Control Systems Engineering for Neural Prostheses

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Basic Idea:

- Use electrical stimulation, possibly in addition to active or passive external orthoses, to control movement.
- Control can be open loop (pre-programmed), closed loop, adaptive, discrete event driven [and combination of the above].
These are hard control problems

- Nonlinear components
- Time-varying components, with time-varying response delays
- System components not well understood—modeling problem

Requires system and component modeling and identification
These are hard control problems

- Hybrid systems (both continuous time responses, and discrete event aspects)
- Complex, multi-levels of control
- Complex highly-redundant, coupled mechanical systems

Requires new or modified control system designs and methods
These are hard control problems

- Sensor Limitations:
  - Mounting and calibration problems of internal sensors
  - Mounting, calibration, power and biocompatibility problems of implanted sensors
  - Signal acquisition and processing problems of existing intact biological sensors
These are hard control problems

- Actuator Limitations:
  - Limited number of nerves/muscles that can be stimulated [channel limitations]
  - Coupled stimulation, unnatural stimulation (e.g., motor units recruited in wrong order, all at once)
Co-Adaptation

An additional complication:

- Brain/CNS adapts to use attached hardware and software ["neural plasticity"]
- Some engineered systems also learning/adapting to neural system responses
- This co-adaptation could involve each part (organic, engineered) working together, or working against each other
- An open topic for both theoretical and experimental research
- Relevant for BCI but probably also for spinal stimulation and Deep Brain Stimulation
Modeling Electrically-Stimulated Musculotendon Subsystems

- Most work has built on normally innervated muscle models (work of [Hill, 1938])
- Combination of experimentally-obtained response data, theoretical modeling
Modelling Muscle Stimulated Under Isometric Conditions

- Reasonably well approximated by a second order linear system, in series with a memoryless nonlinearity that captures recruitment properties.
Identification of Muscle Model Parameters

- Off line, continuous time model, muscle under isometric loading conditions, pulse frequency modulation
  - Mannard and Stein – J. Phys. 1973; second order linear constant parameter models
  - Model fit gain, poles, zeroes (or damping ratio and natural frequency)
  - Done in cat muscle
Modeling Electrically-Stimulated Musculotendon Subsystems

- Real-time identification using discrete-time, second order model
  - Isometric conditions
  - PW stimulation only (constant pulse frequency)
  - Identification using pseudo-random binary sequence input (PRBS)—approximates white noise
  - Used Recursive Least Squares identification algorithm to fit model parameters
- Findings:
  - Open loop stable models
  - Parameters change with fatigue
- Reference: Bernotas, Crago, Chizeck 1986 IEEE TBME
Plantaris muscle response to PRBS input (solid line). Stimulus period = 30 ms, pulse amplitude = 13.5, muscle length was −10 mm from MPL. Filled circles are model outputs calculated during recursive least squares estimation.
Identification of Muscle Model Parameters

- Real-time, discrete time, constant pulse frequency (PW modulation)
- Using recursive least squares estimation
  - Bernotas, Crago, Chizeck (1986 IEEE TBME) - 2\textsuperscript{nd} order model, isometric, cat muscle—for identification
  - Allin and Inbar (1986, 1986a IEEE TBME) – human upper extremity, 3\textsuperscript{rd} order model
  - Lan, Crago, Chizeck (IEEE TBME 1991) – isometric and non-isometric, cat muscle—for identification and adaptive control
Three Factor Multiplicative Model

- Nonlinear model that considers active torque (or force) generated by muscle to be the product of:

  "active torque generated by muscle" =

  [torque generated by stimulation of muscle] *
  [torque-muscle length factor] * [torque-muscle velocity factor]
Three Factor Multiplicative Model

- Crago (1992- IEEE TBME) – length dependence
- Veltink, Chizeck, Crago, El-Bialy (1992 IEEE TBME) – full 3 factor model
- Shue, Crago, Chizeck – (1995- IEEE TBME) – data fit to 3-factor model
Simultaneous Identification of Recruitment Nonlinearity and Muscle Dynamics

- Adding Fit Hammerstein polynomial representation of recruitment nonlinearity while fitting linear dynamics model
Identification of Muscle Model Parameters

- Required imposition of equality constraints on the identified model
- Tested in human subjects, quadriceps stimulation using percutaneous intramuscular electrodes
  - Chia, Chow, Chizeck (IEEE TBME 1991)
Identification of Muscle and Mechanical Load--Paraplegic Knee Joint

- Identification of paraplegic knee dynamics when freely swinging—no stim
  - Franken, Veltink, Tijmsmans, Nijmeijer, Boom (IEEE TRE 1993, 1995)
Identification of Muscle and Paraplegic Knee Joint

- Empirical methods to estimate leg dynamics
  - Stein, Zehr, Lebiedowska, Popovic, Scheiner, Chizeck (1996 IEEE TRE)

- Combinations of PW and IPI stimulation and leg dynamic estimates—paraplegic human subjects
  - Chizeck, Chang, Stein, Scheiner, Ferencz (IEEE TBME 1999)
Control of Single Joint

- Closed loop control, continuous time model, PW and IPI modulation—demonstrating feedback benefits
  - Crago, Peckham, Thrope (1980)—used simple map to do PW or IPI modulation, depending on controller output signal size

- Later work: Digital closed loop controller for regulation of muscle force by recruitment modulation
Closed Loop Control of Single Joint

- X is recruitment curve linear approximation
- Controller cancels muscle dynamics
- Muscle model parameters identified separately off-line
  - Wilhere, Crago, Chizeck (IEEE TBME 1985)

Fig. 5.13: A block diagram of the digital closed-loop control system for the regulation of muscle force via recruitment modulation. D(Z) is a discrete model of the controller, G(Z) a discrete model of the muscle. Adapted from Wilhere et al., 1985 © IEEE.

\[ G(z) = \frac{g_1z + g_0}{(z + g_2)(z + g_3)} \quad D(z) = \frac{(a_1z - a_0)(z + g_2)(z + g_3)}{(z - 1)(z - b_0)(g_1z + g_0)} \]
Alternative—just use first order digital controller (no muscle model cancellation)

\[ D(z) = \text{gain} \frac{z - m}{z - 1}. \]

- Chizeck, Crago, Kofman (IEEE TBME 1988)
Adaptive Control—use input/output measurements to fit the muscle model, and use model in control calculations

- PW modulation, second order model, one-step ahead minimum-prediction error adaptive controller
  Bernotas, Crago, Chizeck (1987 IEEE TBME)
- AC=adaptive
- FPC=fixed parameter

Under different loading conditions
“Stiffness Control” of Single Joint

Crago, Nakai, Chizeck IEEE BME, 1991
Fig. 2. Costimulation mapping. This is the contents of “C.MAP” in Fig. 1. On the controller output axis (horizontal), $d_e$ and $d_f$ define the range in which SP modulation will be prohibited; $\nu_f$ and $\nu_e$ define the costimulation range. $PWF_{\text{min}}$ and $PWE_{\text{min}}$ correspond to the threshold PW’s for the flexor muscle and extensor muscle respectively; $PWF_{\text{max}}$ and $PWE_{\text{max}}$ are the minimal PW’s for the flexor and extensor; and $PWF_{\text{mid}}$ and $PWE_{\text{mid}}$ define the costimulation PW’s for flexor and extensor.
“Stiffness Control” of Single Joint

- Co-stimulation of opposing muscles
- PW and IPI Modulation for control
  - Chizeck, Lan, Streeter-Palmieri, Crago (1991 IEEE TBME)
High frequency stim used at transitions

Stimulus period (pulse frequency) modulation improves tracking
Applying controllers to Neural Prostheses

- Application-specific controllers (upper extremity for grasp, lower extremity for standing, for walking) involved discrete-event issues, hierarchical structures, sensor-related issues
- Hierarchical structures