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

Christian Klauer[1], Thomas Schauer[1], Jörg Raisch[1,2]
[1]Control Systems Group, Technische Universität Berlin
[2]Max-Planck-Institut für Dynamik komplexer technischer Systeme, Fachgruppe System- und Regelungstheorie, Magdeburg

Kontakt: klauer@control.tu-berlin.de

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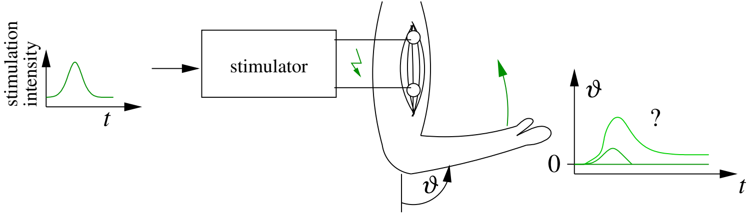
Functional Electrical Stimulation (FES)

- 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.

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.

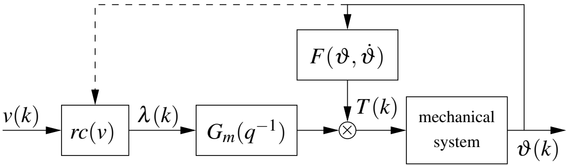
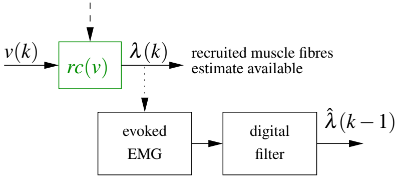
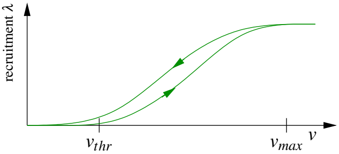


Figure: Assumed neuro-musculo-skeletal system.

Non-linear Recruitment Curve

Model for the number of recruited motor units due to FES



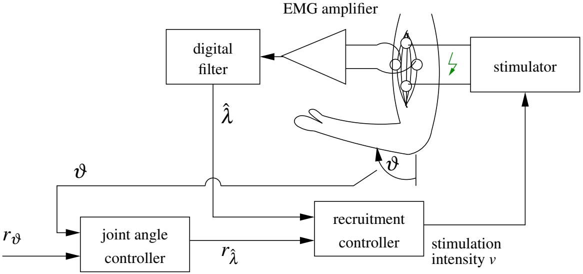


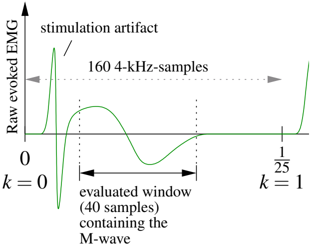
- A static non-linear function describes the number of recruited motor units in dependence of the stimulation intensity v.
- Commonly there are hysteresis effects along with a time variant behaviour.
- Using a detailed model would require a high identification effort.

Estimation of the recruitment: An electrical response called evoked electromyography (eEMG) is measured.

Cascaded Feedback Control Strategy

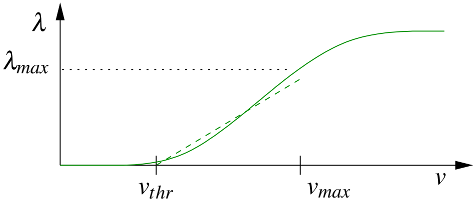
Proposed solution: Feedback of the muscular recruitment index λ in an inner loop. The stimulation intensity is adjusted.





- Measurement and signal processing of eEMG gives $\hat{\lambda}$, the controlled variable.
- At an higher level the joint-angle ϑ is controlled by using the reference $r_{\hat{\lambda}}$.
- Sampling rate: 25Hz

Model reduction: A linear model of the recruitment function $rc(v)$ is used.



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

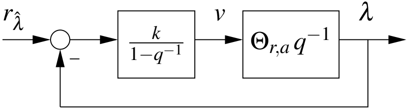
- Identification of $\Theta_{r,a}$ and $\Theta_{r,b}$ by least squares for each subject
- During control, the offset $\Theta_{r,b}$ can be treated as a constant disturbance.

Resulting plant transfer function: $G(q^{-1}) = \Theta_{r,a}\, q^{-1}$

Recruitment Controller (λ-Controller)

I-controller: A discrete-time integrating controller K without time delay is choosen.

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



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.

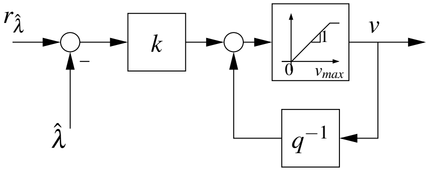


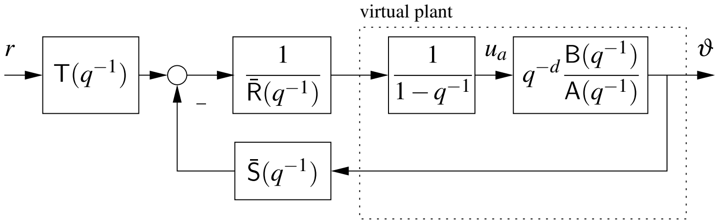
Figure: Recruitment controller with anti-windup strategy.

Model: Identification of a second order ARX-model from $r_{\hat{\lambda}}$ to ϑ:

$$\vartheta(k) = \frac{q^{-d}\mathsf{B}(q^{-1})}{\mathsf{A}(q^{-1})} r_{\hat{\lambda}}(k) \qquad d = 3 \qquad \begin{aligned} \mathsf{B}(q^{-1}) &= b_0 \\ \mathsf{A}(q^{-1}) &= 1 + a_1 q^{-1} + a_2 q^{-2}. \end{aligned}$$

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

- 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[nd] order polynomials:

$$\mathsf{A}_{cl}(q^{-1}) = \mathsf{A}_1(q^{-1}) \cdot \mathsf{A}_2(q^{-1}).$$

Diophantine equation

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

Pre-filter Polynomial T

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

$$\mathsf{T}(q^{-1}) = \frac{\mathsf{A}_1(q^{-1})\mathsf{A}_2(1)}{\mathsf{B}(1)}.$$

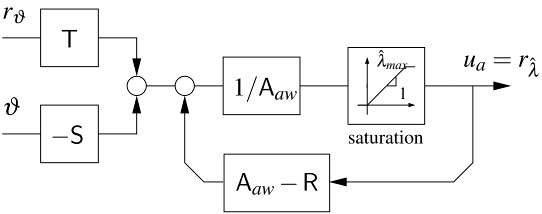


Figure: Implementation of the top level controller to avoid integrator windup.

Saturation observer polynomial

$$\mathsf{A}_{aw}(q^{-1}) = \mathsf{A}_1(q^{-1}).$$

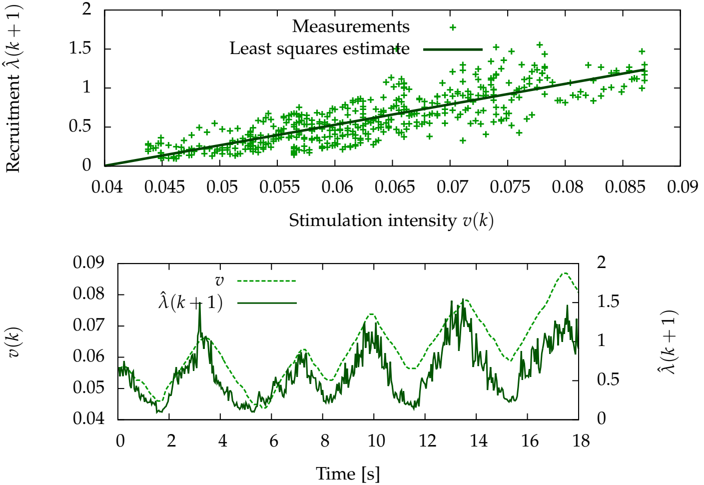


Figure: Identification of the recruitment model (6) using least squares ($\Theta_{r,a} = 26.3$ and $\Theta_{r,b} = -1.04$).

Rise time: 200ms

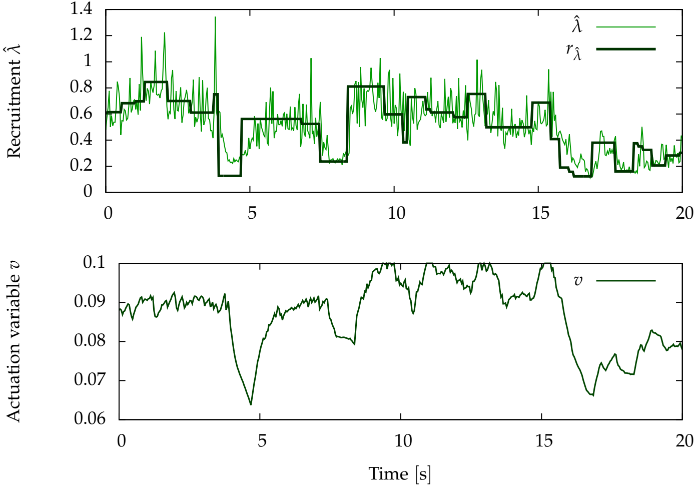


Figure: Evaluation of the recruitment controller (RC).

Rise time: 700ms

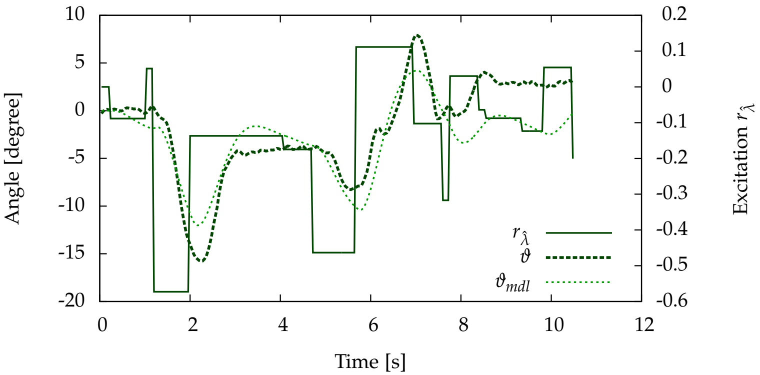


Figure: Identification and validation of the linear model from $r_{\hat{\lambda}}$ to ϑ.

Results: Elbow Joint-Angle Control

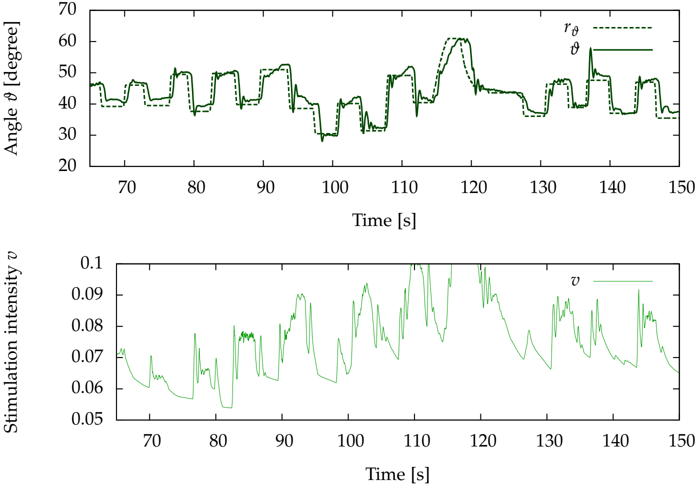


Figure: Results of an joint-angle control experiment for a healthy subject using the underlying recruitment controller.

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)

Joint-angle control

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

Future

- Adaptive control: Closed-loop online identification.

Thank You for your attention!