Proceedings of the 2005 IEEE
Engineering in Medicine and Biology 27th Annual Conference
Shanghai, China, September 1-4, 2005

Life-like Control for Neural Prostheses: "Proximal Controls Distal"

Dejan B. Popović, *Member IEEE*, Mirjana B. Popović, and Thomas Sinkjær, *Senior Member IEEE*

Abstract—**We describe the model and implementation of the hierarchical hybrid method for controlling of the lower-arm (pronation/supination and elbow flexion/extension) in humans with disabilities. The control follows the strategy found in able-bodied humans where the movement is planned based on the task and the most distal part of the arm; yet, the command starts from the most proximal segment. The controller uses a black box of the movement and relies on temporal and spatial synergies. The driving signals are the shoulder flexion/extension velocity and acceleration, the outputs are four stimulation patterns for the control of elbow flexion/extension and pronation/supination. The operation is discrete at the voluntary and coordination levels, and continuous at the actuator level. The repertoire of movement that were considered was limited to a set of typical daily activities within the normal workspace in the sitting position only. The main application of this control is the therapeutic electrical stimulation in post-stroke hemiplegic patients.**

I. "PROXIMAL CONTROLS DISTAL" MODEL FOR NEURAL PROSTHESES

NICHOLAI Bernstein was the first who formally addressed the motor control system as a *black box* [1]. His main conclusions included the following: 1) control has a hierarchical structure, 2) feedback is used to tune the descending commands, 3) time delays are inevitable; hence, feedback must be combined with the predictive descending commands, and 4) human sensory-motor system is highly redundant, and the constraints are being developed through the learning of movement. Bernstein investigated input-output relations, and this lead to the important finding that the constraints that are implemented result with temporal and spatial synergies between the proximal and distal bodily segments. He also suggested that the motor execution is planned based on the most distal segment and the task; yet, the motor execution starts from the most proximal segment.

Here, we described the artificial control for a neural prosthesis (NP). The NP was anticipated as a therapeutic instrument that should augment movements in hemiplegic patients with innervated muscles responsible for the forearm and hand movements. The system operation was modeled as a set of mappings between inputs and outputs. The relations found suitable for input-output description are *If-Then* rules, where the *If* part describes the sensory and motor state of the system, while the *Then* part of a rule defines the corresponding motor activity that should be initiated [2,3]. The *If-Then* operation in biology is called a reflex; hence, the man-made control was termed Artificial Reflex Control. This modeling belongs to the class of hybrid control systems [4-6]. In essence, it decomposes the movement into time windows (discrete control), and defines synergies between the state space variables by the *If-Then* rules (continuous control).

Several reasons were the basis for adopting the hybrid modeling. The key reason was to reduce the complexity. This was accomplished by incorporating models of dynamic processes at different levels of abstraction. The other important features was that hybrid systems comprise hierarchical organization that helped managing of the complexity. The higher levels in the hierarchy require less detailed models (discrete abstractions) of the functioning of the lower levels, necessitating the interaction of discrete and continuous components.

Functional movements of the hand can be analyzed as a sequence of the following three processes: Reaching, Grasping, and Releasing (RGR). The *Proximal Drives Distal* model of the RGR hypothesizes that there is a high connectivity between individual joint movement and a hierarchical organization of control [7]. The decision, voluntary control level provides the specification where, how, and what a movement should accomplish. This decision is received by a rule-base controller. A rule-base controller operates as a finite automaton, and implements the state model of movement that is cloned by a heuristic of machine classification using data acquired in able-bodied humans. The spatial mapping was implemented by using the rule-based methods, and it is executed in time windows determined at the higher control level (temporal synchrony). The temporal synchrony and spatial synergies were demonstrated general for all users [7]. The generation of stimulation profiles followed heuristic methods.

II. TEMPORAL SYNCHRONIES AND SPATIAL SYNERGIES

We studied 20 young able-bodied subjects. The subjects were seated in front of a desk and performed RGR movements: drinking from a small bottle, drinking from a mug, handling a CD disk, writing with a pen, using the mobile telephone, eating finger food, and handling a juice box. The said tasks comprised palmar, lateral, and precision

---

Manuscript received May 2, 2005. This work was supported in part by the Danish National Research Foundation, Denmark, and the Ministry for Science and Environmental Protection of Serbia, Belgrade, SCG

D.B. Popović is with the Department of Health Science and Technology Aalborg University, Denmark and Faculty of Electrical Engineering, University of Belgrade, Serbia. (+45 96358726; fax: +45 98154008; e-mail: dbp@ smi.auc.dk).

M.B. Popović is with the Department of Health Science and Technology Aalborg University, Denmark and Center for Multidisciplinary Studies, University of Belgrade, Serbia.

T. Sinkjær is with the Department of Health Science and Technology Aalborg University, Denmark.

0-7803-8740-6/05/$20.00 ©2005 IEEE.

grasps of small, and medium objects of different weights. The objects were positioned at various locations within the working space defined with two attributes: distance and laterality. The subjects repeated at least 20 times each functional task using the dominant arm. The recordings were repeated in three independent sessions on different days. The order of tasks was randomly changed, and the subjects were asked to accomplish functions slow.

Flexible goniometers (Penny and Giles, Biometrics, U.K) were used to record shoulder flexion/extension, shoulder adduction/abduction, elbow flexion/extension, forearm pronation /supination, wrist radial/ulnar deviation, wrist palmar/volar flexion, and index finger flexion/extension at the metacarpal joint. The sampling rate was 100 samples per second. Joint angles were low passed filtered at 30 Hz with the 4th order Butherworth filters. The recorded data was first interpolated with the third order spline method, and then normalized for the duration (Fig. 1). This normalized data was used to estimated joint angular velocities and accelerations. The data was tabulated in a form suitable for application of radial basis function artificial neural network (RBF ANN). The data from 16 subjects was used to train the networks, and the data from the four subjects to validate the generalization of the results.

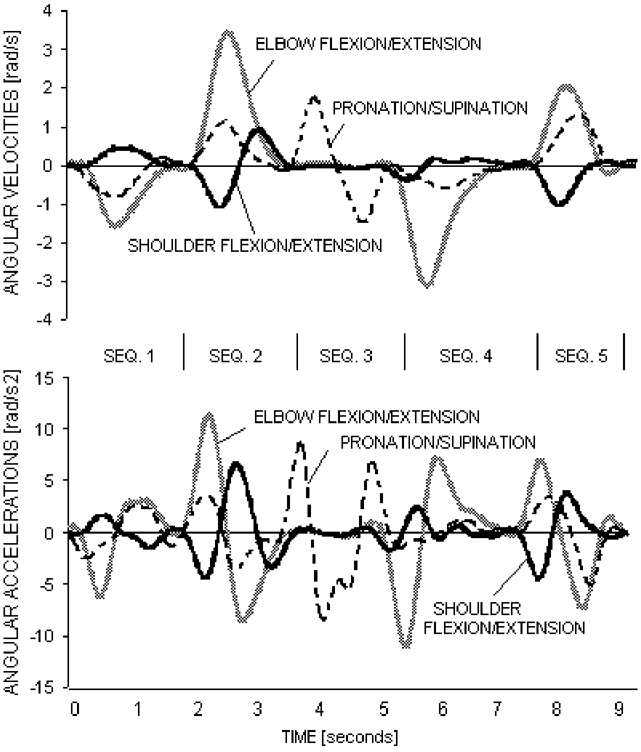

Fig. 1: A characteristic example of the velocity and acceleration profiles in the elbow joint (ELB FL/EXT), forearm (PRON/SUP), and shoulder joint (SHO FL/EXT). Five sequences are described in the text. The profiles were estimated from the normalized and averaged recordings in the able-bodied volunteers.

The temporal synchrony was determined by analyzing the *velocity space* (Fig. 1, top panel). The timing from the proximal joints was used as a cue. Automatic division into sequences was done by determining the instants when the absolute value of shoulder flexion/extension angular velocity was within the preset small value (threshold).

This analysis lead to the minimum of five sequences: Sequence 1- starting the movement and moving the hand to the object post including the grasp, Sequence 2 - moving the object from the object post to the point of use, Sequence 3 - using the object, Sequence 4 - returning the hand to the object post and releasing the object, and Sequence 5 - returning the hand to the initial position of the hand (Fig. 1). When the times were determined it became possible to divide the total data into five subsets, each corresponding to one of the sequences of the functional movement.

CORRELATION COEFFICIENTS					
BETWEEN THE TASKS EVALUATION					
TRAINING DATA (NO coupling)					
PAL→LAT	0.89	0.56	0.64	0.56	0.86
PAL→PRE	0.79	0.46	0.35	0.3	0.6
LAT→PRE	0.4	0.29	0.29	0.5	0.62
BETWEEN THE SUBJECTS (STANDARD) EVALUATION					
TRAINING DATA (STRONG coupling)					
SH→ELB	0.99	0.89	0.84	0.86	0.98
SH→PRON	0.94	0.94	0.99	0.94	0.92
VALIDATION DATA (STRONG coupling)					
SH→ELB	0.94	0.90	0.83	0.77	0.97
SH→PRON	0.91	0.94	0.99	0.99	0.91
BETWEEN THE DISTANCE EVALUATION					
TRAINING DATA (STRONG coupling)					
SH→ELB	0.95	0.97	0.98	0.95	0.97
SH→PRON	0.92	0.93	0.92	0.95	0.96
VALIDATION DATA (STRONG coupling)					
SH→ELB	0.93	0.90	0.89	0.92	0.91
SH→PRON	0.94	0.91	0.97	0.92	0.87
BETWEEN THE DIRECTION (LATERALITY) EVALUATION					
TRAINING DATA (NO coupling)					
SH→ELB	0.66	0.31	0.27	0.25	0.57
SH→PRON	0.38	0.35	0.40	0.33	0.49
	SEQ. 1	SEQ. 2	SEQ. 3	SEQ. 4	SEQ. 5

Table I: Summary data for the drinking from the mug session. The evaluation was done between the subjects (standard), between short and long distances, and between two directions (laterality). The correlation coefficients show the training and validation results for all five sequences. The acronyms are SH - shoulder flexion / extension, ELB – elbow flexion / extension, PRON – pronation / supination, PAL – palmar grasp, LAT - lateral grasp, and PRE – precision grip.

Artificial neural networks with radial basis function were applied to determine spatial synergies, that is mappings between the joint angles in the *acceleration space*. The goal was to find which among six joint angular accelerations were correlated. Specifically we were interested in the correlation between the shoulder flexion/extension angular acceleration, and the joint accelerations of more distal joints (elbow flexion/extension, forearm pronation/supination, wrist rotations, and fingers flexion/extension). The analysis

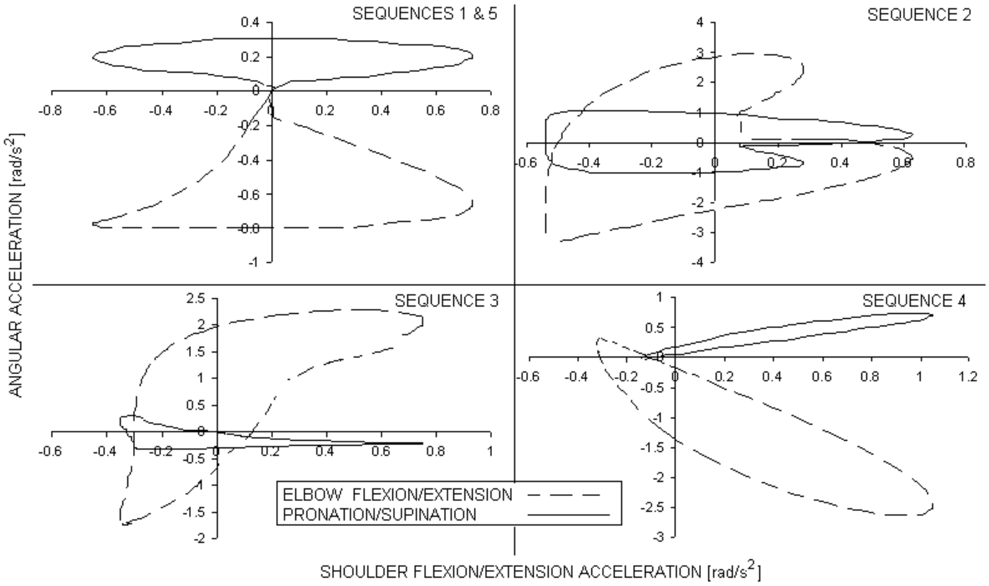

Fig. 2: The acceleration space mapping for the task "Drinking from the mug". The mappings were obtained from the data presented in Fig. 1. The sequences are defined in the text.

of correlation between the movements was performed for the data used for the training (16 subjects), and for the validation data (4 subjects). The set of typical mappings that show high correlation is in Fig. 2.

Table I shows the correlation coefficients for the said spatial synergies. The detailed description of the implementation of the RBF ANN is presented elsewhere [8].

The described mappings directly suggest that the shoulder flexion/extension can be used as the control input for the sensory driven control of forearm movement. This is to say that a sensor that records the shoulder flexion/extension joint angle provides sufficient information to be used within the rule-based control of the forearm for a set of typical daily activities within the limited workspace on the desk. The command interface must include the task and the laterality command.

III. STIMULATION PARADIGM

A self-contained controller for functional electrical stimulation systems was designed and integrated into the Belgrade FET system [9]. The development was motivated by the need to have a general purpose, easy to use controller capable of stimulating desired muscle groups, thus restoring complex motor functions. The designed controller can regulate the frequency, pulse duration, and charge balance on up to eight channels, and execute pre-programmed and sensory-driven control operations.

For pilot study in three hemiplegic patients we used heuristic methods. The subjects were more than 6-month post unilateral stroke affecting the dominant right arm, with moderate spasticity (Drawing test score = 1.8±0,3 [10], and the upper extremity Fugl-Meyer score = 32±3). We fixed the frequency at 50 pulses per second, and used a steep exponential rising edge of the stimulation pulses in order to minimize pain. We varied on-line the stimulation intensity by varying the pulse amplitude between 0 and 50 mA, and the pulse duration between 100 and 500 μs in a manner that was tolerable by patients; yet, resulted with functional movements. The generation of stimulation profiles used heuristics and the predicted joint state (angular acceleration). The zero acceleration was controlled by setting the co-contraction level of agonists and antagonists, while the movement was achieved either by reciprocal inhibition or agonist activation. An additional feature integrated in the control was the natural like triphasic (agonist-antagonist-agonist) pattern of activation.

The key element for providing functional fingers and forearm movement in presence of inevitable spreading of stimulation with surface electrodes is correct positioning of the electrodes. The stimulation paradigm used in this system relies greatly on the co-contraction that stabilizes the wrist joint, and prevents from undesirable wrist movements during the grasping and releasing of the objects. Two multi-field electrode arrays [11] were positioned over the following muscle groups: *Flexor Digitorum Profundus m.* and *Flexor Digitorum Superficialis m.*, and *Extensor Digitorum Communis m.* and *Extensor Indicis m.*, *Extensor Pollicis Longus m.* and electrodes over the *Extensor Pollicis Brevis m.*, and the Thenar muscle group (*Abductor Pollicis Longus m.* and *Opponens Pollicis m.*). the remaining two channels were applied over the *Biceps Brachii m.* and *Triceps Brachii m.*

The shoulder joint was instrumented with a joint angle sensor, and the microcomputer within the stimulator estimated the angular acceleration, and used rule-based control in an open-loop mode.

The patient controlled the operation by volitionally moving his upper arm alike slow movement. He started the operation by pressing the switch and selecting the task and laterality. He could use the switch to over ride the movement if he was anticipating that something is wrong.

The horizontal axis in Fig. 3 is time. No units are shown on the axis since the timing depends on the voluntary coordination abilities of a patient who uses the NP. The time for movement varied between 5 and 10 seconds, and it depended on the time needed to accomplish the activity desired. The stimulation intensities are shown relative to the stimulation resulting with the tetanic contraction (MAX).

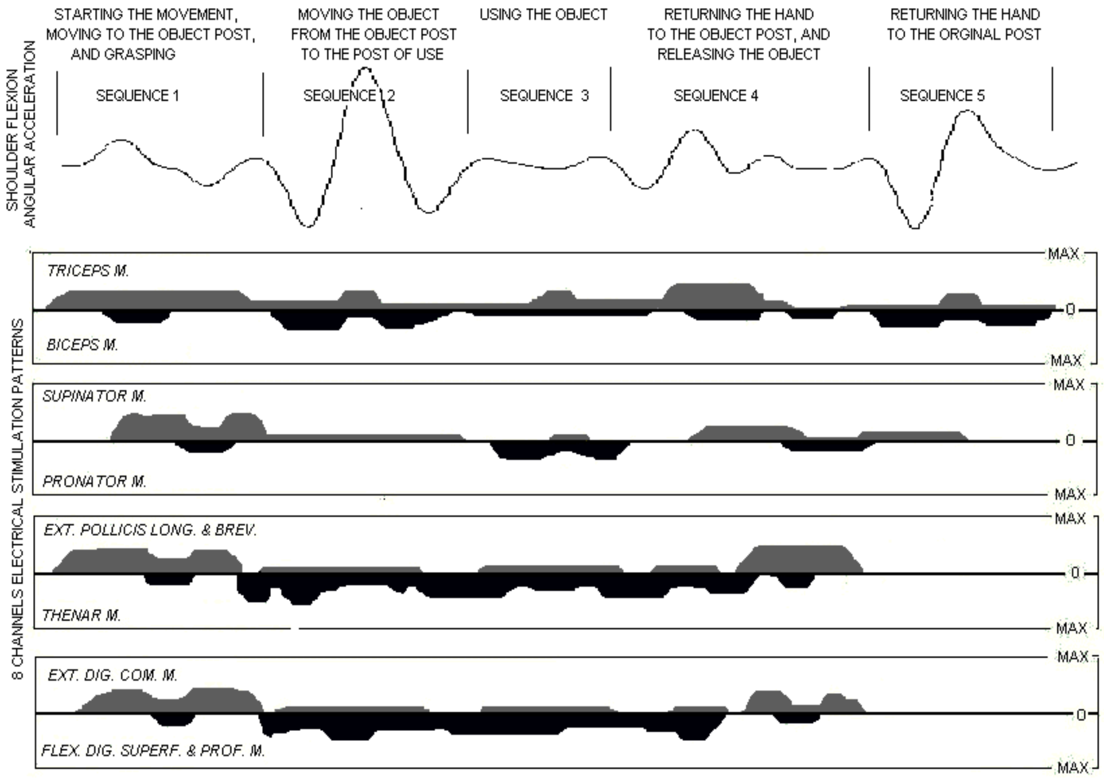

Fig. 3: The diagram of stimulation patterns. The agonist and antagonists are shown in opposing directions to indicate their opposite effect on movement. The user volitionally control the upper arm (top trace). The rule based control "reads" the acceleration information from the shoulder and generate stimulation.

IV. CONCLUSION

This paper presents a method that implements the "proximal segment drives distal segments" control for a NP that is suitable for the therapeutic treatment of humans with paretic upper extremities. The hypothesis that was used for the design of the control was that the functional movements typical for daily activities are activated with the adjustments of the trunk posture, and shoulder movement. The analysis of the correlation indicated that this hypothesis is valid with the following conditions: the task and laterality have to be specified (no or low correlation), and the distance has to be within the limited workspace (25 to 80 percent of the length of the extended arm). The task specification includes the following features: lateral, palmar, and precision grasps.

The application of this therapeutic NP is primarily foreseen in post-stroke hemiplegic patients. This application assumes that the users have minimal voluntary drive of the distal muscles. The experience from earlier studies in therapeutic stimulation indicates that the NP promoted the recovery better if it was applied in patients before they have developed compensatory mechanisms of control and before they reached the stable phase of hemiplegia [12].

REFERENCES

[1] N. A. Bernstein, *The Coordination and Regulation of Movements*. Pergamon Press, London (original work in 1926-1935), 1967.

[2] R. Tomović, D. B. Popović, R. B. Stein, *Nonanalytical Methods for Motor Control*. Singapore, World Sci Pub, 1995.

[3] D. B. Popović, T. Sinkjær, *Control of Movement for the Physically Disabled*, Springer, London, 2000.

[4] P. J. Antsaklis, A. Nerode, Hybrid control systems: An introductory discussion to the special issue *IEEE Autom Control* AU-43:457-459, 1998.

[5] P. U. Lima, G. N. Saridis, Intelligent controllers as hierarchical stochastic automata *IEEE Trans Syst Man Cybern* SMC(B)-29(2):151-63, 1999.

[6] M. S. Branicki, Multiple Liapunov Functions and other analysis tool for switched and hybrid systems, *IEEE Trans Autom Control* AU-43:475-482, 1999.

[7] M. B. Popović, Control of Neural Prostheses for Grasping and Reaching; *Med Eng Phys* 25(1):41–50, 2003.

[8] S. D. Iftime, L. L. Egsgaard, M. B. Popović, Automatic Determination of Synergies by Radial Basis Function Artificial Neural Networks for the Control of a Neural Prosthesis, *IEEE Trans Neur Sys Eng Rehab*, 2005. (accepted)

[9] N. Jorgovanović , S. Došen, R. Petrović, G. Bijelić, Novel Electronic Stimulator for Electrotherapy, *Proc. 49th Conf. of ETRAN*, June 5-9, Budva, Montenegro, 2005. (in press)

[10] Eder C, Popović MB, Popović DB, Stefanović A, Schwirtlich L, Jović S. The Drawing Test: Assessment of coordination abilities and correlation with the clinical measure of spasticity. *Arch Phys Med Rehabil*, 86:289-295, 2005

[11] Popović-Bijelić A., Bijelić G, Jorgovanović N, Bojanić D, Popović DB, Popović MB. Multi-Field Surface Electrode For Selective Electrical Stimulation, *Artif Organs*, 29(6):448-452, 2005

[12] Popović DB, Popović MB, Sinkjær T, Stefanović A, Schwirtlich L. Therapy of Paretic Arm in Hemiplegic Subjects Augmented with a Neural Prosthesis: A Cross-over study, *Can J Physio Pharmacol*, 82(8/9):749-756, 2004.