Linearisation of electrically stimulated muscles by feedback control of the muscular recruitment measured by evoked EMG

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Introduction

Functional Electrical Stimulation (FES)

- Application of electrical current pulses to a muscle for inducing force.
- The pulses (20 to 60Hz) are modulated through pulsewidth and current amplitude.

Common difficulties of feedback control for FES

- Muscular fatigue (generally proposed solutions: Adaptive Control Strategies, integral action)
- The outcome of a stimulation pattern is difficult to predict.
- Complex models require long lasting identification experiments. Parameters are difficult to identify.

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Hill-type muscle model and succeeding mechanical system

- Non-linear recruitment function $rc(v)$.
- The dynamic transfer function $G_m(q^{-1})$ models chemical processes.
- The static function $F$ describes the dependency of the muscular torque on the joint motion.

Figure: Assumed neuro-musculo-skeletal system.
Non-linear Recruitment Curve

Model for the number of recruited motor units due to FES

- A static non-linear function describes the number of recruited motor units in dependence of the stimulation intensity $v$.
- Commonly there are hysteresis effects along with a time variant behaviour.
- Using a detailed model would require a high identification effort.

**Estimation of the recruitment:** An electrical response called evoked electromyography (eEMG) is measured.
**Proposed solution:** Feedback of the muscular recruitment index $\lambda$ in an inner loop. The stimulation intensity is adjusted.

- Measurement and signal processing of eEMG gives $\hat{\lambda}$, the controlled variable.
- At an higher level the joint-angle $\vartheta$ is controlled by using the reference $r_{\hat{\lambda}}$.
- Sampling rate: 25Hz
Model reduction: A linear model of the recruitment function $r_c(v)$ is used.

$$\hat{\lambda}(k) = \Theta_{r,a} q^{-1} v(k) + \Theta_{r,b} + e(k), \quad v_{thr} \leq v(k) \leq v_{max}$$

- Identification of $\Theta_{r,a}$ and $\Theta_{r,b}$ by least squares for each subject
- During control, the offset $\Theta_{r,b}$ can be treated as a constant disturbance.

Resulting plant transfer function: $G(q^{-1}) = \Theta_{r,a} q^{-1}$
**I-controller:** A discrete-time integrating controller $K$ without time delay is chosen.

$$K(q^{-1}) = \frac{k}{1 - q^{-1}}$$

The resulting closed-loop behaviour is then:

$$r_{\hat{\lambda}} \rightarrow \hat{\lambda} : T(q^{-1}) = \frac{GK}{1 + GK} = \frac{\Theta_{r,a}k q^{-1}}{1 + (\Theta_{r,a}k - 1) q^{-1}}.$$

The adjustable closed-loop pole $z_\infty = 1 - \Theta_{r,a}k$ is chosen such that a desired rise time is achieved without noise amplification.
Since the actuation variable is bounded to the range defined by $v \in [0, v_{max}]$ and because of the integrating controller, an anti-windup strategy is used.

Due to this, undesired closed-loop behaviour in case of saturation is prevented.

Figure: Recruitment controller with anti-windup strategy.
Model: Identification of a second order ARX-model from $r_\lambda$ to $\vartheta$:

$$\vartheta(k) = \frac{q^{-d}B(q^{-1})}{A(q^{-1})} r_\lambda(k) \quad d = 3$$

$$B(q^{-1}) = b_0$$

$$A(q^{-1}) = 1 + a_1q^{-1} + a_2q^{-2}.$$ 

Outer loop: Joint-angle control by $r_\lambda$.

- A pole-placement approach is used for the design of a digital polynomial controller.
- To include integral action, a virtual plant is introduced.
Desired closed-loop polynomial

$A_{cl}$ is factorised into two 2\textsuperscript{nd} order polynomials:

$$A_{cl}(q^{-1}) = A_1(q^{-1}) \cdot A_2(q^{-1}).$$

Diophantine equation

$$\overline{A}(q^{-1})\overline{R}(q^{-1}) + \overline{B}(q^{-1})\overline{S}(q^{-1}) = A_{cl}(q^{-1}).$$

Pre-filter Polynomial $T$

- Used to cancel the factor $A_1$ of the closed-loop polynomial.
- Ensures unity gain of reference to output behaviour.

$$T(q^{-1}) = \frac{A_1(q^{-1})A_2(1)}{B(1)}.$$
Saturation observer polynomial

$$A_{aw}(q^{-1}) = A_1(q^{-1}).$$
Results: Identification of the Recruitment Function

![Graph showing recruitment function and stimulation intensity](image)

**Figure:** Identification of the recruitment model (6) using least squares ($\Theta_{r,a} = 26.3$ and $\Theta_{r,b} = -1.04$).

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Results: $\lambda$-control test

**Rise time:** 200ms

Figure: Evaluation of the recruitment controller (RC).
Results: Identification of $r_\lambda \rightarrow$ Joint-Angle Relationship

Rise time: 700 ms

Figure: Identification and validation of the linear model from $r_\lambda$ to $\vartheta$. 
Results: Elbow Joint-Angle Control

![Graph showing joint-angle control results](image)

**Figure:** Results of an joint-angle control experiment for a healthy subject using the underlying recruitment controller.
Conclusions

\textbf{λ-control}

- The recruitment function can be linearised by feedback of eEMG.
- Reduced effort for identification (hysteresis, threshold and non-linearity of $rc(v)$ can be skipped)

\textbf{Joint-angle control}

- The obtained angle tracking performance can be further improved by non-linear approaches

\textbf{Future}

- Adaptive control: Closed-loop online identification.
Thank You for your attention!