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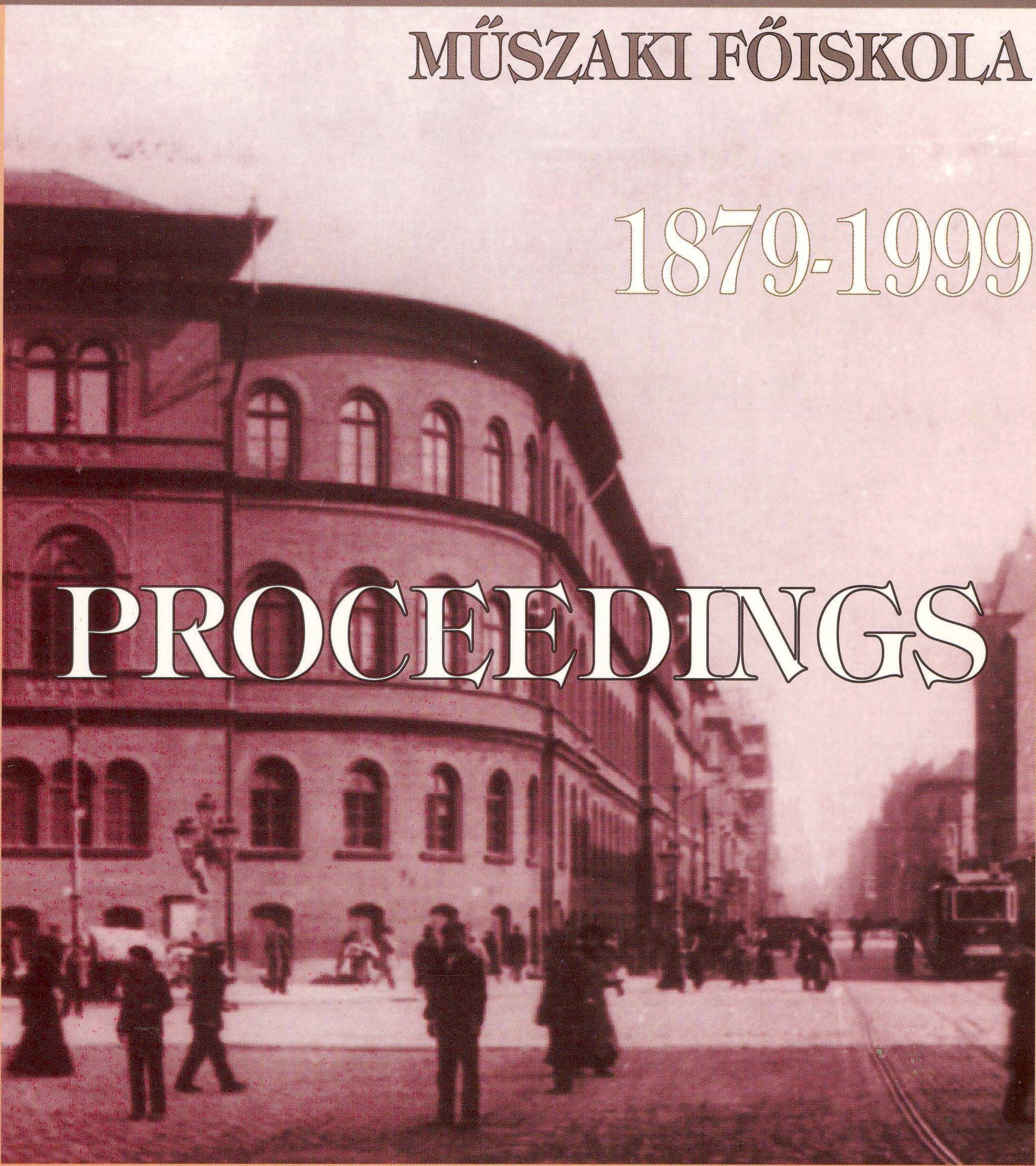

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Selection of Appropriate Uniform Structures for an Adaptive Control of Robot Under Environmental Interaction

József K. Tar
Bánki Donát Polytechnic
Dept. of Information Technology
H-1081 Budapest, Népszínház utca 8.Hungary
E-mail: jktar@zeus.banki.hu

László Horváth
Bánki Donát Polytechnic
Department of Manufacturing Engineering
H-1081 Budapest, Népszínház utca 8.Hungary
E-mail: jbito@zeus.banki.hu

Imre J. Rudas
Bánki Donát Polytechnic
Dept. of Information Technology
H-1081 Budapest, Népszínház utca 8.Hungary
E-mail: rudas@zeus.banki.hu

J.A. Tenreiro Machado
Instituto Superior de Engenharia do Porto
Dep. de Eng. Electrotécnica
Portugal
E-mail: jtm@dee.isep.ipp.pt

Abstract — A special approach for the adaptive control of approximately and partially known mechanical systems under unmodeled external dynamic interaction was recently invented and investigated from several aspects. As a combination of the application of uniform structures and co-operating ancillary procedures it overcomes the limitations of classical feedforward neural network-based approaches. Besides being found to be efficient, the method may have room for further improvement due to choosing the best one of the possible simple uniform structures as well as of the way of co-operation between the different ancillary tools. These new aspects are taken into account in the present investigations also including global parameter optimization in an external loop. The results are presented as simulations made for a 2 DOF rotary arm for the simplicity. As a conclusion indication is gained for a newer possibility of global optimization.

I. INTRODUCTION

Strong non-linear dynamic interaction between the robot and its environment in technological processes means a hard problem in robot control not completely solved even in our days. Insufficient and inaccurate knowledge about the dynamic properties of the robot arm itself make this problem even more complicated. The need for developing universally useful robot-controllers makes it undesirable to build in the controller some particular model of the robot, its environment, and that of the interaction between them.

It was found to be possible to achieve this goal via combining a special trade-off between the classic Hard Computing and Soft Computing, and some ancillary tools based on a special version of PID/ST, simple fuzzy sets and membership functions, regression-analysis, and non-linear filtering techniques and learning methods. Some details of the method were recently published in [1].

The above method has several variations depending on the particular uniform structures applied as well as on the possible ways of the co-operation between the ancillary methods also used. Alternative uniform structures --with respect to that in [1]-- already were investigated in [2], too. Possible application for technological operation also was found to be attractive [3].

For learning a great variety of methods ranging from several variants of the *steepest descent method* [4], application of activation functions of tunable shape [5], combination of standard backpropagation with Genetic Algorithms [6], and semi-stochastic Complex Algorithm [7] can be cited as examples. In general it can be stated, that if the necessary "size" of the uniform structure, and as a consequence, the number of the parameters to be tuned, is too big, fast and efficient learning algorithm for real-time control can scarcely be constructed. From this point of view any reduction in the size of the problem as well as in the possible range of the unknown parameters is a significant advantage.

From the point of view of *parameter tuning* the recently introduced method combines different methods as follows:

- *"classic hard computing"* in the calculations based on the ancillary part based on a simplification of regression analysis;
- *"rigid linguistic rules"* expressed in the terms of *fuzzy sets* for the tuning of those parameters in the case of which *a priori knowledge* is available; however, in contrast to the *classic fuzzy controllers* applying fuzzification, fuzzy relations and defuzzification for gaining their crisp output, in our case the membership functions of possible values in the interval [0,1] are considered as *"normalized measures"* indicating whether *to what extent the considered terms can be taken into account* in the control; this means a considerable simplification, too;
- a special version of the *"Adaptive Simplex Algorithm"* is used for tuning those non-linearly coupled control parameters for the adjustment of which no simple *a priori* rules are available:.

Regarding the position of the parameters tuned by the Simplex Algorithm within the control in the present approach there are

a) *"internal loop parameters"* requiring fast tuning within an *internal control loop;* practically these parameters are related to *rotation angles* and *exponential shrinking/dilatation factors* in the Lie groups representing the *uniform structures* applied in the control;

b) *"external loop parameters"* requiring slow tuning; these parameters are applied in the ancillary methods and normally are used as *reference values* --built in certain *fuzzy membership functions*-- in the *"assessment"* of several properties of the control; the appropriate value of these parameters can be set roughly *"experimentally"* for obtaining an acceptable control; however, slow real-time tuning can help in finding their *optimum* value; since these numerical values also determine how the control task is *"distributed"* between the simultaneously applied co-operating methods, the optimum setting can change in time, therefore it is expedient to keep them adjusted in real-time;

c) *"immediately calculated parameters"* determined simply by multiplying the content of a memory buffer by a constant and adding the new value to it; this method is used among others for determining the *integrating factor* in the self-tuned PID part and a parameter determining *"how fast"* trajectory reproduction is required in the given phase of the control;

It can be expected that if the number of the free parameters is large enough the problem of environmental interactions and imprecise system model can be coped with simultaneously.

The small and fast changes in the directly tuned parameters can be reckoned as a fast, dynamic, "*incomplete or partial system identification*" with time-varying "identified" parameters.

II. DETAILS OF THE METHOD APPLIED

The uniform structure HERE applied originate from the Euler-Lagrange equation of motion considered at the following level of abstraction:

$$\sum_j M_{ij}(\mathbf{q})\ddot{q}_j + \sum_{js}\frac{\partial M_{ij}}{\partial q_s}\dot{q}_s\dot{q}_j - \sum_{sj}\frac{\partial M_{sj}}{\partial q_i}\dot{q}_s\dot{q}_j + \frac{\partial V(\mathbf{q})}{\partial q_i} = Q_i \tag{1}$$

in which "**M**" is the symmetric positive definite inertia matrix approximated as the sum of only partly coupled positive semi-definite symmetric matrices as

$$\mathbf{M} = \sum_{i<j} 5\exp(\xi_{ij})\begin{bmatrix} 1+\sin^2\varphi_{ij} & -0.5\sin 2\varphi_{ij} \\ -0.5\sin 2\varphi_{ij} & 1+\cos^2\varphi_{ij}\end{bmatrix} + \\ +diag\langle \exp(\mu_{11}) \quad . \quad . \quad . \quad \exp(\mu_{nn})\rangle \tag{2}$$

(In the sum the only non-zero terms are in the $(i,i)^{th}$, $(j,j)^{th}$, $(i,j)^{th}$ and $(j,i)^{th}$ matrix elements of the nxn sized matrices, respectively.) The individual terms correspond to the rotation of the positive semi-definite diagonal matrices "mixing" only the components in the i^{th} and the j^{th} direction with angle φ_{ij}:

$$\mathbf{O}(\varphi_{ij})\begin{bmatrix} 1_{(ij)} & 0 \\ 0 & 2_{(ij)}\end{bmatrix}\mathbf{O}^T(\varphi_{ij}) \tag{3}$$

The rotated matrix "evenly" stretched/shrank by the common factor $5\times\exp(\xi_{ij})$. This structure always remains sensitive with respect to the rotation (the rotated diagonal matrix always considerably differs from the unit matrix, which would be "insensitive"). The sum is "extended" over the different possible sub-spaces by taking into account the possible i<j variations, therefore each non-diagonal term in **M** can be modeled without introducing too much coupling between the rotations and shrinks. By using the additive matrix of diagonal terms it becomes possible to increase the main-diagonals without influencing the already set off-diagonals. Though this approximation has more variables $[2(n^2-n)/2+n]$ than the "orthodox" one based on the singular value decomposition as

$$\mathbf{O}(\{\varphi_{ij} | i<j\})diag\langle\exp(\xi_{11})...\exp(\xi_{nn})\rangle\mathbf{O}^T(\{\varphi_{ij} | i<j\}) \tag{4}$$

having only $[(n^2-n)/2+n]$ independent parameters, its "behavior" is far more "decent" than that of (4):

- In the "orthodox" structure the internal diagonal matrix may be proportional with the unit matrix leading to insensibility with respect to all of the rotational parameters which in this case may "meander" arbitrarily during tuning.
- Occurrence of even a slight difference from the "proportional to unit matrix" may result in quickly increasing sensitivity with respect to the rotations.
- In the "orthodox" structure the orthogonal matrices can be constructed as the product of orthogonal ones. This leads to the need of making considerable number of matrix products when calculating the proper terms in (1). In contrast to that
- The novel structure always remains "evenly" sensitive to rotations.
- By considering the matrix parameters as the functions of the robot's generalized coordinates as $\xi_{ij}(\mathbf{q})$, $\varphi_{ij}(\mathbf{q})$, $\mu_{ii}(\mathbf{q})$, for the terms in (1) as

$$\frac{\partial \mathbf{M}}{\partial q_i} = \sum_{s,i<j}\frac{\partial \mathbf{M}}{\partial \varphi_{ij}}\frac{\partial \varphi_{ij}}{\partial q_i} + \sum_{s,i<j}\frac{\partial \mathbf{M}}{\partial \xi_{ij}}\frac{\partial \xi_{ij}}{\partial q_i} + \sum_{s,i}\frac{\partial \mathbf{M}}{\partial \mu_{ii}}\frac{\mu_{ii}}{\partial q_i} \text{ and} \tag{5}$$

$$\dot{\mathbf{M}} = \sum_s \frac{\partial \mathbf{M}}{\partial q_s}\dot{q}_s \tag{6}$$

the calculation of only the simple matrix expressions as

$$\frac{\partial \mathbf{M}}{\partial \xi_{ij}} = \sum_{i<j} 5\exp(\xi_{ij})\begin{bmatrix} 1+\sin^2\varphi_{ij} & -0.5\sin 2\varphi_{ij} \\ -0.5\sin 2\varphi_{ij} & 1+\cos^2\varphi_{ij}\end{bmatrix} \tag{7}$$

$$\frac{\partial \mathbf{M}}{\partial \varphi_{ij}} = 5\exp(\xi_{ij})\begin{bmatrix} \sin 2\varphi_{ij} & -\cos 2\varphi_{ij} \\ -\cos 2\varphi_{ij} & -\sin 2\varphi_{ij}\end{bmatrix} \tag{8}$$

$$\frac{\partial \mathbf{M}}{\partial \mu_{ii}} = diag\langle 0...\exp(\mu_{ii})...0\rangle \tag{9}$$

(As in (2), the only non-zero terms in (7) and (8) are in the $(i,i)^{th}$, $(j,j)^{th}$, $(i,j)^{th}$ and $(j,i)^{th}$ matrix elements.) It is clear that in modeling (1) no matrix products must be calculated: only the linear combination of the partial derivatives in (7-9) is necessary, which means, that though in the new representation more parameters are used than in the orthodox one, the computational complexity of the model is far less in the case of the new representation.

In the control the directly tuned "internal loop" parameters were the $gf_{ikl} = \partial\varphi_{ik}/\partial q_l$, $gk_{ikl} = \partial\xi_{ik}/\partial q_l$ and $gm_{iil} = \partial\mu_{ii}/\partial q_l$ partial derivatives. The estimated inertia was integrated according to these ever varying coefficients. The initial ξ_{ij}, φ_{ij} and μ_{ii} values were equal to 0. This situation was improved step by step by tuning the internal loop parameters according to the Simplex Algorithm in which the optimum of the difference between the desired and the achieved joint accelerations was minimized. This tuning is a rough analogy of controlling a bowl rolling on the surface of a plane in a gravitational field: small variation in tilting the plane can keep the bowl on the appropriate trajectory);

To support this process the following ancillary tools were applied:

- a truncation in the angular velocities at a lower limit when calculating the inertia matrix from dM/dt to achieve good adaptivity for slow motion, too (detailed in [8]);
- a tuned PID term in which the integrating term was calculated as detailed in [8]; its main idea is that the *desired damping of the trajectory reproduction error* is determined on the basis of the equation

$$\ddot{\varepsilon} = -b'\varepsilon - c'\dot{\varepsilon} - k\int_{-\infty}^{t}\varepsilon(t')dt' \qquad (10)$$

in which the control coefficients were depending on the integrated error as

$$\kappa = \frac{c}{2}\left[1 + sigmoid\left(50\left|\int_{-\infty}^{t}\varepsilon(t')dt'\right|\right)\right] \qquad (11)$$

$$c' = c + \kappa,\ b' = \frac{c^2}{4} + c\kappa,\ k = \frac{c^2}{4}\kappa \qquad (12)$$

This expectation corresponds to a relaxation of two time constants: $c/2$ for the PD and κ for the integrated term. Too small value for c corresponds to slow trajectory reproduction, that is too big error in the trajectory, while too big values cause too strong feedback resulting in overshoots and increased noisiness of the control. Here $sigmoid(x)=x/(1+|x|)$.

In the present approach the novelty is that "c" was not kept fixed. For qualifying the "noisiness" of their control the change in the exerted momentum during the cycle time was chosen integrated in a forgetting buffer according to the rule in each cycle as

$$c_{int}(t+1) = \alpha \times c_{int}(t) + |\mathbf{Q}(t) - \mathbf{Q}(t-1)| \qquad (13)$$

Parameter $\alpha\in[0,1)$ is the "forgetting factor". The normalized integral was compared to a reference value experimentally set in the buffer *cCoeff*, and the actual value for c was set from an initial value c_0 as

$$c = c_0\left(1 + 2\frac{cCoeff}{cCoeff + (1-\alpha)c_{int}}\right) \qquad (14)$$

The fraction in (14) can be interpreted as a fuzzy set describing the "smoothness" of the control: for small torque derivatives it approaches 1, while for to fast changes in the torque it converges to zero. This rigid rule means that for strongly varying momentum it is not reasonable to require too big feedback in order to avoid instabilities and overshot, but in the "stable phase" of the control an increase in the feedback may improve accuracy.

- An "*Additional Generalized Force*" term based on a simple version of regression analysis in which the prediction is "qualified" and suppressed according to the noisiness of the environment it originates from (described in details e.g. in [8]); Originally a single variable fuzzy set similar to that in (14) was used in [8], depending only on the "noisiness" of the additional torque calculated on the basis of regression (its argument was called *RCoeff*) having exactly the same forgetting factor as "c" in (14)):

$$R(RCoeff) = RCoeff/\left(RCoeff + (1-\alpha)r_{int}\right) \qquad (15)$$

In the present approach further novelty is, that independently of its noisiness the regression-based term is considered from another aspect, too: to what extent this part of the control can take the whole task of controlling. Simulations revealed that in many cases the originally applied regression term "can take the whole task" giving practically no room for the other parts of the controller to gain role. On the other hand, complete dropping of this term can result in the decay of the control. As the classic values as coefficients zero/1 correspond to dropping/fully applying the regression term, another fuzzy set describing the "*extent of being taken into account*" can be introduced by the use of an appropriate argument $RkCoeff\in[0,\infty]$ defined as

$$R(RkCoeff) = \left(1 + sigmoid(RkCoeff)\right)/2 \qquad (16)$$

In the new simulations the product of (15) and (16) was used as a fuzzy set having two variables. In the slow *external loop* the parameters α, *cCoeff*, *RCoeff*, *RkCoeff* were directly tuned.

In the sequel simulation examples are presented to represent and illustrate the operation of the method.

III. SIMULATION INVESTIGATIONS

In the simulations a 2DOF arm of rotary joints were considered. A damped spring of stiffness *Spr [N/m]* and viscous coefficient *Vis [Ns/m]* attached to the end of the arm represented the environmental interactions.

In Fig. 1 the phase-trajectories, the joint coordinate errors are given for the nominal and the simulated slow motion with a regression term fully taken into account. The fast fluctuation in the torque signal and the similarity of the full and the regression components in the torques indicates that almost the whole task is "solved" by the regression term only. Really, complete dropping of the regression-based term resulted in the decay of the control.

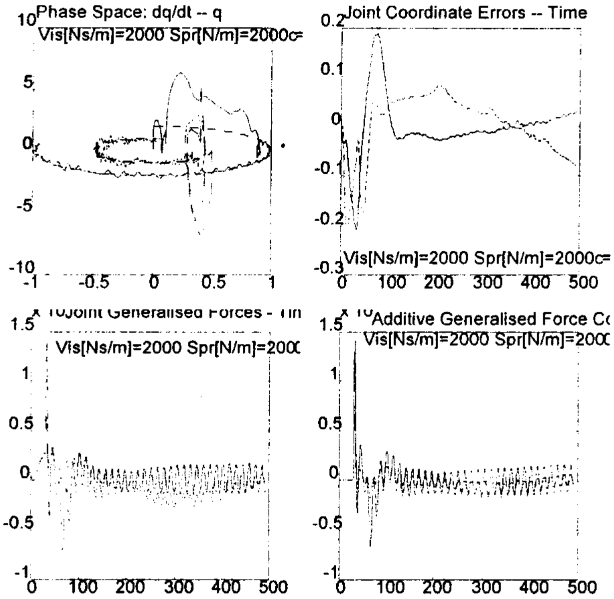

Fig. 1: The phase trajectories, joint coordinate errors, full and regression-based torques for the slow motion under strong environmental interaction (time in 5 ms units) when the regression term is fully taken into account.

In Fig. 2 the same quantities are described when the regression term is taken into account by a fixed factor of 0.5. It can clearly be seen that the initial errors increased, the fast fluctuation disappeared from the regression-based term, and that there is a significant difference between the full torques and their regression-based components. It indicates that the "more intelligent parts" of the control gained more roles in the later phase of the motion. This experience supports the idea that it may be expedient to tune the factor according to which the regression-based term can be taken into account.

In Fig. 3 the appropriate results are displayed for full tuning, and the same desired motion and external interaction as in the case of Figs. 1 and 2. It can well be seen that the initial "transient" part became shorter. The

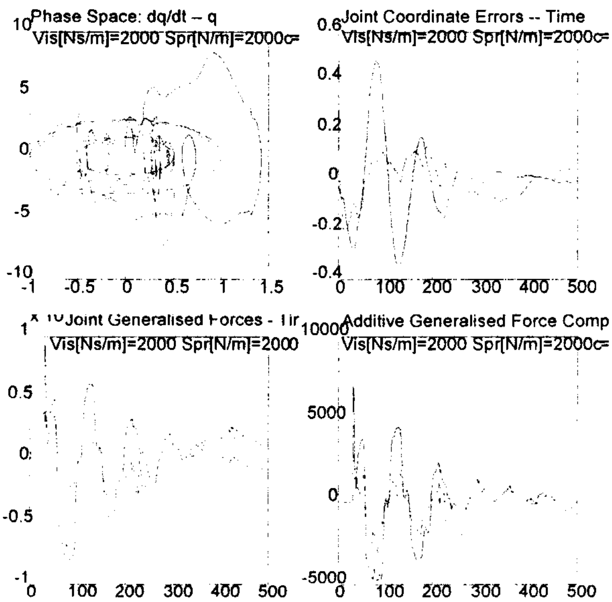

Fig. 2: The phase trajectories, joint coordinate errors, full and regression-based torques for the slow motion under strong environmental interaction (time in 5 ms units) when the regression term is taken into account by a fixed factor 0.5.

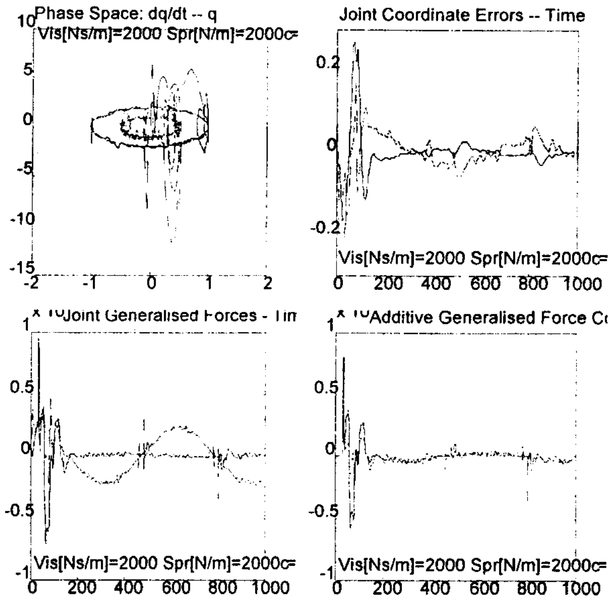

Fig. 3: The phase trajectories, joint coordinate errors, full and regression-based torques for the slow motion under strong environmental interaction (time in 5 ms units) for fully tuned case

torque diagrams reveal that the regression correction took very small role in the latter parts of the motion, while it was quite considerable in the transient phase when the "incomplete system identification" was in an early, very approximate stage.

To reveal background processes in Fig. 4 the estimated inertia matrix's elements and the parameter c describing the required quickness of trajectory reproduction and the value of the membership function according to which the regression term is taken into account are described. Periodicity of the inertial term and the convergence for an optimum value for the other two parameters seem to justify the initial expectations. Further details are described in Fig. 5: the desired and the simulated trajectory, two immediately tuned parameters in the internal loop, the

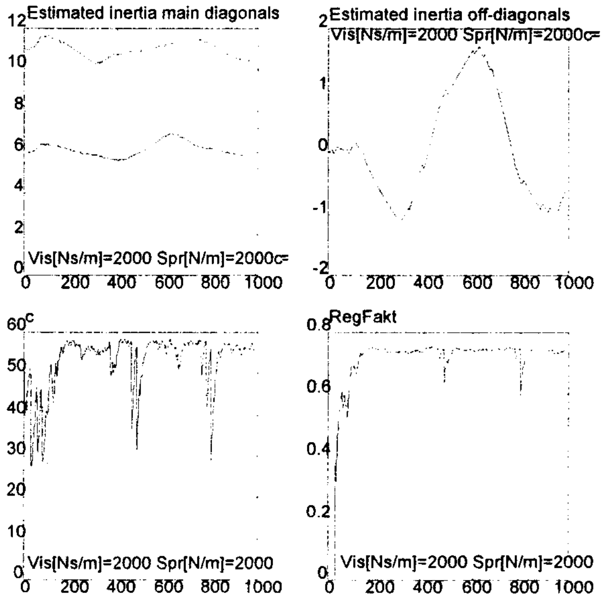

Fig. 4 : The estimated inertia matrix, the exponent of the required trajectory reproduction (c) and the coefficient of the regression term (time in 5 ms units)

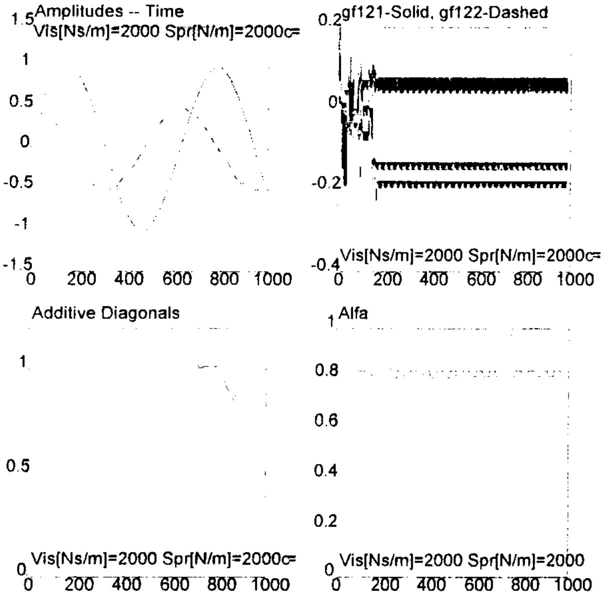

Fig. 5: Further control characteristics: desired and simulated trajectories, certain quickly tuned internal loop parameters, the additive diagonal terms in the inertia matrix, and the forgetting factor tuned in the slow external loop.

additional diagonal terms in the inertia matrix and the forgetting factor α. From the figures it is clear that the end of the "transient phase" corresponds to finding the proper setting for the internal loop parameters. To illustrate the role of the environmental interaction the same motion was considered for free motion of the robot arm in Fig. 6. In Fig. 7 certain control parameters are described for the fast required motion under strong environmental interaction and full tuning.

It is clear that for he fast motion the same tendencies are present as for the slow one. In general the conclusions can be drawn and summarized in the next chapter.

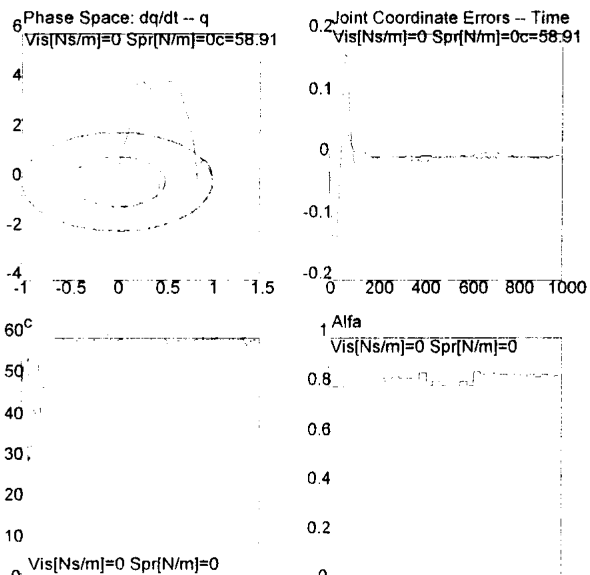

Fig. 6 Certain control characteristics of the free motion of the robot arm for slow desired motion: phase trajectory, trajectory reproduction error, quickness parameter, forgetting factor (time in 5 ms units)

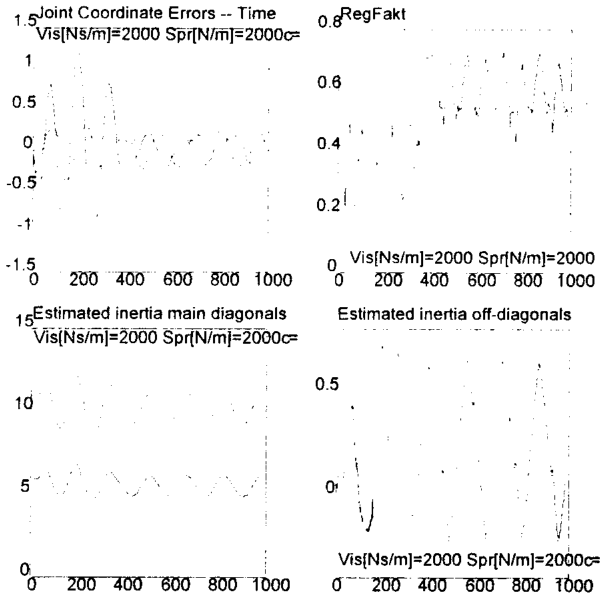

Fig. 7: Certain control parameters for fast motion of the arm under strong environmental interaction

IV. CONLUSIONS

It was illustrated via simulations that the uniform structures constructed of partially decoupled and redundant free parameters adjusted by the Adaptive Simplex Algorithm, combined with an improved version of the classic PID/ST, and a simple version of regression analysis and an external optimizing loop can co-operate successfully.

It also has been shown that the "way of co-operation" of the combined methods can be influenced by slowly tuned parameters.

The synthesis of the individually quite limited methods leads to an efficient control in which the significance of the different components remains comparable and changes according to the task to be executed.

It also has been shown that introduction of simple fuzzy sets itself can be useful without applying the "orthodox way of thinking" as far as the fuzzy controllers are concerned. It is no necessary to introduce fuzzy relations, fuzzification and defuzzification for using the concept of fuzzy sets in the practice. Instead, application of proper, simple and clearly interpretable fuzzy sets as multiplication factors itself can considerably improve the situation.

V. ACKNOWLEDGMENT

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