UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE AND ENGINEERING
ROBOTICS (AER 525F)
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FINAL EXAMINATION
December 18, 2014

Note: Rulers may be used in this test.

2.5 Hours
Exam Type: X

Question 1:

(a) Explain how a generic 6-d.o.f. manipulator should be designed to have an analytically solvable inverse kinematics model. **(5)**

(b) Explain how using a transmission system can help the joint servo controllers in reducing the nonlinear and coupling effects. What are the pay-backs? **(5)**

(c) Explain how the inaccuracy of the inverse dynamics model of a manipulator will affect the performance of its model-based control scheme. **(5)**

(d) Given a table of desired joint displacements, does the joint-space motion control scheme still require a trajectory planner/generator? Why? **(5)**

Question 2:

For the spatial 4 d.o.f. manipulator shown in the figure ($0^\circ \le \theta_1, \theta_2, \theta_4 < 360^\circ$ and $d_3 \ge 0$):

(a) By using Standard Denavit-Hartenberg convention, define link coordinate frames and link parameters, arrange the D-H table, obtain the homogeneous transformation matrices, and then determine ${}^0T_4$. For $\theta_1 = 0$ and links 2, 3 and 4 upright, check whether your computation is correct. **(15)**

(b) Obtain the angular and linear (point *E*) velocities of link 4 relative to and expressed in the base coordinate frame (as functions of joint speeds and manipulator configuration.) **(15)**

(c) At each given (static) configuration, how much torque/force is needed at each joint to balance a force at the end-effector point *E* along $\hat{x}_4$ with a unit magnitude? **(10)**

(d) A camera is attached to the end-effector at point *E* with its view along the direction of $\hat{x}_4$. It records the motion of an object as it is heading right toward the camera (i.e., along negative $\hat{x}_4$) with a speed of v. What is the absolute velocity of the object when it is $1m$ away from the camera and the manipulator configuration is at $\theta_1 = \theta_2 = 0$? Obtain the answer as a function of d_3, θ_4, v, and joint speeds. **(10)**

(e) If joint 4 is fixed so that links 3 and 4 remain aligned at all times, find and show those static configurations where an external force at the end-effector point E in at least one direction can be totally borne by the structure, i.e., no joint torque/force is needed to balance it. **(10)**

(f) If joint 4 is fixed so that links 3 and 4 remain aligned at all times, and joint 1 is fixed ($\theta_1, \dot{\theta}_1 = 0$), and there is no wrench at the end-effector, derive the Lagrangian of the system. Assume links 2, 3 and 4 as rigid bodies with masses m_2, m_3 and m_4, moments of inertia ($I_{C_{zz}}$) I_2, I_3 and I_4, and centres of mass located at B, C and E, respectively. **(10)**

(g) Considering conditions in **(f)**, obtain the torque equation for joint 2. **(5)**

(h) Suppose that a DC brush motor with the following characteristics is available for driving joint 2 (under conditions in **(f)**) using a gearbox with the ratio of η.

r_a: armature resistance b_m: motor bearing viscous friction coefficient

K_m: torque constant K_b: back emf constant I_m: motor inertia

Assuming that the motor inductance and load bearing friction are negligible, find the values of the proportional and derivative gains of a PD controller for joint 2 rotational displacement, if the closed-loop system response is critically damped with the natural frequency of ω_n. **(5)**