Compensating Input Delay during Neuromuscular Electrical Stimulation Control

Nonlinear Controls & Robotics

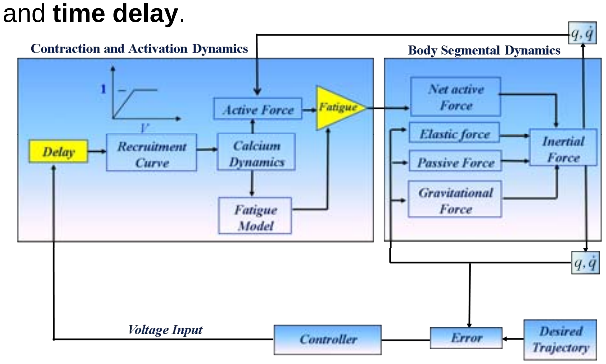
Mechanical and Aerospace Engineering

Neuromuscular Electrical Stimulation (NMES)

NMES is used as a substitute to central nervous system by sending electrical signals through surface or invasive electrodes to restore functional movements such as walking and standing in persons paralyzed due to spinal cord injury or other neurological disorders.

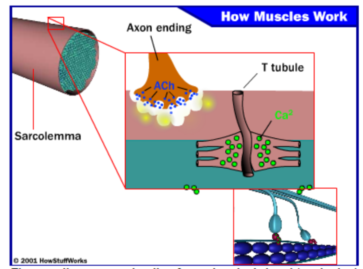
Leg Extension elicited via NMES

Closed-loop control of NMES is necessary to maintain a steady performance over a time-varying muscle dynamics, day to day variations, and person specific deviations. Two primary problems that hinder a satisfactory NMES performance are **muscle fatigue** and **time delay**.



Closed-loop NMES control of time-varying nonlinear muscle dynamics

Electromechanical delay (EMD) is a major technical challenge that hampers the satisfactory NMES control performance. It is defined as the difference in time from the arrival of action potential at the neuromuscular junction to the development of tension in the muscle.



The coupling process leading from electrical signal (excitation) to contraction in skeletal muscle

EMD occurs due to the finite conduction velocities of chemical ions in the muscle in response to the external electrical input.

Delay Compensation

In NMES control the electromechanical delay is modeled as an input delay in the musculoskeletal dynamics. Control of nonlinear systems with actuator delay is a challenging problem because of the need to develop some form of prediction of the nonlinear dynamics. The problem becomes more difficult for systems with uncertain dynamics and bounded disturbances.

Body Segmental Dynamics

Elastic moment — Viscous moment — Delayed active muscle torque

$$M_I + M_e + M_g + M_v + \tau_d = u(t-\tau)$$

Inertial moment — Gravity moment — Disturbance

A control method is developed for an unknown nonlinear muscle dynamic systems with input delay. **Lyapunov Krasovskii (LK) functionals** are constructed to aid the stability analysis which yields a **semi global uniformly ultimately bounded result**.

Position tracking error

$$e_1(t) = q_d(t) - q(t)$$

Delay compensating controller

$$u(t) = K\left[\dot{e}_1 + \alpha e_1 - B\int_{t-\tau}^{t} u(\theta)\,d\theta\right]$$

K, α are known gains; B is a known gain matrix

Stability Analysis

Define Lyapunov function as

$$V(t) = \frac{1}{2}e_1^T e_1 + \frac{1}{2}e_2^T M e_2 + P + Q$$

where P and Q are LK functionals, defined as

$$P = \frac{1}{\tau}\int_{t-\tau}^{t}\left(\int_{s}^{t}\|e_2(\theta)\|^2 d\theta\right)ds \qquad Q = \frac{\bar{b}K}{2}\int_{t-\tau}^{t}\|e_2(\theta)\|^2 d\theta$$

It can be shown that

$$\dot{V} \le \eta_2(\|z\|)$$

Publication

N. Sharma, S. Bhasin, Q.Wang, and W. E. Dixon, Predictor-Based Control for an Uncertain Euler-Lagrange System with Input delay," *American Control Conference, Baltimore,* MD, 2010, *to appear.*