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Control of a Time-delayed 5 Degrees of Freedom Arm Model for use in Upper Extremity Functional Electrical Stimulation

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Abstract— **The goal of this work is to design a controller for a functional electrical stimulation (FES) neuroprosthesis aimed at restoring shoulder and elbow function in individuals who have suffered a high-level cervical (C3-C4) spinal cord injury (SCI). The controller is a mathematical algorithm that coordinates the electrical stimulations applied to the paralyzed muscles such that the arm closely tracks a given desired trajectory. An issue that so far has received little attention is that of time-delays. These delays arise from two sources: (1) the muscle excitation-activation dynamics (10-30ms) and (2) the sampling of the electrical stimulation (80ms at the typical 12Hz stimulation frequency). Using a 5 degrees of freedom (5DOF) arm model we designed and evaluated a novel controller capable of maintaining stable and accurate tracking performance in the presence of time-delays. For a desired trajectory consisting of 10 randomized reaches, the controller achieved excellent tracking performance as measured by the root-mean-square error (RMSE) between the desired and simulated joint angles (RMSE = [1.48°; 0.81°; 2.14°; 3.11°; 2.29°]).**

I. INTRODUCTION

Individuals who have suffered a spinal cord injury (SCI) experience loss of sensation and voluntary motor control below the injury site. When the SCI is located at a high level (C3-C4), this loss typically includes the entire upper extremity. However, the peripheral nerves originating below the injury site, provided they have not sustained damage, can still be excited and their respective muscles retain their ability to generate force. These muscles can be stimulated artificially by applying small electrical currents to either the muscle itself or its nerve, a technique known as functional electrical stimulation (FES) [1,2].

In upper extremity FES, the frequency at which electrical stimulations are applied is limited to 12-15Hz (higher frequencies would significantly increase the fatigue rate of the muscles [2]). This low frequency has two important implications: (1) it imposes a 80ms time-delay between the stimulations determined by the controller and the muscles generating force and (2) corrective actions can only be taken once every 80ms. This makes control of the FES-enabled arm significantly more difficult. Previous studies have proposed controllers for upper extremity FES neuroprostheses (e.g. [3,4]), however the issue of time-delays has so far been neglected.

The goal of this work is to design a controller that allows a FES-enabled arm to accurately track a given desired movement trajectory even in the presence of time-delays.

II. METHODS

A. The arm model

We designed and evaluated the controller using a model-based approach [5]. The 5DOF musculoskeletal arm model used in this study was presented in [6]. Figure 1 shows the degrees of freedom of the model along with the coordinate reference frame convention. The upper arm and the forearm were each modeled by a single rigid link. The shoulder joint was modeled as a series of three revolute frictionless joints according to a Y-Z'-Y'' convention [7]. This means that the arm first rotates about its Y-axis (plane of elevation), then rotates about its new Z-axis (angle of elevation) and finally rotates about its new Y-axis (internal/external rotation). Similarly, the elbow joint was modeled as a series of two revolute frictionless joints, according to an X-Y convention [7]. Here the first rotation about the X-axis corresponds to elbow flexion-extension. The forearm is then allowed to rotate about its new Y-axis, corresponding to pronation-supination. Table 1 lists the DOFs and their respective joint limits.

TABLE 1. ARM MODEL DOFS AND RANGE OF MOTION

Degree of freedom		Min angle [deg]	Max angle [deg]
q_1	Plane of elevation	-90	90
q_2	Angle of elevation	5	90
q_3	Internal rotation	-55	70
q_4	Elbow flexion	5	140
q_5	Forearm pronation	5	170

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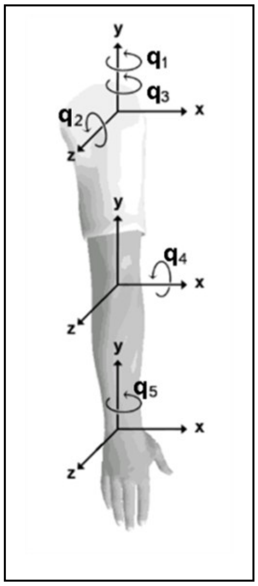

Figure 1. Coordinate frame definition for the 5DOF arm model. The shoulder DOFs follow a Y-Z'Y'' convention. while the elow DOFs follow a X-Y convention

The equations of motion for the 5DOF arm can be derived as:

[redacted] (1)

Where $q(t)$, $\dot{q}(t)$ and $\ddot{q}(t)$ are vectors of the joint angular positions, velocities and accelerations, *M(.)* is the joint-space inertia matrix, *C(.,.)* are the Coriolis/centrifugal effects, *G(.)* denotes the effects of gravity and τ is the vector of joint torques delayed by a time *T*.

The arm dynamics depend on the body segment inertial parameters: each arm segment has its own mass, length and center of gravity location. The hand was modeled as a point mass located at the end of the forearm. The values for these inertial parameters were set to the mean values found by combining the work of [8] and [9] (see Table 2).

TABLE 2. SEGMENT INERTIAL PARAMETERS OF THE ARM MODEL

Parameter		Value
Upper arm	***Mass***	1.980kg
	Length	0.282m
	Center of Gravity	0.148 m
Forearm	***Mass***	1.177kg
	Length	0.269m
	Center of Gravity	0.129m
Hand	***Mass***	0.447kg

Even with FES, SCI subjects typically have insufficient muscle strength to support their arm against gravity, necessitating the use of an arm support system. For the purpose of this work we assumed a constant upward force of 9.9N acting at the wrist. The magnitude of this force was chosen such that the arm remains in a static equilibrium at its resting position: hanging from the side, elbow flexed at 90º with the hand palm facing down.

B. *The controller*

The proposed controller is given as:

[redacted]

(2)

where

[redacted] (3)

[redacted] (4)

[redacted] (5)

where $q(t)$ and $\dot{q}(t)$ are the current joint angular positions and velocities, $q_d(t)$, $\dot{q}_d(t)$ and $\ddot{q}_d(t)$ are the desired joint angular positions, velocities and accelerations, and α, β and k ϵ ℝ+ are tunable parameters. This controller is an extension of the work of Sharma ([10,11]), who proposed a time-delay compensating controller for the lower extremity. The main difference between the controller proposed in [10,11] and (2), is the addition of a feedforward component. The purpose of this feedforward component is to cancel nonlinear effects a priori and decouple the dynamics, making the overall system easier to control.

To reflect the 12Hz stimulation frequency, the joint torques as predicted by the controller were also sampled at 12Hz before acting on the arm dynamics. The controller parameters were tuned by hand, resulting in α:=16, β:=11 and k:=0.4.

C. *Performance and performance requirements*

As a measure of tracking performance we used the root-mean-square error (RMSE), defined as:

[redacted]

(6)

Where n is the number of data points.

The movement intent q_d was chosen as a series of 10 target-to-target reaches, where the target joint angles were sampled from uniform distributions covering the range of motion of each joint. The time allotted to reach each target was set to 5s. For this transient phase, the trajectory was chosen such as to minimize jerk [12]. After this transient phase, a 2s plateau is imposed before the desired trajectory moves on to a new target.

III. RESULTS

Figure 2 shows the simulated tracking performance achieved by the 5DOF arm model under the proposed controller (). The five panels show the simulated and desired trajectories for each of the five DOFs. Their respective RMSE value can be found in the upper right corner of each panel. Note that the simulated trajectories closely track the desired trajectories. Over-and undershoots remain small and there is no discernible oscillatory behavior. The highest RMSE (3.11º) was found for the fourth DOF (i.e. elbow flexion/extension), while the lowest RMSE (0.81º) was found for the second DOF (i.e. angle of elevation).

IV. DISCUSSION

The goal of this work was to design a controller that allows the FES-enabled arm to accurately track a given desired trajectory in the presence of time-delay. Our simulation results show that the controller achieves excellent tracking performance as indicated by the low RMSE values and the absence of oscillatory behavior and significant over-and undershoots.

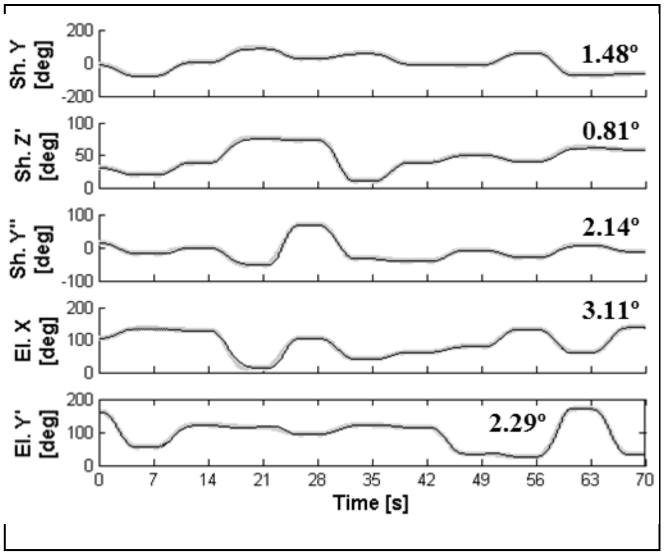

Figure 2. Tracking performance for the proposed controller. The desired joint angles are plotted in gray, while the simulated joint angles are shown in black. The RMSE between the desired and simulated joint angles for each DOF is shown in the upper right hand corner of each subplot.

However, many challenges still remain. Under normal operating conditions, many other perturbations are expected to act on the arm besides time-delays. These include muscle fatigue, sensor noise, imperfect knowledge of the arm dynamics and external forces and torques as the arm interacts with its environment. Future work will focus on evaluating the proposed controller for these additional perturbations and, if simulation studies prove successful, proceed to evaluation in a clinical setting with a FES neuroprosthesis user in the loop.

V. CONCLUSIONS

This work proposes a controller with time-delay compensation for a 5DOF arm model. Simulation results show that the proposed controller achieved stable, accurate tracking of a given desired trajectory in the presence of 12Hz control signal sampling (i.e. 80ms time-delay). Future work will focus on evaluating the controller for additional perturbations expected under normal operating conditions.

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