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Towards the restoration of hand grasp function of quadriplegic patients based on an artificial neural net controller using peripheral nerve stimulation - an approach

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Abstract. We propose a closed loop strategy for the control of hand grasp movements for paralyzed patients which is based on an artificial neural network (ANN). For this goal an ANN controller applies functional neuroelectrical stimulation (FNS) to a peripheral nerve with the aim to initiate axonal stimulation patterns similar to those generated by the central nervous system. In this paper we present the results of simulated closed loop position control experiments that were carried out in real time. Training and testing of our control strategy were based on data gained in vivo from a pig's limb while applying FNS. Despite of muscle fatigue and other nonlinear disturbances our control strategy results in high control quality.

Introduction

The aim of the GRIP-project[1] (Inte**GR**ated System for the Neuroelectr**I**c Control of Gras**P** in Disabled Persons) is to develop a feedback control system to regulate simple hand grasp movements of patients with quadriplegia [1]. An overview of research on the field of grasp control is given in [2].

In general a grasp control system can use two different stimulation sites. The involved muscle groups can either be stimulated directly via e.g. surface electrodes or indirectly utilizing the corresponding peripheral nerves. The latter is used for functional neuroelectrical stimulation (FNS). The advantages of FNS compared to direct muscle stimulation are the higher sensitivity range of this approach and the decreased danger of muscle fatigue or cramps. FNS strongly depends on the used controller's ability to provide various neuroelectric stimulation patterns that are similar to the corresponding axonal stimuli in biological systems. In the past, different kinds of (mostly model free) feedback control strategies have been applied for grasp control systems. A comparison of the applied control algorithms can be found in [5].

For quadriplegic patients an initially short training time of the control system is favorable in order to start off quickly with an exercise program for the regeneration of muscle structure. During muscle training the control system must learn to change its behavior with the growing abilities of the patient. Due to these conditions, we propose a system for grasp control based on an artificial neural network (ANN). Compared to the approach using look up tables (LUT) [6] a trainable ANN controller offers several advantages: training and retraining easily enables the ANN to adapt to the individual needs of different patients and to their changing abilities.

An overview of the proposed grasp control scheme is shown in figure 1. The

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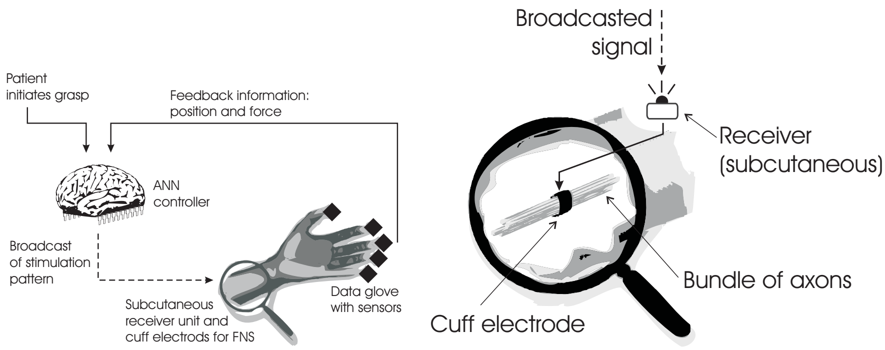

Figure 1: *Left illustration: proposed scheme of the closed-loop system for grasp control. Right illustration: implementation scheme for a subcutaneous receiver unit and the cuff electrode around the nerve.*

patient defines strength and position for a desired grasp. Receiving these parameters, the ANN controller generates appropriate neuroelectrical stimulation patterns and broadcasts them to a subcutaneous receiver unit connected to a programmable stimulator chip. This stimulator has a connection to a cuff electrode manufactured of flexible polyimide [4]. The electrode encloses nerves leading to the major muscles of the forearm which are responsible for basic grasp movements. Resulting movements of hand digits and surface forces are registered by sensors of a data glove and used as feedback information for the ANN controller which can thus regulate its output. A detailed description of the system is given in [3].

Data

The data used for the training and testing of the proposed ANN control approach was recorded during an in vivo animal experiment. Pigs were chosen as the appropriate animal model since their neuromuscular conditions are similar to those in the anatomy of humans.

During the experiment the radial nerve in the axilla of a frontal limb of the anesthetized animal was stimulated using the hardware described above. Initially, a position of the used cuff electrode and suitable pole sites had to be determined in order to provide optimal selectivity of wrist muscle activation [9]. The FNS resulted in a wrist movement which was well defined by the rotation angle around the wrist joint.

As the animal's physical characteristics tended to change under the influence of narcotics, the number of trials had to be restricted to seven. The setup of the *in vivo* experiments performed for data recruitment is shown in figure 2. The left illustration shows the setup for the FNS stimulation trials. Each trial lasted 29 seconds. During this time the axillary nerve was stimulated using a triangle shaped pattern while the resulting wrist position was recorded. To reduce possible fatigue effects, well defined intertrial resting periods were applied. The stimulation pattern for FNS was linearly varied in pulse width (PW) from 0 to 300 μsec and back, whereas stimulation frequency (25 Hz) and amplitude (270 μA) were kept constant.

The right illustration in figure 2 shows the triangular stimulation pattern together with the resulting recorded position trajectories. Fatigue and other

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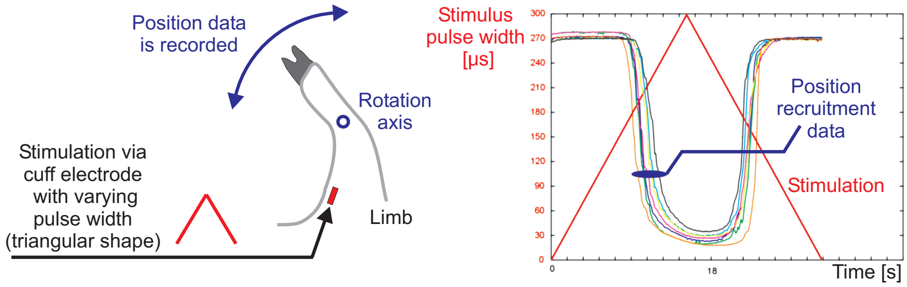

Figure 2: *Left illustration: Setup of the data recruitment experiment. Right illustration: FNS stimulation patterns and seven resulting position trajectories.*

nonlinear characteristics of the biological system are responsible for remarkable differences in the measured position trajectories of consecutive trials, e.g. during maximum stimulation intensity a variation in position between the trials of about 10 percent was observed.

Please notice the asymmetrical response of the wrist position upon the symmetrical PW stimulation pattern. The most extreme position values can be observed around second 18 (about four seconds after the maximum PW values were applied). This time delay will inherently hamper any kind of control approach for this biological system.

Training of the ANN Based Controller

During preliminary investigations [3] we have identified the FlexNet network construction and training algorithm to be able to handle the requirements for neuromuscular stimulation. Starting with input and output neuron layers only this algorithm incrementally builds a (rather deep and narrow) MLP architecture during the training phase. Using Rprop learning for the weight adaption, FlexNet determines the best suited position in existing or new layers for competing groups of candidate neurons in the current network. These abilities of FlexNet relieves experimenters from the costly search for good network structures and learning rates during time critical animal experiments.

For position control the network needs the target position values and the feedback information about the actual limb position as input. Based on this information, the ANN calculates convenient pulse width values (PW) for the FNS (see figure 3).

Data from four of the seven recruitment trials (see figure 2) was chosen randomly for the training of the ANN. Two trials were used for testing the network performance during the training phase. The remaining trial was used for the creation of the look up table (LUT) for the simulated position control experiment.

Based upon the training trials, 2700 training vectors were computed. Each vector coded the network input (position target and position feedback) and the desired network output (PW value for stimulation) for a certain time step t. The training vectors were randomized and used for the FlexNet training.

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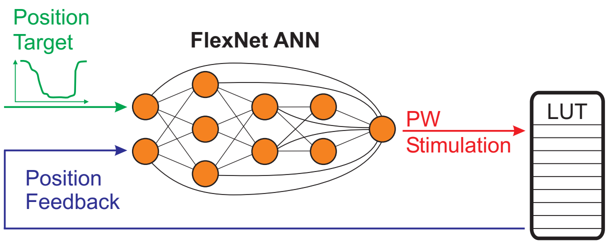

Figure 3: *Scheme of the closed loop position control based upon a FlexNet controller. The limb movement is simulated using a look up table (LUT).*

Results

After training, the resulting FlexNet had 16 hidden neurons and showed 5 percent absolute averaged error on the test data. The network training resulted in a 2-2-2-2-2-8-1 structure with a total number of 155 weights.

Based upon this trained ANN, a simulated closed loop control experiment was performed. Therefore a look up table (LUT) was created that could deliver a position value upon a given PW stimulation value created by the network (see figure 3). Ideally the LUT should be filled with unambiguous pairs (PW,Position). But as all the recruitment data trials showed a strong asymmetry and therefore were ambiguous, it was decided to fill the LUT with values from the first half of the previously selected trial only and thus to reduce ambiguity.

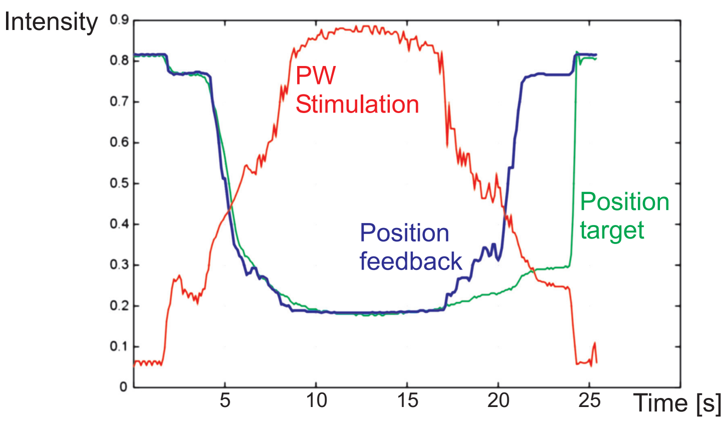

Figure 4: *Results of the simulation of closed loop position control. The simulation was carried out as described in figure 3.*

The simulation of the closed loop control resulted in good control performance as visualized in figure 4. In the first half of the simulation, the controlled position trajectory follows the position target trajectory quite well. Small overshooting of the position values around second two and seven are immediately controlled by a decreasing PW intensity. The trajectory of the applied PW stim-

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ulation is smooth. Only slight PW oscillations occurred during the experiment. During the second half of the experiment the control quality is decreasing. As pointed out before, the biological system from which the recruitment data was taken showed strongly differing characteristics for the second halves of all trials compared to their first halves. As the LUT could only be designed to respond properly for one half (the raising part of the PW trajectory), the decrease in control quality is explainable. Control results similar to figure 4 were obtained for other randomly chosen data combinations for the test set, training set and the LUT.

It's worth realizing that the ANN always tries to use the lowest PW values possible to reach a desired position target value which will be advantageous regarding possible fatigue effects. The reason for this behavior is not yet clear and will be subject of future investigation.

Conclusion

In this paper we have described a system for the restoration of simple hand grasp function of quadriplegic patients. We focused on the ANN based controller for the closed loop control of limbs using functional neuroelectrical stimulation.

The proposed control system was simulated in a closed loop environment. A FlexNet ANN controller was trained using data obtained by functional neuroelectric stimulation of a pig's limb. After training, the ANN performed well with an averaged absolute test error of 5 percent.

Based on the presented results, future experiments with *in vivo* closed loop control using the pig model will be done. Reflecting the results obtained by the simulation encourages the further use of FlexNet for this purpose.

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