Control of industrial robots

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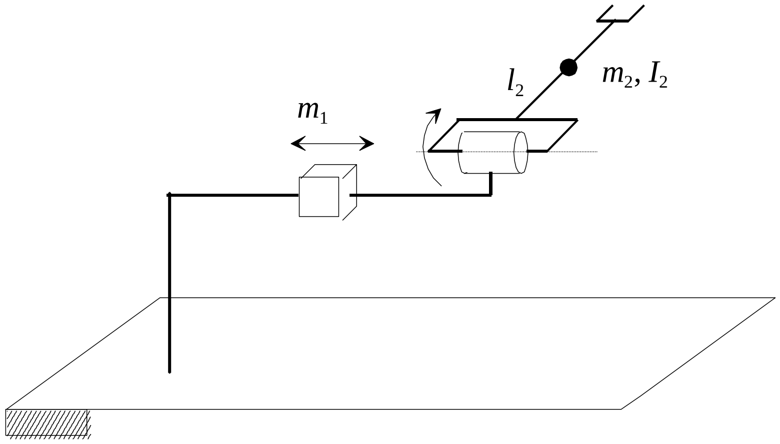
Warnings:

- This file consists of **8** pages (including cover). All the pages should be signed.
- 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.

Use this page ONLY in case of corrections or if the space reserved for some answers turned out to be insufficient

Exercise 1

Consider the manipulator sketched in the picture:



1.1 Find the expression of the inertia matrix of the manipulator.

1.2 Write the complete dynamic model for this manipulator.

1.3 Consider the adoption of a “PD + gravity compensation” for this manipulator. Write the expressions of the two control variables.

1.4 Write the expression of the Lyapunov function candidate which allows to prove stability of the equilibrium point for the controlled system.

Exercise 2

Consider the generation of a position trajectory in the Cartesian space. Select as an initial point $\boldsymbol{p}_i$ = [2, 1, 2] and as a final point $\boldsymbol{p}_f$ = [0, 0, 0].

2.1 Write the expression of a segment connecting the initial and the final points, parameterized with the natural coordinate.

2.2 Assume a travel time $T = 3\ s$. Design a trajectory, which covers the path determined in the previous step, using a cubic dependence on time.

2.3 Compute the maximum linear velocity and the maximum linear acceleration of the end effector along the trajectory designed in the previous step. If one of these maximum values exceeds the corresponding limit value how would you modify the trajectory generation?

2.4 Suppose that the manipulator is kinematically redundant for the task of end effector positioning. Explain what null-space motions are and how they can be expressed.

Exercise 3

Consider the design of the position/speed control for a servomechanism affected by elasticity. The following physical parameters are known:

$J_m = 0.2 \times 10^{-3}$ $Kg\ m^2$ [moment of inertia of the motor]

$n = 100$ [transmission ratio]

3.1 Making an experiment where the motor is mechanically locked and the load is perturbed, a lightly damped oscillation of the load is obtained, with period $T_1 = 0.0628$ s. Making instead an experiment where the motor-transmission-load is free to vibrate, a lightly damped oscillation of the load is obtained, with period $T_2 = 0.0314$ s.

Based on these data, estimate the values of the moment of inertia J_l of the load and of the stiffness constant K_{el} of the transmission.

3.2 Find the values of the proportional gain K_{pv} and of the integral time T_{iv} of the speed controller in such a way to approximately maximize the damping of the closed loop poles.

3.3 Write the expression of the loop transfer function of the speed control and sketch the Bode diagram of the frequency response (amplitude only).

3.4 Suppose that you want to use a notch filter for the servomechanism of this exercise. Write the expression of the transfer function of the notch filter and sketch the Bode diagram of the frequency response (amplitude only).

Exercise 4

4.1 Write the dynamic model of a robot manipulator when a system of forces is applied at the end effector, specifying the meaning of the symbols used.

4.2 Write the expression of an impedance controller for the whole manipulator, based on inverse dynamics control.

4.3 Write the expression of a translational impedance and of a rotational impedance.

4.4 Make reference now to the single degree of freedom mechanism sketched in the picture and suppose you want to design an implicit impedance controller, which makes use of the measure of the force *F*.

Sketch the block diagram of the control scheme.