**PROJECT for FINAL EXAMINATION**

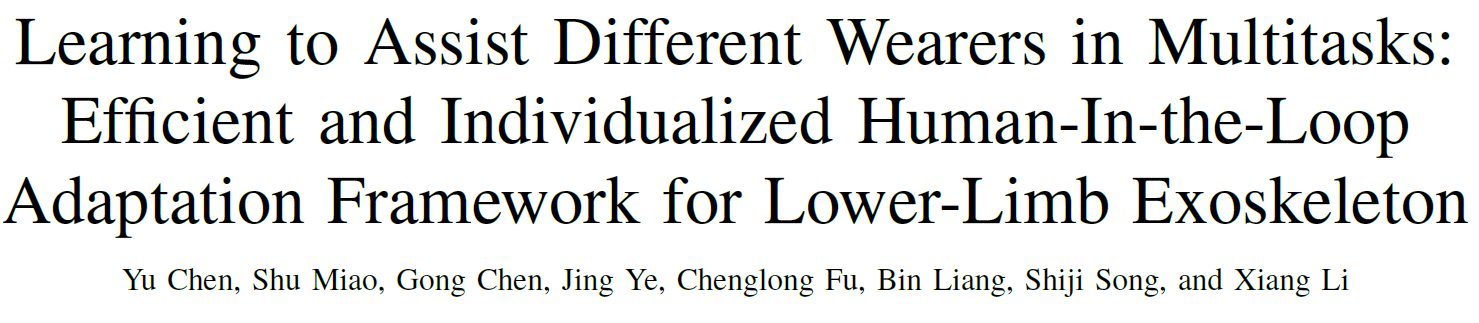
Subject: **Advanced Control Theory** Level: Master’s program

Class: **MST 2024** Lecturer: **Assoc. Prof. Do Xuan Phu**

Assigned date: **3 November 2024** Submitted date: **23 November 2024 @ 9:00 AM**

**Problem (100 pts)**:

Read the article as follows:



1. Define “**trajectory generation**” and “**interaction control**” following the content of the manuscript. (10 pts)

Trajectory generation:

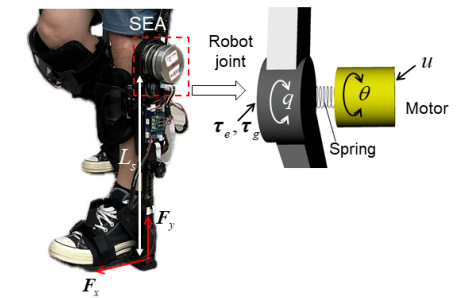
* **Trajectory generation**:

Trajectory generation in the context of exoskeletons refers to the process of creating and optimizing movement paths that the exoskeleton follows to help the wearer. This process is guided by a cost function—a mathematical objective that evaluates and shapes the trajectory based on specific criteria, such as comfort, flexibility, and adaptability. By incorporating these factors, the cost function ensures that the generated trajectories are efficient, comfortable, and well-suited to the wearer’s individual needs, creating a user-centred experience across various tasks like walking, climbing stairs, and squatting. Advanced kinematic models further refine these trajectories, allowing smooth transitions in speed, slope, and other movement variations for improved adaptability. This framework relies solely on proprioceptive sensors (Proprioceptive sensors are devices that detect and provide feedback on the position, movement, and force within the body or a robotic system) within the exoskeleton, enhancing portability and usability.

* **Interaction control:**

In this manuscript, interactive control is defined as the process of controlling robot exoskeletons to follow a given trajectory while ensuring user safety. This is achieved by incorporating principles of human behaviour and biomechanics, specifically through the application of physical impedance in the limbs to resolve physical conflicts, such as discrepancies between the user’s intended motion and the current joint angle of the exoskeleton.

1. Use **figure 2**, find **the governing equation following the free-body-diagram**, and then **summarize** following the proposed model as shown in the manuscript. (5 pts)



Components:

1. Motor Torque: The control input u is applied by the motor, affecting the joint through the spring.
2. Elastic Spring: Between the motor and joint, which store energy and feedback, thereby ensuring structural safety.
3. Interaction Torque: This represents the net torque at the joint, influenced by the control input, elastic response of the spring, and external loads.
4. Ground Reaction Forces: Resulting from the ground reaction forces Fx and Fy at the foot of the exoskeleton.
5. Length of the shank: Ls
6. Rotational Angles:
   1. q: Rotational angle of the robot joint
   2. 0: Angle of the motor rotor

**Free Body Diagram**

**Governing equation:**

* Torque generated by spring in the SEA between the motor and the joint:
* The net torque applied by the motor to the joint after accounting for the spring torque:

* Torque resulting from the ground reaction forces:
  + The overall equation:
* We have:

For an object that changes its state of motion around an axis, the moment of inertia is here to measure the rotation of the system – this is describing the rotation of the knee joint, so this is the govern equation:

* For rotational systems, Newton’s second law in rotational form:

Where:

1. I: the moment of inertia
2. : the angular acceleration of the joint
3. : the sum of torques acting on the joint

* From that we can come up with this system:
  + Motion Status:

**Summarize:** From the above and the aim of this manuscript we just focus on Motion Status, so with the following equation (1) in the manuscript:

With some additional concepts for complex dynamics as Coriolis matrix, gravitational torque acting on the joint, but in the overall, it is still following the concept of Newton’s second law in rotational form:

1. Why we use the **equation (2)** in the manuscript? Translate the meaning when apply this equation. (5 pts)

* We use the equation (2) in the manuscript because:
  + Equation (1) describes the dynamics of the robot joint (i.e., the exoskeleton’s movement), but it does not directly account for the characteristics or performance of the motor driving the system. Without Equation (2), the control would only focus on the joint behaviour, regardless of the motor's capabilities. This could make the system less effective and even unsafe if the motor is not adequately controlled, especially if it is not strong enough or if its control is not finely tuned.
  + Equation (2) is used to control the motor’s behaviour. It allows the motor to generate the required bending and stretching forces for the exoskeleton’s movement while using the spring in the SEA to store energy. This energy storage helps reduce the motor’s workload, preventing it from overexerting and potentially overheating. By moderating the motor’s output through Equation (2), the system achieves a balance between control effectiveness and motor safety.

1. Why we use the **equation (7)** in the manuscript? How about the system when changing ? (5 pts)

This question will be related to the formation of formula (5) and its transformation into (6) and then (7), so we will start from formula (5):

* For formula (5), the main meaning of this formula is still to control the motor so that it is in sync with the joint - creating stability for the skeletal system in motion, but that is not enough because there are also phase differences in the response time between the moving joint and the motor, so in the article, formula (3) - which is about input control - is separated into motor control and joint control
* The separation of motor control and joint control is because the response time of the joint will be faster than the response time of the motor.

1. Use **figure 3**, **define the offline learning, HIL optimization, and impedance control** following the model in the manuscript. **What is the role of the impedance control when applying in the robotic**? (10 pts)

**Offline learning:**

**Outputs:**

* **To: HIL Optimization: Translated parameters – Anomaly score**
* **To: Impedance Control: Anomaly score**

Following the model in the manuscript, in this phase, data from previous human-exoskeleton interactions or simulations are analysed to understand optimal movement patterns and determine control parameters that will enhance performance. Key goals include reducing tracking errors and maximizing user comfort. The output of this phase includes *translated parameters*—optimized values for control settings that guide the exoskeleton’s response. Additionally, an *anomaly score* is generated to detect any unexpected or unsafe behaviour in the system.

**HIL optimization:**

**Outputs:**

* **To Impedance Control: Trajectory**

During HIL optimization, the *translated parameters* from offline learning are tested and fine-tuned in a real-time, hardware-inclusive environment (either on the actual exoskeleton or a high-fidelity simulator). This phase refines the movement *trajectory* to ensure it is feasible and safe for physical application, accommodating real-world interactions and feedback.

**Impedance control:**

**Output:**

* **Control output to Exoskeleton**

The impedance control module uses the *trajectory* from HIL optimization and the *anomaly score* from offline learning to generate the final *control output* sent to the exoskeleton’s actuators. This control output defines how the exoskeleton should move to follow the desired trajectory while adapting to the user’s natural movements. By modulating stiffness and damping in response to user input, impedance control allows the exoskeleton to interact smoothly and compliantly with the user.

**Role of Impedance Control in Robotics:**

Impedance control is an important control method in robotics, especially in exoskeleton systems that assist and interact with humans. This method allows robots to adjust their responses based on the interaction forces from the user or the environment, ensuring flexible and agile interactions. By adjusting the three main dynamic components of stiffness, damping, and virtual mass, impedance control allows robots to respond strongly or softly to position changes, maintain stability and absorb vibrations, and create a suitable sense of inertia when the robot accelerates or decelerates. As a result, impedance control helps to minimize conflicts with the user, increase stability, and create flexible and friendly interactions, especially when assisting with moving or lifting activities. In this role, impedance control not only enhances comfort but also ensures user safety, becoming the foundation for robots to assist humans effectively and naturally in complex tasks.

1. Use the **equation (12)**. Why we use this equation? Give an example with the equivalence function as shown in **equation (12)** for the learning section. (5 pts)

-> Equation 12: VAE from machine learning -> <https://www.geeksforgeeks.org/variational-autoencoders/>

-> Def and app of VAE: https://www.ibm.com/think/topics/variational-autoencoder

*LV AE*(**x***t*) = *||***x***t -* **x**ˆ*t||*2 + *KL*[*N* (*µ, σ*)*, N* (0*,* ***I***)] (12)

VAE means Variational Auto Encoders. This function is called loss function and

1. Use **the equations (20-22)**. Translate the meaning of this group equation and explain the meaning of every parameter in these equations. (10 pts)

(20)

Where:

* (21)
* (22)
* (18)

**Equation 20:** ILWR (Incremental Locally Weighted Regression)

This group of the equation means to achieve trajectory parameterization. The algorithm ILWR is used for training on pre-recorded trajectories (joint movements overtime) and learns to approximate the mean trajectory .

**Equation 21:** This equation updates by incorporating both the past value of and the forgetting factor. It allows the model to adjust weights smoothly over time without needing to remember all historical data explicitly.

**Equation 22:** This error term is a composite measure of the model’s deviation from the desired trajectory, accounting for position, velocity, and acceleration. It guides the weight updates in Equation (20) by showing how far the current model output is from the ideal trajectory at each time step.

**Equation 18:** Localized weight to each trajectory segment, letting the ILWR algorithm adjust weights with greater precision by concentrating on specific parts of the data.

: the mean trajectory, which is calculated by taking the average of the joint trajectories recorded across multiple wearers performing multiple tasks.

t: period of time.

: represents the weights of the *i*-th joint to be updated which can be treated as the trajectory parameters - this is the current weight of the i-th joint at time t

: Gaussian-like kernel functions that determines how much influence each joint’s data has on the weight update

h: width, typically set as 2.5J – controls the spread of the kernel function

: center, evenly space in

: positive constant (weight given to velocity) in the error calculation

: positive constant (weight given to position) in the error calculation

: a forgetting factor – the factor that helps the model the intentional process of removing specific data or influences from a model’s training history, often to update its knowledge for better performance.

: auxiliary variable used to control the rate of weight update

: regression error, representing the difference between the current model output and the desired trajectory at time t

: being the demonstration on joint *i* (i.e., the i-th element of the vector )

**​**: The velocity of the mean trajectory for joint i (the speed of movement for each joint)

: The acceleration of the mean trajectory for joint i (the radpidly of the joint’s movement changes)

8. Use **section VI**.

(a) Use **Matlab**, **simulate the proposed control in this section**. Please show the code in the word file. **Discuss the simulation results**. (25 pts)

(b) Use **bang-bang model of the optimal control** and then applying to the model in the manuscript. Simulate the bang-bang control by Matlab and discuss the results. Please show the code in the word file. (25 pts)

*In (a) and (b), you choose the best figure to show the performance of your simulation.*

**IMPORTANT NOTE:**

1. DON’T COPY ANY PART OF THE WORK OF YOUR FRIEND!!! YOU WILL OBTAIN **ZERO SCORE** FOR THIS HOME PROJECT IMMEDIATELY!!!

2. PLEASE DEFINE ALL PROBLEM **BY YOURSELF**

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**1.** *Please* ***print and sign******YOUR SIGNATURE*** *on the first page (use the* ***blue colour pen****). Submit the work to* ***Ms Tiên (assistant of MST program) after sending the file to my email.***