STEVENS INSTITUTE of TECHNOLOGY
THE INNOVATION UNIVERSITY

Mechanical Engineering Department

ME 655-WS (BME656-WS) Wearable Robotics and Sensors

Virtual Lab Experience III

The single-DOF exoskeleton shown in **Fig. 1** is designed to assist the motion of the wearer's left hip joint in the sagittal plane during treadmill walking.

The robot's hip joint O, which is modeled as an ideal revolute joint, is supported by a rigid frame (not shown in the picture). The robot's actuator is modeled as a pure torque generator τ_R, and the robot's structure is approximated with a rigid bar having mass m_R and barycentric moment of inertia I_{RC}, as indicated in the figure.

The exoskeleton is rigidly attached to the wearer's leg, which is also modeled as a rigid bar rotating about the same revolute joint, with parameters: m_H, I_{HC}, and L_H. The combined effect of the hip extensor and flexor muscles is approximated with a torque generator τ_H.

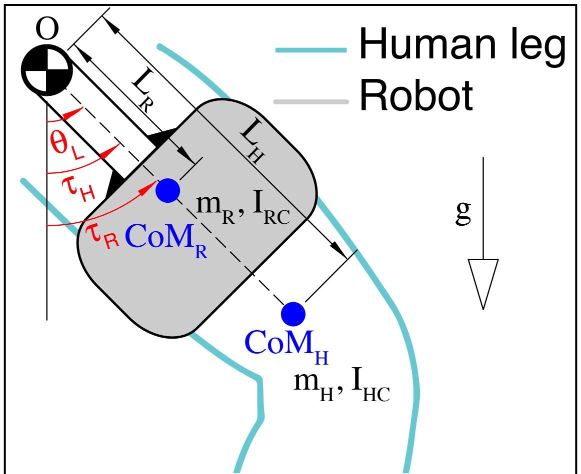

Fig. 1: Model of the hip exoskeleton & human leg. **CoM_R**, **CoM_H** = center of mass of the robot link and human leg; **m_R**, **m_H** = mass of the robot link and human leg; **I_{RC}**, **I_{HC}** = moment of inertia of the robot link and human leg about an axis perpendicular to the plane of motion and passing through the CoM (I_{HC} is assumed constant over the gait cycle, despite changes in the knee and ankle angles); **L_R**, **L_H**= position of CoM_R and CoM_H relative to the hip joint, along the longitudinal axis of the link.

The effects of the ground reaction forces during the stance phase of the gait cycle are neglected, therefore the system's weight and the torques τ_H, τ_R are the only external forces/torques acting on the system. The provided Matlab/Simulink files include:

I. Desired trajectories for the left and right hip joints (and their time derivatives) over 1 minute of treadmill walking
II. A simple model of the wearer's motor control system (for the left leg), which tracks a desired trajectory ($\theta_{L,des}$, $\dot{\theta}_{L,des}$, $\ddot{\theta}_{L,des}$).

The desired trajectory $\theta_{L,des}$, $\dot{\theta}_{L,des}$, $\ddot{\theta}_{L,des}$ is known to the wearer but *unknown to the robot's controller*. However, the robot controller can measure τ_H and the actual trajectory followed by the user θ_L. We also assume that the wearer has full state feedback and can sense the torque applied by the robot τ_R.

The objective of this simulation-based assignment is to develop two assistive controllers for the robot to reduce the torque τ_H required by the wearer to track the desired trajectory.

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PART A:

1. Using the provided model of the human motor control system, generate a plot of the torque τ_H required to steer the system along the desired trajectory $(\theta_{L,des}, \dot{\theta}_{L,des}, \ddot{\theta}_{L,des})$, assuming that the robot is passive (τ_R=0). Plot $\theta_{L,des}$ and θ_L vs. time and verify that the human motor control system can track the desired trajectory.
2. Write the inverse dynamics of the overall system (robot + human leg), and implement it as a Simulink block, to estimate the overall torque $(\tau_R + \tau_H)$ required to guide the system along a given trajectory. Test your model by feeding $(\theta_{L,des}\,, \dot{\theta}_{L,des}\,, \ddot{\theta}_{L,des})$ and checking that the output matches τ_H determined at point (1).
3. Using Simulink, design a pool of *Adaptive Frequency Oscillators* (AFOs) to compute on-line the estimates $\hat{\theta}_{L,AFO}$, $\hat{\dot{\theta}}_{L,AFO}$ and $\hat{\ddot{\theta}}_{L,AFO}$ (i.e., the real-time estimates of θ_L, $\dot{\theta}_L$ and $\ddot{\theta}_L$) and the phase of the gait cycle φ_1 based on the angle θ_L measured from the wearer. Suggested parameters for the AFO (M, ε, ν) are given in the Matlab file. Assuming the AFO is activated at $t_{START,AFO} = 5s$, provide a plot of θ_L and $\hat{\theta}_{L,AFO}$ vs. time to verify convergence.
4. Use the outputs $\hat{\theta}_{L,AFO}$ and $\hat{\ddot{\theta}}_{L,AFO}$ as inputs to a <u>*model-based assistive controller*</u> based on the inverse dynamics obtained at point (2). The aim of the controller is to provide the user with an assistive torque τ_R equal to 50% of the torque required to follow $\hat{\theta}_{L,AFO}$, $\hat{\dot{\theta}}_{L,AFO}$ and $\hat{\ddot{\theta}}_{L,AFO}$. Assuming that the controller is activated at $t_{START,CTRL} = t_{START,AFO} + 10s$, validate the controller by plotting the new user's effort $\tau_H$vs. time. Compare the results with those obtained at point (1).
5. Using Simulink, implement a *Kernel-based nonlinear filter* to obtain $\check{\tau}_H$, a smooth real-time estimate of the wearer's torque τ_H as a function of the gait phase φ_1 obtained with the AFO. Suggested parameters for the Non-linear Filter (N, h, λ) are given in the Matlab file. Provide a plot of τ_H and $\check{\tau}_H$ vs. time to verify convergence.
6. Use the nonlinear filter as a <u>*model-free assistive controller*</u> by setting $\tau_R = \check{\tau}_H$ into the robot controller. Assuming that the controller is activated at $t_{START,CTRL} = t_{START,AFO} + 10s$, provide a plot of τ_H and $\check{\tau}_H$ vs. time. Compare the results with those obtained at point (4). Which assistive controller is more effective? Provide quantitative data to justify your answer.

PART B:

7. Using the *Complementary Limb Motion Estimation* (CLME) method, approximate the *Left* hip joint angle and angular velocity $(\bar{\theta}_L, \dot{\bar{\theta}}_L)$ based on the corresponding variables of the contralateral leg $(\theta_R, \dot{\theta}_R)$ using a best linear unbiased estimator (BLUE). Design an appropriate *Kalman Filter* to map the output of the BLUE $(\bar{\theta}_L, \dot{\bar{\theta}}_L)$ to coherent estimates $(\tilde{\theta}_L, \dot{\tilde{\theta}}_L)$. Use *only the first 30 seconds* of the provided dataset to train the BLUE (gain *K* and offset *k*) and derive the parameters of the Kalman Filter (covariance matrices *Q, R*). Validate the CLME method and Kalman Filter in a Simulink model. In two separate figures, plot θ_L, $\bar{\theta}_L$, $\tilde{\theta}_L$ vs. time and $\dot{\theta}_L$, $\dot{\bar{\theta}}_L$, $\dot{\tilde{\theta}}_L$ vs. time.

[Extra credits] Compute an alternative estimate $\breve{\theta}_L$ using the non-linear filter developed at point (5), and plot the measured angle θ_L along with the estimates from the AFO (obtained at point 3), NLF, and KF (obtained at point 7) vs. time in the same figure. Which method is the most accurate? Provide quantitative data to justify your answer.

<u>Requested Deliverables</u>

- A thorough, well organized report on your system and development
- Output plots should be commented in detail
- All related files (MATLAB, Simulink, etc.)