Improved Simulation Based Investigation of the Effect of Time Resolution in a Novel Adaptive Control for Classical Mechanical Systems

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Abstract:
In this paper the novel modeling and control technique developed at Budapest Tech is investigated in the adaptive control of a typical paradigm, i.e. in the case of an approximately and partially modeled cart plus double pendulum system. Though from many points of view this control is akin to the traditional soft computing it also has certain significant specialties. It commences its operation on the basis of a rough estimated model that is step-by-step adjusted on the basis of the observed behavior of the controlled system. Its novelty consists in its main feature that in contrast to the traditional approaches that try to build up some "complete" and "permanent" system model it is satisfied with "temporal" and "partial" models that are valid only in the actual dynamic environment of the system, that is only in some "spatio-temporal vicinity" of the actual observations. The benefits are the use of small, simple, lucid uniform structures and short algebraic operations. The drawbacks are limited circle of applicability and the need for continuous, fast observations, model maintenance, and action. From this point of view the frequency of the necessary model-corrections is of crucial importance. In the past the new technique was found to be applicable for various physical systems via "preliminary" simulations in which the integration of the equations of motion happened by the simplest 1st order finite element approach in the time domain. At the end of the summer of 2004 INRIA issued its SCILAB 3.0 containing the improved numerical simulation tool called "Scicos". Due to it new prospects were opened for making "professional" and in the same time "convenient" simulations for studying the sensitivity of the method in connection with the frequency of the system-identification loop. In the paper the basic principles of the adaptive control, the typical tools available in Scicos, and others developed by the authors, as well as the improved simulation results and conclusions are presented.

1 Introduction

A new approach for the adaptive control of imprecisely known dynamic systems under unmodeled dynamic interaction with their environment was initiated in [1]. In the family of the adaptive control methods this new one lays between the linear

PID/ST and the parameter identification approaches. Instead of the supposed analytical model's parameters the controller is tuned as in the PID/ST control, but it uses several parameters of some abstract Lie groups fit to the needs of the “non-linear control”. In the same time these parameters may be considered as that of the system model, though they do not belong to a detailed, analytical system-description. This „non-analytical modeling” is akin to the Soft Computing philosophy, too. In this approach adaptivity means that instead of the simultaneous tuning of numerous parameters, a fast algorithm finding some linear transformation to map a very primitive initial model based expected system-behavior to the observed one is used. The so obtained „amended model” is step by step updated to trace changes by repeating this corrective mapping in each control cycle. Since no any effort is exerted to identify the possible reasons of the difference between the expected and the observed system response it is referred to as the idea of "Partial and Temporal System Identification". This anticipates the possibility for real-time applications. Regarding the appropriate linear transformations several possibilities were investigated and successfully applied. For instance, the „Generalized Lorentz Group” [2], the „Stretched Orthogonal Group”, the “Partially Stretched Orthogonal Transformations” [3], and a special family of the „Symplectic Transformations” [4] can be mentioned.

The key element of the new approach is the formal use of the „Modified Renormalization Transformation”. The „original” version was widely used e.g. by Feigenbaum in the seventies to investigate the properties of chaos [5-7]. This (originally scalar) transformation modifies the solution of an $x=f(x)$ fixed-point problem. Since the adaptive control can be formulated as a fixed-point problem, too [8], this transformation was considered a possible candidate for the solution of the task of the adaptive control. The modification of the original transformation was necessary due to phenomenological reasons. Satisfactory conditions of the complete stability of the so obtained control for Multiple Input-Multiple Output (MIMO) systems were also highlighted in [8] by the means of perturbation calculation. This means the most rigorous limitation of the circle of possible application of the new method. To release this restriction to some extent “ancillary” but simple interpolation techniques and application of “dummy parameters” were also introduced in [8]. The applicability of the method was investigated for electro-mechanical and hydrodynamic systems via simulation [9-10]. In this paper a quite simple but lucid typical paradigm, a cart conveying a double pendulum is chosen to be the subject of the adaptive controller.

Typical problems arise when the motion of the system is simulated by the use of its “exact” equations of motion and a finite element method regarding the time-resolution. The selection of the length of the interval between the discrete time-steps considered may seriously concern the numerical results of the calculations. This length has to be decreased till the effect of the decrease cannot be observed in the numerical results. It has to be stressed that in the case of a real time control system the cycle time of the control commands cannot be chosen to be arbitrarily small. The "internal" loop of a complex controller can be realized by fast hardware and simple calculations while the "external adaptive loop" may need more calculations and may have relatively long cycle-time. During these finite "external" time intervals the torque/force values exerted by the drives can be supposed to be constant while the contribution by the Coriolis and gravitational terms of the exact equations of motion can be traced in a finer resolution in the simulations and in the internal loop.

In the sequel at first the paradigm is set mathematically. Following that the basic principles of the adaptive control are described. Following the presentation of the typical simulation results the conclusions are drawn.

2 The dynamic model of the cart - double pendulum 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:

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

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]. On the basis of (1) it is easy to express the inverse dynamical equations of motion in closed analytical form used for simulation purposes. In the sequel the principles of the adaptive control are detailed.

3 Principles of the adaptive control

From purely mathematical point of view the control task 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 $\mathbf{e}=\varphi(\mathbf{i}^d)$. The system has its inverse dynamics described by the unknown function $\mathbf{i}^r=\psi(\varphi(\mathbf{i}^d))=\boldsymbol{f}(\mathbf{i}^d)$ 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 $\mathbf{i}^r$ values. The function $\boldsymbol{f}()$ can considerably vary in time, and no any possibility exists to directly "manipulate" its nature: 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. On the basis of the modification of the method of renormalization transformation widely applied in Physics the following "scaling iteration" was suggested for finding the proper deformation:

$$\begin{gathered}\mathbf{i}_0;\mathbf{S}_1\mathbf{f}\left(\mathbf{i}_0\right)=\mathbf{i}_0;\mathbf{i}_1=\mathbf{S}_1\mathbf{i}_0;\ldots;\mathbf{S}_n\mathbf{f}\left(\mathbf{i}_{n-1}\right)=\mathbf{i}_0;\\ \mathbf{i}_{n+1}=\mathbf{S}_{n+1}\mathbf{i}_n;\mathbf{S}_n\xrightarrow[n\to\infty]{}\mathbf{I}\end{gathered}\tag{2}$$

in which the $\mathbf{S}_n$ matrices denote some linear transformations to be specified later. As it can be seen these matrices map 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 (2) 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 mathematically unambiguous (2) 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 (2) the problem can be made mathematically well-defined. Since the calculation of the inverse of one of the matrices is needed in each control cycle it is expedient to choose special matrices of fast and easy invariability. Within the block matrices the response arrays may be extended by adding to them a "dummy", that is a 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 [4] were applied for this purpose. In general, the Lie group of the Symplectic Matrices is defined by the equations

$$\mathbf{S}^T\Im\mathbf{S}=\Im\equiv\left[\begin{array}{c|c}\mathbf{0}&\mathbf{I}\\\hline-\mathbf{I}&\mathbf{0}\end{array}\right],\ \det\mathbf{S}=1\tag{3}$$

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 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 matrix

$$[\mathbf{m}_1, \mathbf{m}_2, \mathbf{m}_3, \mathbf{m}_4, \mathbf{m}_5] = \begin{bmatrix} \ddot{q}_1 & -\ddot{q}_1 & e_1^{(3)} & e_1^{(4)} & e_1^{(5)} \\ \ddot{q}_2 & -\ddot{q}_2 & e_2^{(3)} & e_2^{(4)} & e_2^{(5)} \\ \ddot{q}_3 & -\ddot{q}_3 & e_3^{(3)} & e_3^{(4)} & e_3^{(5)} \\ d & -d & e_4^{(3)} & e_4^{(3)} & e_4^{(5)} \\ D & \dfrac{\ddot{\mathbf{q}}^2 + d^2}{D} & e_5^{(3)} & e_5^{(4)} & e_5^{(5)} \end{bmatrix} \quad (4)$$

in the blocks of a bigger one as

$$\mathbf{S} = \left[\begin{array}{c|c} \mathbf{0} & \dfrac{-1}{s}\mathbf{m}^{(1)} \quad \dfrac{-1}{s}\mathbf{m}^{(2)} \quad -\mathbf{e}^{(3)} \ldots -\mathbf{e}^{(5)} \\ \hline \mathbf{m}^{(1)} \quad \mathbf{m}^{(2)} \quad \mathbf{e}^{(3)} \ldots \mathbf{e}^{(5)} & \mathbf{0} \end{array} \right] \quad (5)$$

in which the $\mathbf{e}^{(3)}, \ldots, \mathbf{e}^{(5)}$ symbols denote unit vectors that lie in the orthogonal sub-space of the first two columns of the matrix, d is the "dummy" parameter used for avoiding singular transformations, and

$$D^2 \equiv \ddot{\mathbf{q}}^T \ddot{\mathbf{q}} + d^2, s = 2D^2 \quad (6)$$

The unit vectors can be created e.g. by using El Hini's algorithm [3], which, while rotates vector **b** to into the direction of vector **a**, leaves the orthogonal sub-space of these vectors invariant. So if the operation starts with an orthonormal set $\{\mathbf{e}^{(1)}, \ldots, \mathbf{e}^{(5)}\}$ 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 $\{\mathbf{e}^{*(2)}, \ldots, \mathbf{e}^{*(5)}\}$ 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 set $\mathbf{e}^{*(1)}$ unchanged because it is orthogonal to the two vectors determining this special rotation.)

With the above completion the appropriate operation in (2) 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. Since amongst the conditions for which the convergence of the method was proven near-identity transformations were supposed in the perturbation theory, a parameter ξ measuring the „*extent of the necessary transformation*", a "*shape factor*" σ, and a „*regulation factor*" λ can be introduced in a linear interpolation with small positive ε_1, ε_2 values as

$$\xi := \frac{\left|\mathbf{f}-\mathbf{i}^d\right|}{\max(\left|\mathbf{f}\right|,\left|\mathbf{i}^d\right|)+1}, \quad \lambda = 1+\varepsilon_1+\left(\varepsilon_2-1-\varepsilon_1\right)\frac{\sigma\xi}{1+\sigma\xi}, \quad \hat{\mathbf{i}}^d = \mathbf{f}+\lambda\left(\mathbf{i}^d-\mathbf{f}\right) \tag{7}$$

This interpolation reduces the task of the adaptive control in the more critical sessions and helps to keep the necessary linear transformation in the vicinity of the identity operator. In the forthcoming simulations the following numerical data were used: d=100, σ=22, ε_1=0.2, ε_2=0.1. They were selected "experimentally".

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 could be achieved exactly only in the possession of the exact dynamic model of the physical system to be controlled. Instead of the exact actual dynamic model detailed in (1) the constant 1×**I** (**I**= unit matrix) matrix was used as the inertia matrix, and the Coriolis and inertial terms were modeled by the constant vector $[1,\ 1,\ 1]^T$. This evidently corresponds to a very rough approximation of the reality in which m_1=m_2=10 *kg*, L_1=2 m. L_2=3 *m*, *M*=4 *kg*, were chosen.

In Fig. 1 the Scicos model of the simulation scheme based on the simple, kinematically designed, non-adaptive PID controller, the "rough" and the "exact" system models is presented. The typical "built in" elements as the integrator, the "source elements" as the constants, the clock, the "*periodic event generators*", and the only "sink", that is the multiple oscilloscope simulator called "*Mscope*" can well be identified in the figure. The other blocks contain "user-developed functions" as the trajectory generator "*Trajgen*", the model of the PID controller, the rough and the exact system models and the "*Vector Subtractors*". These user-developed functions can be given as common SCILAB instructions that are "interpreted" by Scicos. To speed up the operation of the simulator an alternative method is loading and compiling the user functions instead of directly writing them in the user blocks. (In this case the user block contains only a simple call for the compiled function.) The compilation of the necessary user functions at the beginning can be prescribed in the so-called "*Context*" box of the simulator. The here defined variables behave as "*global*" ones from the point of view of the user-defined functions. They can be referred to as "global" variables in the heading (beginning lines) of the user's functions. The "wires" correspond to the traditional function calls via the stack making the use of the simulator similar to data flow programming. (The global variables can directly be modified by the functions without the use of any "wire".)

To improve this "non-adaptive controller" measurement of the "desired" and the "realized" joint coordinate accelerations was needed. Within the frames of Scicos this can be done by averaging these signals for finite time-intervals using event driven integrators that reset their initial value to a prescribed one when the appropriate event happens. (The length of the time-interval can be obtained by integrating the constant function 1.) In the possession of the averaged joint coordinate accelerations the special symplectic matrix described in (4) and (5) can be updated as a *global variable*. The values of the *desired joint coordinate accelerations* are kept constant due to a "*Vector Shift Register*" during the integration. Therefore the cycle-time of the external adaptive loop approximately corresponds to the duration of this integration plus that of the necessary calculations.

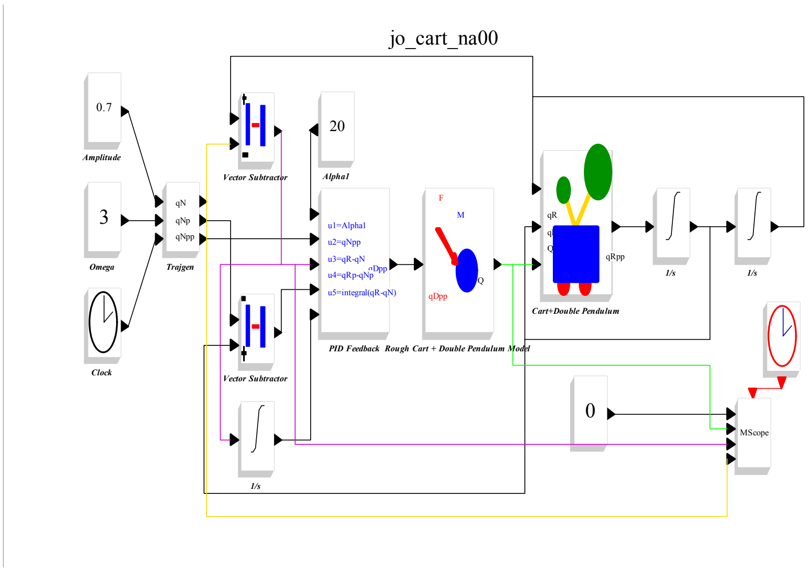

Figure 1. Scicos simulation scheme based on the simple, kinematically designed, non-adaptive PID controller, the "rough", and the "exact" system models

It is worth noting that all the elements of this non-adaptive scheme can conveniently be realized by relatively simple components. The only "exception" can be the sensors measuring the joint coordinate accelerations. (These are not too "simple" tools.)

Fig. 2 describes the Scicos scheme of the adaptive controller developed on the basis of the above principles. It can be noted that the special symplectic matrices that are used for the deformation of the desired joint coordinate accelerations are *global variables,* too. In this manner the use of complicated wirings can be avoided in the figure.

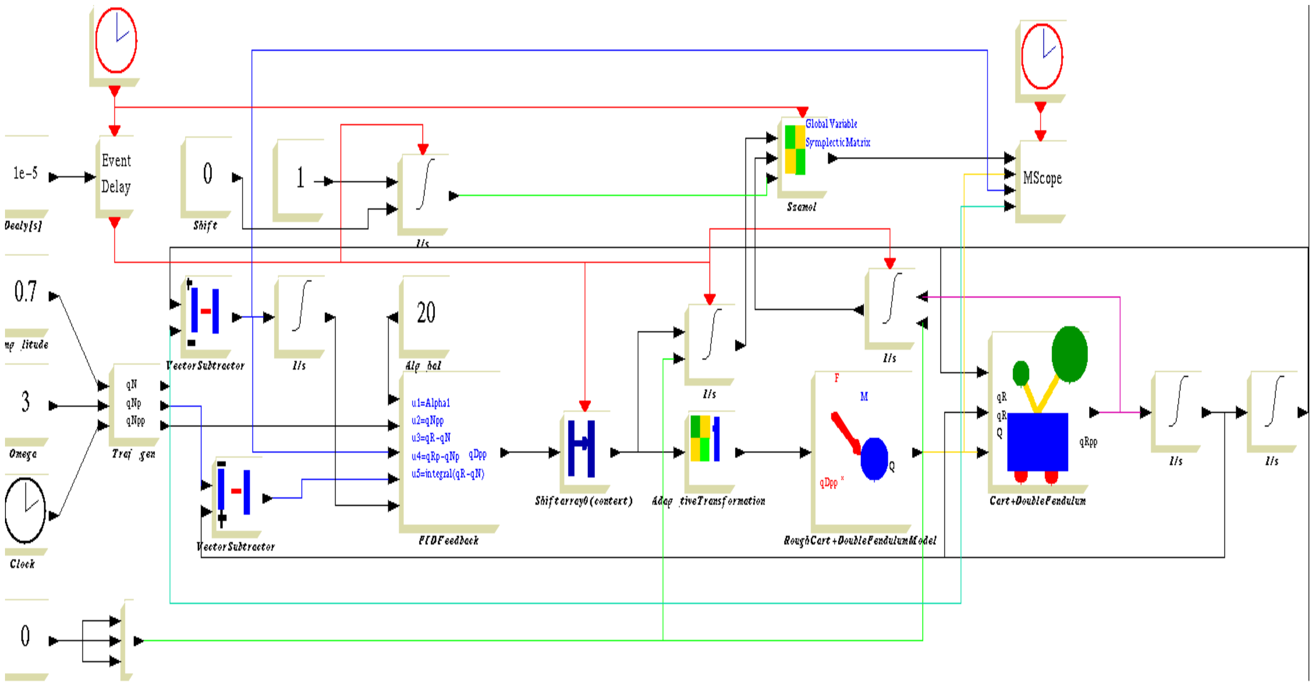

Figure 2. Scicos simulation scheme of the adaptive controller based on the simple, kinematically designed PID-type desired error relaxation, the periodic events driven integrators, on the “rough”, and the “exact” system models.

In Fig. 2 the “chequered” blocks correspond to the program block making and applying the symplectic identification. The “desired trajectory” required 3×0.7=2.1 *rad/s* maximal rotational velocity and 6.3 *rad/s*^{2} maximum rotational acceleration. In the case of the longer arm of 3 *m* length this corresponds to 6.3 *m/s* maximal linear velocity and 18.9 *m/s*^{2} maximal tangential and 13.3 *m/s*^{2} radial acceleration. For the 10 *kg* mass of the pendulum this means 189 *N* and 133 *N* forces in both orthogonal directions.

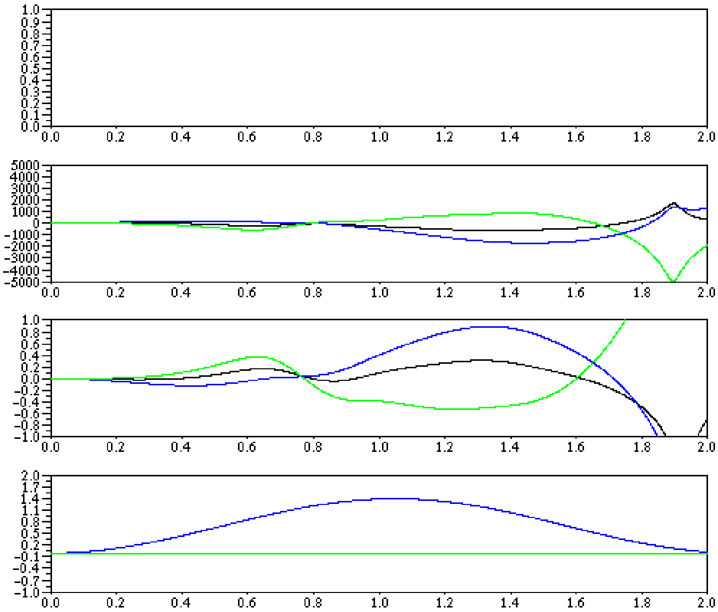

Fig. 3. The operation of the non-adaptive controller: empty box: the room for the adaptive signal (now missing); 2nd box: the generalized forces [in *Nm* for Q_1 and Q_2, *N* for Q_3]; 3rd box: the joint coordinate errors [in *rad* for q_1 and q_2, *m* for q_3]; 4th box: the nominal trajectory [in *rad* for q_1 and q_2, *m* for q_3] vs. time [*s*].

In Fig. 3 the operation of the non-adaptive controller can be seen. (Each simulation was carried out with the default settings of Scicos prescribing 0.0001 for the *integrator absolute tolerance*, 1D-06 for the *integrator relative tolerance*, and 1D-10 value for the *tolerance on time*.) It is clear that the trajectory tracking error has the same magnitude as the amplitude of the desired motion.

The adaptive counterpart of the simulation in Fig. 3 is presented in Fig. 4. It belongs to 1 *ms* cycle time for the external loop. The considerable improvement in the trajectory reproduction and the limitation of the generalized forces is apparent. From the order of magnitude 1 *m* or *rad* it went down to the order of magnitude 10^{-4}. In this case, due to the rough asymmetry of the controlled system this time resolution was found to be the smallest one at which the adaptive controller was found to be stable. Bigger resolution lead to the appearance of “chaotic” control signals.

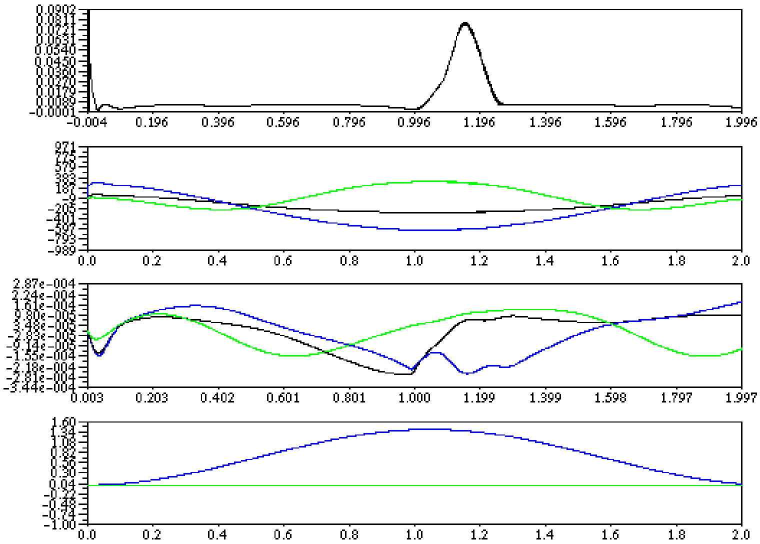

Fig. 4. The operation of the adaptive controller (the adaptive counterpart of Fig. 3): 1st box: the norm of the ($\mathbf{S}_n$-**I**) matrix (characteristic to the adaptive signal); 2nd box: the generalized forces [in *Nm* for Q_1 and Q_2, *N* for Q_3]; 3rd box: the joint coordinate errors [in *rad* for q_1 and q_2, *m* for q_3]; 4th box: the nominal trajectory [in *rad* for q_1 and q_2, *m* for q_3] vs. time [*s*]. The cycle time of the external controller is 1 *ms*.

In the simulation presented in Fig. 5 a “symmetric trajectory” was prescribed that means more modest burden for the controller when the horizontal position of the cart has to be stabilized. In this simulation 4 *ms* cycle time was found to be possible for achieving good results.

5 Conclusions

At the end of the Summer of 2004 INRIA issued its SCILAB 3.0 containing an advanced numerical simulation tool called “Scicos”. Due to it new prospects were opened for making “professional” and in the same time “convenient” simulations for studying the sensitivity of the novel adaptive control developed at the Budapest Tech in connection with the frequency of the system-identification loop. A quite simple but lucid typical paradigm, a cart conveying an asymmetric double pendulum system was chosen to be the subject of the adaptive controller. While the “internal” loop of a complex controller can be realized by fast hardware and simple calculations the “external adaptive loop” may need more calculations and may have relatively long cycle-time. Normally typical problems arise when the motion of such a system is simulated by the use of its “exact” equations of motion and a finite element method for time-resolution. The selection of the length of the interval between the discrete time-steps considered may seriously concern the numerical results of the calculations. Though the necessary resolution strictly depends on the dynamics of the process to be controlled, it can be stated the sophisticated modeling tool of Scicos resulted in more rigorous values than the formerly applied, more primitive estimations. However, the difference is not “crucial”, it was found to be of 1 to 2 ratio in the studied case. It became clear that the in the future it is expedient to use the services of Scicos in similar modeling and simulation investigations.

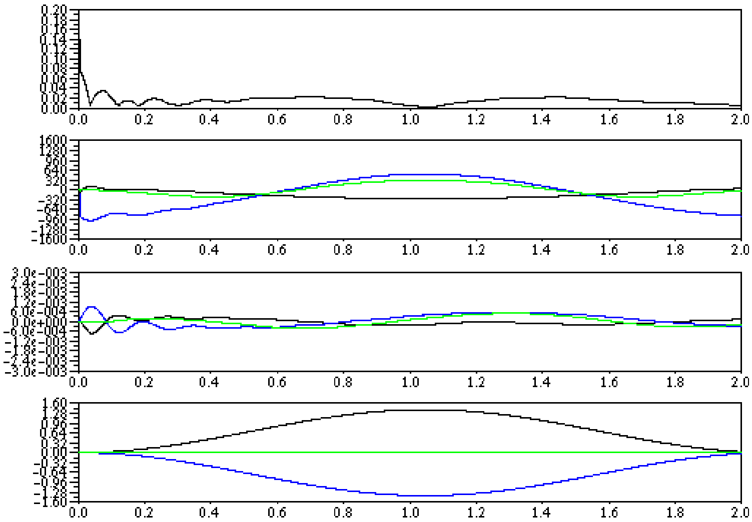

Fig. 5. The operation of the adaptive controller for “symmetric” nominal trajectory: 1st box: the norm of the ($\mathbf{S}_n$-$\mathbf{I}$) matrix (characteristic to the adaptive signal); 2nd box: the generalized forces [in *Nm* for Q_1 and Q_2, *N* for Q_3]; 3rd box: the joint coordinate errors [in *rad* for q_1 and q_2, *m* for q_3]; 4th box: the nominal trajectory [in *rad* for q_1 and q_2, *m* for q_3] vs. time [*s*]. The cycle time of the external controller is 4 *ms*.

6 Acknowledgment

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