Robotics: Science and Systems

Introduction & Overview of Robotics

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RSS: Course Details
Lectures

Course lecturer: Dr. Zhibin (Alex) Li

Time: 09:00-10:50 [Lecture attendance is essential]

Venue:
Mondays, G.16 Seminar Room - Doorway 4 (Medical School)

Thursdays, Elliot Room (Minto House)
Course structure

- Lecture + Tutorial + Practical
- Theory -> Coding -> Real systems

Accessment:

Examination 50%, Practicals 40%, homework 10%
Tutorials

- Two optional time slots within a week; Two groups, each group is approx. half of a class
- Mondays: 11:00 - 12:00 [Appleton Tower, 3.09 workroom; Week 2 - Week 9] - first tutorial is on 23-Sep-2019
- Thursdays: 11:00 - 12:00 [Appleton Tower, 3.09 workroom; Week 2 - Week 9] - first tutorial is on 26-Sep-2019
Practicals

Two Groups: each team of 2-3 people

**Group 1 Lab:**

Mondays: 15:00 - 17:00 [Appleton Tower, 3.01/3.02 Robotics lab] - first practical: 23-Sep-2019

**Group 2 Lab:**

Thursdays: 15:00 - 17:00 [Appleton Tower 3.01/3.02 Robotics lab] - first practical: 26-Sep-2019
Robotics: Key Components
Quiz: What Tools Do We Need?

Can you name some of the things we need in order to move the Valkyrie from the start position to the end goal, picking up the object?
What Tools Do We Need?

- **Localisation**: (Where am I?)
- **Mapping**: (What does the area look like?)
- **Motor Control**: (How to move the motors?)
- **Sensor Filtering**: (Cleaning sensor information)
- **Motion & Path Planning**: (How do I get there?)
- **Dynamics**: (How do I move limbs (quickly)?)
- **Kinematics**: (How do I move my limbs (slowly)?)
- **System Identification**: (What are the properties of the system?)
- **Sensor Filtering**: (Cleaning sensor information)
- **Coordinate Transformation**: (Where am I in relation to the world?)
- **Optimisation**: General: How do I minimise some cost function? QP: How do I move the whole body?
What is this course intended for?

❖ Give you sufficient exposure to fundamental topics relevant to robotics
  ➢ Planning
  ➢ Dynamics, Kinematics and Control
❖ Give you hands on experience (tutorial + practical) in conceptualising a robotic solution to a problem
  ➢ Build a robot (by making design decision)
  ➢ Program it
  ➢ Compete in a real-world environment
Outline of overview of robotics

- Definition: what are robots?
- Elements of robotics
  - Mechanism & mechanical design
  - Actuation
  - Sensing
  - Motion capabilities: manipulation, locomotion & localization
  - Artificial Intelligence (AI)
  - Level of robot intelligence
- Areas of robotics
  - Industrial/civil applications
  - Educational purposes
  - Research directions
- Robot control
- Summary of key RSS elements
- Robotics in real-world application: a field test
Low/Mid/High Level Control

- **Low-level control:**
  - Example: where to place a leg as robot takes its next step
  - Generally, continuous-valued problems
  - Short time scale (under a second); high frequency loop

- **Intermediate level control:**
  - Navigating to a destination, or picking up an object
  - Continuous or discrete valued problems
  - Time scale of a few seconds

- **High level control:**
  - What is the plan for moving these boxes out of the room?
  - Discrete problems, long time scale (minutes)

(From: https://www.cs.cmu.edu/afs/cs/academic/class/15494-s07/lectures/architectures.pdf)
What are robots?
An interdisciplinary area of science & engineering that covers: mechanical engineering, electrical engineering, computer science, and AI.

The word “robot” was introduced to the public by Czech writer Karel Čapek in his play R.U.R. (Rossum's Universal Robots) in 1920. In Czech, the same as other Slavic languages, “robota” means “labour” or “work”.

Original purpose of robots, *automatic/autonomous labour* that frees humans from tedious jobs.
Rossum's Universal Robots

© Edward Alderton Theatre, image by Kevin Coward

Robotics is the science & technology that deals with a variety of elements related with developing such machines or mechatronic devices, eg design & fabrication of the hardware, sensing & controls, and the applications.
UK’s first robot, and most interestingly, it is a humanoid robot.

Built in 1928 by Captain Richards & A.H. Reffell

See more at: http://www.sciencemuseum.org.uk/visitmuseum/plan_your_visit/exhibitions/eric
Robots: machines that automate some behavior

The first industrial robot: Unimate

George Charles Devol developed the prototype of Unimate in 1950s, the first material handling robot employed in industrial production work.

The first Unimate robot was sold to General Motors in 1961.
Robots: machines that automate some behavior

High-speed motion control

Robot Kinematics & Dynamics
System Identification
Kalman Filter
Digital System & control
Design of Advanced Controllers
Trajectory Planning and Motion Planning
Robots: machines that automate some behavior

Sorting parcels in warehouse application
Robots: machines that automate some behavior

Spot-mini and Handle robots from Boston Dynamics
Robots: machines that automate some behavior
Robots: machines that automate some behavior

Related RSS elements:
- Robot Kinematics & Dynamics
- System Identification & State Estimation
- Kalman Filter
- Digital System & control
- Design of Advanced Controllers
- Optimization
- Model Predictive Control
- Trajectory Planning and Motion Planning

Valkyrie Robot, © University of Edinburgh
Mechanism & mechanical design
Design of humanoid robots

Honda Asimo robots
Design of humanoid robots

HRP robots

Robots are getting lighter and stronger
Biomimetic robot

©Festo robot
Biomimetic robot
Biomimetic robot

Van der Waals forces

Biomimetics and Dexterous Manipulation Lab, Stanford
Smart mechanism

Metamorphic robots kings, see video

From Prof. Jian S. Dai, King's College London: http://nms.kcl.ac.uk/jian.dai/research.html
Design of energy-efficient robotic legs

Smart design of using soft elements for strong en...
Smart mechanism: ostrich runner

Related field/knowledge: Newtonian & Solid Mechanics, Rigid body dynamics (momentum, force acting on rigid body, kinetic & potential energy).
Articles: IEEE/ASME Transactions on Mechatronics.
Actuation
High-power actuators

Actuator of the previous example: torque control, high power
Soft actuators

Variable impedance by active control

Different variable damping actuator principles: (a) friction, (b) MR, (c) variable orifice fluid damper.

The mechanical design and actuators of these systems are *not* the scope of RSS, but essential for real robotic systems.

To control these robots, it requires knowledge and skills in:

- Robot Kinematics & Dynamics
- Kalman Filter
- Digital System & control
- Design of Advanced Controllers
- Optimization
- Trajectory Planning and Motion Planning
Cutting Edge of Robotics

Key challenges due to
1. Close interaction with multiple objects
2. Multiple contacts
3. Hard to model non-linear dynamics
4. Guarantees for safe operations
5. Highly constrained environment
6. Under significant autonomy
7. Noisy sensing with occlusions

...classical methods is difficult to scale up!
Sensing
Torque sensors

Force/torque sensing

6-axis FT sensor typically mounted on the end-effector

© 2017 ATI Industrial Automation, Inc.
Position sensors

Absolution position sensors

Mechanical absolute encoders

Optical absolute encoders (13 tracks)

Schematics of optical absolute encoders (3 tracks)
Position sensors

Relative position sensors, usually have higher resolutions.

Signal processing, low-pass filters and Kalman filter, etc.
Motion capabilities: manipulation, locomotion & localization
Motion capabilities: manipulation

Retrieving an object in a clustered environment.

Motion capabilities: locomotion

Bipedal walking in presence of external pushes

Motion capabilities: localization

State estimate drifts, robot approaches the target with decreasing accuracy: TRIAL 5

Robot is localized and reaches the target: TRIAL 5

Kinematics-Inertial State Estimation (No Localization) Localization using Proposed AICP
Related RSS elements in these systems

- Robot Kinematics & Dynamics
- Localization and Mapping
- Path & Motion Planning
- Kalman Filter
- Digital System & control
- Design of Advanced Controllers
- Optimization
- Model Predictive Control
- Trajectory Planning and Motion Planning
Artificial Intelligence (AI)
In the 1940s and 50s, a lot of discussion was held by scientists from different fields on the possibility of creating an artificial brain.

Can machines think? In 1950, Alan Turing proposed Turing Test: a human judge engages in a natural language conversation with a human and a machine designed to generate performance indistinguishable from that of a human being.
A natural language conversation, is that a human or a machine?

Hi, what is the news about Harvey?

Alana_live
[eliza-e557b16-2017-08-12-1858] Sorry I don't have access to that document.

I mean the hurricane.

Alana_live
[eliza-e557b16-2017-08-12-1858] So, what is your guilty pleasure?

Ok. What is the news about Harvey hurricane?

Alana_live
[persona-e557b16-2017-08-12-1858] Thank you! I am still learning. What do you want to talk about next? I can tell you an interesting fact or chat about politics, news, or movies..

news on Harvey hurricane

Alana_live
[eliza-e557b16-2017-08-12-1858] So what is the last concert you went to?

news on Harvey

Alana_live
[eliza-e557b16-2017-08-12-1858] Anyway, what are your plans for the rest of the day?

news on Harvey

Alana_live
[news_api-f5f1472-2017-08-11-1640] I heard on the radio that The Specter of Climate Change Hangs Over Hurricane Harvey. Was Hurricane Harvey the result of climate change? Do you want to know more?
The Dartmouth workshop

In 1956, a summer workshop for artificial intelligence, named the *Dartmouth Summer Research Project on Artificial Intelligence* open a new field of AI.

In John McCarthy’s proposal, he stated that the conference was

"to proceed on the basis of the conjecture that every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it."

Archive of Dartmouth workshop: http://raysolomonoff.com/dartmouth/
The *Dartmouth workshop*

The Proposal states:

“We propose that a 2 month, 10 man study of artificial intelligence be carried out during the summer of 1956 at Dartmouth College in Hanover, New Hampshire. The study is to proceed ...... We think that a significant advance can be made in one or more of these problems if a carefully selected group of scientists work on it together for a summer.”

1956, birth of the field of artificial intelligence (AI) research.

Golden age of AI 1956–1974

Development of humanoid robot occurred in this golden age. Waseda University, Japan, initiated the WABOT project in 1967, and in 1972 completed the WABOT-1, the world's first full-scale intelligent humanoid robot.
AI winter

AI, cannot be exempted from the hype cycle for new technology.

In 2012, Deep Convolutional Neural Networks won the large-scale ImageNet competition by a significant margin over shallow machine learning methods.

Deep learning: more hidden layers, which enable composition of features from lower layers, potentially modeling complex data with fewer units than a similarly performing shallow network.
New era of deep learning, 2014

2014, DeepMind developed Deep Q-learning capable of learning how to play Atari video games using only pixels as data input. [video]
Alpha-Go vs Lee Sedol, 2016

AlphaGo is a narrow AI specialized in playing the board game Go.

Go (game)

From Wikipedia, the free encyclopedia

This article is about the board game. For other things named "Go", see Go.

Go (traditional Chinese: 圍棋; simplified Chinese: 围棋; pinyin: wéiqi; Japanese: 囲碁; rōmaji: igo[nb 2]; Korean: 바둑; romaja: baduk[nb 3]; literally: "encircling game") is an abstract strategy board game for two players, in which the aim is to surround more territory than the opponent.

The game was invented in ancient China more than 2,500 years ago, and is therefore believed to be the oldest board game continuously played today.[2][3] It was considered one of the four essential arts of the cultured aristocratic Chinese scholars in antiquity. The earliest written reference to the game is generally recognized as the historical annal Zuo Zhuan[nb 4][5] (c. 4th century BCE).[6]
What AI and robotics still cannot do? Can you see it?

Reliable control of physical interaction is hard in a real world.
Machine learning for solving robotics problems

Self-learning locomotion control
AI algorithms self-learn human-like dynamic walking

Credits: Chuanyu Yang, Advanced Robotics Lab, University of Edinburgh

Related RSS elements: Machine Learning for Robot Control
Machine learning for solving robotics problems

Valkyrie robot

Related RSS elements: Machine Learning for Robot Control
Level of robot intelligence
Robot intelligence

Level 5: Human intelligence level
Level 4: Task-level programming
Level 3: Structured programming
Level 2: Motion primitive programming
Level 1: Point to point programming
Areas of robotics
Diversity of categorization

By applications/services: welding, warehouse, cleaning, robots

By particular (actuation) technology: hydraulic, pneumatic robots

By the environment of the applications: aerial, aquatic, ground, space, underwater robots

By morphologies: robot arms, humanoid, insect (bio-inspired) robots

By features of functionality: wheeled, legged robots

There are usually multiple ways of defining the type of robots.
Robots in industry

YASKAWA: motoman.com
FANUC: fanuc.eu/uk/en/robots
Kawasaki Robotics: robotics.kawasaki.com
ABB: new.abb.com/products/robotics
KUKA: kuka.com
Schunk: schunk.com/be_en/homepage
Universal Robots: universal-robots.com
Industrial robots

YASKAWA

Fanuc

KUKA

ABB

Schunk

UR
Car assembly in Tesla

Picture source: pinterest.com
Robot Control
Historically, robotics strongly involves the realization of physical motions, and most robots are essentially motion systems (“robota” → labour).

Therefore, the majority of robotics research focuses on:

1. Sensors
2. Actuators
3. Control

Particularly, as sensing and actuation problems are being solved gradually, more effort is made towards control, or more precisely speaking, autonomy.

Automation → Autonomy → Intelligence
Concept of control

What is control?

1. Apply action or influence to achieve an expected outcome.
2. It needs to apply actions, an actuation or an agent.
3. It needs sensor feedback, a probe, if a feedback control system.

Generally, control (feedback control) is about reasoning about how to apply actions given the feedback information in order to achieve a goal.
The 5 levels of robot intelligence are about how to control a robotic system.

Three levels of control:

1. Servo/tracking control (SISO, MIMO)
2. Optimization, optimal control
3. Machine learning

The first two are model-based approaches, where knowledge of mechanics and physics is required. Knowledge is given a priori, computationally cheap.

Machine learning is a model-free approach, it ‘learns’ the model through data in a statistical manner. Model is built by big data, computationally expensive.
Open-loop control

Examples:

1. Traffic light system, only the request is the input, the rest is pre-programmed regardless of the situation;
2. Fountain;
3. Or your washing machine;
4. :
Closed-loop control

Closed-loop (feedback) control: monitors feedback, uses the deviation signal to control the action so as to reduce the deviation to zero.

Note: closed-loop (feedback) control, closed-loop and feedback are mutually exchangeable words.
Closed-loop control

Closed-loop (feedback) control uses negative feedback.

A centrifugal governor is a good example of a mechanical controller.

Invented in 1788 by James Watt to control the steam engine.
Robot control

Three levels of control:

1. Servo/tracking control
2. Optimization, optimal control
3. Machine learning

- Typically featured by stable, robust, and dynamic motions
- Typically featured by a diversity of intelligent behaviors

In many cases, as shown before, robot control attempts to exploit kinematics and dynamics of the system.
Why kinematics matter?

Explore all configurations, maximize or validate reachability.
Why dynamics matter?

Can an object ($\rho > 0$) stay above the water?

Stone skipping
Why dynamics matter?

Tasks and performance that can only be achieved by dynamic motions
Why intelligent behaviors matter?

Most robotic applications are particularly programmed for solving specific problems. However, what if we want more universal or versatile machines?
Why behaviors matter?

Human intervention & supervision.
Why behaviors matter?

Human intervention & supervision.

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Roadmap for robotics
## Summary of key RSS elements

<table>
<thead>
<tr>
<th>Topic</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Robot Kinematics &amp; Dynamics</td>
<td>J. J. Craig, Introduction to Robotics: Mechanics and Control</td>
</tr>
<tr>
<td>State Estimation &amp; Kalman Filter</td>
<td>Peter Corke, Robotics, Vision and Control, Springer-Verlag.</td>
</tr>
<tr>
<td>Path &amp; Motion Planning (mobile)</td>
<td>S. Thrun, W. Burgard and D. Fox, Probabilistic Robotics.</td>
</tr>
<tr>
<td></td>
<td>Peter Corke, Robotics, Vision and Control, Springer-Verlag.</td>
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<tr>
<td><strong>Trajectory Planning and Motion Planning (articulated)</strong></td>
<td>Siciliano, B., et al., Robotics: Modelling, Planning and Control.</td>
</tr>
<tr>
<td><strong>Digital System &amp; Control</strong></td>
<td>Peter Corke, Robotics, Vision and Control, Springer-Verlag.</td>
</tr>
<tr>
<td><strong>Design of Advanced Controllers</strong></td>
<td>Franklin, Gene F., et al., Feedback control of dynamic systems.</td>
</tr>
<tr>
<td><strong>Optimization</strong></td>
<td>Yoshihiko Nakamura, Advanced Robotics: Redundancy and Optimization.</td>
</tr>
<tr>
<td><strong>Model Predictive Control</strong></td>
<td>J.M. Maciejowski, Predictive control : with constraints.</td>
</tr>
</tbody>
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Robotics, making a better world

Field test of robots in a post-earthquake scenario, video.