Stimulation of Peripheral Nerves for Restoration of Hand Function of Quadriplegic Patients Using an Artificial Neural Net Based Controller

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Abstract. In this paper we describe a closed-loop functional neuroelectrical stimulation (FNS) system based on an Artificial Neural Network controller to regulate hand grasp movements of patients with quadriplegia. Using an Artificial Neural Network (ANN) as the kernel of the feedback control system makes it possible to generate FNS stimulation patterns for nerves that are similar to the corresponding axonal stimuli generated by a biologic system. Here, we describe the application of an ANN already investigated for neuromuscular stimulation regarding the use in FNS: FlexNet. FlexNet requires little training time and show good generalization behaviour. It can cope with nonlinearities and react flexible in new situations by producing adequate output. Due to its small size it is suitable for an implementation in real time. After a short introduction to the scheme of the feedback control system developed during the GRIP-project and the used techniques for axonal stimulation we take a closer look on the ANN controller. We show the results of our investigations for data sets obtained during *in vivo* experiments in pigs.

1 Introduction

The aim of the GRIP[1]-project (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 hand grasp movements of patients with quadriplegia. An overview of recent research on the field of grasp control is given in [1].

A system for grasp control must be able to initiate movement of the paralyzed hand. Designing a system of functional neuroelectrical stimulation (FNS) it is necessary to use a controller that can provide various neuroelectric stimulation patterns which are similar to the corresponding axonal stimuli in biological systems. This prevents the muscles from clenching up and offers the biggest possible

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[1] The GRIP-project is granted by the European Community under ESPRIT IV RLTR Project #26322. Find the latest information about the GRIP-project on http://www-ti.informatik.uni-tuebingen.de/ grip/.

freedom of movements to the quadriplegic. Further, the patient asks for short training time to start off with the system in order to regenerate muscle structure fast. In the following time, the system must learn to change its behaviour with the growing abilities of the patient during usage.

Due to these conditions, we propose a system for grasp control based on an Artificial Neural Network (ANN). An overview of the system is shown in figure 1. A detailed description about the system is given in [2].
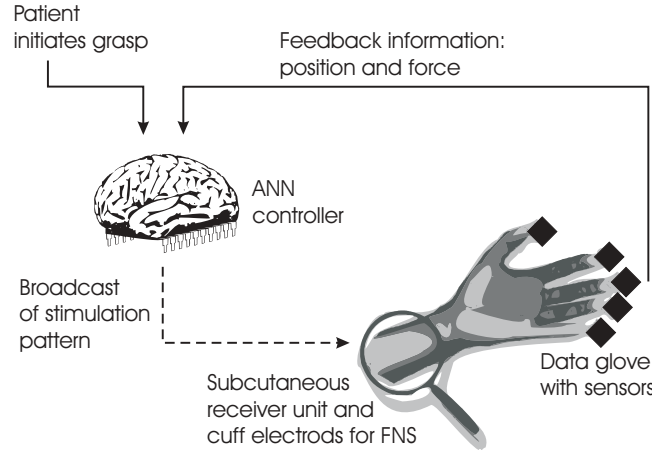
**Fig. 1.** Scheme of the closed-loop system for grasp control

The patient initiates a grasp movement of a certain strength. The ANN controller receives information of the desired grasp force and generates appropriate neuroelectrical stimuli signals. The signals are sent to a subcutaneous receiver unit which is connected to a cuff electrode (see below). Using these electrodes the unit implies stimulation to the axons leading to muscles in the forearm. The resulting movement of the digits and the force applied to the surface of the hand is recorded by sensors of a data glove worn by the patient. The position of the fingers and the forces provide important feedback information which are returned to the ANN controller to regulate its output.

In the past, different kinds of feedback control algorithms have been used. Find a comparison of these algorithms in [3]. Using the grasp control system based on a trainable ANN controller instead of a standard look up table (LUT) controller [4] has several advantages. Such a system can be expected to easily be adapted to the individual needs of different patients and their changing abilities. During prelimanary investigations, we've identified an ANN able to handle the requirements for neuromuscular stimulation: FlexNet [5]. In this paper we focus on FlexNet as the ANN for the proposed closed-loop control of the paralyzed hand investigating its abilities for neuroelectrical stimulation.

After presenting the receiver unit and the cuff electrode, we concentrate on an ANN based controller using FlexNet for closed loop control of a pig's limb.

2 Functional Neuroeletrcial Stimulation Using Cuff Electrode

The principle of the subcutaneous receiver unit and the cuff electrode which are used in the GRIP-project is shown in figure 2.
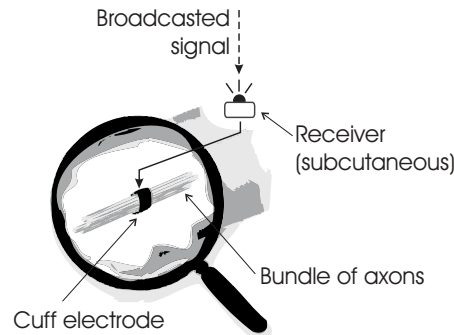
Fig. 2. Implementation scheme for the subcutaneous receiver unit and the cuff electrodes in the forearm.

Stimulation patterns generated by the ANN controller are broadcasted to the subcutaneous receiver unit. The data is spread to up to eight cuff electrodes. They enclose axon bundles leading to the major muscles of the forearm which are responsible for basic grasp movements.

The cuff electrode was developed by the Fraunhofer Institut für Biomedizinische Technik (IBMT), St.Ingbert (Germany). This multipolar electrode for the connection with the peripheral nerve is manufactured of flexible polyimide. An attached programmable 1 channel stimulator chip, developed by the Centre Nacional de Microelectronica (CNM), Barcelona (Spain), works as a receiver unit. For more details about the cuff electrode please refer to [6] [7].

3 Experimental Set Up

In order to validate the approach, an animal model has been choosen. Since the pig has similiar anatomic conditions compared with humans (especially for the nerve sizes), it was designated for *in vivo* experiments. The experimental set up is shown in figure 3.

In the animal model, the patient's intent is replaced by an arbitrary angle trajectory which can be defined by an user. Also, instead of the data glove with
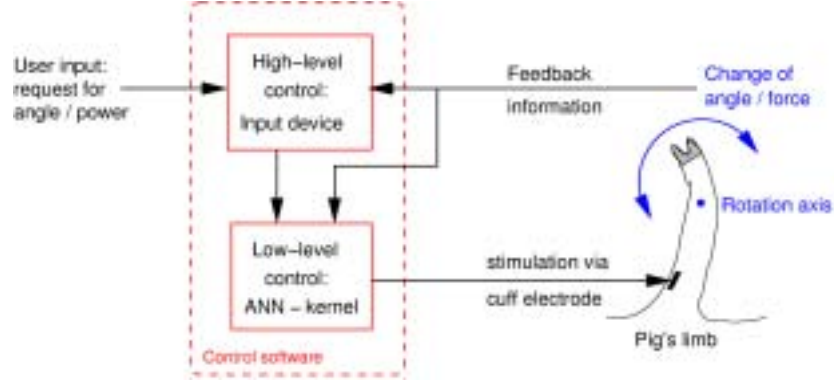
Fig. 3. Scheme of the experimental set up for the closed loop control of a pig's limb.

its sensors for angles and force, only the angle of the rotation axis is measured. Thus, the given trajectory describes an angle dependent on time. Nevertheless, the actual angle position is given to the control software, which is in fact the ANN, and thus close the loop for the control of the pig's limb.

4   Data Set

After calibrating the input data channels, the animal limb is stimulated in a standardized way. During subsequent stimulation trials, feedback data from the angle sensor has been recorded. One stimulation trial takes 27 seconds. Each
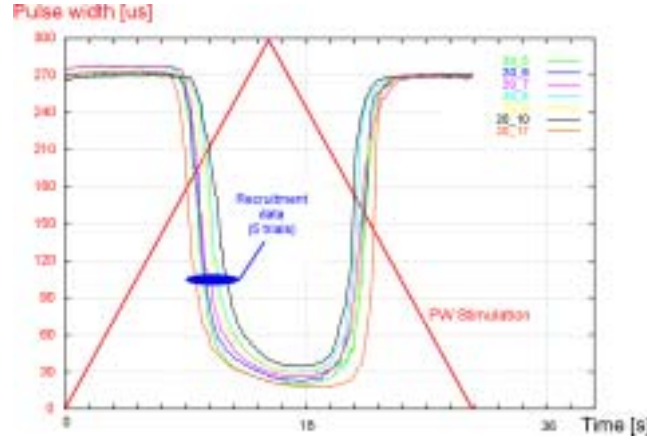
Fig. 4. Data acquisition: The corresponding nerve is stimulated with differtn pulswidth (PW) over 29 seconds (pyramid curve). The corresponding angles are shown for 7 different trials.

trial is repeated several times using exactly the same stimulation ramp (pyramid ramp, see figure 4) and well defined rest periods between the trials in order to reduce fatigue effects. The stimulation ramp varied the pulswidth from 0 to 300 μsec, whereas the stimulation frequency (25 Hz) as well as the stimulation amplitude (270 μA) was kept constant.

This leads to a collection of recruitment data as shown by 7 trials in figure 4. Fatigue and other nonlinear effects that appear due to the individual animal behaviour are responsible for the different feedback response curves of consecutive trials. In order not to avoid pertubations of the biological systems, only a small numebr of trials can be performed.

Finally after the collection of sufficient data sets, the data vectors needed for the ANN training are generated from the recruitment data.

5 Training of the ANN Based Controller

For the position control of the pig's limb (angle), the controller needs the following input information: the arbitrary trajectory as desired target values and the feedback information about the actual limb position. The FlexNet calculates the corresponding output for the stimuli (see figure 5).
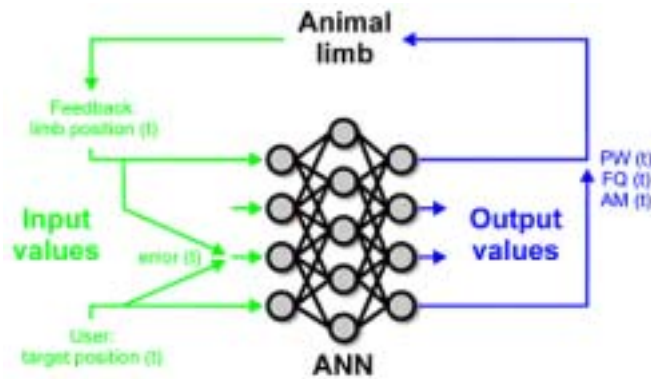
Fig. 5. Scheme for the inputs and outputs of the FlexNet. In this case, only the output for the pulswidth (PW) is used.

Up to now, the ANN was trained to constantly update one of the pulswidth (PW) of stimulation while the remaining parameters (Amplitude AM = 270 μA, Frequency FQ = 25 Hz) were kept constant.

As already mentioned above, in an earlier study [5], FlexNet [8] [9] has been identifed as suitable for the use in neuromuscular stimulation. Thus, it was used here as well for calculating the corresponding stimuli for the neuroelectrical stimulation.

FlexNet is a flexible, easy to use neural network training and network construction algorithm. Starting with input and output neuron layers only, the network structure is defined incrementally during the training process. FlexNet determines the best suited position/layers for competing groups of candidate neurons in the current network before adding them. As this allows for new neurons being added to new, existing or older layers, FlexNet networks not necessarily grow as deep and narrow as networks constructed by Cascade Correlation. It has been shown that FlexNet outperforms variants of Cascade Correlation on many problems, is only little sensitive to herd effects but usually consumes more computation time.

For the training of FlexNet, 4 out of 7 trials shown in figure 4 has been randomly choosen as training data set. For each time step t, a vector containing the desired target value and the actual target positon as input as well as the desired pulswidth as output, has been computed. The actual target position was read out of a look up table representing the reaction of the limb for the corresponding PW stimuli. Thus, the training data set consists of 2700 vectors. The remaining 3 trials were used for validation of the trained net.
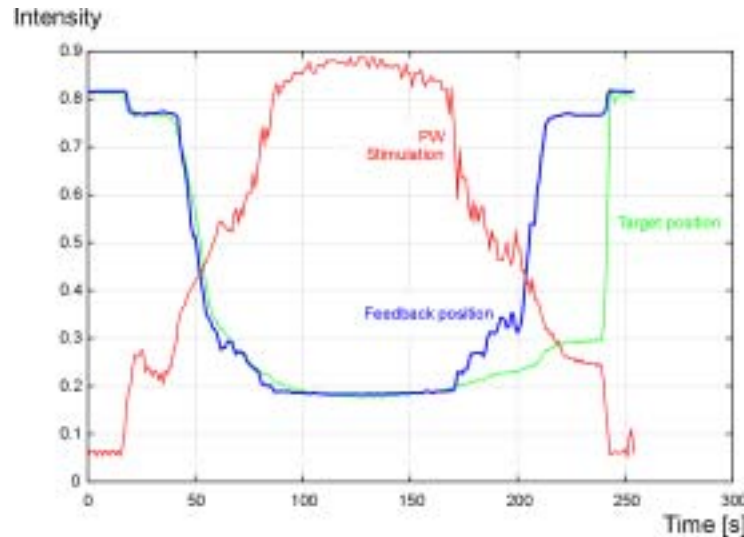
6   Results

After a training time of less than 10 min the training of the FlexNet was completed performing less than 1200 training epoches. The resulting FlexNet had 16 hidden neurons and showed a training error of less than 5 perecent absolute averaged error. The evolution of the training error is shown in figure 6. The net structure was 2-2-2-2-2-8-1 with a total number of 155 weights.

Fig. 6. Evolution of training error for FlexNet.

Based on the data described above and the trained FlexNet, a simulated closed loop control experiment was performed. A look-up table (LUT) filled with values from the first half of trial 20_7 in figure 4 was used instead of a real animal. In order to simulate the time delay for the reaction of the animal, the LUT was implemented on a second computer. Thus the communication time between the computers represents the reaction time between the stimuli and the movement of the pig's limb.

Fig. 7. Result for a closed loop simulation. In the first half of the curve, the obtained angle values follows very good the target values, whereas in the second half the error grows. This was due to the used look up table simulating the feedback position of the pig's limb.

The simulation of the closed loop control resulted in good control performance as visualized in figure 7. In the first half of the curves, the resulting feedback position follows very good the target postion. In the second half, the result isn't as good as in the first half. This is due to the fact, that the LUT incorporated only information from the first half of trial 20_7. Thus, the behaviour of the limb for the movement into one direction corresponding to a certain stimuli doesn't fit with its behaviour for the opposite direction and the same stimuli. This must be taken into account in further experiments. Similiar results were obtained for both remaining trails randomly designated as validation trials.

Taking into account, that the data set reflects a quite unstable biological system in terms of identical response for the same stimuli (refer figure 4), the control performs very good as shown in figure 7. It's worth to note, that the ANN always try to use the lowest PW possible to obtain the desired target value which will be advantageous regarding fatigue effects.

7   Conclusion

In this paper we've described a system for restoration of lost hand function of quadriplegic patients. We focused on the artificial neural net based controller for closed loop control. The whole system was tested using a data set obtained by functional neuroelectric stimulation controling the angle of a pig's limb. After training, the obtained FlexNet perform an averaged absolute error of less than 5 percent. Using FlexNet as ANN for the controller, simulation of the closed loop control scheme basing on the data set of a pig's limb showed good performace.

To conlcude, basing on these results, experiments for *in vivo* closed loop control using the pig model will be done. Reflecting the results obtained by the simulation encourage the use of FlexNet for this purpose.

Acknowledgement

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