THE APPLICATION OF THE EVOLUTION STRATEGY (EVS) AS A CONTROLLER USED IN FES

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ABSTRACT

The evaluation of the control dynamics of the paralysed limbs in FES is not satisfiying till now. The electrode - nerve - muscle - skeletal system performes strongly nonlinear in space and time. Therefore one way to control the limbs might be by statistical search strategies. The EVS was tested in its capabilities as controller with the strategy being structured according to preknowledge of the system. The control qualities were compared with the ones of simple and of adaptive deterministic controllers in simulations and reality.

INTRODUCTION

The Functional Electrical Stimulation (FES) renders restoration of muscle function in spinal cord injuries. A lot of muscles are responsable for a smooth and precise movement of the limbs. To achieve this, it is necessary to stimulate separately all muscles. Thus on the one hand a accurate motion is achieved on the other hand sufficient controllability is granted, only limited by physiological boundaries. The limb consists of quiet a number of elements, which are separately controlled and in a complex manner mechanical coupled. The mathematical model of the complete muscle-skeletal-system may be derived only at great expense, because of its nonlinearities and many degrees of freedom. For the analysis of the dynamic characteristics of the limbs the Black-Box-Method (based on the input-output relation) is not useful because of the numerous connections between inputs and outputs.

It is difficult to control a single muscle via surface electrodes induvidially. In most cases several muscles or parts of them are stimulated simultaneously. In controller synthesis all muscles, which are influenced by one controller, have to be lumped together in one plant. Therefore it becomes more and more complex to describe these coupled elements of the system be controlled. One controller serves all muscles (or parts of them) in a stimulated group at the same time with the same stimulation parameters. However the stimulation - contraction characteristic of each of them is differently disturbed by stochastic processes. In case of incorrect location of the surface electrodes controllability is no more secured.

To avoid all these problems in formulating the plant mathematically an optimization algo-rithm is used as a controller without prerequiring any knowledge of the plant.

EVOLUTION-STRATEGY (EVS)

The EVS is appropriate to solve nonlinear, time variant, stochasticly disturbed, multimodal and multiparametric optimization problems. In equivalence to biological evo-lution, this strategy utilizes two principles: Mutation and selection. This strategy aims to find an optimal solution for a problem by taking success and failure into account. To gain an optimal solution a quality factor of a control criterion is minimized. The n input para-meters, which are influencing the system, are altered by chance in order to minimize the quality factor. The EVS is a stochastic strategy. In comparison with the Experimental Gradient Strategy it has an increasing speed of convergence by parameter dimension n3 [1]. The search direction depends not on the actual gradient at the local point, it is deter-mined by Gaussian distribution. Therefore the search procedure will not so often end in a minor minimum. The step length of the search is selected from an ensemble with Gaussian Distribution. The starting point in the multi-dimensional parameter space can be chosen at will.

The search for the minimum of the quality factor in space is executed in three steps:

Mutation : Assuming that Q_E is the actual quality factor of the parameter vector to the parent $\underline{i}_E^{(g)}$, within the interval of time g, a stochastic vector $\underline{z}^{(g)}$ is added to produce a descendant

$$\underline{i}_N^{(g)} = \underline{i}_E^{(g)} + \underline{z}^{(g)}. \qquad (1)$$

The components of the stochastic vector $\underline{z}^{(g)}$ are Gaussian distributed, of which with the mid value $m=0$ and the standard deviation $= \sigma_g$.

Testing : The new parameter vector $\underline{i}_N^{(g)}$ is inputed to the system to create the new quality factor Q_N.

Selection : The parent quality factor Q_E and the descendant one Q_N are compared one with another and the vector with the worse factor is eleminated:

for $Q_N > Q_E$ $\underline{i}_N^{(g)}$ will be eliminated and $\underline{i}_E^{(g+1)} = \underline{i}_E^{(g)}$ (2)

for $Q_N \leq Q_E$ $\underline{i}_E^{(g)}$ will be eliminated and $\underline{i}_E^{(g+1)} = \underline{i}_N^{(g)}$ (3)

This algorithm is simple and well to adapt on computation. The selection of the quantity of the standard deviation is deceisive for the convergence of this algorithm. When choosing a small standart deviation the EVS converges very slowly, with a large one the EVS performes like the Monte-Carlo-Method: Each point of the parameter space might then be selected with equal chance . The target point of the search will be reached not precisly or only after a long time. The speed of convergence might be increased by the adaption of stepwith in dependance to topology of the quality factor. In [1], [2] and [3] it was shown, that a variable stepwith depending on the likelihood of success shortens the search for the minimum. It was found that with some assumptions the standard deviation have to be increased (factor 1/0.85) or be reduced (factor 0.85) according to the li-kelihood of the success (w_e).

$$\sigma_{g+1} = \begin{cases} \sigma_g * 0.85, & \text{if } w_e \leq 0.2 \\ \sigma_g / 0.85, & \text{if } w_e > 0.2 \end{cases} \tag{4}$$

(5)

EVOLUTION STRATEGY AS A CLOSED-LOOP CONTROLLER

The EVS was tested as an on-line controller in FES. It is no need to formulate the plant mathematicaly. Instead of a control algorithm, which has to be calculated according to the existing knowledge of the plant, a search strategy minimizes the error signal according to formula (1) - (3).

The vector s contains the control quantities i.e. the angles of the limbs to be reached.The state vector i consists of the actual values of the angles. The error signal vector is used to determine the quality factor, which is a global scalar measure of the error signal. The con-trol criterion is the sum of the differences of the control quantities and controlled variables:

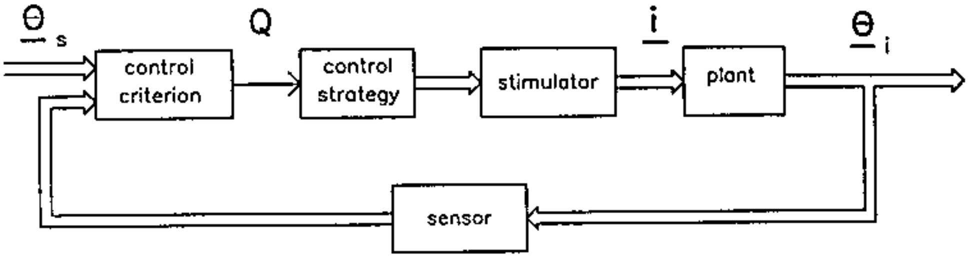

Figure 1: Control loop with EVS as controller

$$Q = \sum_{k=1}^{n} |\Theta_{sk} - \Theta_{ik}| \tag{6}$$

It has to be mentioned that the elements of the state vector are only angle values and no differentiated ones. To execute dynamic control the derivatives of the angles have to be measured too.

If one angle is influenced directly by one stimulation channel (with variable amplitude and constant pulswidth and frequency), the dimension n of the state vectors is equal to the quantity of the stimulation parameters. Therefore the search space has dimension n and the coordinates are the variable stimulation parameters. The size of *space is bounded by the technical properties of the stimulation equipment (amplitude* is from 0 to 100mA). During the search the variation of the stimulation parameters are not allowed to exceed there maximum values.

In general the search strategy can be formulated as following:

Search a control pulse vector $\underline{i}$, which minimizes the quality factor

$Q = F(\underline{\Theta}_s, \underline{\Theta}_i)$.

EXPERIMENTAL EVALUATION OF THE EVS

In [3] the EVS was tested as a control strategy in simulations and experiments. The angles of the ellbow and the and the shoulder joint have been the controlled variables and have been measured continiously. The muscles in the range of the shoulder and the upper arm have been stimulated with surface electrodes.

The time constants of the system have been rather large, therefore they limite the rate of mutation. In addition the muscles reacted only with a delay time to the stimulation. There-fore the stimulation parameters could be mutated only twice per second. Frequency and pulswidth have been kept constant, the amplitude was varied in 256 steps between 0mA and 100mA.

The influence of step width modulation on the number of mutations during the search of minimum was investigated at different conditions:

- *The search of the minimum with constant step width and start of the search near the target position: about 30 mutations.*
- *The search of the minimum with constant step width and start of the search distant from the target position: more than 100 mutations.*
- *The search of the minimum with variable stepwidth (controlled by the likelihood of success) and start of the search distant from the target position: about 40 mutations.*

The results show, that the convergence of this search algorithm is granted. Arbitrary motions do not influence the convergence, only the number of search steps increases in 50 mutations.

Selecting the best conditions by starting the search close to the target position and choosing variable stepwidth the setting of the control takes at least 15 seconds. That is obvious, because this controller has no knowledge of the plant.

MODIFICATIONS TO SPEED UP THE CONVERGENCE RATE

To accelerate the control setting the search of minimum should start close to the target position. This will be better achieved if some preknowledge of the plant is incorporated into the parameter configuration the search is starting at.

The value of quality is determined as distance between the vectors of control quantities and controlled variables:

$$Q = \left[\sum_{k=1}^{n} (\Theta_{sk} - \Theta_{ik})^2 \right]^{1/2} = \sum_{k=1}^{n} Q_k \tag{7}$$

The following assumptions grant convergence of the modified EVS:

- *The functional relation between a controlled value and its stimulation parameter is monotone independent of couplings and influences by the other stimulation paramters.*
- *At each stimulation channel only one parameter (amplitude) is variable; but the controllability must be guaranted.*

Therefore the direction of mutation and search in space is determined. The search di-rection of the next stimulation paramter has the same sign as the error signal. By this the space of search is reduced to $1/2^n$ nd part of the original one. The stochastic vector, which will be added to the parent vector, is modelled by

$$\underline{z}^{(g)} = \left[\frac{x_{d1}}{|x_{d1}|} z_2 , \frac{x_{d2}}{|x_{d2}|} z_n , \ldots , \frac{x_{dn}}{|x_{dn}|} z_n , \right] \tag{8}$$

with

$$z_j = |z_j'| \, Q_j / K_j \tag{9}$$

where z_j' is a stochastic value determined by the Gaussian Distribution with the mid value m=0, the standard deviation $\sigma=1$ and a value of quality Q_j. The K_j is a constant chosen at will, which includes an estimation of the relation between the stimulation parameter and its controlled value. Therefore the adaption of stepwidth [1] is not needed.

The advanteges of these modifications are:

- *The search algorithm doesn't stop in minor minimums*
- *The control setting is accelerated*
- *There is less oscillation during the stimulation response*

THE SIMULATION RESULTS

The simulation uses a dynamic model of 4th order [4]. It describes a pair of muscles (agonist, antagonist) with one degree of freedom. This model is extended by nonlinear and time variant components. To determine the parameters of the system, stimulation responses of a knee angle are identified. The knee angle of a sitting person may only be in-fluenced by the stimulation of the quadriceps muscle and by the gravity. The model was derived by applying steps like stimulation patterns of varying amplitude to the limb.

The following controllers have been tested:

- *EVS-controller based on the original optimization algorithm,*
- *EVS-controller based on the modifications,*
  both starting the search for minimum with actual stimulation parameters and with a constant factor K_j (equation (9)), therefore an estimation of the magnitude of the stimulation and the step response is not considered,
- *adaptive Deat-Beat-controller,*
- *adaptive PID-controller,*
  both with predetermined values of the first control variable.

During the use of the Deat-Beat- or PID controller the model is continiously adapted to a controlled system of 2nd order. The sampling frequency is 6.67Hz (period=150msec). Using the EVS strategies the mutation rate is 2.0Hz (period = 500msec), because the step response will be quasi steady-state within 500 msec at most.

The criterions for judging these controllers are the control setting and the control of disturbances.

The modified EVS control algorithm has steadied out 4 times faster than the original one. The overshoot of the modified one is essentially smaller too, because the step width is dependent upon the error signal. The stochastic disturbances are controlled equally well by both. Therefore only the EVS with the modified search algorithm is compared in the following diagramm with a PID- and Deat-Beat-controller.

Input	Controller	J_x	δ_m	t_r	t_s
Small	DB	0.6	4.9	1.35	1.35
Step	PID	0.8	2.6	2.25	2.25
$\delta\Upsilon = 20^{\circ}$	EVS_{mod}	1.6	0.5	4.05	4.05
High	DB	48	18	2.70	6.30
Step	PID	73	12	3.60	9.00
$\delta\Upsilon = 50^{\circ}$	EVS_{mod}	155	3	8.55	8.55

$\delta\Upsilon$ is the magnitude of the step (unit=degree) applied on the system. t_r is the rise time (unit=second), that is the time required for the response to rise to 95 % of its final value. t_s is the settling time (unit=second), that is the time required for the response curve to reach and to stay within a range of 5% of the final value.

$\delta_m = [(\Theta_{imax} - \Theta_{iend})*100/\Theta_{iend}]$ is the maximum overshoot and

$J_x = \sum_j (\Theta_{sj} - \Theta_{ij})^2$ is the square control area (unit degree^2).

Compared with the Deat-Beat- and the PID-controller the EVS-controller needs more time to steady out. The EVS controller has no essential overshoot like the other ones, because of the adaption of the step width to the error signal. If the parameters of the PID-controller are adjusted in such a way, that overshoots hardly happen, its control properties are comparable with the one of the EVS-controller.

EXPERIMENTAL RESULTS

Executing the experiment the leg of a non handicapped person is mounted on a device, which is able to measure the angle at the knee. The controlled variable is the angle of the knee. It is controlled by the stimulation of the quadriceps muscle (Stimulation parameters: frequency: 20Hz, pulswidth: 300µs, amplitude: 0..100mA) and by the gravity.

The PID-, the Deat-Beat- and the modified EVS-controller are tested. In comparison these controllers possess the same quality of the control as in the simulations.

The results are shown in Figure 2 to Figure 4 :

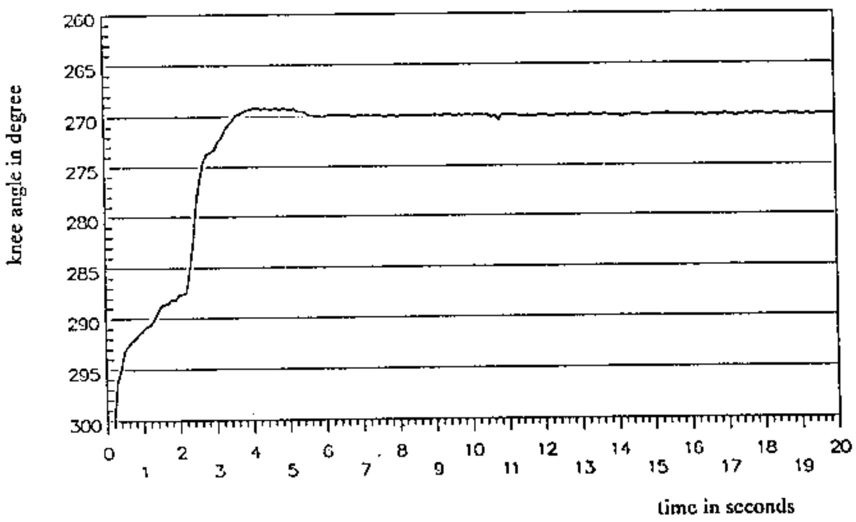

Figure 2: Deat-Beat-controller (final value = 270°)

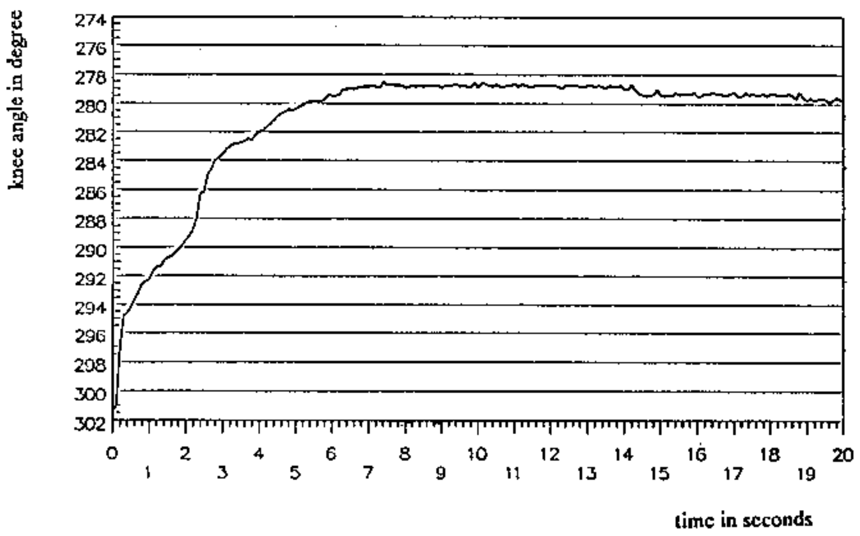

Figure 3: PID-controller (final value = 280°)

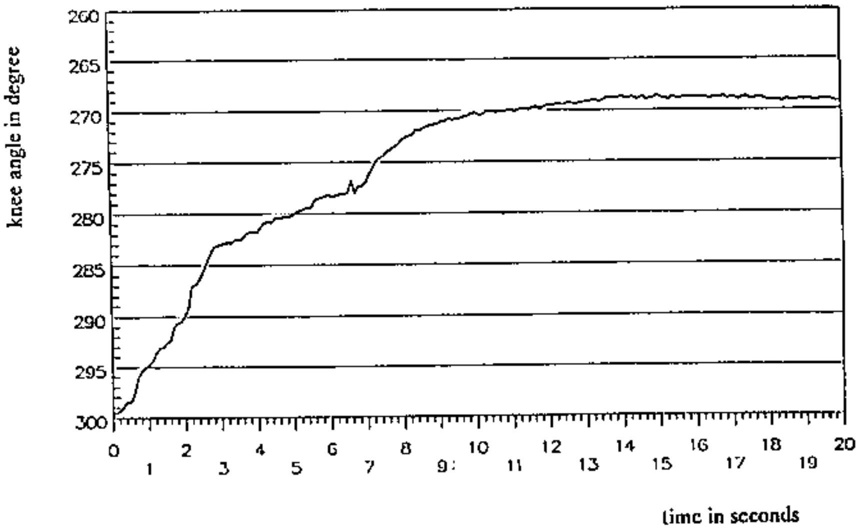

Figure 4: EVS-controller (final value = 270°)

CONCLUSIONS

The EVS is capable to be used as an on-line controller. Primarily this control strategy is slower than the deterministic ones. In case of controlling one variable the EVS takes twice the time to reach the steady state. Modifications of the EVS accelerate the speed of convergence. The renunciation of a mathematical formulation of the plant is of advantage, because the problem of decoupling the variables is circumvented. Therefore the advantage of the application of the EVS increases with the dimensionality of control problems and will be more and more superior in its control dynamics to deterministic controllers.

REFERENCES

1 Rechenberg, I.: Evolutionsstrategie. Frommann-Holzboog, 1973

2 Schwefel, H.-P.: Numerische Optimierung von Computer-Modellen mittels der Evolutionsstrategie. Birkhäuser Verlag, 1977.

3 Nürnberg, H.G.: Steuerungs- und Regelungskonzepte für die funktionelle Stimulation gelähmter Muskulatur. Dissertation, Institut für Biokybernetik und Biomedizinische Technik, Universität Karlsruhe, 1985.

4 Nürnberg, H.G.; Vossius, G.: The Applicability of the Evolution Strategy to the Control of Paralyzed Limbs through FES. IFAC 10th World Congress on Automatic Control 5 (1987), p.37-43.

5 Nguyen T.V.: Ein Regelkonzept zur Erzeugung kontrollierter Bewegungen von gelähmten Gliedmaßen mit Hilfe elektrischer Stimulation. Dissertation, Institut für Biokybernetik und Biomedizinische Technik, Universität Karlsruhe, 1982.

6 Helgason, Th.; Lukas, P.; Vossius, G. : Anwendung der Evolutionsstrategie als Regelalgorithmus bei der FES. Biomedizinische Technik, Band 34, 1989.

7 Peters, T.; Koralewski, H.E.; Zerbst, E.: The Evolution Strategy - A Search Strategy Used in Individual Optimization of Electrical Parameters for Therapeutic Carotid Sinus Nerve Stimulation. IEEE, Vol.36, No.7 (668-675), 1989

5 Nguyen T.V.: Ein Regelkonzept zur Erzeugung kontrollierter Bewegungen von gelähmten Gliedmaßen mit Hilfe elektrischer Stimulation. Dissertation, Institut für Biokybernetik und Biomedizinische Technik, Universität Karlsruhe, 1982.

6 Helgason, Th.; Lukas, P.; Vossius, G. : Anwendung der Evolutionsstrategie als Regelalgorithmus bei der FES. Biomedizinische Technik, Band 34, 1989.

7 Peters, T.; Koralewski, H.E.; Zerbst, E.: The Evolution Strategy - A Search Strategy Used in Individual Optimization of Electrical Parameters for Therapeutic Carotid Sinus Nerve Stimulation. IEEE, Vol.36, No.7 (668-675), 1989