Welcome to Applied Robotics (FRTF20)

LECTURE 1

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Applied robotics FRTF20

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Course program (see www.control.lth.se and Canvas)

FRTF20 - Applied Robotics

Tillämpad robotteknik, 7.5 hp

General Information

Elective for: D4-mai, E4, F4, I4, M4-me, M4-prr, MD4, Pi4, MPRR2
The course will be given in English

Aim

The purpose of the course is to give basic knowledge in industrial robotics where theory is applied on industrial applied problems. The purpose is to provide an understanding on how theory within the subject of the course can be applied in a practical way from an engineering point of view to create models for analysis, simulation and programming, and create solutions on problems which focus on efficient use of robots in industry.

Learning outcomes
Theory and Practice

• Time and venues: see Canvas/TimeEdit
  (need to register, log on with your STIL-account)
• Lectures (online/pre-recorded/flipped classroom)
• Exercises (kinematics, dynamics / matlab)
• Lab-exercises 1-3 (RobotStudio)
  – Hands-on exercises in RobotLab
• Hand-ins kinematics/dynamics pass/ grade 3
• Project work; report + demo
• Optional servo-lab
• Optional take-home exam for higher grade (4-5)
Practical issues

• Read the Covid-teaching policy at

http://www.control.lth.se/education/covid-19-teaching-policy-at-automatic-control-fall-2020/
Recommended course literature

Spong, M.W., Hutchinson, S., and Vidyasagar, M.,
Robot Modeling and Control,
John Wiley and Sons, 2006

Lecture notes by Leonid Freidovich
(based on Spong et al)
Available on Canvas@Lund
Software

RobotStudio

(PC-based robot simulation, ABB Robotics)

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

Matlab/Simulink

http://petercorke.com/Robotics_Toolbox.html
(NOTE! USE version >= 10)

http://en.wikibooks.org/wiki/Robotics_Kinematics_and_Dynamics
Optional material (recommended)

Peter Corke’s robot-academy

http://petercorke.com/wordpress/resources/robot-academy
Optional reading (recommended)

Peter Corke’s robot toolbox (matlab)

http://petercorke.com/Robotics_Toolbox.html
NOTE! USE latest version (10.x)

Available as e-book at
https://link.springer.com/content/pdf/10.1007%2F978-3-319-54413-7.pdf
from LU-network.
Optional reading (recommended)

"Modern Robotics: Mechanics, Planning, and Control," by Kevin Lynch and Frank Park

- Available pdf book
- Video lectures
- Rotations based on screw-theory and exponential representations

http://hades.mech.northwestern.edu/index.php/Modern_Robotics
Projects - examples
[info/choice week 2]
2020: Special projects related to Construction Robotics

To be able to program robust pick-and-place sequences in an accurate brick-laying scenario (see pictures above) it is crucial for very exact placement of the building bricks, that a good enough localization for gripping first can be determined followed by an accurate measurement how the brick was positioned within the gripper.

Workshop on Construction Robotics
October 22
Compulsory Hands-On exercise

Please sign up for the first RobotStudio exercise including a compulsory hands-on exercise

Alternatives

Thursday  Sept 3, 17.15-19,    IKDC:108
Friday    Sept 4, 8.15-10,      IKDC:108

Announcement on Canvas with direct link to signup-list

Preparation: Read hand-out before coming to the lab!
Robots – What kinds of robots?

Industrial robotics
Mobile Robotics
Service robotics
Entertainment

Multi-disciplinary:
Nonlinear control, mechatronics, real-time embedded systems...
Some Robot Classifications

- **“Entertainment Robotics”**
  - Wheeled and Walking Robots, such as Asimo from Honda
  - Toys such as Aibo from Sony, [https://us.aibo.com/](https://us.aibo.com/)
  - Boston dynamics [https://www.bostondynamics.com/](https://www.bostondynamics.com/)

- **Service Robotics**
  - Trilobite - Robot Vacuum Cleaner from Electrolux
  - Husqvarna lawn mower
  - The Helpmate - Hospital Robots

- **Industrial Robotics**
  - Serial-Type Robots
  - Parallel Kinematic Machines
  - Arc and Spot Welding (Number 1 Application)
  - Spray Painting, Grinding, Milling, Polishing
Real-time coordination in collaborative machining

Lund University and Güdel AG exhibit real-time coordination between robots with significantly different types of kinematics and control systems. Requiring different robots to work together is an example of the heterogeneous situation that is typical at SMEs. The state of the art motion-coordination software is demonstrated by collaborative machining of parts for wooden boxes. Here, a Güdel parallel-kinematic concept robot and a standard ABB serial-kinematic robot complement each other well to solve the task: The parallel robot offers exceptional stiffness and accuracy for machining, and the serial robot can perform both handling and rough-cut machining. These two relate to the project’s demonstrator currently deployed at a Swiss woodworking company, with software services being loosely coupled for flexible configuration while supporting tight real-time control loops for efficiency during production.

https://www.youtube.com/watch?v=1kkXDWQQTIo&list=PLEh-D3GZjSvGk3BMxKbjx9nzmREW&j=index=6&t=0s
Medical robotics

da Vinci-robot by Intuitive surgery


https://www.youtube.com/watch?v=7sTfD_mStwE

https://www.youtube.com/watch?v=C17-bGquIjI
Robotics in this course

The following conceptual problems must be resolved to make a robot succeed in performing a typical task:

- Forward Kinematics
- Inverse Kinematics
- Velocity Kinematics/Jacobians
- Dynamics
- Path Planning and Trajectory Generation
- Motion Control
- (Force Control)
- Sequence programming (and task description)
Robotics

• The application, tooling, design of robots…
Degrees of freedom

- An object has \( n \) degrees of freedom (DOF) if its configuration can be minimally specified by \( n \) parameters.
- The number of DOF is equal to the dimension of the configuration space.
- For a robot manipulator:
  
  \[
  \text{number of joints} = \text{number of DOF}
  \]

Example: The GiftWrapper
Robot arm

Tool center point (TCP)
Forward and Inverse kinematics

• **Forward kinematics:**
  - Given angles find tooltip pose (pose: position+orientation)

• **Inverse kinematics:**
  - Given desired tool pose find joint angles

  Possibly several different solutions
Workspace

• Joint limitation taken into account
Robot motions

• Point-to-point motion
  – **MoveL** - Moves the tooltip (TCP) of the robot linearly
  – **MoveJ** – “joint interpolation” (usually ends up with *curved Cartesian motion*)

• Path generation
  – Geometric path

• Trajectory tracking
  – Geometric path AND time matters
  – At what time are you in what position with what velocity/acc etc

**Fanta Challenge**
[http://www.youtube.com/watch?v=SOESSCXGhFo](http://www.youtube.com/watch?v=SOESSCXGhFo)
Ethical Issues

• A company should not use robots to replace workers, unless they are forced to by global competition. What is your opinion?

• A robot should do hazardous and strenuous jobs that workers cannot or do not want to do.

• Robotics can create new jobs - in engineering and science – and save jobs in high-cost countries.

• Robotics can increase product quality and repeatability.

• Robotics is finding new applications in the domestic service market which potentially can give people more spare time.
Robots Create Jobs

ROBOTICS will be a major driver for global job creation over the next five years. The announcement is based on a study conducted by the market research firm, Metra Martech, "Positive Impact of Industrial Robots on Employment".

One million industrial robots currently in operation have been directly responsible for the creation of close to three million jobs, the study concluded. A growth in robot use over the next five years will result in the creation of one million high quality jobs around the world. Robots will help to create jobs in some of the most critical industries of this century.
Advantages of robotics

• Reduced cycle times (in some cases from 30 mins to 3 mins – replacing slower TIG welders with MIG welders)

• One twin robot welding cell can replace 10 manual stations (frees up floor space and welding equipment)

• Less environmental damage – as fume extraction from one station is easier to handle than 10 stations.

• Consistent and repeatable product quality

• Easier to keep good employees because of interesting technology environment
Industrial robot as defined by ISO 8373:
An **automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes**, which may be either fixed in place or mobile for use in industrial automation applications.

**Reprogrammable**: whose programmed motions or auxiliary functions may be changed without physical alterations;

**Multipurpose**: capable of being adapted to a different application with physical alterations;

**Physical alterations**: alteration of the mechanical structure or control system except for changes of programming cassettes, ROMs, etc.
<table>
<thead>
<tr>
<th>Principle</th>
<th>Kinematic Structure</th>
<th>Photo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Articulated Robot</td>
<td><img src="image" alt="Articulated Robot" /></td>
<td><img src="image" alt="Articulated Robot" /></td>
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<tr>
<td>SCARA Robot</td>
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**Revolute joints**
Prismatic joints

**Flexpicker**:  [https://www.youtube.com/watch?v=cajVzpJKjdw](https://www.youtube.com/watch?v=cajVzpJKjdw)

**PKM Gantry-Tau**:  
[http://www.smerobot.org/15_final_workshop/download/half%20resolution/D1_Parallel_Kinematic_512x288_500kBit.wmv](http://www.smerobot.org/15_final_workshop/download/half%20resolution/D1_Parallel_Kinematic_512x288_500kBit.wmv)
Some statistics

http://www.ifr.org/industrial-robots/statistics/

2021: 3.8 Million Industrial Robots in the World’s Factories

Estimated worldwide operational stock of industrial robots 2016-2017 and forecast for 2018*-2021*

+16% on

*forecast

'000 of units

2009 1,021
2010 1,059
2011 1,153
2012 1,235
2013 1,332
2014 1,472
2015 1,632
2016 1,828
2017 2,098
2018* 2,408
2019* 2,778

Source:

Positive trend
Industrial areas

Key Industries: Automotive, Electronics & Metals

Annual installations of industrial robots at year-end worldwide by industries 2016-2018

- Automotive: +2%
- Electrical/electronics: -14%
- Metal and machinery: -1%
- Plastic and chemical products: +32%
- Food: +48%
- All others: +44%

Source: World Robotics 2019
Industrial areas

Technological Developments expanding Robot Adoption

Today
- More intelligent components, e.g. Smart Grippers
- Greater Connectivity, e.g. “Plug & Play” Interfaces and Cloud Computing
- Easier to Use, e.g. “Programming by Demonstration”

Tomorrow
- “Machine learning” enables Robots ....
  ▪ to learn by trial-and-error or by video demonstration.
  ▪ to self-optimise.
  ▪ to communicate with other machines to improve entire processes.
- New business models, e.g. Robots as a Service (RaaS)
Automotive example: production of Tesla S

https://www.youtube.com/watch?v=8_lfxPI5ObM
Human-machine collaboration

- The break-through of the human-machine collaboration is just beginning

- People without experience in using robots can program and integrate a robot in the process because it
  - is capable of understanding human-like instructions
  - has modular plug-and-produce components

- Major challenge safety
  - The robot is working close to the worker without a fence
  - Lightweight robots with integrated vision guidance and better sensor
  - ISO: Technical Specification for collaboration of humans and industrial robots in order to provide reliable safety requirements.
Collaborative industrial robots still a niche

Collaborative and traditional industrial robots

- Traditional Industrial Robots
- Collaborative Robots

2018: 409,000 units, 14,000 collaborative
2017: 389,000 units, 11,000 collaborative

Source: International Federation of Robotics
New Industrial Robot Designs

- Control engineers and mechanical design engineers must work together at concept stage (controller tuning stage too late)
- Parallel (stiff) designs increase resonance frequencies
- Control structures should be tested on elasticity models already at concept stage (e.g., Matlab/Simulink)
Force and vision – reaction time crucial

Applications and enabling technology ....
Ball-and-dart-catching robot
https://www.youtube.com/watch?v=XP7yWhN6V-k
Robotics in this course

• The following conceptual problems must be resolved to make a robot succeed in performing a typical task:
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  – Inverse Kinematics
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  – (Force Control)
  – Sequence programming (and task description)
Robot task example

Figure 1.19: Two-link planar robot example. Each chapter of the text discusses a fundamental concept applicable to the task shown.
Forward kinematics

Figure 1.20: Coordinate frames attached to the links of a two-link planar robot. Each coordinate frame moves as the corresponding link moves. The mathematical description of the robot motion is thus reduced to a mathematical description of moving coordinate frames.
Inverse kinematics

Figure 1.21: The two-link elbow robot has two solutions to the inverse kinematics except at singular configurations, the elbow up solution and the elbow down solution.
Rotations within a frame

Descriptions in different frames

\[ \vec{V}_1 = x^0_p \vec{x}_0 + y^0_p \vec{y}_0 \]

\[ \vec{V}_2 = x^1_p \vec{x}_1 + y^1_p \vec{y}_1 \]
Rotations in 2D

Rotations in 3D

\[
R_1^0(\theta) = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\{=: R_{z,\theta}\}
Composition of rotations

The rotations around the current $y$-axis and $z$-axis are basic rotations

\[
R_{y_0, \phi} = \begin{bmatrix}
\cos \phi & 0 & \sin \phi \\
0 & 1 & 0 \\
-\sin \phi & 0 & \cos \phi \\
\end{bmatrix} = R_1^0, \quad R_{z_1, \theta} = \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1 \\
\end{bmatrix} = R_2^1
\]

Therefore, the overall rotation is $R_2^0 = R_1^0 R_2^1$, i.e.

\[
R_2^0 = \underbrace{R_{y_0, \phi}}_{\text{first}} \quad R_{z_1, \theta} = \underbrace{\begin{bmatrix}
\cos \phi & 0 & \sin \phi \\
0 & 1 & 0 \\
-\sin \phi & 0 & \cos \phi \\
\end{bmatrix}}_{\text{second}} \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1 \\
\end{bmatrix}
\]
Frame-to-frame: rotations and translation

\[ P^0 = H_1^0 P^1 \]

\[ H_1^0 = \begin{bmatrix}
(x_1^0)_x & (y_1^0)_x & (z_1^0)_x & (o_1^0)_x \\
(x_1^0)_y & (y_1^0)_y & (z_1^0)_y & (o_1^0)_y \\
(x_1^0)_z & (y_1^0)_z & (z_1^0)_z & (o_1^0)_z \\
0 & 0 & 0 & 1
\end{bmatrix} \]

\[ P^1 = \begin{bmatrix}
x_1^1 \\
y_1^1 \\
z_1^1 \\
1
\end{bmatrix} \]

\[ P^0 = \begin{bmatrix}
x_p^0 \\
y_p^0 \\
z_p^0 \\
1
\end{bmatrix} \]

\[ H_1^0 \] is the homogeneous transformation (HT) matrix between 0-frame and 1-frame.

\[ \begin{bmatrix}
x_p^0 \\
y_p^0 \\
z_p^0 \\
1
\end{bmatrix} = \begin{bmatrix}
(x_1^0)_x & (y_1^0)_x & (z_1^0)_x & (o_1^0)_x \\
(x_1^0)_y & (y_1^0)_y & (z_1^0)_y & (o_1^0)_y \\
(x_1^0)_z & (y_1^0)_z & (z_1^0)_z & (o_1^0)_z \\
0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
x_1^1 \\
y_1^1 \\
z_1^1 \\
1
\end{bmatrix} \]
\[ P^0 = H_1^0 P^1 \]

\[ P^0 = \begin{bmatrix} p^0 \\ 1 \end{bmatrix} = \begin{bmatrix} R_1^0 p^1 + d^0 \\ 1 \end{bmatrix} = \begin{bmatrix} R_1^0 \\ \mathbf{0}_{1 \times 3} \\ H_1^0 \end{bmatrix} \begin{bmatrix} p^1 \\ 1 \end{bmatrix} \]

and the change of coordinates formula

\[ p^0 = R_1^0 p^1 + d^0 \]

becomes

\[ P^0 = H_1^0 P^1 \]

or, in more details,

\[
\begin{bmatrix}
  x_p^0 \\
  y_p^0 \\
  z_p^0 \\
  1
\end{bmatrix} = \begin{bmatrix}
  (x_1^0)_x & (y_1^0)_x & (z_1^0)_x & (o_1^0)_x \\
  (x_1^0)_y & (y_1^0)_y & (z_1^0)_y & (o_1^0)_y \\
  (x_1^0)_z & (y_1^0)_z & (z_1^0)_z & (o_1^0)_z \\
  0 & 0 & 0 & 1
\end{bmatrix} \begin{bmatrix}
  x_p^1 \\
  y_p^1 \\
  z_p^1 \\
  1
\end{bmatrix} = \begin{bmatrix}
  R_1^0 & o_1^0 \\
  \mathbf{0}_{3 \times 3} & 1
\end{bmatrix} \begin{bmatrix}
  p^1 \\
  1
\end{bmatrix}
\]
Representing Positions & Orientations

\[ B R_K = \begin{pmatrix} B e_{xK} & B e_{yK} & B e_{zK} \end{pmatrix} = \begin{pmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{pmatrix} \]
Homogeneous Transformations

A 4x4 Matrix that describes “3-Space” with information that relates Orientation and Position (pose) of a remote space to a local space

This 3x3 ‘Sub-Matrix’ is the information that relates orientation of Frame_{rem} to Frame_{Local} (This is called R the rotational Submatrix)

N vector projects the X_{rem} Axis to the Local Coordinate System

O vector projects the Y_{rem} Axis to the Local Coordinate System

A vector projects the Z_{rem} Axis to the Local Coordinate System

D vector is the position of the origin of the remote space in Local Coordinate dimensions
Exercise

A cube measuring 200mm on a side is placed in the center of the table. A camera is situated directly above the center of the cube.

1. Find the homogeneous transformations relating Frames 1, 2 and 3 to the base frame 0.

2. Find the homogeneous transformations relating Frame 3 to Frame 2.