Robotics Exam

Chalmers Phd examination

Amir Saman Mirjalili

2024

Contents

Abstract

This document contains some basic exercises that evaluate your suitability for working in my research group at Chalmers. Please provide your solutions in the form of PDF (we highly appreciate LateX skills) and also working code (wherever asked) in a language of your choice (preferably C++, Matlab, Ruby, Julia or Python1).

Contents

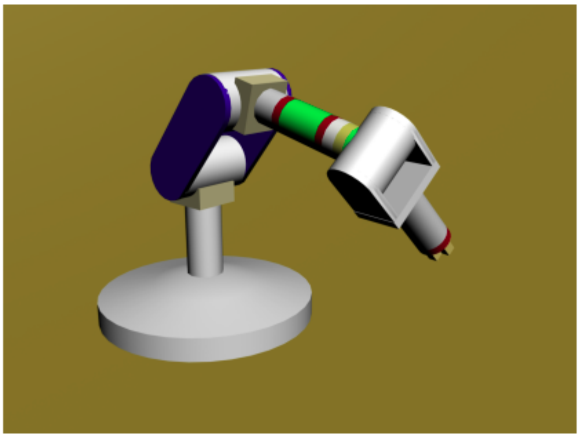
Chapter 2

Mechanics

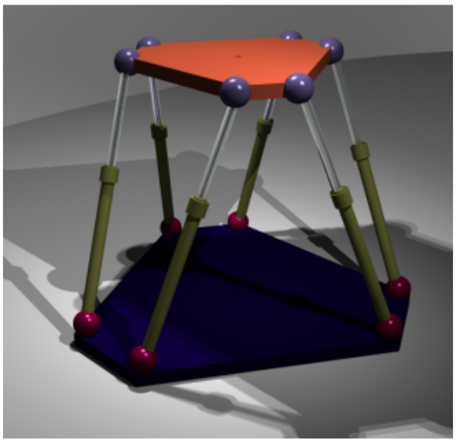
Topology and Mobility Analysis

2.0.1 Exercise 1

In this exercise, we will analyze the topology and mobility of two different robot configurations: a 6-DOF serial robot and a parallel robot (Stewart platform). Figure 2.1 shows a comparison of these two types of robots.



(a) 6-DOF Serial Robot



(b) Parallel Robot

Figure 2.1: Comparison of 6-DOF Serial Robot and Parallel Robot

Let's start by analyzing the 6-DOF serial robot in more detail. Figure 2.2 illustrates the joint axes and links of this robot.

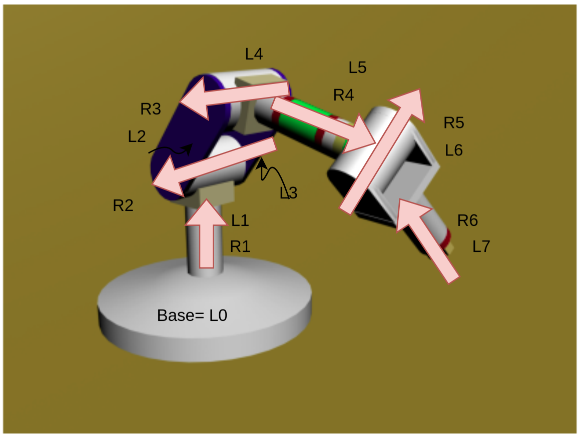


Figure 2.2: Joint axes and links of the 6-DOF serial robot

Solution: 8-Link Serial Robot

The serial robot described in Figure 2.1a and detailed in Figure 2.2 is a typical example of an industrial robotic arm. It consists of the following components:

- **Base (L_0)**:
  - This is the fixed part of the robot, usually mounted on the ground or a stable platform.
  - It serves as the reference frame for the entire robot structure.
- **Seven Moving Links (L_1 to L_7)**:
  - These are the rigid bodies that make up the robot's arm.
  - Each link connects to the next via a joint, forming a chain-like structure.
  - L_7 is typically the end-effector or the link to which a tool or gripper is attached.
- **Revolute Joints (J_0 to J_6)**:

  - These joints connect the links and allow rotational motion between them.
  - Each joint has one degree of freedom, allowing rotation around a single axis.
  - The joints are typically labeled J_0, J_1, J_2, J_3, J_4, J_5, and J_6.

- **Connectivity**:
  - Base (L_0) is connected to L_1 via J_0
  - L_1 is connected to L_2 via J_1 and to L_3 via J_2
  - L_2 is connected to L_4 via J_3
  - L_3 is connected to L_4 via J_4
  - L_4 is connected to L_5 via J_5
  - L_5 is connected to L_6 via J_6
  - L_6 is connected to L_7 via J_7

- **Kinematic Chain**:
  - The robot forms an open kinematic chain, starting from the base and ending at the end-effector.
  - Each joint adds one degree of freedom to the robot.

- **Degrees of Freedom**:
  - With seven revolute joints, this robot has 7 degrees of freedom (7-DOF).
  - This allows the end-effector to achieve any position and orientation within its workspace.

Connectivity Graph

Based on Featherstone's [2] definition, the connectivity graph for this robot represents each link as a node and each joint as an edge connecting the nodes, clearly showing the serial nature of the robot's structure with parallel connections.

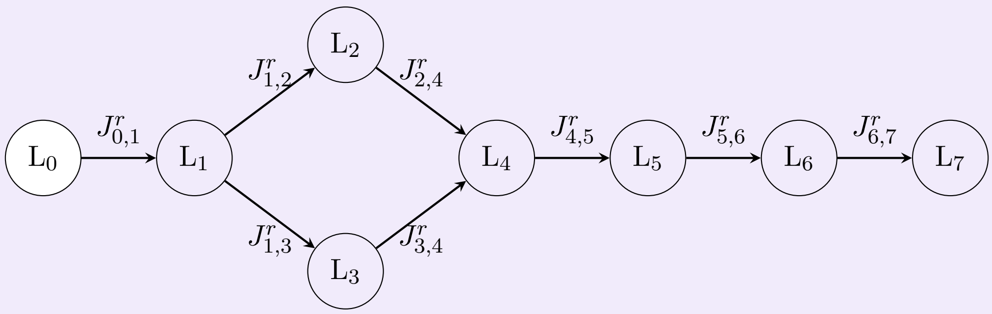


Figure 2.3: Connectivity graph for an 8-link serial robot with parallel connections

In this topological graph:

- Nodes (circles) represent links L_0 to L_7.
- Edges (arrows) represent joints J_0 to J_7.
- The white node (L_0) represents the fixed base.
- The graph clearly shows the serial chain structure of the robot with parallel connections.

Solution: Connectivity graph for the 6-SPS parallel robot (Stewart platform)

Now, let's analyze the connectivity of the parallel robot (Stewart platform) shown in Figure 2.1b. Figure 2.4 illustrates the connectivity graph for this 6-SPS parallel robot.

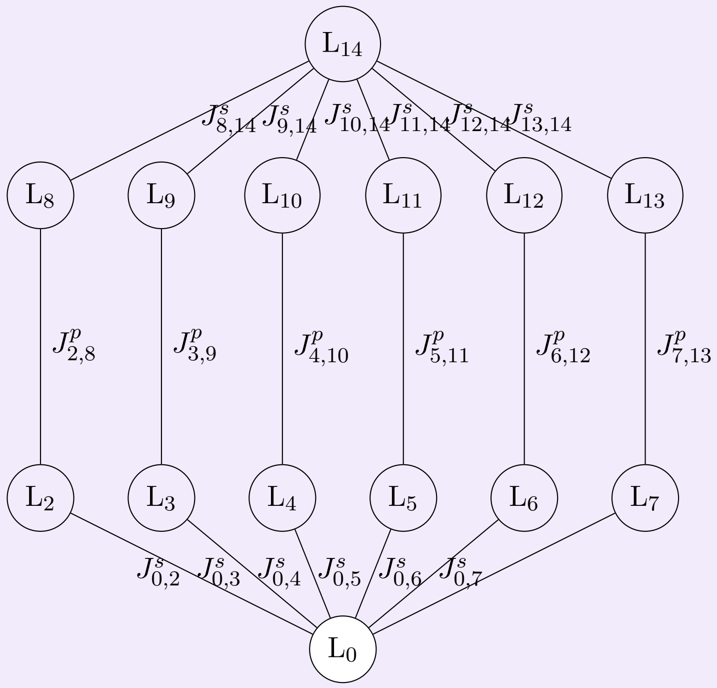


Figure 2.4: Connectivity graph for the 6-SPS parallel robot (Stewart platform)

Connectivity Graph: The graph represents the structure of a 6-SPS (Spherical-Prismatic-Spherical) parallel robot, also known as a Stewart platform.

Components:

- **Base ($\mathbf{L_0}$):** Represented by the white node at the bottom.
- **End-Effector ($\mathbf{L_{14}}$):** Represented by the top node, it's the moving platform.
- **Legs:** Six kinematic chains, each composed of two links:
  - Lower links: L_2 to L_7
  - Upper links: L_8 to L_{13}

Joints:

- **Spherical Joints (S):**
  - Base to lower links: $J^s_{0,i}$ where $i = 2, 3, ..., 7$
  - Upper links to End-Effector: $J^s_{j,14}$ where $j = 8, 9, ..., 13$
- **Prismatic Joints (P):**
  - Between lower and upper links: $J^p_{i,j}$ where $i = 2, 3, ..., 7$ and $j = i + 6$

Structure: Each of the six legs follows an SPS (Spherical-Prismatic-Spherical) configuration, connecting the base to the end-effector. This arrangement provides the robot with 6 degrees of freedom (3 translational and 3 rotational).

2.0.2 Exercise 2

The Chebyshev–Grübler–Kutzbach criterion estimates the degree of freedom (DOF) of a kinematic chain, that is, a coupling of rigid bodies by means of mechanical constraints. The general mobility of a robot can be estimated by the following criteria [5]:

$$F = \lambda(n - j - 1) + \sum_{i=1}^{j} f_i - f_p, \tag{2.1}$$

where

- F – degrees-of-freedom of the mechanism
- λ – degree-of-freedom of the space ($=3$ for planar and spherical mechanisms, $=6$ for spatial mechanisms)
- n – number of links in the mechanism including the base
- j – number of binary joints of the mechanism
- f_i – degrees of relative motion permitted by joint i
- f_p – total number of passive degrees-of-freedom

Solution:

Let's compute the mobility of the two robots shown in Figure 2.1 using Equation 2.1.

1. 6-DOF Serial Robot

For the serial robot (Figure 2.1a):

- $\lambda = 6$ (spatial mechanism)
- $n = 8$ (7 moving links + 1 base)
- $j = 7$ (7 revolute joints)
- $\sum_{i=1}^{j} f_i = 7$ (1 DOF per revolute joint)
- $f_p = 0$ (no passive degrees-of-freedom)

Applying Equation 2.1:

$$\begin{aligned} F &= \lambda(n - j - 1) + \sum_{i=1}^{j} f_i - f_p \\ &= 6(8 - 7 - 1) + 7 - 0 \\ &= 6(0) + 7 \\ &= 7 \end{aligned}$$

The mobility of the 6-DOF serial robot is 7, which matches our earlier analysis.

2. 6-SPS Parallel Robot (Stewart Platform)

For the parallel robot (Figure 2.1b):

- $\lambda = 6$ (spatial mechanism)
- $n = 14$ (12 leg links + 1 base + 1 platform)
- $j = 18$ (12 spherical joints + 6 prismatic joints)
- $\sum_{i=1}^{j} f_i = 42$ (3 DOF per spherical joint $\times$ 12 + 1 DOF per prismatic joint $\times$ 6)
- $f_p = 6$ (1 passive DOF per leg, rotating around its axis)

Applying Equation 2.1:

$$\begin{aligned} F &= \lambda(n - j - 1) + \sum_{i=1}^{j} f_i - f_p \\ &= 6(14 - 18 - 1) + 42 - 6 \\ &= 6(-5) + 42 - 6 \\ &= -30 + 42 - 6 \\ &= 6 \end{aligned}$$

The calculated mobility of the 6-SPS parallel robot is 6, which is correct.

Simplified Formula for Serial Robots

For serial robots, we can simplify Equation 2.1 because:

- The number of joints is always one less than the number of links ($j = n - 1$)
- There are typically no passive degrees-of-freedom ($f_p = 0$)

Substituting these into Equation 2.1:

$$\begin{aligned} F &= \lambda(n - j - 1) + \sum_{i=1}^{j} f_i - f_p \\ &= \lambda(n - (n - 1) - 1) + \sum_{i=1}^{j} f_i - 0 \\ &= \lambda(0) + \sum_{i=1}^{j} f_i \\ &= \sum_{i=1}^{j} f_i \end{aligned}$$

Therefore, the simplified formula for serial robots is:

$$F = \sum_{i=1}^{j} f_i \tag{2.2}$$

This means that for serial robots, the mobility is simply the sum of the degrees of freedom of all joints.

Application to Parallel Mechanisms

The extended Chebyshev–Grübler–Kutzbach criterion (Equation 2.1) works accurately for parallel mechanisms when we account for passive degrees-of-freedom. In the case of the Stewart platform:

1. Each spherical joint contributes 3 DOF to $\sum_{i=1}^{j} f_i$. 2. Each prismatic joint contributes 1 DOF to $\sum_{i=1}^{j} f_i$. 3. Each leg has 1 passive DOF (rotation around its axis), contributing to f_p.

By including these passive degrees-of-freedom in our calculation, we obtain the correct mobility of 6 for the Stewart platform without needing additional simplifications or corrections.

This demonstrates the importance of considering passive degrees-of-freedom when analyzing the mobility of complex parallel mechanisms.

2.0.3 Exercise 3

It seems almost magical that a simple formula like the Chebychev–Grübler–Kutzbach criterion can be used to estimate the general mobility of a system. Does it always work? Can you find some counter-examples where this formula fails?

Solution:

While the Chebychev–Grübler–Kutzbach criterion is a powerful tool for estimating the mobility of many mechanical systems, it does not always work correctly. This paper [3] addresses most of mechanisms that the mobility criteria failed to predict their DOF. Here we state several situations where the formula can fail to accurately predict the degrees of freedom of a mechanism. Let's explore some of these cases:

1. Overconstrained Mechanisms

Some mechanisms are overconstrained yet still mobile due to special geometric conditions. The Chebychev–Grübler–Kutzbach criterion often predicts zero or negative mobility for these systems, even though they can move.

Example: Bennett's Linkage

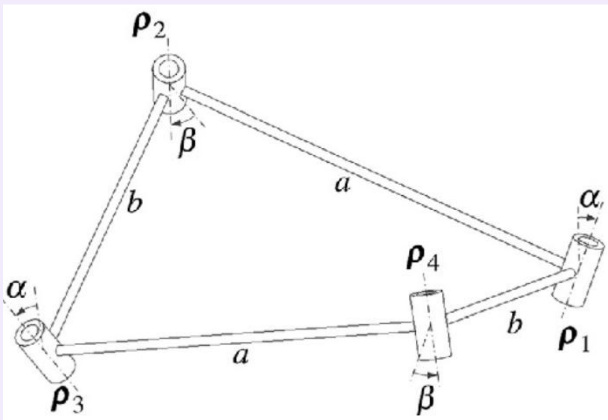


Figure 2.5: Bennett's Linkage [4]

Bennett's linkage is a spatial 4-bar linkage with one degree of freedom. However, applying the Chebychev–Grübler–Kutzbach criterion:

- $\lambda = 6$ (spatial mechanism)
- $n = 4$ (4 links)
- $j = 4$ (4 revolute joints)
- $\sum_{i=1}^{j} f_i = 4$ (1 DOF per revolute joint)
- $f_p = 0$ (no passive DOF)

$$
\begin{aligned}
F &= \lambda(n - j - 1) + \sum_{i=1}^{j} f_i - f_p \\
&= 6(4 - 4 - 1) + 4 - 0 \\
&= 6(-1) + 4 \\
&= -2
\end{aligned}
$$

The formula predicts -2 DOF, but the mechanism actually has 1 DOF due to its special geometry.

2. Mechanisms with Redundant Constraints

Some mechanisms have redundant constraints that don't affect mobility but are counted in the formula.

Example: Parallel Manipulator with Redundant Actuation Consider a planar parallel manipulator with three legs, each containing an actuated prismatic joint, where only two actuators are needed for full mobility.

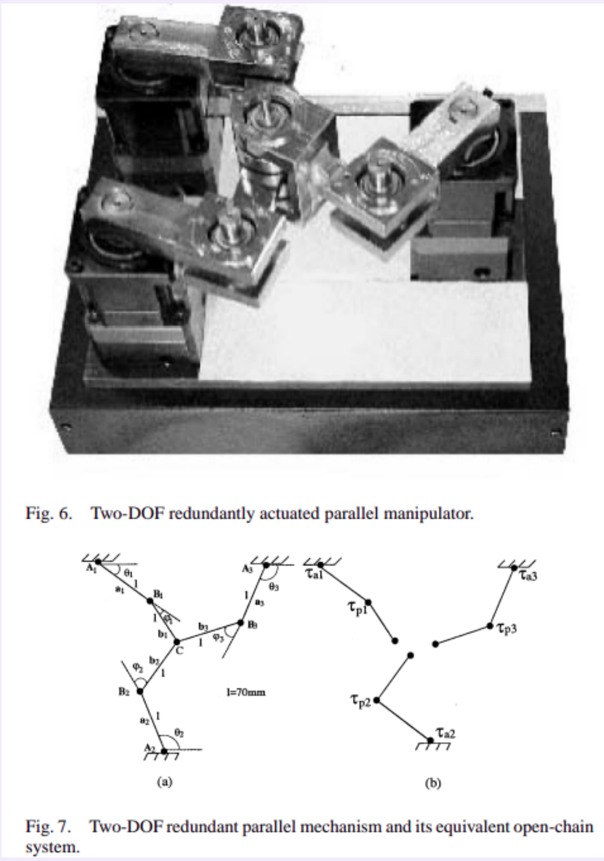


Figure 2.6: Two-DOF redundantly actuated parallel manipulator [1]

Applying the formula:

- $\lambda = 3$ (planar mechanism)
- $n = 8$ (1 base, 1 platform, 6 leg links)
- $j = 9$ (3 prismatic + 6 revolute joints)
- $\sum_{i=1}^{j} f_i = 9$ (1 DOF per joint)
- $f_p = 0$ (no passive DOF)

$$
\begin{aligned}
F &= \lambda(n - j - 1) + \sum_{i=1}^{j} f_i - f_p \\
&= 3(8 - 9 - 1) + 9 - 0 \\
&= 3(-2) + 9 \\
&= 3
\end{aligned}
$$

The formula predicts 3 DOF, which is correct, but it doesn't account for the redundant actuation.

3. Mechanisms with Special Configurations

Some mechanisms can change their mobility in certain configurations, which the formula doesn't capture.

Example: Bricard's Flexible Octahedron This mechanism can transition between 0 and 1 DOF depending on its configuration, but the Chebychev–Grübler–Kutzbach criterion always predicts the same mobility.

4. Mechanisms with Higher Pair Joints

The formula assumes lower pair joints (e.g., revolute, prismatic). It may not accurately predict mobility for mechanisms with higher pair joints (e.g., cam-follower systems).

Conclusion

While the Chebychev–Grübler–Kutzbach criterion is a valuable tool for initial mobility analysis, it has limitations. It's important to consider:

- Special geometric conditions
- Redundant constraints
- Configuration-dependent mobility
- The nature of the joints involved

In complex or unusual mechanisms, additional analysis methods (e.g., screw theory, instantaneous kinematics) may be necessary to accurately determine mobility.

Geometry and Kinematics

2.0.4 Exercise 4

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Solution:

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2.0.5 Exercise 5

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Solution:

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2.0.6 Exercise 6

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Dynamics

2.0.7 Exercise 7

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Solution:

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2.0.8 Exercise 8

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2.0.9 Exercise 9

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Solution:

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Contents

Chapter 3

Control

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Exercise 10

Exercise 11

Exercise 12

Contents

Chapter 4

Questionnaire

Question 1

During your studies, please select if you have taken any formal/related courses in:

- Mechanics or Applied Mechanics
- Mechanism Theory
- Machine Design
- Rigid Body Mechanics or Multi-Body Dynamics
- Modeling and Control of Robot Manipulators
- Humanoid Robotics
- Biomechanics
- Linear Control Theory
- Non-Linear Control Theory

- Introduction to Robotics
- Artificial Intelligence or Machine Learning
- Linear Algebra
- Advanced Calculus
- Probability Theory
- Object Oriented Programming

Additionally, mention your grade along with maximum possible grade in the applicable subjects.

Question 2

How do you find the overall difficulty level of the exercises? Categorize the exercises.

- Easy
- Medium
- Hard

Question 3

What kind of additional help did you seek while solving the exercises?

- Textbooks
- Wikipedia
- Research papers
- Other online sources
- Friends/Colleagues

Question 4

Please categorize your attempt to solve the exercises into:

- Solved without any external reference
- Solved with the help of known textbooks

- Solved with the help of online content (Wikipedia, online blogs etc.)
- Solved after reading research papers

List the exercise numbers in front of each option above.

Question 5

Please select the programming languages where you have a working knowledge.

- C/C++
- Python
- Matlab
- Julia
- Ruby
- Mathematica

Question 6

Please specify if you have worked with any symbolic manipulation packages.

- Matlab Symbolic Toolbox
- Maple
- Singular
- Sympy

Question 7

Have you worked with any industrial robot platforms?

- Universal robots
- KUKA robots
- St¨aubli robots
- PUMA 560
- Others

Question 8

Have you ever built your own robot as a hobby or group project at the University? If yes, describe your robot and your role in the project.

Question 9

Have you worked with a version control system? If yes, which one?

- Git
- SVN

Question 10

Do you have LateX skills?

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