ENPM640: Rehabilitation Robotics Final Exam

(Due: Tuesday, December 22, 2020)

Instructions:

i. Attempt **all** questions. Partial credit will be given for the *correct approach*.
ii. This is a take-home exam. Your submission must be returned no later than **5 PM ET** by the due date listed above. Late submissions will **not** be considered.
iii. Your final answer for each problem must be "boxed" for easy identification.
iv. Please write neatly for me to identify your approach.
v. You may choose to only write main steps in your approach and the final answer (boxed).
vi. Return your solutions as a single scanned PDF file named as "*John Doe ENPM808J Final Exam*".
vii. You have an option to attempt the Bonus Question.
viii. Submit your PDF file online on Canvas.

Problem Description:

You are required to develop a modular exoskeleton for rehabilitating knee function in persons with stroke. The robot is specifically aimed to rehabilitate knee motion in the flexion-extension degree of freedom during *initial stance* as indexed by the duration between initial contact and heel-rise events. As a starting point, normative knee angle and normalized moment trajectories are shown in Figure 1.

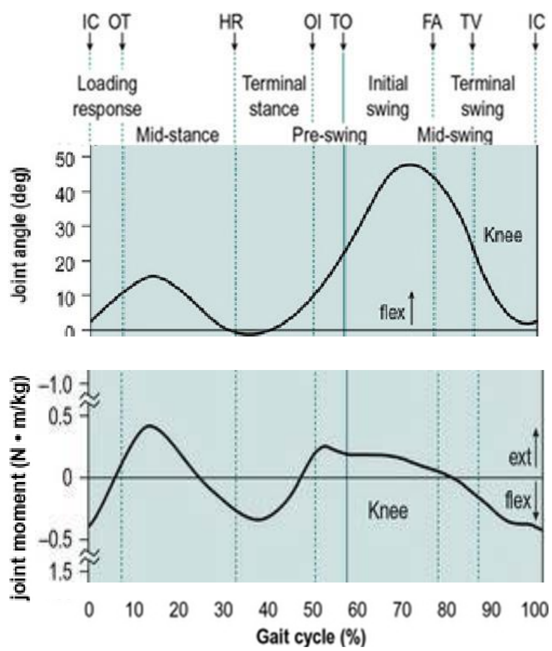

Figure 1: Knee kinematics and kinetics during walking in healthy adults. IC=Initial Contact, HR: Heel-Rise, TO: Toe-Off.

Part A: Rehabilitation Robot Hardware Selection (40 Points)

(A-1) Assume that this robot is being designed for a mean body mass of 100 kg. Further assume that the distance from the point of attachment of the robot to the knee joint i.e. the moment arm, is 5 cm. A design specification is that the total mass of the motor and that of the actuator should not exceed 1.75 kg. Another design specification is that the max linear displacement of the actuator (i.e. linear range of motion from minimum compression to max extension; also known as the "stroke") should be as close as possible to the moment arm (i.e. 5 cm). Select the appropriate model (max static thrust, stroke length) of the "Feedback Rod Linear Actuators" by Firgelli Automations (see https://www.firgelliauto.com/products/feedback-rod- actuator#ptab-specifications – click on the tab "*Specifications*" to see details of the different models). If there are multiple actuator candidate models, choose the one with the highest transmission ratio. Your selection should clearly show that the end-effector max *static* thrust meets the peak torque biomechanical requirement and the stroke length need. Next, select the appropriate model (peak torque) of "RBE(H) Series" by Kollmorgen (see Attachment I) that produces the 110% of the required end-effector torque while absorbing less than 15 A of current at peak torque (the latter requirement determines the winding model i.e. "A", "B" or "C"). If there are multiple candidate models, choose the one with the lowest mass.

(A-2) Let the average vertical ground reaction force generated due to the entire body mass of a stroke subject be 192.5 N-s. Choose a linear absolute magnetic encoder (LA11 Series by RLS – see Attachment II) with a resolution better than 0.35 μm and a minimum count frequency higher than 5 MHz (clue: you will also need to calculate the mean speed of the actuator during the paretic single support stance duration). If multiple candidate models are found, choose the one with the least edge separation (μs).

Part B: Rehabilitation Robot Controller Design (60 Points)

(B-1) Design a one-dimension slot controller for ~15% of the single support paretic stance duration (say, T_1 – for visualization, see top panel in Figure 1). In calculating T_1, use the value calculated above (in sec) for encoder selection. The 1-D slot controller acts during this time period with the appropriate positional end-points (per Figure 1, initial commanded angle θ_0 of 5°and peak commanded angle ~ θ^*20° during T_1). Assume that initial slot height b_0 (around θ_0) and final slot height b_1 (around θ^*) are 3° and 1°, respectively. Using this information and assuming a sampling frequency of 10 kHz, derive expressions for the commanded reference trajectory $\theta_{ref}(i)$ (a straight line with an intercept as a function of the sampling instant i. Plot the top edge $t(i)$ and bottom edge $b(i)$ dynamics of the slot as a function of the sampling instant i. Does the slot collapse as desired? What are absolute positions of the top and bottom edges of the slot at 20 ms?

(B-2) Assume that at the time of peak commanded position (i.e., at $t = T_1$), the actual knee angle and angular velocity is $\theta(T_1) = 10°$ and $v(T_1) = 57.3°/s$, respectively. Then, if the knee joint angle is *outside* the 1-D slot whose dynamics are calculated in part (B-1), what is commanded end-effector torque T_a as per a simple impedance control law? Assume that the commanded controller gains are $K = 25$ Nm/rad and $B = 0.5$ Nm-rad/s. Having knowledge of the actuator transmission ratio and motor torque constant from part (A), what is the commanded current to the motor at this time and under this scenario?

(B-3) Now assume that the knee robot is modeled as shown in Figure 2.

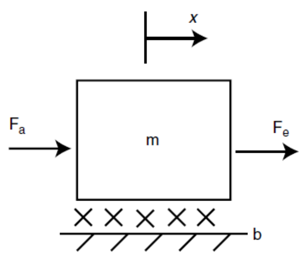

Figure 2: Simple model of the knee robot. Mass m is the sum total of the actuator and motor masses.

As an alternative to pure force feedback or pure Simple Impedance Control (SIC), we wish to deploy Natural Admittance Control (NAC). The NAC is characterized by gains K_f and K_v, while the SIC is characterized by gains K and B. For frictional loss of 0.75 N-s/rad and SIC damping gain $B = 2$ N-s/ rad, calculate the value of K_v such that the closed-form equation of motion behaves like a pure mass-spring system (clue: choose K_v such that the velocity term in the closed-form EoM must vanish).

Part C (Bonus Question) Arm Robot Design (10 Points)

Consider a 1-DOF modular rehabilitation robot designed to improve the range of motion of the elbow joint impaired post-stroke. The robot deploys a slot controller such that actuator dynamics outside and inside the slot utilize a simple impedance controller (SIC) and a damping controller, respectively. Assume that the robot utilizes the minimum jerk trajectory as the virtual reference with an initial position of 0 cm to a final position of 10 cm within a time period of 1 s. Further assume that the slot controller creates the initial and final slots with heights 5% and 2.5% of the final position, respectively. The SIC uses position and velocity gains of 100 N/m and 1 Ns/m, respectively while sampling data at 200 Hz. For this problem, you are required to use MATLAB.

(C-1) Using MATLAB, draw a plot of the top and bottom edge trajectories of the slot controller as a function of sampling time. Overlay the reference trajectory on this plot. Verify your plot using boundary conditions (i.e., initial/final slot heights and reference end-point positions). Note that slot and reference dynamics should be expressed in terms of sampling instant rather than time itself. Next, add bounded noise to the reference trajectory to simulate actual movement. You may do so by adding normally distributed random numbers (MATLAB function: *randn*) to the reference trajectory. Overlay this trajectory in the plot generated so far. For verification, you should see some instants where the actual movement is inside the slot, while for other instants the actual movement is outside the slot.

(C-2) Calculate and plot (separate figure than C-1) the commanded (i.e., actuator) force trajectory based on the control law (SIC or damping controller).

Part D (Bonus Question) Anklebot Performance (10 Points)

The lower extremity modular ankle robot ("Anklebot") for gait rehabilitation is described in the article by Roy et al. (2009). Consider the problem of estimating ankle angles from linear encoder data. Assume an average actuator length of 30 cm, transverse length of 3 cm (indicated by the constant $x_{tr,len}$ in the appropriate equation(s) of the article), and the moment arm (i.e. distance of the ankle joint to the point of attachment of robot end effector on foot) to be 60% of foot length. Using the anthropometric data figure given in Attachment III, plot the *average actuator displacement* (mean of x_{right} and x_{left}) versus whole-body height when the ankle angle in dorsiflexion is estimated to be 30°. Be cognizant of the non-negative constraint on the average actuator displacement.