Control of Industrial Robots

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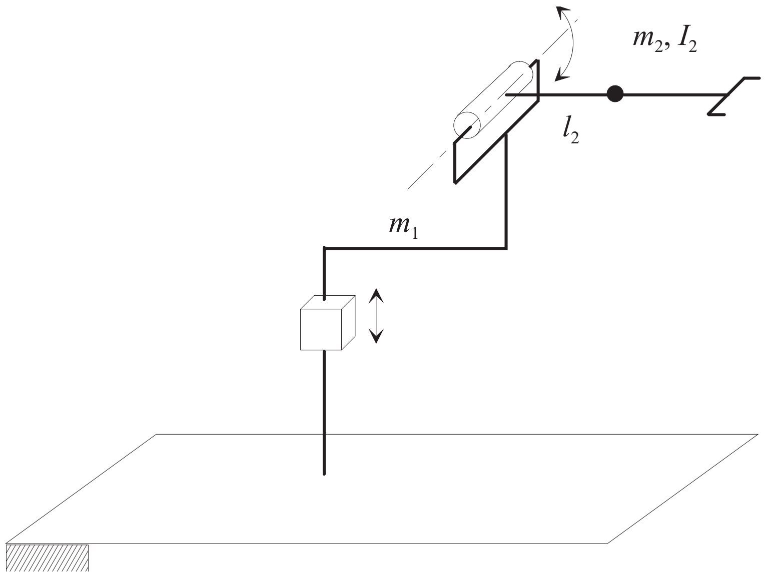
Warnings

- This file consists of **8** pages (including cover).
- During the exam you are not allowed to exit the room for any other reason than handing your work or withdrawing from the exam.
- You are not allowed to withdraw from the exam during the first 30 minutes.
- During the exam you are not allowed to consult books or any kind of notes.
- You are not allowed to use calculators with graphic display.
- Solutions and answers can be given **either in English or in Italian**.
- Solutions and answers must be given **exclusively in the reserved space**. Only in the case of corrections, or if the space is not sufficient, use the back of the front cover.
- The clarity and the order of the answers will be considered in the evaluation.
- At the end of the test you have to **hand this file only**. Every other sheet you may hand will not be taken into consideration.

EXERCISE 1

1. Consider the manipulator sketched in the picture:



Find the expression of the inertia matrix $\mathbf{B}(\mathbf{q})$ of the manipulator[1].

[1]The cross product between vector $a = \begin{bmatrix} a_1 \\ a_2 \\ a_3 \end{bmatrix}$ and $b = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \end{bmatrix}$ is $c = a \times b = \begin{bmatrix} a_2b_3 - a_3b_2 \\ a_3b_1 - a_1b_3 \\ a_1b_2 - a_2b_1 \end{bmatrix}$

2. Compute the gravitational terms for this robot.

3. Ignoring the Coriolis and centrifugal terms, write the dynamic model of the manipulator and show that this model is linear with respect to a certain set of dynamic parameters.

4. The linearity of the model in a set of dynamic parameters allows to setup experiments for the identification of such parameters. For a generic manipulator, explain what are the variables that need to be recorded during the experiments. With reference to the dynamic model of this exercise, is it possible to experimentally identify the mass of the first link?

EXERCISE 2

1. Explain what is the purpose of the kinematic calibration of a robot manipulator and why it is needed.

2. In the kinematic calibration of a robot manipulator the following equation is used:

$$\Delta\mathbf{x} = \mathbf{\Phi}\Delta\zeta$$

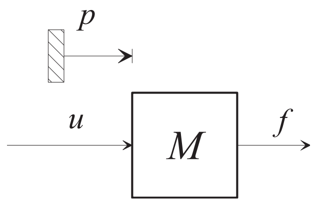
Explain the meaning of each symbol used in such equation, as well as the size of the vectors.

3. Based on the above equation, explain how the kinematic calibration can be performed.

4. Consider now a kinematically redundant manipulator. Write the general solution of the inverse kinematics at velocity level. Is the pseudoinverse matrix that appears in this equation the same pseudoinverse of the kinematic calibration problem?

EXERCISE 3

1. Consider a simple mass as in this picture:



   Write the expression of an (explicit) impedance controller that can assign a prescribed and complete impedance relation.

2. Still making reference to a single degree of freedom mechanism, sketch the block diagram of an admittance controller. What is the assumption that must be enforced on the motion control system in order to claim that the prescribed impedance is actually achieved?

3. The admittance controller can be used to implement one of the possible collaborative modes between the robot and the human. Explain what is this mode and how admittance control can enable such collaborative mode. In particular, specify whether all the three elements of an impedance relation (mass, spring and damper) are used in this case.

4. The speed and separation monitoring is another collaborative mode. Making reference to the following picture, write the inequality that needs to be satisfied according to this safety standard. Is the measurement of the human position needed in this standard and is it needed in the power and force limiting standard?