Design of feedback control strategies for an arm neuroprothesis combined with an exoskeleton

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Abstract— **For restoration of reaching function in patients with upper motor neuron lesion a noval control strategy for a neuroprosthesis was developed within the EU project MUNDUS. By applying controlled Functional Electrical Stimulation (FES) to the shoulder deltoid muscle and the biceps, functional arm movements can be achieved. An exoskeleton with three DOF partially compensates for gravitation and allows to lock joint angles for holding purposes. This is exploited by a feedback control strategy to reduce muscular fatigue. The control algorithm that sequentially controls the joint angles according to a given reference one after another is designed. The feasibility of the approach was demonstrated by successfully applying the strategy to one spinal cord injured (SCI) subject.**

I. INTRODUCTION

For SCI individuals with a high lesion, Schill et al. [2] developed the system OrthoJacket - an active FES-hybrid orthosis for the paralyzed upper extremity. The system combines FES controlled grasping with a electrical / pneumatic actuation of shoulder movements and a flexible fluid actuator for support of elbow-joint movements. No FES is used for movement generation at the shoulder or elbow joint.

Within the EU project TOBI another FES-hybrid orthosis is developed for SCI patients which supports grasping and elbow-joint movements by FES [3]. However the system requires fully intact shoulder functions to realize arm movements. To avoid an excessive stimulation of the biceps during holding tasks an in flexion direction self-locking, electrically de-lockable elbow-joint is used within the orthosis. No automatic feedback control of movements is provided by the system.

This contribution presents the first feedback control system that uses full FES actuation for restoring reaching functions. The combination of FES with a passive, gravitiy compensating, exoskeleton is a novel approach. Muscular fatigue can be significantly reduced by such a setup as the required amount of muscular force is less compared to normal movements. The additional usage of electrically lockable brakes at the joints reduces the onset of muscular fatigue even further as no muscle function is required to hold an arm position.

II. EXPERIMENTAL SET-UP

Arm movements are induced by four stimulation channels activating three parts (anterior, posterior and medial) of the deltoid muscle located at the shoulder and the biceps. The stimulation intensities are the pulses charges. The exoskeleton (developed within MUNDUS by TU-Wien, Vienna) enables free motion for the following DOF that may be also locked by brakes:

- Horizontal shoulder rotation (anterior and posterior deltoid)
- Shoulder abduction (medial deltoid)
- Elbow flexion (biceps)

The rotation of the forearm around the upper arm axis (inner shoulder rotation) is locked by the exoskeleton. For each remaining DOF the corresponding angles are acquired. The positions of target objects are detected in 3D space by a KINECT-based marker tracking system developed within MUNDUS by Fraunhofer IESE. The mapping between the exoskeleton angles and the position is bijective and is described by an kinematic model. Since the coordinate frame of the marker tracking system is not necessarily equal to the one used for the kinematic model, a transformation (translation and rotation) between two coordinate frames is required. The parameters of the full transformation as well as all parameters of the kinematic model (lengths of the upper- and forearm, inner shoulder rotation angle) are estimated by a non-linear optimization procedure using measurements from at least 12 different arm positions. Another calibration step is to acquire the maximum tolerable stimulation intensities for each muscle along with a calibration experiment for identifying the dynamics of the shoulder abduction movement induced by FES. The detection of the patient's intention is gathered either by an eye-tracking module or by a BCI-interface both developed within MUNDUS by Politecnico di Milano and the Machine Learning Group at TU Berlin respectively.

III. ARM MOTION FEEDBACK CONTROLLER

A sequential control of each DOF is applied: While a joint angle for one DOF is controlled by adjusting the corresponding stimulation intensity to match a pre-calculated angular reference position, the other ones are locked by the exoskeleton brakes. This results in a fully decoupled system with regard to crosstalk between the DOFs. For this reason a light model with few parameters can be used for controller design which dramatically reduces the effort for parameter identification. The movements to a given position is divided into three steps: Control of the shoulder abduction **(A)**, control of the shoulder rotation **(B)** and control of the elbow flexion **(C)**. The calculation of an angular reference

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The research leading to these results has received funding from the European Community's Seventh Framework Programme under grant agreement no. 248326 within the project MUNDUS.

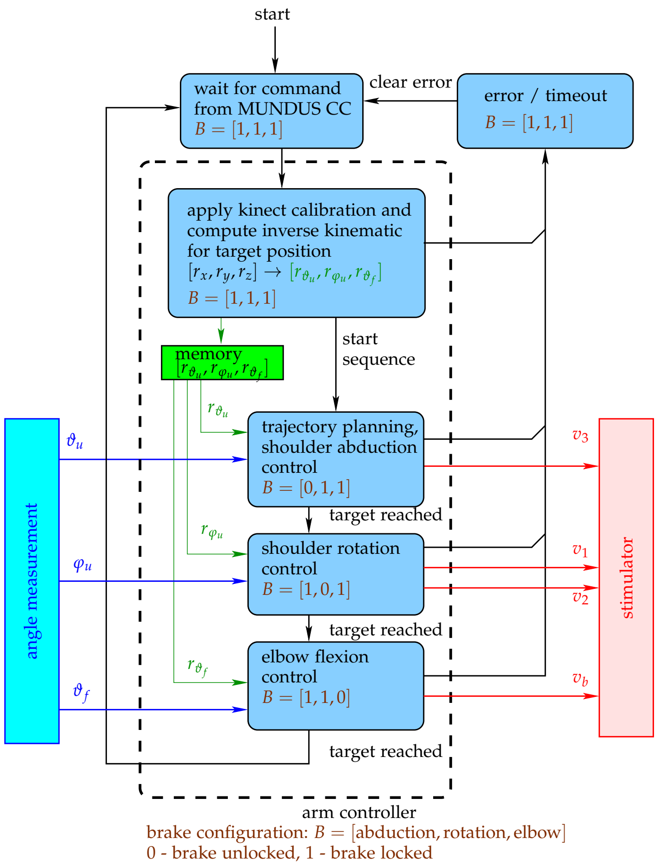

Fig. 1. The state machine of the arm controller is shown. Each of the continuous feedback controllers is executed in a separate state. The states are activated in a sequence. The calculation of the inverse kinematics is done after a command for movement was received and prior to the control sequence.

position is achieved by calculating the inverse kinematics for a given 3D target position.

All movements are initiated by commands received from an external high level control system, the MUNDUS Central Controller (MUNDUS CC, developed in MUNDUS by Hocoma AG), which processes the information collected by the eye-tracker / BCI module.

The entire control system is designed as finite state machine (cf. Fig. 1). This structure forms a hybrid control system since some states also contain continuous feedback controllers.

For the shoulder abduction, a digital controller based on a previously identified dynamic transfer function model is automatically designed using the pole-placement method [1] in the calibration phase. Control of the horizontal shoulder rotation as well as the elbow-joint angle is basically achieved by constantly ramping-up the stimulation intensity until the reference angle is reached and subsequent locking by the corresponding brake.

The stimulation pulses are applied to the muscle using the stimulation system REHASTIM (HASOMED GmbH, Magdeburg, Germany). The real-time dynamic block simulation system OPENRTDYNAMICS[1] was used for implementation of the controller structure, the calibration procedures and network communication to a QT4-GUI.

[1] http://openrtdynamics.sf.net

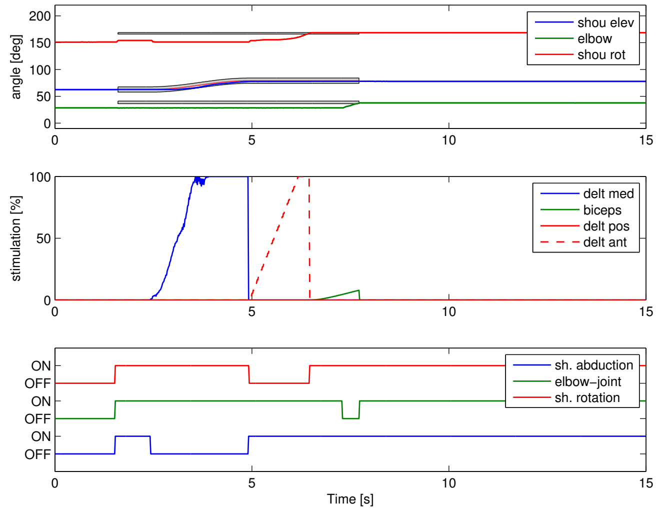

Fig. 2. Result for a movement from the table to the mouth. The angles along the reference tolerance band are shown in the first plot. The second plot shows the stimulation intensities applied by the controller and the third subplot illustrates the brakes states.

IV. RESULTS

Fig. 2 shows the first results of the control system with a SCI subject. Depicted is the movement from a hand position at a table to the mouth. The reference angles are shown as tolerance bands along with the measured ones. All joint angles were sequentially controlled until the references are reached due to the stimulation intensities shown in the middle sub plot. In the lower sub plot the activation state of each brake is outlined.

V. CONCLUSION

The developed system is the first feedback controlled and purely FES actuated neuroprosthesis for restoring reaching and does not require any residual function at the shoulder and elbow level. Because of the chosen sequential control strategy the system is very robust and easy to adapt to an individual subject, which forms the main requirement for clinical environments. Of course the system will be used in conjunction with FES or robotic induced grasping to enable full arm and hand functionality.

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