Comparison of the Operation of the Centralized and the Decentralized Variants of a Soft Computing Based Adaptive Control

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Abstract:
A new branch of Computational Cybernetics based on principles akin to that of the traditional Soft Computing (SC) is applied for the control of two inaccurately and incompletely modeled, coupled dynamic systems. Eeach of them contains an internal degree of freedom neither directly modeled nor controlled (actuated) by the controller. Two alternative approaches are considered: the decentralized and the centralized ones. In both cases, as a starting point, the method uses a simple, incomplete dynamic model to predict the propagation of the state of the modeled degrees of freedom also influenced by the motion of the unmodeled internal ones by nonlinear coupling. In the centralized approach this rough, incomplete and inaccurate initial model contains all the observable and controllable joints. In the case of the decentralized approach two similar initial models are applied for the two coupled subsystems separately. The controllers are restricted to the observation of the behavior of the generalized coordinates the models of which are available for them. In this latter case the number of the unmodeled and uncontrolled degrees of freedom per controller is higher than that of the controlled ones. On the basis of the previous research it was expected that both approaches have to be efficient and successful. Simulation examples are presented for the control of two double pendulum-cart systems coupled by a spring and two bumpers modeled by a quasi-singular potential. It was found that the centralized and the decentralized approaches are able to "learn" and to manage this control task with a very similar efficiency. Since in many technical fields the application of simple decentralized controllers is desirable the present approach seems to be promising and deserves further attetion and research.

1 Introduction

The basic components of Soft Computing were almost completely developed by the sixties. In our days it roughly is a kind of integration of neural networks, fuzzy systems enhanced with high parallelism of operation and supported by several deterministic, stochastic or combined parameter-tuning methods (learning). Its main advantage is evading the development of intricate analytical system models. Instead of that typical problem classes has been identified for the solution of which typical uniform architectures has been elaborated (e.g. multilayer perceptron, Kohonen-network, Hopfield-network, Cellular Neural Networks, CNN Universal Machine, etc.). Fuzzy systems also use membership functions of typical (e.g. trapezoidal, triangular or step-like, etc.) shapes, and the fuzzy relations can also be utilized in a standardized way by using different, even parametric classes of fuzzy operators. The "first phase" of applying traditional SC that is the identification of the problem class and finding the appropriate structure for dealing with it, normally is easy. The next phase, i.e. determining the necessary size of the structure and fitting its parameters via machine learning is far less easy. For neural networks certain solutions starts from a quite big initial network and apply dynamic pruning for getting rid of the "dead" nodes [1]. An alternative method starts with small network, and the number of nodes is increased step by step (e.g. [2-3]). Due to the possible existence of "local optima", for a pure "backpropagation training" inadequacy of a given number of neurons cannot be concluded simply. To evade this difficulty "learning methods" also including stochastic elements were considerably improved during the recent years (e.g. [4-7]). In spite of this development it can be stated that for strongly coupled non-linear MIMO systems traditional SC still has several drawbacks. The number of the necessary fuzzy rules strongly increases with the degree of freedom and the intricacy of the problem. To reduce modeling complexity fuzzy interpolation methods were developed and checked [8]. The conventional fuzzy modeling techniques also need further investigation and development [9]. Similar problems arise regarding the necessary number of neurons in a neural network approach. External dynamic interactions on which normally no satisfactory information is available influence the system's behavior in dynamic manner. Both the big size of the necessary structures, the huge number of parameters to be tuned, as well as the "goal" varying in time still are serious problems.

Realizing that "generality" and "uniformity" of the "traditional SC structures" excludes the application of plausible simplifications made the idea rise that by addressing narrower problem classes a novel branch of soft computing could be developed by the use of far simpler and far more lucid uniform structures and procedures than the classical ones.

The first steps in this direction were made in the field of Classical Mechanical Systems (CMSs) [10], based on the Hamiltonian formalism detailed e.g. in [11]. This approach used the internal symmetry of CMSs, the Symplectic Group (SG) of Symplectic Geometry in the tangent space of the physical states of the system. The "result" of the "situation-dependent system identification" was a symplectic matrix compensating the effects of the inaccuracy of the rough dynamic model initially used as well as the external dynamic interactions not modeled by the controller. By the use of perturbation calculus it was proved that under certain restrictions this new approach could be successful in the control of the whole class of classical mechanical systems [12]. It is interesting that the method of Taylor series extension combined with the Hamiltonian formalism is widely used in our days for problem solution, e.g. [13, 14]. Later it became clear that all the essential steps used in the control could be realized by other mathematical means than the symplectic matrices related to some phenomenological interpretation. Other Lie groups defined in similar manner by some basic quadratic expression like in the case of the Generalized Lorentz Group [15], the Stretched and the Partially Stretched Orthogonal Matrices [16], or symplectic matrices of special structure [17]. In these approaches the Lie group used in the control does not describe any internal physical symmetry of the system to be controlled.

Another important aspect in connection with incomplete modeling is the existence of two possible alternative approaches: application of a single, complex rough initial model containing each modeled degree of freedom, or tackling the problem in a “decentralized” manner in which certain subsystems are controlled by independent controllers modeling and controlling only certain degrees of freedom of the subsystem in their care. In this case, from the point of view of the local, decentralized controllers, any dynamic coupling between the locally controlled subsystems appears as external perturbations influencing the behavior of the subsystem under their local control. This problem was disscussed in details in a plenary speech by D’Andrea in conection with the dynamic coupling of wings located in each other’s vicinity in flowing air [18].

Since the novel soft computing approach offers simple and convenient implementation for both approaches, and according to the former investigations it was found to be able to manage the consequances of dynamic coupling with unmodeled and uncontrolled subsystems [19, 20], it was expedient to investigate its operation in “decentralized use” and comparing the so obtained results with that of the “centralized use”. In the sequel at first the paradigm is set mathematically, and following that the basic principles of the adaptive control is described. Following the presentation of the typical simulation results the conclusions are drawn.

2 The dynamic model of the coupled system

Let the cart consist of a body and wheels of negligible momentum and inertia having the overall mass of M [kg]. Let the pendulums be assembled on the cart by parallel shafts and arms of negligible masses and lengths L_1 and L_2 [m], respectively. At the end of each arm a ball of negligible size and considerable masses of m_1 and m_2 [kg] are attached, respectively. The Euler-Lagrange equations of motion of this system are given as follows:

$$\begin{bmatrix} Q_1 \\ Q_2 \\ Q_3 \end{bmatrix} = \begin{bmatrix} m_1 L_1^2 & 0 & -m_1 L_1 \sin q_1 \\ 0 & m_2 L_2^2 & -m_2 L_2 \sin q_2 \\ -m_1 L_1 \sin q_1 & -m_2 L_2 \sin q_2 & (M + m_1 + m_2) \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{bmatrix} + \\ + \begin{bmatrix} -m_1 L_1 \cos q_1 \dot{q}_1 \dot{q}_3 - m_1 g L_1 \cos q_1 \\ -m_2 L_2 \cos q_2 \dot{q}_2 \dot{q}_3 - m_2 g L_2 \cos q_2 \\ -m_1 L_1 \cos q_1 \dot{q}_1^2 - m_2 L_2 \cos q_2 \dot{q}_2^2 \end{bmatrix} \quad (1)$$

in which g denotes the gravitational acceleration [m/s^2], Q_1 and Q_2 [$N\times m$] denote the driving torque at shaft 1 and 2, respectively, and Q_3 [N] stands for the force moving the cart in the horizontal direction. The appropriate rotational angles are q_1 and q_2 [rad], and the linear degree of freedom belongs to q_3 [m].

In the present paper the 1st rotational and the linear degrees of freedom were the controlled and actuated ones, while the second rotary axis is without observation, control, and actuation that means that Q_2 took the constant value zero. Furthermore, two pieces of the above described subsytems were coupled along their linear direction of motion by the forces $Q_3^A = -Q_3^B$ given in [N] as

$$Q_3^A = k\left(q_3^B - q_3^A - L_0\right) + \frac{A}{\left(\varepsilon_{bump} + q_3^B - q_3^A - 1.5\times L_0\right)^2} - \frac{A}{\left(\varepsilon_{bump} + q_3^B - q_3^A - 0.5\times L_0\right)^2} \quad (2)$$

in which k desribes a spring stiffness in [N/m] units, and L_0 [m] belongs to the zero spring force separation. To model the buffers two non-linear terms are applied that are very sharp near the $0.5\times L_0$ and $1.5\times L_0$ separations, while in the "internal points" it is very flat. It is described by two parameters, namely by the "strength" A [$N\times m^2$], and a small parameter ε_{bump} [m] determining the "nearness" of the singularity of these coupling forces. In the sequel the principles of the adaptive control are detailed.

3 Principles of the adaptive control

From purely mathematical point of view the can be formulated as follows. There is given some imperfect model of the system on the basis of which some excitation is calculated to obtain a desired system response $\mathbf{i}^d$ as $\mathbf{e}=\boldsymbol{\varphi}(\mathbf{i}^d)$. The system has its inverse dynamics described by the unknown function $\mathbf{i}^r=\boldsymbol{\psi}(\boldsymbol{\varphi}(\mathbf{i}^d))=\boldsymbol{f}(\mathbf{i}^d)$ and resulting in a realized response $\mathbf{i}^r$ instead of the desired one, $\mathbf{i}^d$. Normally one can obtain information via observation only on the function $\boldsymbol{f}()$

considerably varying in time, and no any possibility exists to directly "manipulate" the nature of this function: only $\mathbf{i}^{d}$ as the input of $\boldsymbol{f}()$ can be “deformed” to $\mathbf{i}^{d*}$ to achieve and maintain the $\mathbf{i}^{d}=\boldsymbol{f}(\mathbf{i}^{d*})$ state. [Only the *model function* $\boldsymbol{\varphi}()$ can directly be manipulated.] On the basis of the modification of the method of renormalization widely applied in Physics the following "scaling iteration" was suggested for finding the proper deformation:

$$
\begin{gathered}
\mathbf{i}_{0};\mathbf{S}_{1}\mathbf{f}\left(\mathbf{i}_{0}\right)=\mathbf{i}_{0};\mathbf{i}_{1}=\mathbf{S}_{1}\mathbf{i}_{0};\ldots;\mathbf{S}_{n}\mathbf{f}\left(\mathbf{i}_{n-1}\right)=\mathbf{i}_{0};\\
\mathbf{i}_{n+1}=\mathbf{S}_{n+1}\mathbf{i}_{n};\mathbf{S}_{n}\xrightarrow[n\to\infty]{}\mathbf{I}
\end{gathered}
\tag{3}
$$

in which the $\mathbf{S}_n$ matrices denote some linear transformations to be specified later. As it can be seen these matrices maps the observed response to the desired one, and the construction of each matrix corresponds to a step in the adaptive control. It is evident that if this series converges to the identity operator just the proper deformation is approached, therefore the controller „learns” the behavior of the observed system by step-by-step amendment and maintenance of the initial model. Since (3) does not unambiguously determine the possible applicable quadratic matrices, we have additional freedom in choosing appropriate ones. The most important points of view are fast and efficient computation, and the ability for remaining as close to the identity transformation as possible. For making the problem mathematicaly unambiguous (3) can be transformed into a matrix equation by putting the values of **f** and **i** into well-defined blocks of bigger matrices. Via computing the inverse of the matrix containing **f** in (3) the problem can be made mathematically well-defined. Since the calculation of the inverse of one of the matrices is neeeded in each control cycle it is expedient to choose special matrices of fast and easy invertibility. Within the block matrices the response arrays may be extended by adding to them a “dummy”, that is physically not interpreted dimension of constant value, in order to evade the occurrence of the mathematically dubious 0→0, 0→finite, finite→0 transformations. In the present paper the special symplectic matrices announced in [17] were applied for this purpose. In general, the Lie group of the Symplectic Matrices is defined by the equations

$$
\mathbf{S}^{T}\Im\mathbf{S}=\Im\equiv\left[\begin{array}{c|c}\mathbf{0}&\mathbf{I}\\\hline-\mathbf{I}&\mathbf{0}\end{array}\right],\ \det\mathbf{S}=1
\tag{4}
$$

The inverse of such matrices can be calculated in a computationally very cost-efficient manner as $\mathbf{S}^{-1}=\Im^{T}\mathbf{S}^{T}\Im$. In our particular case the symplectic matrices of the decentralized approach are constructed from the desired and the observed joint coordinate accelerations corresponding to the response of the mechanical system to the excitation of torque and force by the use of the block of the matrix

$$[\mathbf{m}_1,\mathbf{m}_2,\mathbf{m}_3,\mathbf{m}_4]=\begin{bmatrix} \ddot{q}_1 & -\ddot{q}_1 & e_1^{(3)} & e_1^{(4)} \\ \ddot{q}_3 & -\ddot{q}_3 & e_2^{(3)} & e_2^{(4)} \\ d & -d & e_3^{(3)} & e_3^{(4)} \\ D & \frac{\ddot{q}_1^2+\ddot{q}_3^2+d^2}{D} & e_4^{(3)} & e_4^{(4)} \end{bmatrix} \tag{5}$$

as

$$\mathbf{S}=\left[\begin{array}{cccc|ccc} & \mathbf{0} & & & \frac{-1}{s}\mathbf{m}^{(1)} & \frac{-1}{s}\mathbf{m}^{(2)} & -\mathbf{e}^{(3)}-\mathbf{e}^{(4)} \\ \hline \mathbf{m}^{(1)} & \mathbf{m}^{(2)} & \mathbf{e}^{(3)} & \mathbf{e}^{(4)} & & \mathbf{0} & \end{array}\right] \tag{6}$$

in which $\mathbf{e}^{(3)}$, $\mathbf{e}^{(4)}$ denote two unit vectors that lie in the orthogonal sub-space of the first two columns of the block matrix, d is the "dummy" parameter used for avoiding singular transformations, and

$$D^2 \equiv \ddot{q}_1^2+\ddot{q}_3^2+d^2,\ s=2D^2 \tag{7}$$

The unit vectors can be created e.g. by using El Hini's algorithm [16], which, while rotates vector **b** into the direction of vector **a**, leaves the orthogonal sub-space of these vectors invariant. So if the operation starts with an orthonormal set $\{\mathbf{e}^{(1)},\ldots,\mathbf{e}^{(4)}\}$ and at first it is rigidly rotated until $\mathbf{e}^{(1)}$ becomes parallel with the 1st column of **M**, its 2nd column will lie in the orthogonal sub-space of the 1st one spanned by the transformed $\{\mathbf{e}^{*(2)},\ldots,\mathbf{e}^{*(4)}\}$ set. In the next step this whole set can rigidly be rotated until the new $\mathbf{e}^{**(2)}$ becomes parallel with the 2nd column of **M**. (This operation leaves the previously fixed $\mathbf{e}^{*(1)}$ invariant because it is orthogonal to the two vectors determining this special rotation.) With the above completion the appropriate operation in (3) evidently equals to the identity operator if the desired response just is equal to the observed one, and remains in the close vicinity of the unit matrix if the non-zero desired and realized responses are very close to each other. In the case of the centralized control similar symplectic matrices were created from the column $\left[\ddot{q}_1^A\ \ddot{q}_3^A\ \ddot{q}_1^B\ \ddot{q}_3^B\ d\ D\right]^T$ that contains the observable and controllable joints of subsystems A and B, too.

Since amongst the conditions for which the convergence of the method was proved in [12] near-identity transformations were supposed while using perturbation calculus, a parameter ξ measuring the „extent of the necessary transformation", a "shape factor" σ, and a „regulation factor" λ were introduced in a linear interpolation with small positive ε_1, ε_2 values as

$$\xi := \frac{|\mathbf{f}-\mathbf{i}^d|}{\max(|\mathbf{f}|,|\mathbf{i}^d|)},\quad \lambda = 1+\varepsilon_1+(\varepsilon_2-1-\varepsilon_1)\frac{\sigma\xi}{1+\sigma\xi},\quad \hat{\mathbf{i}}^d=\mathbf{f}+\lambda(\mathbf{i}^d-\mathbf{f}) \tag{8}$$

This interpolation reduces the task of the adaptive control in the critical sessions and helps to keep the necessary linear transformation in the vicinity of the identity operator. Other important fact concerning the details of the numerical calculations is the ratio of $\|\ddot{\mathbf{q}}\|$ and d in (5). The controller has *a priori* information only on the *nominal* accelerations, but for the appropriate error-relaxation much higher *desired* accelerations may occur. For this purpose a slowly forgetting integrating filter was introduced to create a weighting factor for $0<\beta<1$ as

$$w(t_i) := \sum_{j=0}^{\infty} \beta^j \left\|\ddot{\mathbf{q}}^{\mathbf{Des}}(t_{i-j})\right\| \Big/ \sum_{s=0}^{\infty} \beta^s \tag{9}$$

and in (5) instead of the actual values ($\ddot{\mathbf{q}}$) the actual weighted ones $\ddot{\mathbf{q}}/w$ were taken into account. The numerical realization of such a filter is very easy: the content of a buffer has to be multiplied by β in each control cycle, and the new $\|\ddot{\mathbf{q}}^{Des}\|$ value has to be added to it. It also is easy to calculate the sum of the weights in the denominator of (9): $\Sigma=1/(1-\beta)$. In the forthcoming simulations the following numerical data were used: d=80, β=0.92, σ=0.5, ε_1=0.2, $\varepsilon_2=10^{-5}$ were chosen.

4 Simulation results

In the simulations for the desired relaxation of the trajectory tracking error a simple PID-type rule was prescribed by the use of purely kinematic terms. This error relaxation colud be achieved exactly only in the possession of the exact dynamic model of the system to be controlled. Subsystem *A* had the following numerical data: $m_1^A=10$ *kg*, $m_2^A=10$ *kg*, $L_1^A=2$ *m*, $L_2^A=2$ *m*, $M_A=4$ *kg*. In order to introduce asymmetry into the system subsystem *B* had the following data: $m_1^B=20$ *kg*, $m_2^B=10$ *kg*, $L_1^B=3$ *m*, $L_2^B=1$ *m*, $M_B=6$ *kg*. The coupling spring had the stiffness of $k=10^4$ *N/m*, the “bumper’s force constant” was 10^3 $N\times m^2$, and $\varepsilon_{bump}=10^{-3}$ *m*. The separation belonging to the zero sprong force was $L_0=3$ *m*.

Instead of the exact actual dynamic model the constant diagonal inertia matrix containing the elements 10 [$kg\times m^2$] or [*kg*] in its main diagonal, and having the numerical value 10 in the matrix elements in the role of the sum of the gravitational and Coriolis terms was used in both the centralized and the decentralize cases. (Only the sizes of the appropriate arrays were different to each other.) The cycle-time of the controller was supposed to be 1 [*ms*], and this interval was divided into 50 sub-intervals of equal length for calculation (simulation) purposes.

Typical results are presented for the phase space of the coupled subsystems in Fig. 1 for the nonadaptive, the adaptive decentralized, and the adaptive centralized controllers. It reveals that the modeling deficiencies resulted in quite big error in the phase space in the case of the nonadaptive controller, while both kinds of the

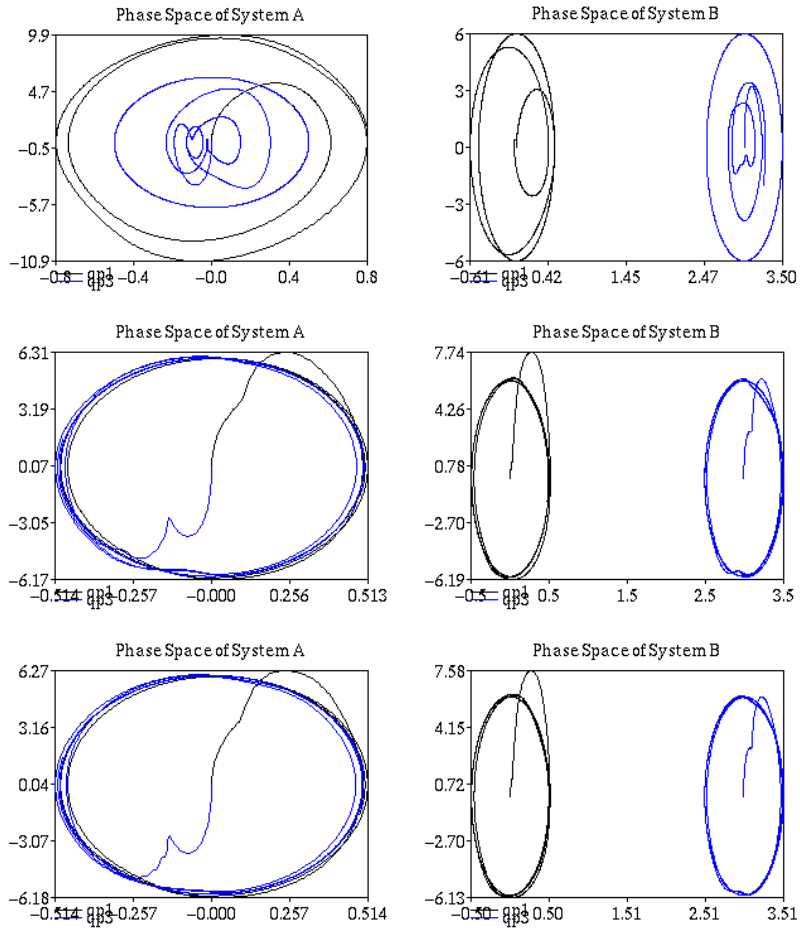

Figure 1. The phase space of susbsystems *A* and *B* in the case of the non adaptive controller (1st column), the adaptive decentralized controllers (2nd column), and the adaptive centralized controller: the phase space of the simulated motion for the controlled joints q_1 [*rad/s vs. rad*], q_3 [*m/s vs .m*].

adaptation considered considerably improves the trajectory tracking. This becomes quite evident due to Fig. 2 describing the trajectory tracking errors belonging to the above considered cases. Fig. 3 conveys information on the norms of the appropriate symplectic transformations revealing that these matrices are realy in the vicinity of the idantity operator.

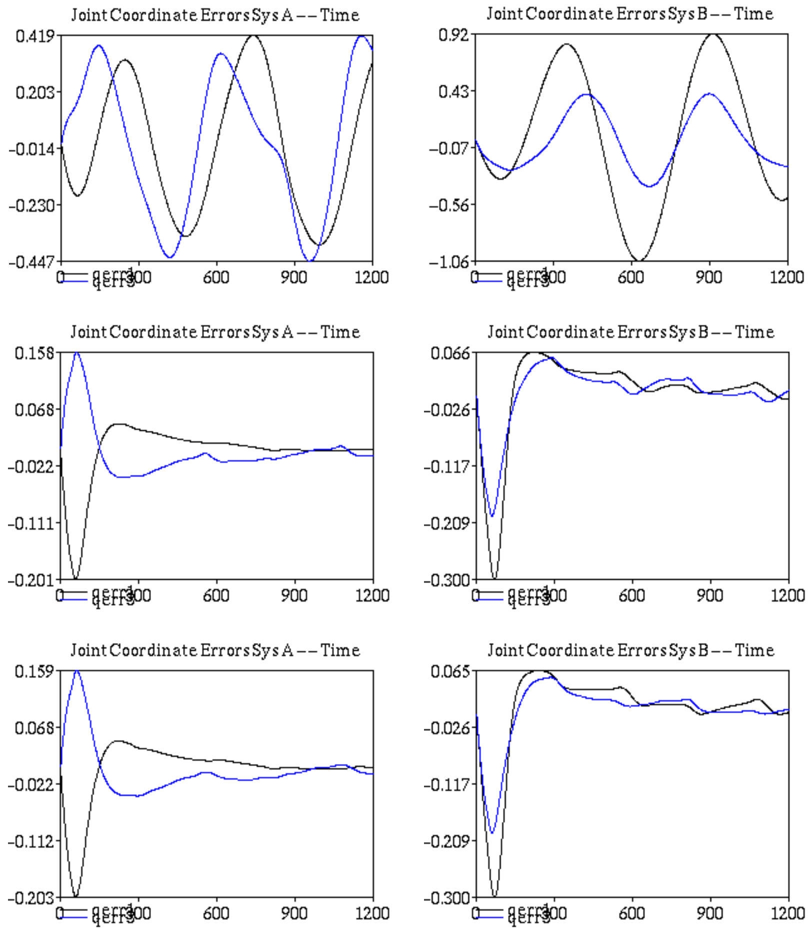

Figure 2. The trajectory tracking errors of susbsystems *A* and *B* in the case of the non adaptive controller (1st column), the adaptive decentralized controllers (2nd column), and the adaptive centralized controller vs. time [*ms*]: δq_1 [*rad*], δq_3 [*m*].

5 Conclusions

In this paper the behavior of the "decentralized" application of an adaptive control method based on a novel branch of Computational Cybernetics were compared to each other. The approximately modeled, coupled non-linear subsystems also had unmodeled and uncontrolled internal degrees of freedom. The simulation results

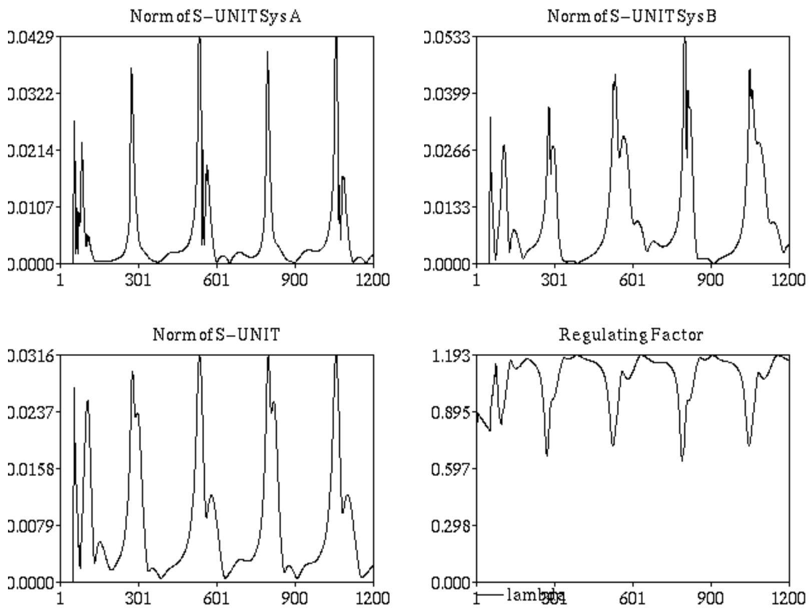

Figure 3. The norms of the actual symplectic transformations minus the unit matrix for susbsystems *A* and *B* in the case of the decentralized controllers (1^{st} row), the norm of the actual symplectic transformation minus the unit matrix and the regulating factor λ for the adaptive centralized controller vs. time [*ms*]:

well illustrated that both ways of the application of adaptivity considerably improved the quality of the trajectory reproduction and successfully compensated the effects of coupling between the subsystems. These results anicipate that this novel method can be a useful means for a practically advantageous decentralized control of various coupled, incompletely and inaccurately modeled subsystems.

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