Feedback control of arm movements for a hybrid assistive system to support daily upper limb activities

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Abstract – This contribution investigates the restoration of reaching function in patients with upper motor neuron lesion. Within the EU project MUNDUS a novel control strategy for a neuro-prosthesis has been developed. Functional arm movements are generated by applying controlled Neuro-Muscular Electrical Stimulation (NMES) to the shoulder deltoid muscle and the biceps. In addition to this, a spring-based exoskeleton with three DOFs 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 sequentially controls the joint angles according to given references one after another. This robust approach was evaluated with healthy subjects at first and then successfully applied to spinal cord injured (SCI) people. A mean hand positioning error of less than 5 cm was observed for the employed control system.

1 Introduction

The restoration of grasping function by Neuro-Muscular Electrical Stimulation (NMES) in spinal cord injured people with high lesion has been studied by several research groups in the past. Even commercial neuro-prosthetic systems have been realised using transcutaneous and implanted stimulation technology. However, these systems require sufficient residual voluntary elbow and shoulder function for carrying out the reaching movements.

Unfortunately, tetraplegic patients with very high lesions do not fulfil these requirements. To remedy these shortcomings, active NMES-hybrid orthoses have been proposed by other research groups to induce elbow- and shoulder-joint movements by body-attached electrical, pneumatic or hydraulic drives.

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

Within the EU project TOBI another NMES-hybrid orthosis is developed for SCI patients which supports grasping and elbow-joint movements by NMES [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 controlled NMES-hybrid orthosis for restoring reaching functions that involves solely a passive, gravity compensating, exoskeleton. This NMES-hybrid orthosis is part of the Multimodal Neuroprosthesis for Daily Upper Limb Support – MUNDUS – which was developed within the EU Project MUNDUS.

2 Methods

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 exoskeleton (cf. Fig. 1) was developed in the project MUNDUS by the Vienna University of Technology and enables free motion for the following three DOF that may be also locked by brakes:

(1) horizontal shoulder adduction/abduction (rotation) (angle φ_u; actuated by anterior deltoid/posterior deltoid with control signals $v_{d,a}$ and $v_{d,p}$),

(2) shoulder abduction/adduction (angle ϑ_u; actuated by medial deltoid/gravity with control signal $v_{m,d}$),

(3) elbow flexion/extension (angle ϑ_f; actuated by biceps/gravity with control signal v_b).

The rotation of the forearm around the upper arm axis (inner shoulder rotation) is locked by the exoskeleton. For each DOF the corresponding angle is acquired. Positions of target objects are detected in 3D space by a Kinect-based marker tracking system developed by the MUNDUS partner Fraunhofer IESE. The mapping between the exoskeleton angles and the 3D hand position is bijective and is described by a rigid body kinematic model. Another important transformation is between the Kinect and exoskeleton coordinate

Figure 1: MUNDUS System: User with exoskeleton, drinking object and eye-tracker for object/task selection.

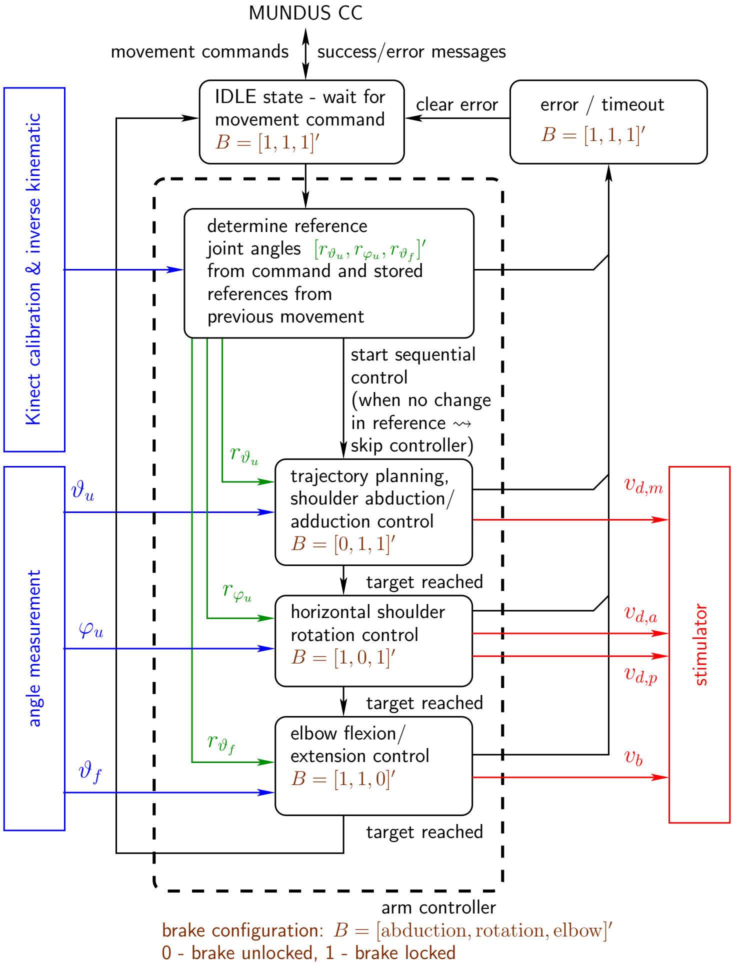

Figure 2: Real-time arm NMES control system shown in form of a state automaton.

systems. The parameters of both transformations can be automatically determined from recorded raw angles of the exoskeleton and the raw Kinect data for the hand position by a nonlinear optimisation using the Gauss-Newton method with analytically calculated Jacobians. This allows for a nearly arbitrary placement of the Kinect camera. In addition, this optimisation also returns the following parameters of the exoskeleton: lengths of the lower and the upper arm as well as the adjusted humeral shoulder rotation.

The patient's intentions can be detected 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.

Sequential feedback control is used to adjust the stimulation intensities (pulse charges) in order to drive the hand to desired 3D positions in the reachable work space. Each DOF is controlled separately, one after the other while all other DOFs are locked. 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 each controller design which dramatically reduces the effort for parameter identification. The movements to a given 3D position is divided into three consecutive steps: 1st) control of the shoulder abduction/adduction, 2nd) control of the horizontal shoulder rotation and 3rd) control of the elbow flexion/extension. Accordingly, the real-time arm NMES control system represents a state automaton (cf. Fig. 2). This system is also a hybrid control system since some states contain continuous feedback controllers.

For the shoulder abduction/adduction, a time-discrete feedback controller is deployed. The used pole-placement design is based on an identified transfer-function model [1]. 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 locked by the corresponding brake.

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

All movements are initiated by commands received from a high level control system, the MUNDUS Central Controller (MUNDUS CC, developed in MUNDUS by Hocoma AG) which processes among others

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

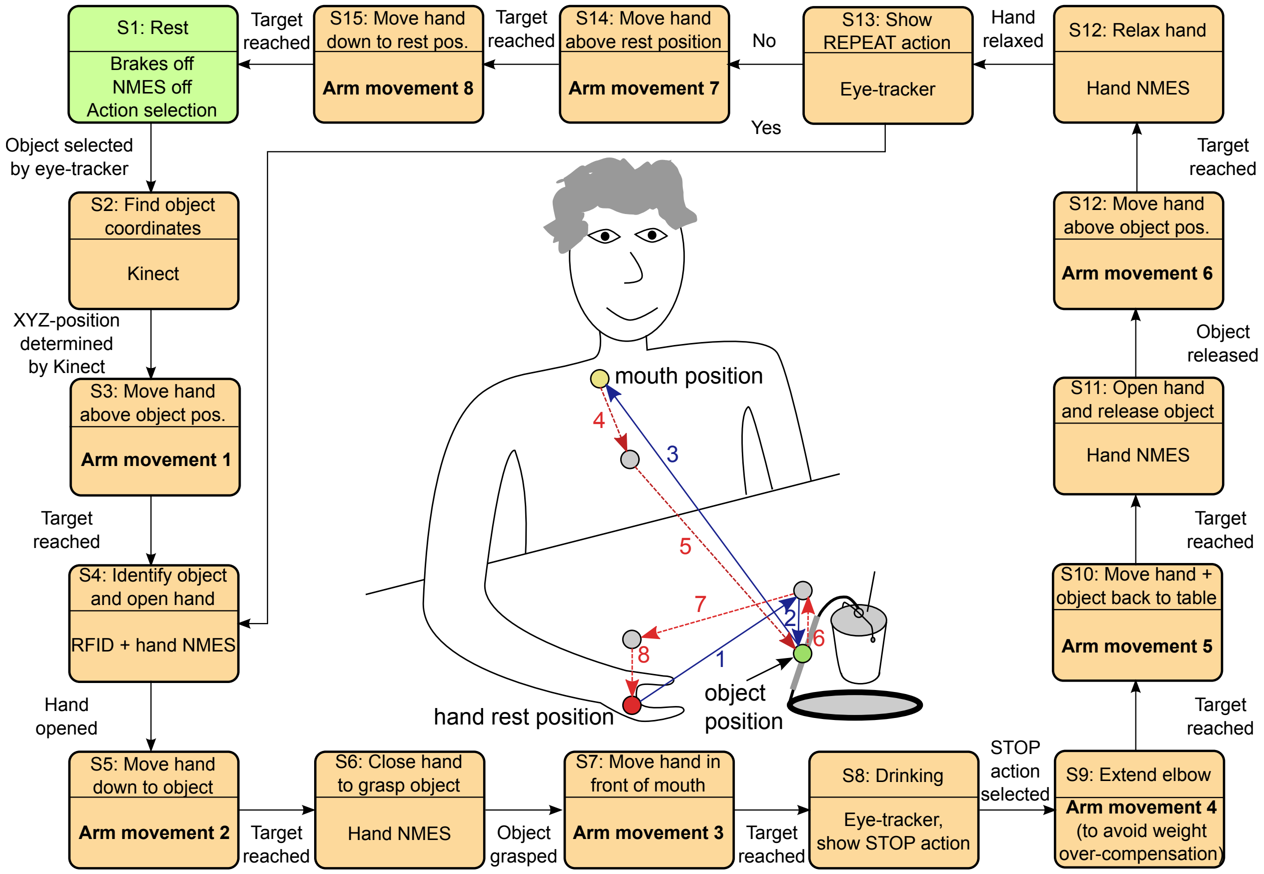

Figure 3: The state automaton inside the MUNDUS Central Controller (CC) to realise the "Drinking" use case starting from an arm rest position and returning to this position again. The states (S3,S5,S7,S9,S10,S12,S14,S15) with arm movements trigger another state machine inside the real-time arm NMES control module (cf. Fig. 2). The references for the rest position as well as for the mouth position may be stored in the MUNDUS CC as angular references during the system calibration phase. The object position is online determined by the Kinect system by tracking a green marker on the object handle.

the information collected by the eye-tracker or BCI module. Possible MUNDUS CC movement commands are: (1) go to a desired 3D position (given in measured raw 3D Kinect coordinates), (2) go to a desired 3D position (given in reference angles of the exoskeleton), (3) increase/decrease shoulder abduction by a certain amount and (4) extend/flex elbow joint by a certain amount. For all commands, new angular references are determined by the real-time control system using, if required, also stored old references from the last movement and the inverse kinematics.

Based on the elementary movement commands outlined above, complex movement sequences are possible by a combination of multiple commands issued in series. Within MUNDUS CC, different sequences are stored and executed for different scenarios. An example for the "Drinking" use case is outlined in Fig. 3. Hand functions can be realised by another NMES module (developed within MUNDUS by École Polytechnique Fédérale de Lausanne). This module deploys a new stimulation system for array electrodes [4] in order to achieve precise finger movements.

It should be noted that the straight lines shown in the centre of Fig. 3 do not represent the actual hand movements. As outlined before, each movement between the points is generated by sub movements composed by the sequential activation of the above outlined three controllers for the three DOFs.

3 Results

The control system was evaluated with healthy subjects for the "Drinking" use case at first. The Fig. 4 shows exemplary the recorded angles together with their references (bands) and used control signals (stimulation intensities as well as brake control signals). The vertical dashed lines indicate the time periods of the controlled arm movements that have been introduced and numbered in Fig. 3. An unwanted slipping of the horizontal shoulder brake can be observed after 45, 62, and 92 seconds. The observed mean positioning errors for two healthy users are reported in Table 1.

First tests of the novel NMES-hybrid orthosis were also carried out with SCI people. The subjects could basically use the system to perform daily activities such as drinking, pressing a button, touching another person or the own body in conjunction with NMES induced grasping.

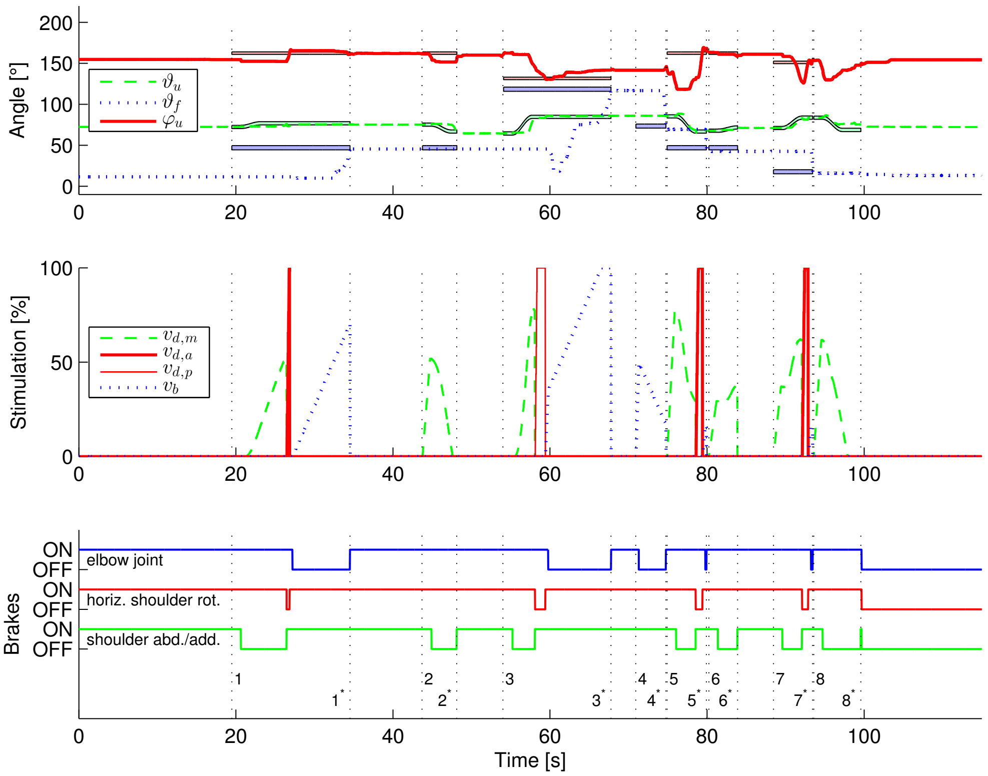

Figure 4: Recorded data of a healthy subject for the “Drinking” use case.

Subject (healthy)	Mean positioning errors [m]					
	all positions		mouth		above object	
	via exo	via Kinect	via exo	via Kinect	via exo	via Kinect
A	0.032	0.045	0.021	0.034	0.018	0.005
B	0.026	0.033	0.018	0.019	0.028	0.0015

Table 1: Mean positioning errors [m] for five “Drinking” sequences per subject measured via the exo-sensors or via the Kinect.

4 Discussion and Conclusions

The first results show that feedback control of the NMES-hybrid orthosis is feasible. However the observed positing errors can not be neglected and may require some residual ability of the user for volitional correction of the achieved hand position. For the “Drinking” use case the small error at the mouth might be compensated by minor head movements. Reasons for the observed errors are diverse. One major problem is the too weak brake for the horizontal shoulder rotation in the current design that causes unwanted slipping. In addition, the current design assumes that the exoskeleton with the arm represents a rigid body system. This is certainly not perfectly true in reality. Another short coming of the developed system is the fact, that elbow extension and shoulder adduction are only induced by gravity. This requires a carefully adjusted weight compensation on the exoskeleton. Any overcompensation of the weight could drive the arm movement into a dead lock. Big advantages of the used control strategy are its robustness and the simple adaptation to new users/sessions. These advantages have to be paid by the fact that the movements do not look very physiological and movement sequences are not time optimal. In summary, at the first time a clinically usable NMES-hybrid arm orthosis with fully feedback controlled movements could be realised and tested.

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