Intelligent Mechatronic Systems with Signal Processing, Control, and Optimization

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Prof. Seungchul Lee
Introduction

• Since 2013 July: UNIST
  – iSystems Design Lab.

• 2010, Ph.D. from the University of Michigan, Ann Arbor
  – S. M. Wu Manufacturing Research Center
  – The Center of Intelligent Maintenance Systems (IMS)

• 2007, M.S. from the University of Michigan, Ann Arbor

• 2005, B.S. of Electrical Engineering from Seoul National University
• 2001, B.S. of Mechanical Engineering from Seoul National University
My Research Areas

- **Mechatronics (mechanics + electronics)**
  - Undergraduate can do this with fun
  - Robotics
  - Hardware + coding
  - Circuit + digital logic + signal processing + control

- **Machine Learning and Deep Learning**
  - A level of graduate study
  - New research field for mechanical engineering
  - Will bring lots of potentials
  - Math + coding
Today

- 울산과학기술원 학부 수업 ‘메카트로닉스 개론’의 결과물을 토대로 아래의 개념을 쉽게 설명하고자 한다.

- Inverse kinematics
- Multi-agent systems
- Mobile robots
- Quadcopter control
- Fault detection
- Cyber-physical systems (CPS)
- Data acquisition and signal processing
- Machine intelligence
- Human computer interaction (HCI)
- Optimization
‘Introduction to Mechatronics’ at UNIST

• For senior students: [http://isystems.unist.ac.kr/teaching/mechatronics/](http://isystems.unist.ac.kr/teaching/mechatronics/)
Today

• Physical Computing
• Kinematics in Robotics
• Parallel Manipulator (Delta Robots)
• Dynamics and Control
• Signal Processing
• Intelligence with Machine Learning
• HCI
• Optimization
• Epilog
Arduino and Raspberry Pi

- Open-source platform used for building electronics projects
- Micro-controller/micro-computer
- Physical computing
- Easy to use even for non-professionals
- Maker Faire
Physical Computing: Sensors and Actuators

- **Sensor**: allow the microcontroller to receive information about the environment
- **Actuator**: devices that cause something to happen in the physical world
Flex Sensor and Servo Motor
Sensors + Actuators + Microcontroller
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(Industrial) Robot Arms
Robot Arms

The Arm

Actuator
Shoulder
Base
Forearm
End-effector
Main arm

\( \theta_1 \)  \( \theta_2 \)  \( \theta_3 \)
Kinematics

• “Introduction to Robotics” Course in Mechanical Engineering
Robot Playing Piano

• Inverse kinematics, but manually programmed
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Delta Robot (Parallel Manipulator)

Robot Kinematics

\[ \begin{align*}
\vec{r}_1^{\{B\}} + \vec{r}_2^{\{B\}} + \vec{r}_3^{\{B\}} &= \vec{r}_4^{\{B\}} + \vec{r}_5^{\{B\}} = \vec{r}_4^{\{B\}} + R_{BP}^{T} \vec{r}_5^{\{P\}}
\end{align*} \]
Dancing Robot with Signal Processing

• Dancing with music (rule-based and rule-programmed)
• Signal processing (FFT)
Multi-Agent System

- Wireless network
- Internet of Things
- Connected

- Control strategy
- Cooperation

- 국립부산과학관 전시 예정
Mobility: Mecanum Wheel
Idol Robot Group (?)

• Dance with changing formation
• Mobile: position and orientation control
• Localization + Robot Navigation (→ **self driving car**)

![Robot Formation](image1.png)

![Dance Performance](image2.png)
Robot and Light
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Control: PID

- Require more advanced system design
- From open-loop to closed-loop systems

\[e = x^* - x\]
\[u = K_p e + K_i \int e \, dt + K_d \frac{de}{dt}\]

\[
P = kP \times \text{error};
I += kI \times \text{error} \times dt;
D = kD \times (\text{error} - \text{error}_{\text{last}}) \div dt;
U = (\text{int})(P + I + D);
\]
Inverted Pendulum

• A famous control problem
• Feedback control:
  – angle from encoder → command to servo motor
Ball and Plate

• Feedback: vision in the loop
  – Location identification via Computer Vision
Drone and Dynamics

• Quadcopter
(Simpler) Unicopter

- Angle from encoder
- DC motor
Drone Application

- Aerial Surveillance & Monitoring, Observation with Drone
  – Drifting Issue: Hovering and Tracking via vision
Reinforcement Learning

• Require more advanced control scheme
  – State space representation
  – Optimized control scheme (LQR)
  – Deep learning (reinforcement learning): totally different approach

\[ V^*(s) = R(s) + \gamma \max_{a \in A} \sum_{s' \in S} P(s' | s, a)V^*(s') \]
• Signal Processing (DSP)
• Machine Learning and Deep Learning

(Big) Data \[\rightarrow\] Information Intelligence

Machines
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Data Acquisitions
Signal Measurement for Free Fall

Free Fall Experiment
Vibration Issue on SRT High Speed Train
Vibration Issue on SRT High Speed Train
Measured Data: SRT

SRT F: 02F Dongdaegu - Daejeon

Graph showing acceleration data over time for different axes:
- X-axis (top graph)
- Y-axis (middle graph)
- Z-axis (bottom graph)

The data is plotted against datetime in seconds.
Measured Data: KTX
Smoothing and Detection of Abrupt Changes

- Convolution in time
### Kalman Filter

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \hat{x}_{t</td>
<td>t-1} = A\hat{x}_{t-1</td>
</tr>
<tr>
<td>( \Sigma_{t</td>
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<tr>
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<td>( \Sigma_{t</td>
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</tbody>
</table>

- Computationally efficient
  - Recursive
- Bayesian
  - Data fusion
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Robot Playing Piano
Robot Playing Piano
Machine Intelligence

- **Perception**
  - Seeing
  - Hearing
  - Reading
  - Context-aware

- **Thinking (Inference)**
  - Reasoning
  - Decision making

- **Action**
  - Control

- **Sensors**
  - AI

- **Computation**
  - AI

- **Actuators**
  - AI
How to Make Robots Intelligent

• It was programmed by users
• From music notes to autonomously playing
  – Artificial Intelligence from Computer Science

Perception with deep learning
Unsupervised Learning

• Given unlabeled data \( \{x^{(1)}, x^{(2)}, ..., x^{(m)}\} \)

• Goal: group the data into \( k \) partitions

• Solve the following optimization problem:

\[
J = \sum_{n=1}^{m} \sum_{k=1}^{K} r_{nk} \|x^{(n)} - \mu_k\|^2
\]

• Or iterative algorithm (K-means)
Servo Motors in Robot
Supervised Learning

• Given training set, \{ (x^{(1)}, y^{(1)}), (x^{(2)}, y^{(2)}), \ldots, (x^{(m)}, y^{(m)}) \} 

• Want to find a function \( g_\theta \) with learning parameter, \( \theta \)
  – \( g_\theta \) desired to be as close as possible to \( y \) for future \( (x, y) \)
  – i.e, \( g_\theta(x) \sim y \)

• Define a loss function \( l \)
• Solve the following optimization problem:

\[
\text{minimize} \quad f(\theta) = \frac{1}{m} \sum_{i=1}^{m} l(g_\theta(x^{(i)}), y^{(i)}) \\
\text{subject to} \quad \theta \in \Theta
\]
Cognitive Computing

- Smart Sensor (IoT) + Machine Learning

<table>
<thead>
<tr>
<th>Prototype 1</th>
<th>Prototype 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Prototype 1 Image" /></td>
<td><img src="image2" alt="Prototype 2 Image" /></td>
</tr>
</tbody>
</table>
IoT Connected Devices and Cloud

- Big Data
- Data Transmission to Cloud
- Local and Distributed Computing
Industrial 4.0 or the 4th Industrial Revolution

• Data Science and Analytics in Engineering
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Human Computer Interaction (HCI)

• Eventually used by Humans
Human Computer Interaction (HCI)

• Eventually used by Humans
• Intuitive
Human Computer Interaction (HCI)

- Eventually used by Humans
- Interactions: input devices
Human Computer Interaction (HCI)

• Eventually used by Humans
• Interactions: input devices

Keyboard Input
Robot Arm
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Small CNC Machine
Path Optimization

- There are so many possible ways to conduct the given tasks
- Optimization problems

XY Plotter
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Failure, Success and the drive to keep Creating
Failure, Success and the drive to keep Creating

Version 1

Version 2
http://isystems.unist.ac.kr/

All materials (codes + hardware design) are available