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An Adaptive Robot Control for Technological Operations Based on Uniform Structures and Reduced Number of Free Parameters

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Abstract: Grinding and polishing are typical application paradigms in which efficient control is needed for approximately and partially known multivariable, non-linear, strongly coupled mechanical systems (robots) under strong dynamic interaction with an unmodeled environment. A novel adaptive approach to this problem using uniform structures and procedures as well as a passive compliant component as an essential part of the control was recently invented. The method seems to overcome the limitations of the classic approaches as limited speed of motion and supposed separability in the operational space supposing free directions for force/torque components and for free components of translation in their orthogonal sub-spaces . Like Soft Computing, instead developing the formally exact analytical model of the robot, its environment and the dynamic interaction between them the proposed method uses uniform structures but these are derived from the Euler-Lagrange equations considered in a general and formal level of abstraction. In contrast to the general approach fit to a quite wide class of problems, these structures are rather fit to a far narrower task of modeling and control of *mechanical devices.* This results in a drastic reduction in the number of tunable parameters, fast tuning for those parameters for which no *a priori* linguistic rules are available and uses simple fuzzy rules for tuning other parameters for which at least qualitative a priori known tuning rules are known. The proposed technique also is free from "scaling problems" so characteristic to the classic ones. The method is proved and illustrated via simulation in the case of a 3 DOF SCARA arm used for polishing a convex surface as an application paradigm.

Keywords: Adaptive Control, Soft Computing, Uniform Structures, Reduced Number of Free Parameters, Machine Learning

1. Introduction

Fault tolerant control of mechanical devices gained considerable attention in the last years e.g. [1]. A novel and efficient approach was recently invented for the adaptive control of approximately and partially known multivariable, non-linear, strongly coupled mechanical systems under dynamic interaction with an unmodeled environment. It definitely seems to be applicable in certain technological processes in which all the above difficulties are present. The basic idea of the uniform structure and the tunable parameters were published in details in [2]. Its main point is that the uniform structures and the ancillary procedures applied offer ample possibilities for dealing with the effect of the unmodeled environmental interactions and the unknown parameters of the robot itself. As a consequence, via real time machine learning (i.e. fast dynamic partial identification of the system's parameters fairly good phase trajectory reproduction can be achieved. The ancillary methods as well as the basic idea of dealing with the technological details are described in details in the next paragraph.

2. The model of polishing and the rule of the passive component

In the simulation examples till considered the environment in dynamic interaction was represented by damped spring. In the present method a 3DOF SCARA arm having a translational and two rotary joints was completed by a third "link" in the form of a "pipe" parallel with the telescopic shaft and rigidly attached to the end of the second rotary link. The pipe contains a passive elastic component, a spring of a not very large, *a priori known* stiffness and negligible viscous damping. Consequently, from the purely kinematic data of the spring's deformation its force depending on the contact force prescribed for polishing as a technology requirement can be determined. By knowing the location of the surface to be polished the required contact force can be transformed into the desired location of the endpoint of the last rotary link which otherwise may have arbitrary velocity with respect to the workshop's system of reference. Via applying a cardan link for fixing the polishing disc in the case of mechanical contact the disc will always be located in the tangent plane of the surface of the work-piece at the given point. In the case of a relatively precise location of the disk the errors in the positioning of the disk will be transformed into a minor error in the contact force originally prescribed.

Due to the "flexibility" of the cardan shaft in the model of dynamic interaction of polishing —used in the simulation only— an even pressure distribution "p" over the disc's surface was supposed. The small surface element of the disc "$d\mathbf{S}$" gives the following contribution into the torque is

$$d\mathbf{M} = \mu p dS\left(\frac{\mathbf{v}^{TR} + \Omega\times\mathbf{r}}{\left|\mathbf{v}^{TR} + \Omega\times\mathbf{r}\right|}\right)\times\mathbf{r} \qquad (1)$$

The polishing disc was supposed to have a fast rotation therefore for the great majority of the surface of the disk the velocity component originating from the rotation far exceeded the translational component $\mathbf{v}^{TR}$. By neglecting the effect of the central part of the disk this yields the normal component of

$$M_{norm} \approx \int_0^{2\pi} d\varphi \int_0^R dr \mu p r^2 = \frac{\mu p 2\pi R^3}{3} = = \frac{2\mu R}{3} F \tag{2}$$

in which "F" is the absolute value of the contact force pressing the disc against the work-piece, and "μ" denotes the friction coefficient. The net force of friction from the small surface element has a similar expression to (1):

$$d\mathbf{F} = \mu p dS \left(\frac{\mathbf{v}^{TR} + \Omega \times \mathbf{r}}{\left| \mathbf{v}^{TR} + \Omega \times \mathbf{r} \right|} \right) \tag{3}$$

Again, by neglecting the effect of the small central part of the disc the term in the parentheses in (3) corresponds to a rotating unit vector resulting in zero in the integral. Therefore the effect of the contact forces was modeled according to (2).

3. The basic parameters and the ancillary procedures

Regarding the uniform structure applied the Euler-Lagrange equation of motion was considered at the following level of abstraction:

$$\sum_j M_{ij}(\mathbf{q})\ddot{q}_j + \sum_{js} \frac{\partial M_{ij}}{\partial q_s} \dot{q}_s \dot{q}_j - \sum_{sj} \frac{\partial M_{sj}}{\partial q_i} \dot{q}_s \dot{q}_j + + \frac{\partial V(\mathbf{q})}{\partial q_i} = Q_i \tag{4}$$

in which "$\mathbf{M}$" is the symmetric positive definite inertia matrix made of a diagonal and an orthogonal matrix according to the "*Singular Value Decomposition*" as

$$\mathbf{M}(\mathbf{q}) = \mathbf{O}(\mathbf{q})\mathbf{D}(\mathbf{q})\mathbf{O}^T(\mathbf{q}), \tag{5}$$

$$\mathbf{O} = \mathbf{O}^{(1,2)}(\mathbf{q})\mathbf{O}^{(2,3)}(\mathbf{q})\mathbf{O}^{(3,1)}(\mathbf{q}), \quad \mathbf{O}^{(i,j)}(\mathbf{q}) \equiv \mathbf{O}^{(i,j)}(\xi_{ij}(\mathbf{q})), \tag{6}$$

(Similar parameters are applied for the diagonal matrix "$\mathbf{D}$" as the arguments of the *exp()* function.) The directly tuned parameters were the "g_{ijk}" parameters and the estimated inertia was integrated according to these ever varying

$$g_{ijk} \equiv \frac{\partial \xi_{ij}}{\partial q_k}, \quad \mathbf{O}^{(1,2)} = \begin{bmatrix} \cos\xi_{12} & \sin\xi_{12} & 0 \\ -\sin\xi_{12} & \cos\xi_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}, etc. \tag{7}$$

coefficients. In principle such a decomposition can describe the Coriolis forces and other terms quadratic in the angular velocities in (1). This form had the following advantages with respect of the traditional Artificial Neural Network -based descriptions:

- It made it possible to avoid the tedious work of constructing a dynamic model on the basis of the Denavit-Hartenberg conventions which also needs the precise kinematic model of the robot.
- The number and the proper role of each tuned parameters was clearly set and determined from starting the tuning; This number is quite limited in comparison with the possibly required number of neurons in the case of a multilayer perceptron.
- The characteristic ranges of the tuned parameters were set almost completely independently from the particular dynamic properties of the robot modeled by this structure (from 0 to 2π for the rotational ones, and for the exponential terms it is trivial that $exp(-10)$ is very small and $exp(10)$ is very big, that is in the practice when at least an order of magnitude estimation is available for the dynamic data of the robot this scaling can be regarded practically problem-independent.).

The initial model is a pure diagonal matrix proportional to the identity operator. This is improved step by step by tuning the "g_{ijk}" parameters according to the *Simplex Algorithm* in which the optimum of the difference between desired and the achieved joint accelerations is minimized. To support this process the following ancillary tools are applied:

- 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;
- a tuned PID term described in details in [2];
- a truncation in the angular velocities at a lover limit when calculating the inertia matrix according to (5-7) to achieve good adaptivity for slow motion, too;
- a slower external loop simultaneously tuning a "*slope*" in the PID/ST term and a parameter qualifying the "*noisiness*" of the regressional correction also optimizing a longer term integral of the acceleration error.

All the above ancillary tool require minor computational power and also are independent of the particular characteristics of the control problem to be solved.

4. Simulation investigations

In the simulations the robot had the task of polishing a strip on a bell-shaped surface. The strip was located at constant distance from the telescopic axis of the robot. The force with which the polishing disk was requested to press the surface was 1200 N, the spring in the elastic component had the stiffness of Spr=400 N/m. In Fig. 1 the kinematic data of the motion are described.

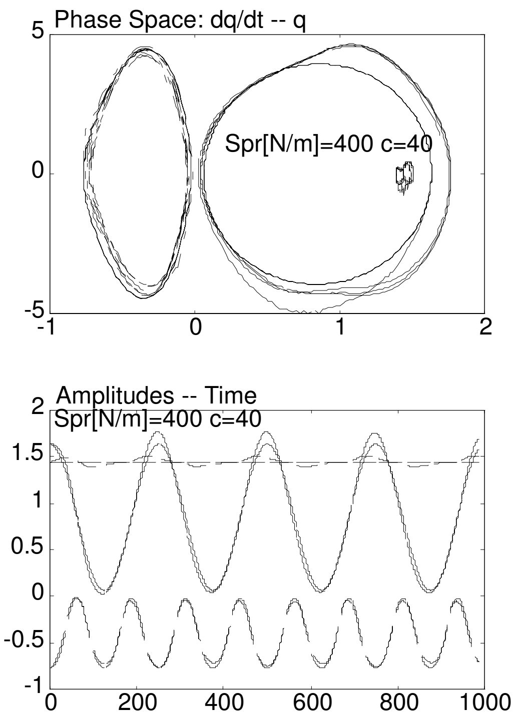

Fig. 1: The phase trajectory and the trajectory for the required (nominal) and the simulated motion (time: 5 ms units).

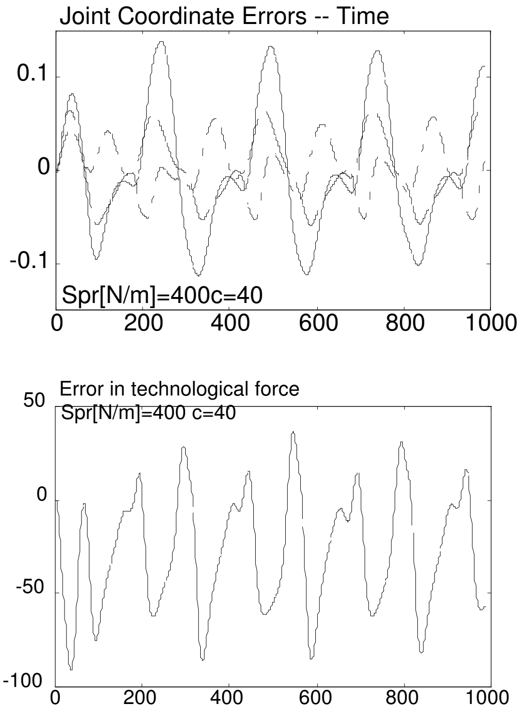

Fig. 2: The error in the trajectory and the contact force versus time (in "m" and "rad" and "N" and 5 ms units, respectively).

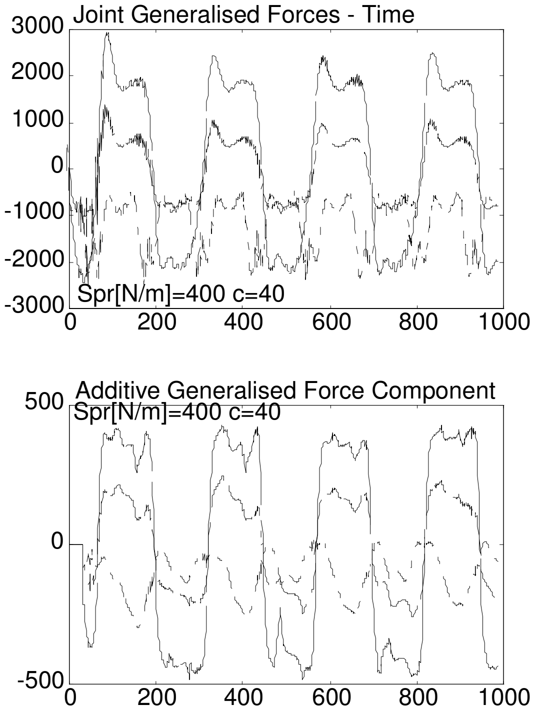

Fig. 3: The full amount of the generalized forces and the regression-based addition versus time (in Nm N and 5 ms units, respectively).

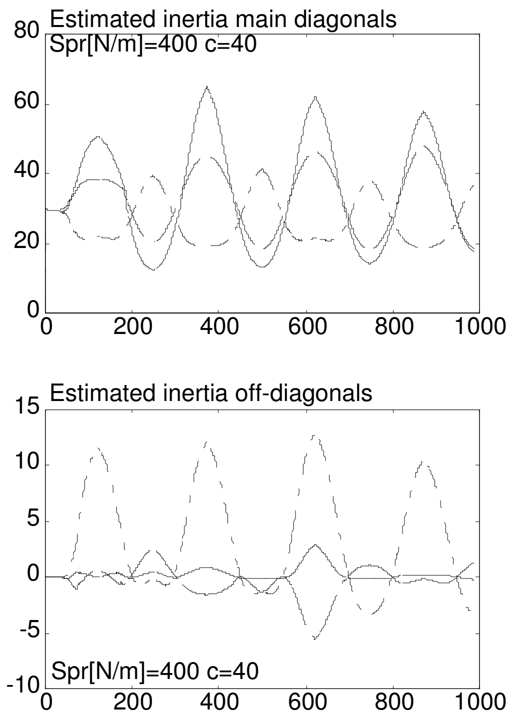

Fig. 4. The estimated "inertia data.

Fig. 2 reveals the *error values* regarding the trajectory and the contact force versus time.

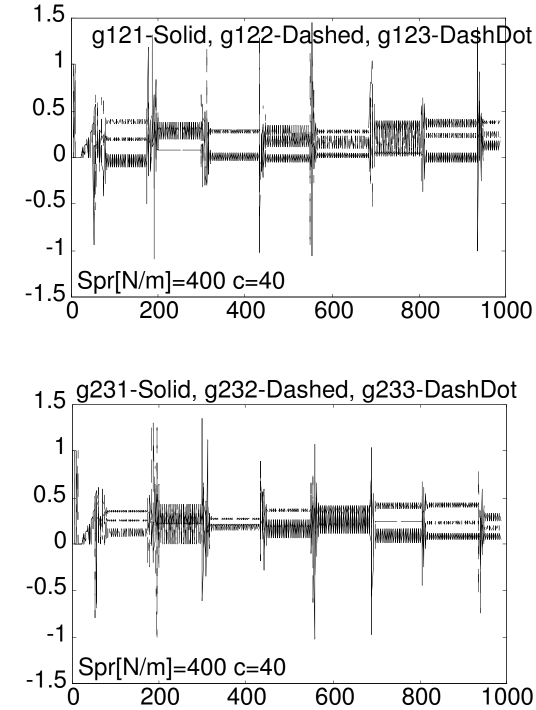

Fig. 5: The variation of six directly tuned parameters.

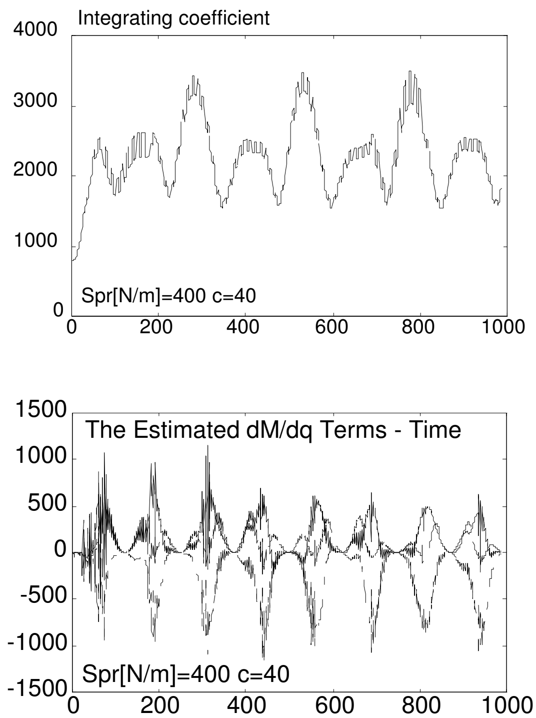

Fig. 6. The variation of the integrating term in the PID/ST part and that of one of the quadratic terms in the Euler-Lagrange equations.

The maximum error in the contact force is about 80 N which is small enough if compared to the requested 1200 N. The error of the first rotational link is about 0.15 rad, the second one keeps its required constant value with the error of about 0.05 rad, while the error of the telescopic axis is about 0.05 m.

Fig. 3 reveals that the regression-based "addition" is quite significant that is this ancillary solution is quite useful in the control.

To disclose the other "background processes" in Fig. 4 the six independent elements of the estimated "inertia matrix" are plotted. The change in these matrix elements is quite considerable which means that this part of the control well cooperates with the other parts, too. The same can be told of the *directly tuned parameters* some of which described in Fig. 5, and of the integrating term of the PID/ST part also displayed in Fig. 6. It is worth noting that the quadratic terms in the Euler-Lagrange equations play a quite important role in the control according to Fig. 6, too.

Regarding the operation of the slower external loop the simulation results did not show considerable drift though considerably different initial values were investigated. It seems that the other parts of the control almost form a local "optimum" for these parameters at least in the cases investigated.

5. Conclusions

It was illustrated via simulations that the proposed method combining an improved version of the classic PID/ST and simple uniform structures with free parameters adjusted by the Simplex Algorithm, and with the ancillary tool of regression analysis can co-operate

successfully. 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. The method is free from scaling problems. It can be regarded as a compromise between the traditional Soft Computing and Hard Computing. The introduction of the passive compliant element makes was successful for technological operations. Further investigations aiming at different robot structures are needed, too.

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7. References

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