Control of industrial robots

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February 20, 2018

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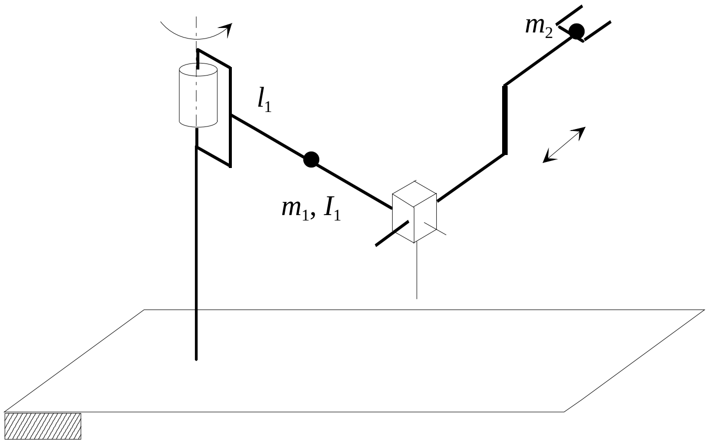
Warnings:

- 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, where the mass of the second link is assumed to be concentrated at the end-effector:



1.1 Find the expression of the inertia matrix $\boldsymbol{B}(\boldsymbol{q})$ of the manipulator.

1.2 Compute the matrix $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ of the Coriolis and centrifugal terms [1] for this manipulator.

1.3 Show that matrix $\boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \dot{\boldsymbol{B}}(\boldsymbol{q}) - 2\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is skew symmetric.

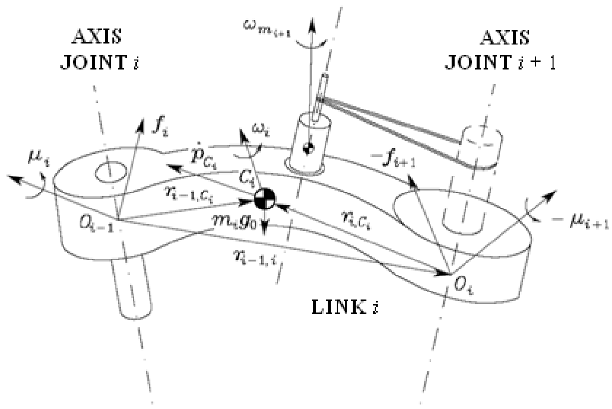
1.4 Compute the expression of the derivative of the kinetic energy $\boldsymbol{T}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \frac{1}{2}\dot{\boldsymbol{q}}^T \boldsymbol{B}(\boldsymbol{q})\dot{\boldsymbol{q}}$ (notice that no gravitational load acts on the manipulator).

[1] The general expression of the Christoffel symbols is: $c_{ijk} = \frac{1}{2}\left(\frac{\partial b_{ij}}{\partial q_k} + \frac{\partial b_{ik}}{\partial q_j} - \frac{\partial b_{jk}}{\partial q_i}\right)$

Exercise 2

2.1 Explain what is meant with “direct dynamics” and with “inverse dynamics” of a manipulator.

2.2 Consider the Newton-Euler method to derive the dynamic model of a manipulator. Making reference to the following picture (neglecting the role of the motor), write the dynamic equations for the single link used in the method.



2.3 Explain what is meant with “forward recursion” and with “backward recursion” in the Newton-Euler method.

2.4 Outline a procedure to compute the direct dynamics of a robot using the Newton-Euler method.

Exercise 3

3.1 Suppose that a trajectory for a scalar variable has to be defined, which achieves the values reported in the following table, at the given instants:

$t_1 = 0$	$t_2 = 2$	$t_3 = 4$	$t_4 = 8$	$t_5 = 10$
$q_1 = 10°$	$q_2 = 20°$	$q_3 = 0°$	$q_4 = 30°$	$q_5 = 40°$

Assign suitable values to the speed at the intermediate points.

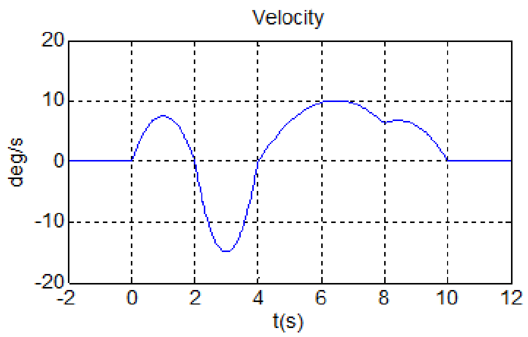
3.2 With reference to the data of this exercise, verify the balance of equations and unknowns if the spline method is used to compute the intermediate values of the speed.

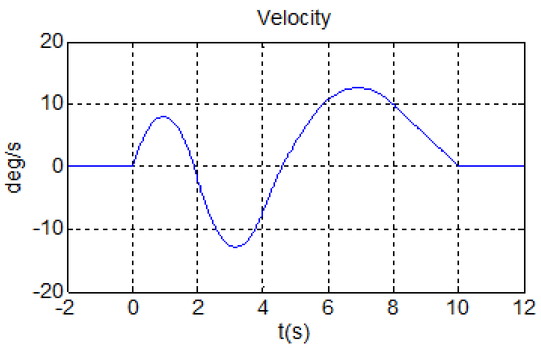
3.3 In the spline method, the following equation has to be solved:

$$\boldsymbol{A}\boldsymbol{v} = \boldsymbol{c}$$

Explain what is the meaning of the symbols used in this equation, what are their sizes, and whether matrix $\boldsymbol{A}$ has any particular shape

3.4 With reference to the data of this exercise, explain which one of the velocity profiles shown in the following pictures has been obtained with the spline method:





Exercise 4

4.1 Write the expression of an inverse dynamics controller in joint space and sketch the related block diagram.

4.2 Assume that a routine for inverse dynamics computation is available. Explain how it can be used in the inverse dynamics controller.

4.3 Tune the gains of the controller in such a way to achieve for each joint of the manipulator a second order closed loop dynamics with real eigenvalues both in -2 rad/s

4.4 Write the expression of an inverse dynamics controller in the operational space.