General Information (IN3140)

Examination in IN3140 - Introduction to Robotics (Spring 2025)

Examination date: June 5th
Examination time: 09:00 - 13:00 (4 hours)
Resources: Relevant formulas and calculators (see bottom of screen)
Permitted materials:

- Spong, Hutchinson & Vidyasagar, *Robot Modelling and Control* (chapter 11, which is missing from the last edition, is also available in Inspera at the bottom of the page)
- Karl Rottman, *Matematisk formelsamling* (also available in Inspera at the bottom of the page)
- Approved calculator

A simple and an advanced calculator are available in Inspera.

The examination consists of thirteen tasks that may be solved in arbitrary order:

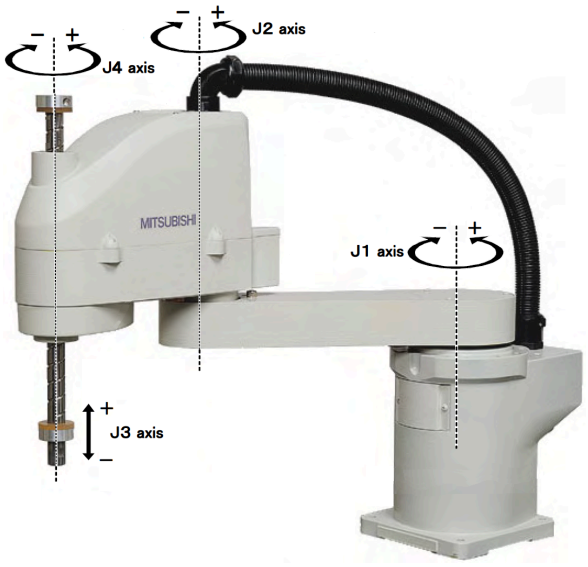
Task 1-6, 7b),are either multiple choice questions or short essay tasks - **they are to be answered on the computer**. There is no penalty for guessing on multiple choice questions.

Task 7a), 8-11 are conventional tasks that will test your knowledge in ROS, kinematics, dynamics and control theory - **these tasks are to be answered by submitting hand drawings.** You use the handed out sketch sheets. It is possible to use several sheets per assignment. See instructions on how to fill in the sketch sheets in the link below the assignment overview.

You are not supposed to submit hand drawings for any other tasks than **task 7a) and task 8-11**. You will NOT be given extra time to fill in the information boxes on the sketch sheets (assignment codes, candidate number, etc.)

1 Manipulator 1

A manipulator of which type is displayed in the following image?



Select one alternative:

- SCARA manipulator
- Spherical manipulator
- PPR manipulator
- Revolute manipulator

Maximum marks: 1

2 Manipulator 2

A manipulator of which type is displayed in the following image?



Select one alternative:

- Spherical manipulator
- Scara manipulator
- RRR manipulator
- Cylindrical manipulator

Maximum marks: 1

3 Inertia calculation

In Dynamics the Inertia (I) of an object can be expressed as a matrix. Given the box and the coordinate frame below:

What is the formula for calculating I_{xy}?

Select one alternative:

- $I_{xy} = -\int_{-1}^{1}\int_{-2.5}^{2.5}\int_{-1}^{1} x^2 + y^2 \quad p(x,y,z)dxdydz$
- $I_{xy} = -\int_{-1}^{1}\int_{-2.5}^{2.5}\int_{-1}^{1} xz + yz \quad p(x,y,z)dxdydz$
- $I_{xy} = -\int_{-1}^{1}\int_{-2.5}^{2.5}\int_{-1}^{1} (z^2(x+y)) \quad p(x,y,z)dxdydz$
- $I_{xy} = -\int_{-1}^{1}\int_{-2.5}^{2.5}\int_{-1}^{1} xy \quad p(x,y,z)dxdydz$

Maximum marks: 1

4 Dynamics Coriolis

The general dynamics of a system can be expressed by the following equation:

$\tau = D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q)$

Given the following Dynamics:

$$\tau = \begin{bmatrix} m_1 L_1^2 \ddot{q}_2 - m_2 L_2^2 s_2 \ddot{q}_1 - m_2 L_1 c_1 s_2 \dot{q}_1 + \frac{1}{2} m_1 g L_1 s_2 \\ m_2 L_1 c_2 \ddot{q}_2 + m_2 L_1^2 L_2^2 c_2 \dot{q}_1 \dot{q}_2 \end{bmatrix}$$

Which expression(s) would describe the **Coriolis and Centrefugal forces** acting on the system?

Select one alternative:

- $\begin{bmatrix} 0 & -m_2 L_1 s_2 c_1 \\ 0 & m_2 L_1^2 L_2^2 c_2 \dot{q}_1 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}$
- $\begin{bmatrix} m_2 L_2^2 s_2 & -m_1 L_1^2 \\ 0 & m_2 c_2 L_1 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}$
- $\begin{bmatrix} m_2 L_2^2 s_2 & 0 \\ -m_1 L_1^2 & m_2 L_1 c_2 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}$
- $\begin{bmatrix} -m_2 L_1 c_1 s_2 & 0 \\ m_2 L_1^2 L_2^2 c_2 \dot{q}_2 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}$

Maximum marks: 2

5 Dynamics Inertial

The general dynamics of a system can be expressed by the following equation:

$\tau = D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q)$

Given the following Dynamics:

$$\tau = \begin{bmatrix} m_1 L_1^2 \ddot{q}_2 - m_2 L_2^2 s_2 \ddot{q}_1 - m_2 L_1 c_1 s_2 \dot{q}_1 + \frac{1}{2} m_1 g L_1 s_2 \\ m_2 L_1 c_2 \ddot{q}_2 + m_2 L_1^2 L_2^2 c_2 \dot{q}_1 \dot{q}_2 \end{bmatrix}$$

Which expression(s) would describe the **Inertia forces** acting on the system?

Select one alternative:

- $\begin{bmatrix} -m_2 L_1 c_1 s_2 & 0 \\ m_2 L_1^2 L_2^2 c_2 \dot{q}_2 & 0 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}$
- $\begin{bmatrix} m_2 L_2^2 s_2 & 0 \\ -m_1 L_1^2 & m_2 L_1 c_2 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}$
- $\begin{bmatrix} -m_2 L_2^2 s_2 & m_1 L_1^2 \\ 0 & m_2 c_2 L_1 \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix}$
- $\begin{bmatrix} 0 & -m_2 L_1 s_2 c_1 \\ 0 & m_2 L_1^2 L_2^2 c_2 \dot{q}_1 \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix}$

Maximum marks: 2

6 AI in robotics

We want to design an autonomous surgical robot that accurately can suture a wound on the patient skin. The mechanical design of the robot is already completed. We now want to make the robot learn how to perform the suturing task effectively.

a) (2%) Why might we prefer to use **AI-based methods** (e.g., machine learning or reinforcement learning) over traditional mathematical modeling to control the suturing behaviour? And what is the role of **sensing** (such as visual or tactile sensors) in supporting this learning process?

b) (4%) We want to make use of **Deep Reinforcement Learning (Deep RL)** to train the robot to perform the suturing. The robot has a **camera sensor** and is controlled using **four controllable actuators**. Please briefly describe what the following RL terms mean in the context of our autonomous surgical robot:

- Agent
- State
- Action
- Policy

c) (2%) To train the robot safely, we want to start training with **simulation**. What is a key problem with relying on simulation for training the robot, and what is **one method** we can use to reduce this problem?

d) (2%) Describe **two common issues** when using **Reinforcement Learning** for robots.

e) (2%) Describe **two motivations** behind using **Evolutionary Robotics** to design robots.

Fill in your answer here

Format

Words: 0

Maximum marks: 12

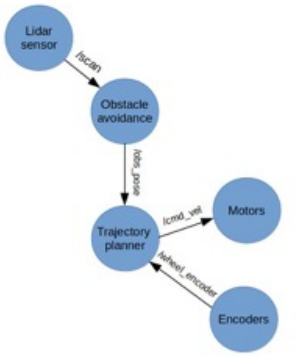
7 ROS

We have a vacuum cleaner robot that autonomously cleans an indoor environment.
The schematics below shows the current **rqt_graph** of the robot, including its different components such as sensors, actuators, and algorithms, and how they communicate with each other. **Now we want to add new functionality to this existing system.**

Currently, the robot detects all obstacles using a Lidar sensor. However, for safer navigation, we want the robot to distinguish between humans and other obstacles during its movement planning.
To achieve this, we will add a camera and the functionality for the robot to detect humans. Once a human is detected, their position will be estimated using the LiDAR, and this information will be included in the robot's planning system.

a) 8% - Complete the rqt_graph to include this functionality in a separate hand drawing, following the same style and structure as the current rqt_graph.

In this exercise you can answer with digital hand drawing. Use the handed out sketch sheets. See instructions on filling out the sketch sheets in the link below the task bar.



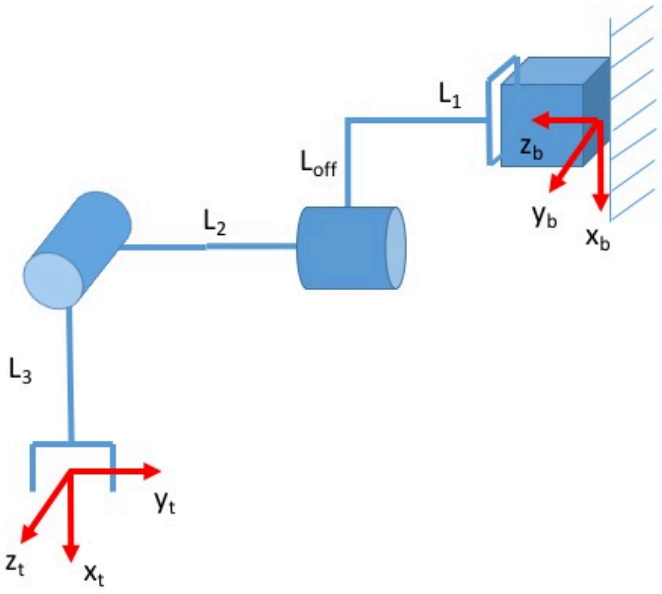
b) 4% What is the difference between a **topic** and a **message** in ROS?
Please explain and give an example based on the robot system described above.
Fill in your answer here

Format

Words: 0

Maximum marks: 12

8 Kinematics



In this exercise you can answer with digital hand drawing. Use the handed out sketch sheets. See instructions on filling out the sketch sheets in the link below the task bar.

The figure above shows the manipulator used in this task. The first prismatic joint in the base of the manipulator moves along the **Z_b - axis**. The position of the center of the prismatic joint in the base (joint 1) and the first revolute joint (joint 2), is given by the length L_1 (variabel of joint 1) and the constant offset, L_{off}, perpendicular to L_1 as shown in the figure. Joint 2 and joint 3 are revolute joints where $\boldsymbol{\theta_2}$ and $\boldsymbol{\theta_3}$ are joint variables for the manipulator with axis of rotation along **Z_b - axis** and **Y_b - axis** (i zero position). The zero position of the manipulator is as shown in the figure. **L_2** is the fixed length between the first and second revolute joint, whereas **L_3** is the fixed length between the second revolute joint and the end effector of the manipulator (tool tip).

The base coordinate system (**b**) where the **Y_b - axis** is pointing towards us out of the screen, and the task coordinate system (**t**) where the **Z_t - axis** is pointing towards us out of the screen is to be used and is shown in the figure.

a) 3% Draw the manipulator workspace (include the outer and the inner boundaries).
b) 6% Assign coordinate frames in accordance with the Denavit-Hartenberg convention to the manipulator in the figure in a separate drawing . Find the Denavit-Hartenberg parameters and place them into a DH-table.
c) 5% Derive the forward kinematics of the manipulator from the base coordinate system to the end-effector.
d) 5% Derive the inverse kinematics of the manipulator.
e) 6% Derive the Jacobian matrix of the manipulator.

Maximum marks: 25

9 Coordinate frame transformations

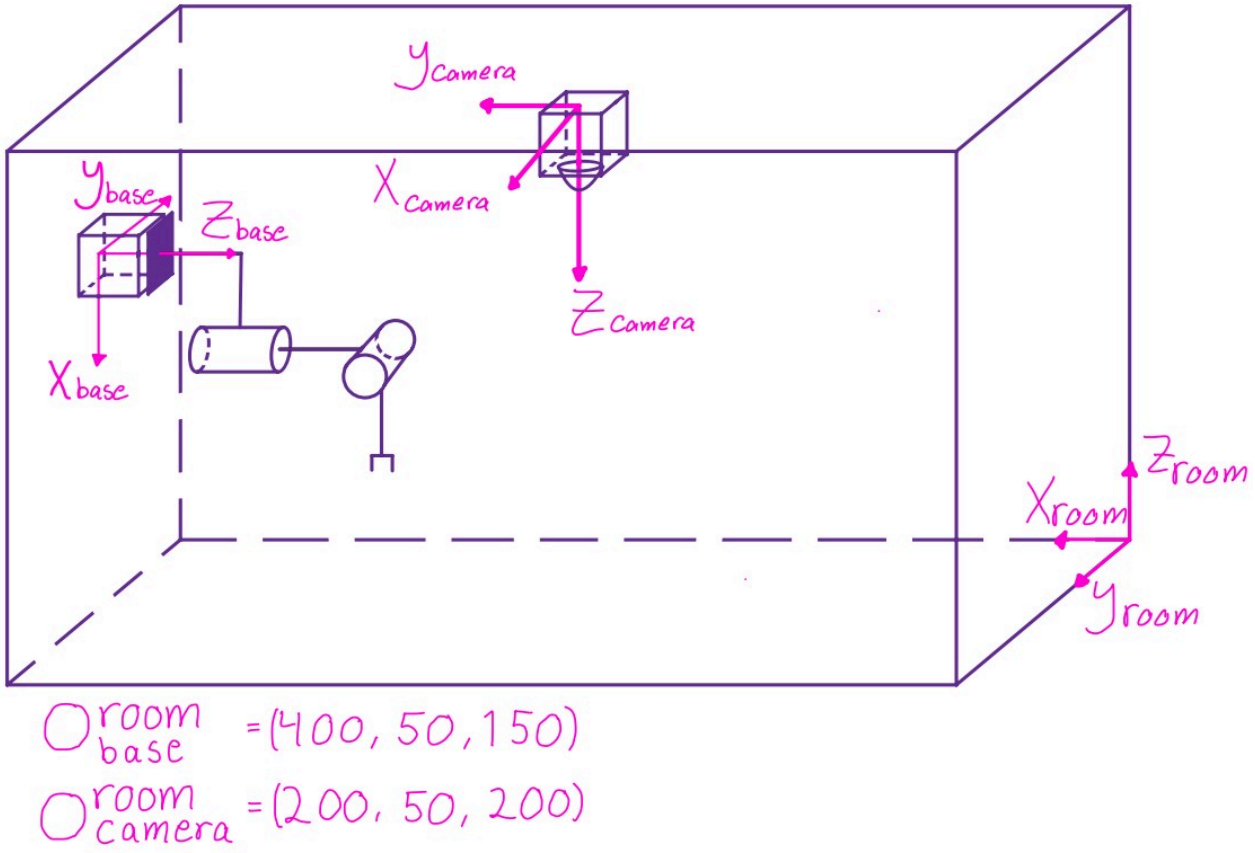
The room contains a manipulator which is the same as in the previous tasks, and a camera with an attached coordinate frame mounted to the ceiling at the center of the roof as shown in the figure below. **The origin of the base (b) coordinate frame of the robot attached to the left wall and the origin of the camera (c) coordinate frame is positioned relative to the room (r) coordinate frame** as indicated in the same figure.

Origin of base given in room coordinates: O^r_b= (400, 50, 150)

Origin of camera given in room coordinates: O^r_c = (200, 50, 200)

Coordinates are given in centimeters, and all corners of the room are right-angled.

In this exercise you can answer with digital hand drawing. Use the handed out sketch sheets. See instructions on filling out the sketch sheets in the link below the task bar.



In all sub questions show how you **derive the expressions** and how you **calculate the final values**:

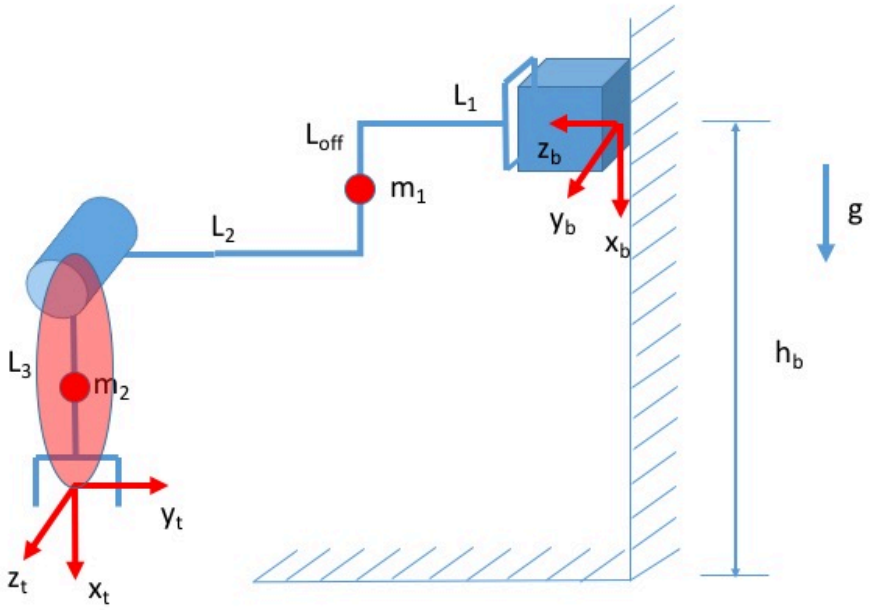
a) 1**%** What is the height, width and depth of the room given in the drawing above?

b) **3%** Find the homogeneous transform from the camera frame to the base frame of the robot (T^c_b)

Fill in your answer here

Maximum marks: 4

10 Dynamics



In this exercise you can answer with digital hand drawing. Use the handed out sketch sheets. See instructions on filling out the sketch sheets in the link below the task bar.

The figure above shows a simplified version of the manipulator from the kinematic task where the first revolute joint (joint 2) is locked ($\theta_2 = 0$). This manipulator has then two degrees of freedom. Assume that the mass of the arm link 1 has a point mass of $\mathbf{m_1}$ and is positioned in the middle of $\mathbf{L_{off}}$ and that the mass of the arm link 2 is a distributed mass $\mathbf{m_2}$ with its center of mass in the middle of arm link 2 at a distance of $L_3/2$ from the axis of rotation (L_3 is the total length of the arm link 2).

Arm link 2 has a moments of inertia in arm link coordinate frame $I = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix}$.

a) 3% Find the **symbolic** expression of the system's potential energy.

b) 9% Find the **symbolic** expression of the system's kinetic energy.

c) 9% Assemble the Lagrangian $\mathcal{L}$ accordingly. Then, derive the dynamics of the manipulator using the Euler-Lagrange formulation. Write the equations of motion in the following form:

$$D(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) = \tau$$

d) 4% What would the main difference be in the dynamic equations if the mass $\mathbf{m_1}$ of the arm link 1 also was a distributed mass?

Maximum marks: 25

11 Control theory

Closed loop transfer function between the input θd and the output θ :

$$\theta = \frac{\theta d(Kp+Ki\frac{1}{s})-D}{Js^2+Bs+Kp+Kds+Ki\frac{1}{s}}$$

a) **3%** What type of controller do we have in this system given this transfer function above?

b) **6%** Draw the corresponding block diagram of this closed loop system

Assume that the system is given a step input $\theta d(s) = \frac{\omega}{s}$ and a constant disturbance $D(s) = \frac{d}{s}$

c) **6%** Use the Final Value Theorem to find the steady state error of the closed loop system given above.

Final Value Theorem: $\lim_{t\to\infty} x(t) = \lim_{s\to 0} sX(s)$

In this exercise you can answer with digital hand drawing. Use the handed out sketch sheets. See instructions on filling out the sketch sheets in the link below the task bar.

Maximum marks: 15