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2nd IEEE International Conference on Intelligent Processing Systems

IEEE ICIPS'98

Gold Coast, Australia, August 4-7, 1998

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On the Tuning of the Lagrangian Parameters in a Uniform Structure in Adaptive Robot Control

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Abstract **— In this paper the application of "uniform structures" formerly introduced for the Hamiltonian description of robots is investigated in the case of a SCARA within the frames of the Lagrangian model. This model does not suffer from measurability problems of the Hamiltonian one. Via simulation it was found that this simple method can improve the control of an imperfectly modeled system under unmodeled environmental interaction. It uses the Lie parameters of the Orthogonal Group and the "Sliding Simplex Algorithm" for on-line tuning the parameters in the uniform structures. This method is very similar to the learning process of Artificial neural Networks. To evade the problem of local optima tuning starts from the estimated vicinity of the Global Optimum at the beginning. It is shown that a fast enough tuning can "stick" in this optimum and it propagates together with it in time as the local dynamics of the system is changes in time.**

1. INTRODUCTION

To gain an appropriate analytical model for controlling an approximately known non-linear, strongly coupled multivariable system still is a difficult task. A special case of this class are mechanical systems fault tolerant control of which gained particular attention even in these years e.g. [1-2]. For robot arms, even in the case of "rigid body approximation" there are open problems: during the motion of the system no satisfactory information can be gained to identify its parameters in real time [3]. For solving such problems classical methods like adaptive and robust solutions as Model Reference Adaptive Control or Variable Structure Controllers still offer ample possibilities (e.g. [4-5]).

As an alternative approach the use of modern, highly parallel Soft Computing methods completely abandoning the mathematical description of the system's dynamic model can be regarded. They use simple and uniform structures not tailored to the particular properties of the task to be solved. Instead, they contain a huge number of free via tuning of which certain adaptivity can be achieved. This process is often called "learning". A new approach aiming at the systematic utilization of mathematical advantages of Hamiltonian Mechanics (HM) in the case of conventional manipulator arms was recently investigated e.g. in [6]. Its was to find a compromise between exact, problem-tailored modeling and the uniformity of Soft Computing: uniformity of HM was regarded as a mathematical tool tailored to a wide class of conservative mechanical systems. The only specific information on the system to be controlled was its degrees of freedom. The role of the analytically non-determined, tunable parameters as well as possibilities for parameter tuning were considered in details e.g. in [7]. Via computer simulation it was established that though this method may have considerable adaptivity, its limitations caused by non- measurability of the conecpts in HM also became evident in certain cases. In the case of a vertical SCARA e.g. the technique formerly used for evading this problem was proved to be less efficient. It used a primitive and "rough" "initial robot model" containing *constant inertia matrix*. This model was later "step by step" so "deformed" by the use of the Lie parameters of the Symplectic Group that this constant matrix was still maintained in the construction of the deformations.

In order to supersede this limitations the Canonical Formalism was temporarily put aside and it was investigated what kind of similarly "uniformed" adaptive or robust improvement can be done within the Lagrangian model. The results of this analysis illustrated with numerical simulations for a 3 DOF SCARA arm are presented in details in this paper.

II. TUNABLE PARAMETERS OF UNIFORM STRUCTURE WITHIN THE LAGRANGIAN MODEL

As is well known in the Lagrangian model of a robot arm the equations of motion for a robot of open kinematic chain has the form of the Euler-Lagrange equations.

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}_i}-\frac{\partial L}{\partial q_i}=Q_i \tag{1}$$

in which $\mathbf{q}$ denotes the *generalized coordinates*, $L(\mathbf{q},\dot{\mathbf{q}})$ is the Lagrangian representing the robot as a *conservative mechanical system*, while $\mathbf{Q}$ represents the sum of the effects of the torques/forces exerted by the drives on the appropriate pivots of the joints, the projection of the external and the friction-caused forces on the joint shafts. In the most cases L has the form of

$$L=\sum_{ij} M_{ij}(\mathbf{q})\dot{q}_i\dot{q}_j - V(\mathbf{q}) \tag{2}$$

with a symmetric inertia matrix $\mathbf{M}$ depending only on the generalized coordinates ad a gravitational term derived from the potential V(**q**). For such systems (1) has the particular form of

$$\sum_j M_{ij}(\mathbf{q})\ddot{q}_j + \sum_{js} \frac{\partial M_{ij}}{\partial q_s}\dot{q}_s\dot{q}_j - \sum_{sj} \frac{\partial M_{sj}}{\partial q_i}\dot{q}_s\dot{q}_j + \frac{\partial L}{\partial q_i} = Q_i \quad (3)$$

In the traditional Computed Torque control **M** is built up by the use of a detailed mechanical model of the robot expressed by the Denavit-Hartenberg Conventions. For a rather complicated robot arm construction of **M** and its necessary derivatives is a complicated and time consuming work. Furthermore, the "fruits" of such calculations are degraded by the presence of the unknown external or environmental interactions so influencing the motion of the robot that they cannot easily be taken into account in **Q**.

For getting rid of such complicated calculations our present proposition is to use the singular value decomposition of the positive definite inertia matrix as $\mathbf{M}(\mathbf{q}) = \mathbf{O}(\mathbf{q})\mathbf{D}(\mathbf{q})\mathbf{O}^T(\mathbf{q})$ leading to the time-derivative

$$\dot{\mathbf{M}} = \dot{\mathbf{O}}\mathbf{D}\mathbf{O}^T + \mathbf{O}\mathbf{D}\dot{\mathbf{O}}^T + \mathbf{O}\dot{\mathbf{D}}\mathbf{O}^T = \mathbf{G}\mathbf{M} - \mathbf{M}\mathbf{G} + \mathbf{O}\mathbf{D}\mathbf{H}\mathbf{O}^T \quad (4)$$

in which, in the case of a three degree of freedom system,

$$\mathbf{G} = \dot{\mathbf{O}}\mathbf{O}^T, \mathbf{H} = \langle \mathrm{H}_{11}, H_{22}, H_{33} \rangle \quad (5)$$

corresponds to the generators of simple Lie groups and they are built up from simple linearly independent generators and the joint coordinate velocities as follows. If **O** is the product of three independent orthogonal matrices combining the elements only the (1,2), (2,3), (3,1) as $\mathbf{O} = \mathbf{O}^{(1,2)}(\mathbf{q})\mathbf{O}^{(2,3)}(\mathbf{q})\mathbf{O}^{(3,1)}(\mathbf{q})$ in which e.g.

$$\mathbf{O}^{(1,2)} = \begin{bmatrix} \cos\xi_{12} & \sin\xi_{12} & 0 \\ -\sin\xi_{12} & \cos\xi_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{etc.} \quad (6)$$

in which the ξ_{kl}, arguments explicitly depend on the generalized coordinates **q**, and the appropriate generators pertaining to the above matrices are

$$G_{kl}^{(i,j)} = \delta_{ik}\delta_{jl} - \delta_{jk}\delta_{il} \quad (7)$$

then **G** as a generator of a Lie group can be expressed as the linear combination of the linearly independent "basis generators" as

$$\begin{gathered} \mathbf{G} = \mathbf{G}^{(1,2)}(g_{121}\dot{q}_1 + g_{122}\dot{q}_2 + g_{123}\dot{q}_3) + \\ + \mathbf{O}^{(1,2)}\mathbf{G}^{(2,3)}\mathbf{O}^{(1,2)T}(g_{231}\dot{q}_1 + g_{232}\dot{q}_2 + g_{233}\dot{q}_3) + \\ + \mathbf{O}^{(1,2)}\mathbf{O}^{(2,3)}\mathbf{G}^{(3,1)}\mathbf{O}^{(2,3)T}\mathbf{O}^{(1,2)T}(g_{311}\dot{q}_1 + g_{312}\dot{q}_2 + g_{313}\dot{q}_3) \end{gathered} \quad (8)$$

and in a similar way

$$\mathbf{H} = diag\left\langle \begin{matrix} (g_{111}\dot{q}_1 + g_{112}\dot{q}_2 + g_{113}\dot{q}_3), \\ (g_{221}\dot{q}_1 + g_{222}\dot{q}_2 + g_{223}\dot{q}_3), \\ (g_{331}\dot{q}_1 + g_{332}\dot{q}_2 + g_{333}\dot{q}_3) \end{matrix} \right\rangle \quad (9)$$

describes the derivative in the diagonal matrix. It is clear that according to the above representation the diagonal matrix **D** is an exponential function of its arguments as

$$\mathbf{D} = \mathbf{D}^{(0)} \langle \exp(\xi_{11}), \exp(\xi_{22}), \exp(\xi_{33}) \rangle \quad (10)$$

in which $\mathbf{D}^{(0)}$ corresponds to some "initial" diagonal matrix. From the above formulas it can be seen that for the arguments of the above expression it holds that $\dot{\xi}_{ij} = \sum_s g_{ijs}\dot{q}_s$. From the equation $\dot{\mathbf{M}}(\mathbf{q}) = \sum_s \frac{\partial \mathbf{M}}{\partial q_s}\dot{q}_s$ it trivially can be concluded that the use of the above representation for the inertia matrix of the robot in the Lagrangian model and its partial derivatives a) provides us with a simple, analytically closed form uniform structure quite independent of the particular construction of the robot arm and its Denavit-Hartenberg parameters, b) for a positive definite initial estimation $\mathbf{D}^{(0)}$ it never leads to a physically non-interpretable non-definite estimation; c) and finally, it can simply be extended for an arbitrary degree of freedom robot arm of open kinematic chain.

The basic idea of the control now can be defined as follows: a) let us have an estimation for the inertia matrix for the robot in a particular initial position; by the use of the singular value decomposition it is easy to find an initial estimation for $\mathbf{D}^{(0)}$ and $\mathbf{O}^{(0)}$ for **M**, and let us neglect the potential term in the Lagrangian; b) at this initial point the equation $\xi_{kl}=0$ holds for the Lie parameters, that is the further stretches/shrinks and rotations start from the identity transformation; d) instead of trying to find closed-form analytical expressions for describing the dependence of the ξ_{kl} arguments on the generalized coordinates let us try to tune the g_{kls} factors starting from the zero value in a way which guarantees an improvement in the calculation of the expected joint coordinate accelerations in comparison with the measured (experimental) values; e) for tuning these parameters the "Sliding Simplex Algorithm" can be used as we id it in the case of certain former investigations; f) since the tuning is started from an almost "exact" model, it is reasonable to suppose that if the tuning is fast enough the representation is "stuck on" or at least remains in the vicinity of the "absolute optimum" achievable by such kind of description.

In connection with this representation the following remarks are to be done, too: a) by the application of the factors g_{kls} a representation quite similar to that used in the feed-forward ANNs is gained; however, our position in the case of this representation is more convenient than if we would use an ANN: the number of the tunable free parameters now is known in advance, and instead of the non-linear transition functions in the neurons of unknown parameters and shape Group Theory provides us with simple sine, cosine, and exponential functions of known parameters; while in the case of an ANN using he standard sigmoid functions the problem of "paralysis" cannot be completely evaded, in our case it may not appear since the effect of an infinite "stretch" in one direction cannot be completely compensated for by a rotation: though in certain directions the rotation can keep finite the effect of the stretch, in other directions commencement of the divergence inevitably reveals itself and it necessarily will be curbed by the parameter tuning; b) in accordance with the simulation results, it is expected that this convenient self-containing property can be lost if we allow additional (gravitational or frictional) terms in the generalized forces; this is the reason for abandoning these terms in the present approach; c) in relation of this "abandoning" it is worth noting that with in the case of a fast tuning of the g_{kls} parameters gaining generally valid model of the system is not expected at all; it is expected only that in the vicinity of the given state of the robot and in the existence of the actual external perturbations the behavior (joint accelerations) of the model approaches that of the real system; from this point of view the given approach can be called as a "partial identification" of the system; d) from this aspect it must be noted that though the "starting point" of the approach is the Lagrangian model of the system, in its further "deformed" form this physical meaning can fade into "oblivion": for instance, if a damped spring is connected to the end-point of the robot arm as "external environmental perturbation", due to it such coupling between the joint accelerations will be brought about which do not occur in the Lagrangian of the system; within the frames of this approach the effects of this coupling will be compensated for by appearing non-zero matrix elements in the estimated inertia which otherwise should remain exactly zero; e) in the view of the idea of "partial identification" or "uniform structures" this "physical shortcoming" does not necessarily mean a real or practical insufficiency: eg., in the case of using an ANN for modeling a system no definite correspondence exists between a given neuron and a physical system-component.

III. SIMULATION EXPERIMENTS

In the simulation examples a 3 DOF SCARA robot arm was investigated to the end-effector of which a damped spring was connected to represent environmental interactions. It brought about dynamic coupling between the originally uncoupled joints of the robot. The viscous damping and the spring coefficient is denoted by "Vis", and "Spr" respectively. In Fig. 1 the effect of moderate external perturbations are described. Fig 2 pertains to the same desired motion with adaptive tracking. (The "noise" observable in the phase trajectory is the consequence of parameter tuning.)

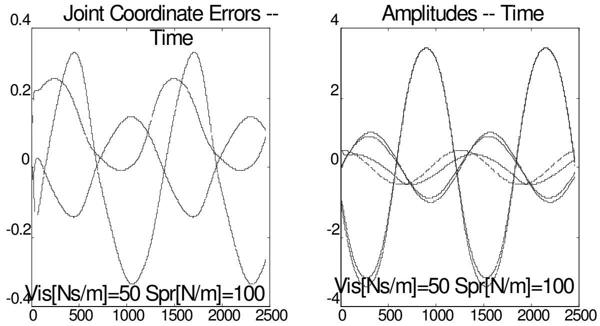

Fig.1 Tracking error, desired and simulated trajectories for moderate external perturbation without adaptivity (time in 5 ms units)

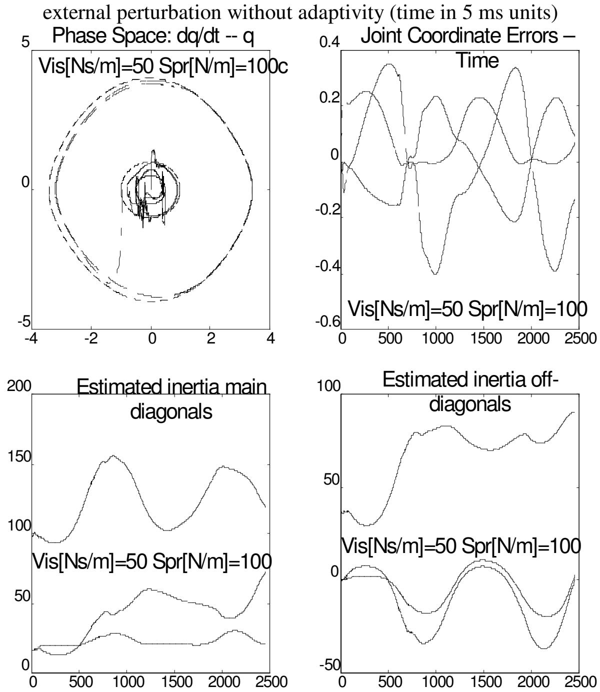

Fig.2 The adaptive version for the same desired motion as given in Fig. 1: the phase trajectory, tracking errors, the estimated inertia matrix elements

Figs. 3-4 reveal that for extremely high viscous interaction the adaptive control can keep the process in bay. (In this case the non-adaptive one completely "decays".)

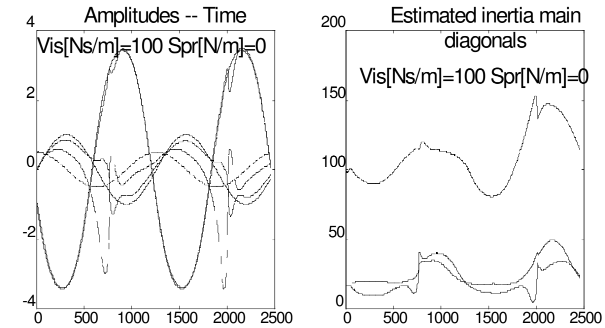

Fig.3 Trajectory tracking, estimated main diagonals of the inertia matrix for the adaptive case for extremely high viscous external interaction

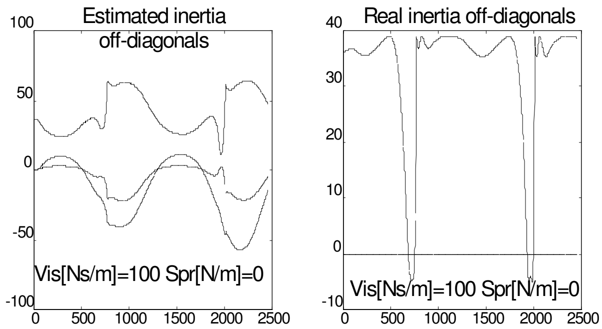

Fig.4. Estimated and real off-diagonals of the inertia extremely high viscous external interaction

Fig. 5 describes the effect of too large spring constant which is far less destructive for the non-adaptive version than the viscous influence is.

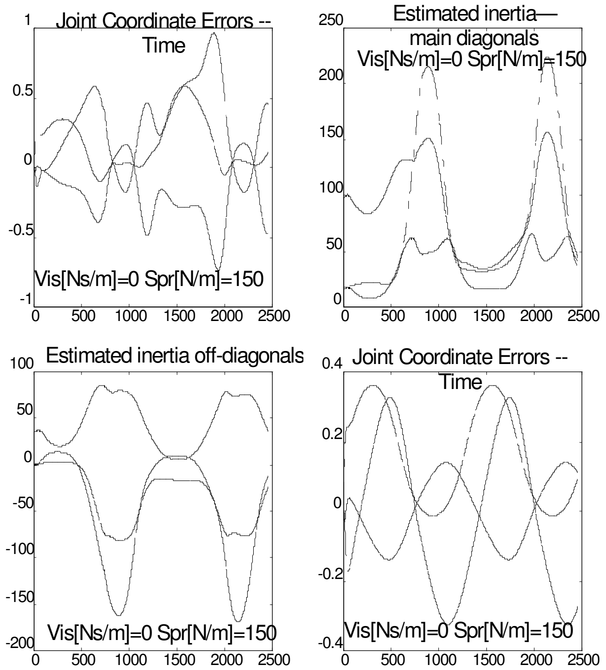

Fig.4. Trajectory tracking, estimated inertia matrix for extremely high elastic external interaction; in the last picture the control's behavior for the same desired motion and external perturbation without adaptivity

IV. CONCLUSIONS

It was proved via simulations that the adaptive version of the control is stable and efficiently keeps the system at bay when the non-adaptive version decays. There is a significant difference in the tracking errors of the adaptive and the non-adaptive control: the error peaks of the adaptive version are narrower than that of the non-adaptive case. This means that the system spends less time in the significantly erroneous zone of the motion in the case of adaptivity. The maximum error does not seem to be reduced due to adaptivity. The significant difference between the actual and estimated inertia matrix reveals that the control tries to compensate for the external influences by considerably changing physical quantities of different nature in its model. Due to stability problems the improvement of the method by adding further generalized force terms requires further investigations. Tuning in the Lagrangian model seems to be a useful tool for improving the control based on the Hamiltonian mechanics and the rough rigid initial model.

V. ACKNOWLEDGMENT

The authors gratefully acknowledge the grant provided by the "FANUC Fund for Research and Development Co-operation" and that of the "National Scientific Research Fund" (OTKA T019032) and the Portuguese-Hungarian Bilateral Science and Technology Cooperation Project P-17/97.

VI. REFERENCES

[1] S. Tosunoglu,: Dynamic Modeling of Compliant Robots for Modular Environment and Fault Tolerant Operations. In *Proc. of Dynamics and Stability, International Conference of Spatial Mechanisms and High Class Mechanism, October 4-6, 1994, Alma Ata, Kazahstan*,Vol. **3.** pp. 27-34.

[2] S.: Tosunoglu, Fault Tolerant Control of Mechanical Systems. In proc. of *IEEE 21st International Conference on Industrial Electronics (IECON'95), 6-10 November 1995, Orlando, Florida*. Vol. 1, pp. 110-115.

[3] , B. Lantos: “Identification and Adaptive Control of Robots”. *International Journal Mechatronics*, Vol. 2, No. 3, 1993, pp. 149-166.

[4] Tenreiro Macahdo: “Variable Structure Control of Manipulators with Compliant Joints”, *IEEE International Symposium on Industrial Electronics, ISIE'93, 1-3 June, 1993, Budapest, Hungary.*

[5] Tenreiro Macahdo, J.A. Alexandra M.S.F. Galhano. “Customuzed Direct Dynamics of Mechanical Manipulators”., *IEEE/ASME 3rd Int. Workshop on Advanced Motion Control, 20-23 March, 1994, Berkeley, California, USA.*

[6] J.K. Tar, I.J. Rudas, J.F. Bitó: "Group Theoretical Approach in Using Canonical Transformations and Symplectic Geometry in the Control of Approximately Modeled Mechanical Systems Interacting with Unmodelled Environment", *Robotica*, Vol. 15, pp. 163-179, 1997.

[7] J.K: Tar, I.J. Rudas, J.F. Bitó, O.M. Kaynak: “Constrained Canonical Transformations Used for Representing System Parameters in an Adaptive Control of Manipulators,”in the Proc. of the *8th International Conference on Advanced Robotics (ICAR97), Monterey, California, USA, 1997. July 7-9*, pp. 873-878.