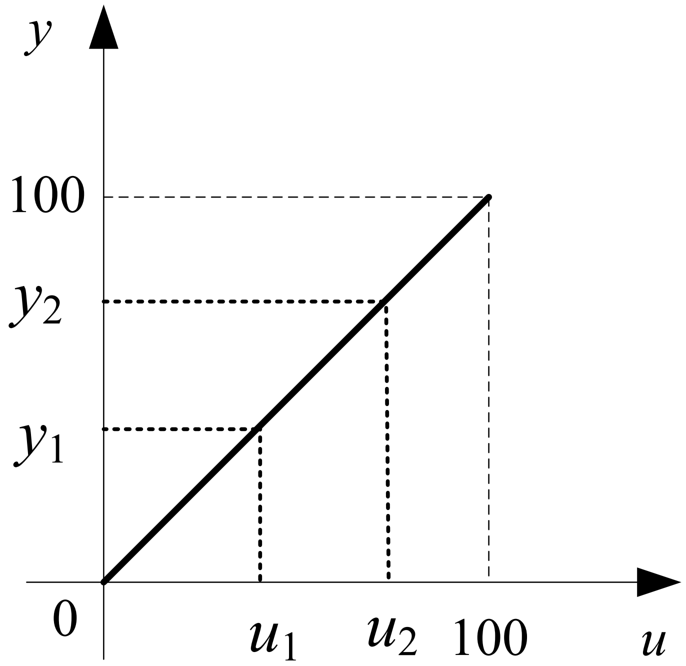
1. With distance increases, the RLI drops for all color sensor.
2. The white color has the highest RLI, and the green color has the lowest RLI.
3. For different colors, the extents of dropping (sensitivities) are different. The sensitivity magnitude decreases when the distance increases.

NON-LINEAR ERROR

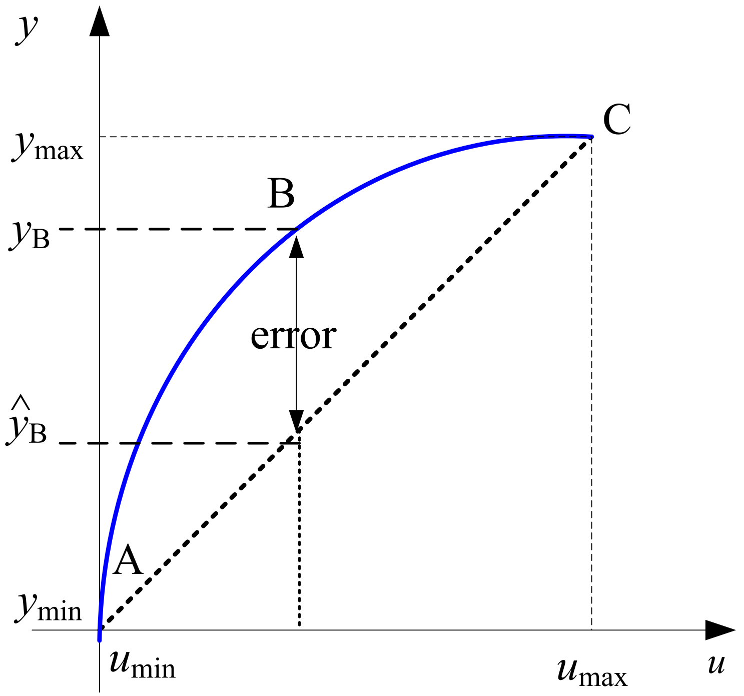
- A non-linear input-output relation deviated from a linear system relation

5. NON-LINEARITY ERROR

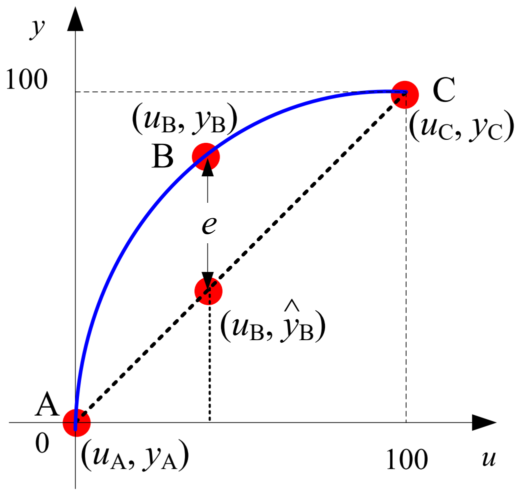
The input-output relation of a linear system.



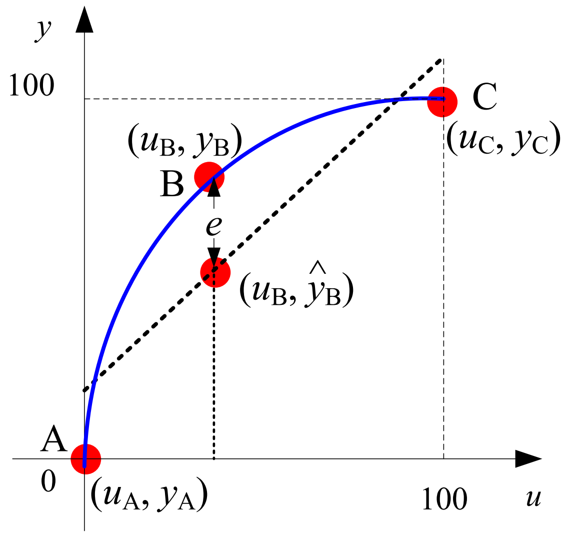
A nonlinear input-output relation deviated from a linear system relation



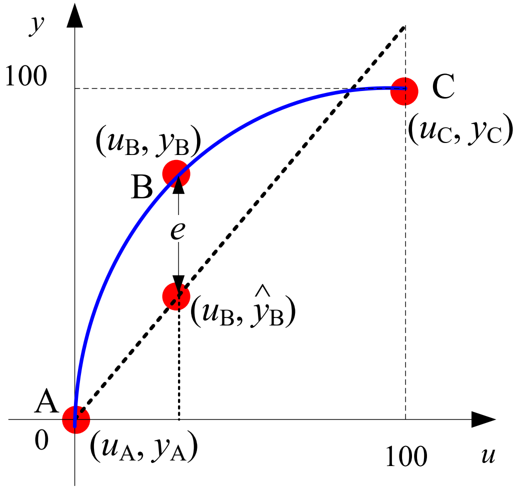
End-to-end linear interpolation



Least-square-fit

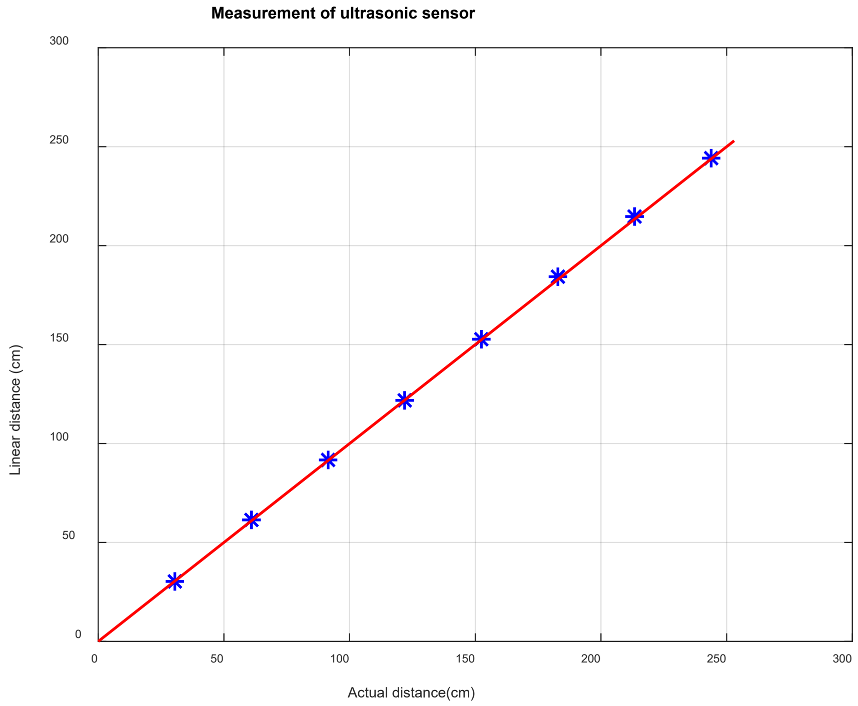


Least-square-fit with specific operating constraints

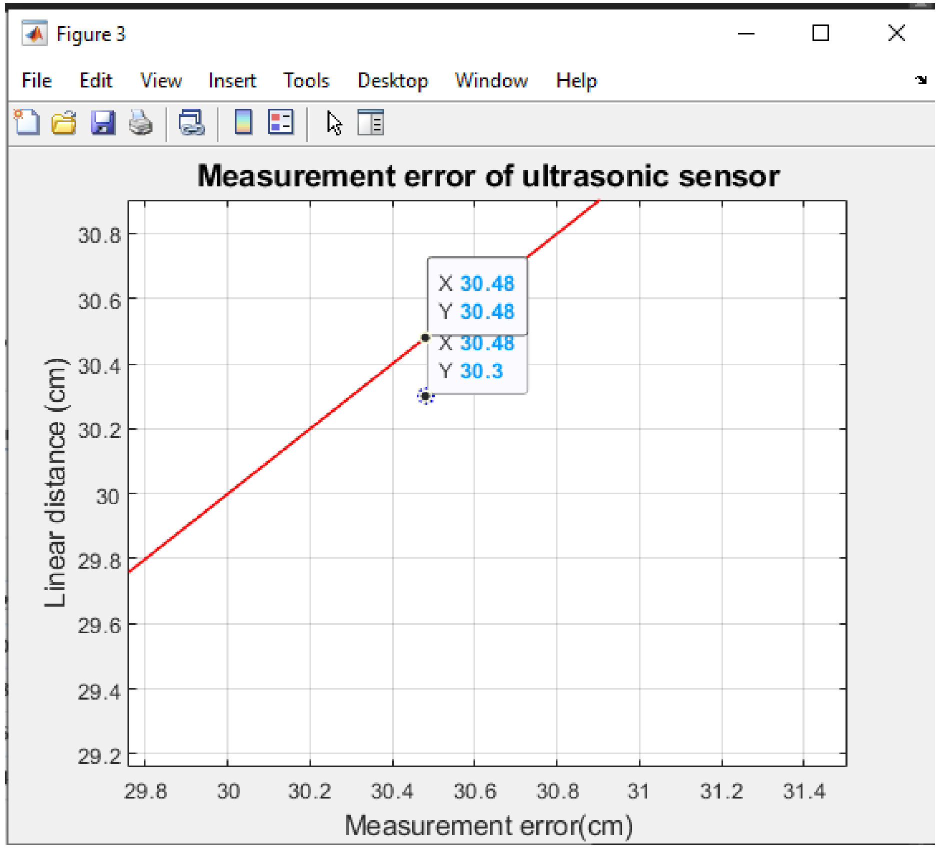


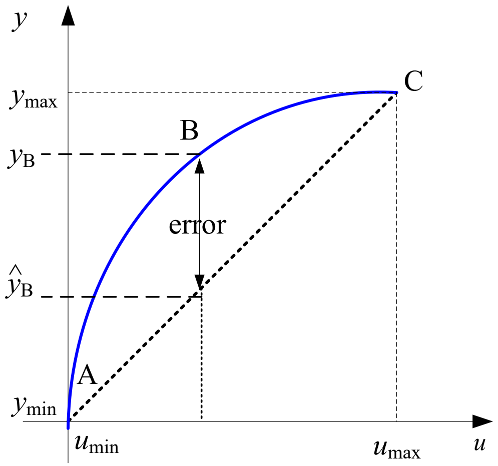
EXAMPLE: NON-LINEARITY ERROR OF ULTRASONIC SENSOR I

Observe the non-linerarity error of the ultrasonic sensor example, as listed in the Table.



EXAMPLE: NON-LINEARITY ERROR OF THE ULTRASONIC SENSOR II





END OF LECTURE 001