Adaptive compensation of torque disturbances and beyond

Citation for published version (APA):
de Jager, B. (1994). Adaptive compensation of torque disturbances and beyond. In *International Conference on Control '94 : 21-24 March 1994, University of Warwick, Coventry, UK. Vol. 2* (pp. 1040-1044). (IEE conference publication; Vol. 389). Institute of Electrical Engineers.

Document status and date:
Published: 01/01/1994

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 16. Nov. 2023

ADAPTIVE COMPENSATION OF TORQUE DISTURBANCES AND BEYOND

Bram de Jager

Eindhoven University of Technology, The Netherlands

ABSTRACT

This paper addresses the problem of adaptive compensation of torque disturbances in the tracking/positioning control of mechanical systems with the aim of (1) reducing the tracking error for tracking and the position error for positioning tasks, (2) increasing the robustness for uncertain parameters, and (3) using the estimated parameters for failure detection/determination and wear indication.

The compensation is incorporated in a standard adaptive nonlinear controller. It merges structural torque disturbance compensation that is important for high velocities and low velocity friction compensation. The stability of the closed loop control system is assessed.

The control scheme proposed is applied and tried out on a simulation model and an experimental system. The results indicate that the compensation method proposed is viable, and the degree of verisimilitude of the compensation model is high enough to enable us to use the values of the adapted model parameters for failure detection/determination and wear indication. The last point, however, requires still some experimental evidence.

It is expected that the method proposed is suitable for implementation on industrial robots, both for accurate tracking/positioning tasks alone as possibly combined with failure detection/determination. The method is not expected to perform well in the presence of large unmodeled dynamics, *i.e.*, for mechanical systems with flexible joints or with flexible links, *e.g.*, for space structures, without further modifications.

1 INTRODUCTION

1.1 Background

In this research we try to clear the way for the following trends we detect in the production, commissioning, and use of robots (all trends aim at reducing the production costs and time to market, and at increasing customer satisfaction by making the use of robots more flexible and cost effective):

- easier controller tuning and commissioning of robots,
- faster movements to reduce cycle times,
- lighter weight for the supporting structure,
- more accurate tracking and position control.

We try to fulfill these trends, effectively making them design goals, by using adaptive control and compensation of torque disturbances. Due to the adaptation there is no need for extensive tuning or the setup of torque corrections with table-look-up methods as used by Armstrong [1, 2]. Owing to the compensation we get high accuracy and can avoid the use of high feedback gains, which could cause instability due to excitation of unmodeled structural vibrations, that may occur at relatively low frequencies because of the small spring constants of flexible systems, whose dynamics are not included in the model used for compensation.

1.2 History and previous research

This research was induced by experiments performed for the research reported in De Jager [3, 4], where a proof of concept is presented for the viability of adaptive extended friction compensation. In effect, the compensation used in that paper did not only cancel friction, but also disturbance torques caused by structural defects, *e.g.*, misalignment, bad bearing, lack of lubrication causing dry friction instead of viscous friction, *etc.*

A further analysis of the experimental results indicated that the tracking errors during the experiments were large when the velocity changed sign. The preliminary conclusion was that the Coulomb friction model used was not adequate for low velocities. We therefore tried to incorporate the friction model used by Canudas de Wit *et al*, [5, 6], and merge these models to one, expectedly better, model.

When we used this approach in our simulations and experiments, the compensation model did appear to have a degree of verisimilitude that made it possible to attach physical significance to some adapted model parameters, enabling their use for further goals then only to compute the compensation torque in the control scheme.

CONTROL '94, 21–24 March 1994. Conference Publication No. 389, © IEE 1994.

The most useful goals seemed to be failure detection/determination and wear indication. Further simulation revealed the usefulness of this approach. Experiments are, however, still to be performed to support the simulation results, but it is a bit difficult (and expensive) to induce representative failures in an experimental system.

1.3 Contribution of research

The main contribution of our work is the merging of the disturbance torque model and the friction model for low velocities, the use of this merged model in a standard adaptive controller, and a stability proof based on the dissipative nature of the friction and disturbance torques, leading to lower tracking errors without the need for high feedback gains and therefore avoiding robustness problems for unmodeled dynamics.

Furthermore, a proof of concept for the use of adapted model parameters in failure detection/determination and wear indication, resulting in a safe and timely shut down or overhaul of the system, is believed to be novel.

1.4 Structure of the paper

We give short descriptions of the following elements of our research, without going into details or presenting rigorous proofs.

First, Section 2 sketches the problems that our research is dedicated to. Then, the robot model, the torque disturbance model, and the low velocity friction model are discussed, followed by a presentation of the adaptive controller and a stipulation of the stability proof. The presentation of the experimental system and its model follows in the first part of Section 4. Next, we give some simulation and experimental results. Section 5 contains the conclusions.

2 THE PROBLEMS

2.1 Reducing tracking/positioning error

When high velocities of the robot end-effector are demanded, without resorting to more powerful and costly motors, one is forced to build light weight structures. To maintain the required maximal position or tracking error, this implies modification of the control scheme. Several ways are open to improve the control system performance.

- The use of high gain feedback, this will however induce stability problems due to the excitation of structural vibration modes that are hardly damped, when these modes are not explicitly taken into account in the controller (unmodeled dynamics).
- More accurate model based feedforward and disturbance torque compensation.

Measures proposed to compensate structural torque disturbances, due to misalignment, bad bearings, *etc.*, also called *extended friction compensation* in [3], are aiming at reducing the tracking errors at relatively high velocities. For low velocities Coulomb friction is especially important.

Normally it is not possible to determine the model parameters with sufficient accuracy, therefore we use adaptation. Only when the model has some degree of verisimilitude, can physical meaning be attached to the adapted model parameters. This implies that both at low and high velocities the model must be accurate.

2.2 Failure detection/determination

We make a distinction between detection (does a failure occur or not) and determination (what caused the failure). Simple measures like detecting a difference between the computed torque and the applied torque necessary to follow a desired trajectory are sufficient for failure detection, but for failure determination more information is needed to be able to determine not only the fact that some part of the system is broken, but also which part to which degree, so appropriate measure can be taken, without being forced to shut the system down in all detected cases.

A possible solution seems to be the use of adapted model parameters. When one or more of these parameters, that are intimately linked with physical phenomena in a more specific part of the structure, are outside some reasonable range of values, this part is probably broken (fast change) or worn out (gradual change).

3 MODELS AND CONTROLLER

3.1 Robot model

The following general model for a multi body system with m control inputs and m DOF (degrees-of-freedom) q is used

$$M(q,\theta)\ddot{q} + C(q,\dot{q},\theta)\dot{q} + g(q,\dot{q},\theta) = f, \quad (1)$$

where $M(q,\theta)$ is the $m \times m$ positive definite inertia matrix, with model parameter vector θ, $C(q,\dot{q},\theta)\dot{q}$ is the m vector of Coriolis and centripetal forces, $g(q,\dot{q},\theta) = g_g + g_f + g_d$ is the m vector of gravitational forces $g_g(q,\theta)$, Coulomb and viscous friction $g_f(\dot{q},\theta)$, and other deterministic torque disturbances $g_d(q,\theta)$, which depend on the DOF, and f is the m vector of generalized control forces (forces or torques). In this model each DOF has its own motor.

Here, we neglect the dynamics of the motors and amplifiers, and the flexibility of the joints and links.

3.2 Torque disturbance model

As torque disturbance model we use the one proposed in [3]

$$g_d(q,\theta) = \theta_{d_1}\sin(\omega_p q)+\theta_{d_2}\cos(\omega_p q)$$

with ω_p the spatial frequency.

This model represents a periodic torque disturbance, *e.g.*, caused by bad bearings, partial lack or uneven distribution of lubricant. The parameter vectors θ_{d_i} are possibly direction dependent to accommodate backlash type phenomena. Both sine and cosine terms have to be used instead of a single $\theta_{d_1}\sin(\omega_p q+\theta_{d_2})$ term to get a model that is linear in the parameters θ_{d_i}, a property of the model that is required by the adaptive controller.

3.3 Friction model

As friction model we use the one proposed in [6]

$$g_f(\dot q,\theta) = (\theta_{f_0}+\theta_{f_1}\sqrt{|\dot q|}+\theta_{f_2}|\dot q|)\operatorname{sgn}\dot q$$

where the parameter vectors θ_{f_i} can be direction dependent to model asymmetric friction. They are also temperature and load dependent and change therefore with time.

This model is a haphazard approximation of the following more elaborate friction model [6]

$$\begin{aligned} g_f(\dot q,\theta) = (&\theta_{f_0}+\theta_{f_1}\exp(-\theta_{f_3}|\dot q|)+ \\ &+\theta_{f_2}(1-\exp(-\theta_{f_4}|\dot q|))\operatorname{sgn}\dot q \end{aligned}$$

with positive θ_{f_i}. The approximation is to get a model that is linear in the parameters θ_{f_i}.

3.4 Adaptive controller

We use an adaptive control scheme proposed by Slotine and Li [7, 8]. This scheme consists of feedforward/feedback components, based on an estimate of the manipulator dynamics (1), and a pure PD component.

The generalized control force f is just the sum of these components

$$f = \hat M(q)\ddot q_r+\hat C(q,\dot q)\dot q_r+\hat g(q,\dot q)+K_v s \tag{2}$$

where $\hat M = M(q,\hat\theta)$, $\hat C = C(q,\dot q,\hat\theta)$, and $\hat g = g(q,\dot q,\hat\theta)$ are the same as the corresponding terms in (1), with $\hat\theta$ an estimate of the model parameters θ, $\dot q_r = \dot q_d+\Lambda\tilde q$ is a virtual reference trajectory, $s = \dot{\tilde q}+\Lambda\tilde q$ is a measure of tracking accuracy, $\tilde q = q_d - q$ is the tracking error, and $q_d(t), \dot q_d(t), \ddot q_d(t)$ represent the desired trajectory.

Adaptation of the estimated model parameters $\hat\theta$ used in $\hat M$, $\hat C$, and $\hat g$ is based on the reasonable assumption that, with an appropriate choice of parameters, the generalized control force (2) is linear in the parameters $\hat\theta$ and can be expressed as

$$f = Y(q,\dot q,\dot q_r,\ddot q_r)\hat\theta+K_v s. \tag{3}$$

Then the adaptation proceeds according to

$$\dot{\hat\theta} = \Gamma^{-1}Y^T(q,\dot q,\dot q_r,\ddot q_r)s. \tag{4}$$

3.5 Stability

The stability proof is based on the dissipative nature of the forces $g(q,\dot q,\theta)$ when physical reasonable values for the parameters θ are used. Then, invoking a result of Ortega and Spong [9], the conditions for the controller parameter matrices, namely K_v, Λ, and Γ^{-1}, that ensure the stability of the closed loop system, are easy to derive

$$K_v > 0 \qquad \Lambda > 0 \qquad \Gamma^{-1} > 0$$

so all these matrices should be positive definite.

Of course, the proof breaks down if the model (1) cannot faithfully reproduce the dynamic behavior of the system. In practice one can always choose the controller parameters such that the closed loop system will be unstable. In this case that is possible by choosing K_v, Λ, and Γ^{-1} too large.

The stability proof is therefore of little practical significance, and its main use is to sort out unsuitable controllers in an early stage, and to be a guidance during the derivation and development of new controllers.

4 SIMULATIONS AND EXPERIMENTS

4.1 Experimental system

The system used for the simulations and experiments is a 2 DOF mechanical system moving in the horizontal plane, an XY-table, with three prismatic joints of which two are coupled by a spindle with adjustable stiffness. A sketch of this system is in Fig. 1.

The main characteristics of the XY-table are

- working area 1 × 1 [m],
- two permanent magnet DC motors, for both the x and y direction,

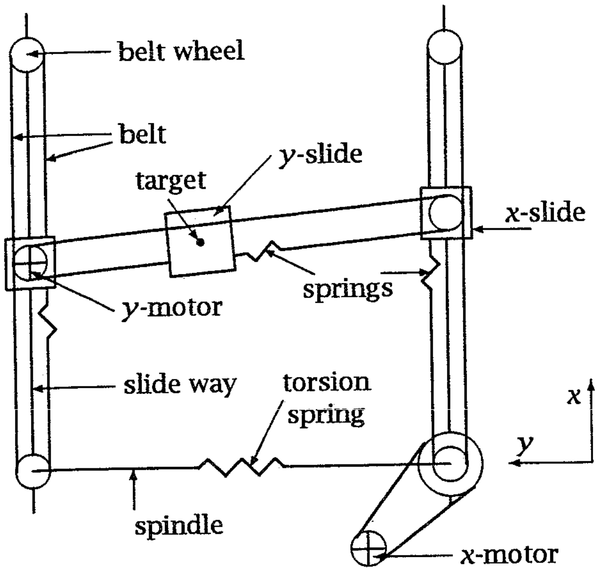

Figure 1: Schematic drawing of XY-table

- current amplifiers for each motor,
- optical encoders mounted on each motor shaft,
- microcomputer based control,
- adjustable dynamics of the system since the torsion spring in the spindle can be replaced, so the spindle stiffness can be changed easily.

The adjustable torsion spring in the spindle can be used to study the robustness of control schemes and to evaluate controllers for systems with flexible joints. The motors are connected by belts and pre-loaded springs with the x-slides and y-slide. The motor currents are controlled by current amplifiers, whose setpoints are generated by the control system.

For the results published here, the stiffest spring in the spindle was used, so no unmodeled dynamics was introduced by it. The main sources of unmodeled dynamics are the springs connecting the belts with the slides.

Because the 2 DOF are almost completely decoupled in a Cartesian coordinate frame, there are no Coriolis and centrifugal forces, making the XY-table a proper system for the study of friction and torque disturbances.

4.2 Evaluation setup

To evaluate the effectiveness of the controller, simulations and experiments were carried out, both for the same system. The task to be performed was tracking a circle with constant angular velocity. This means an harmonic trajectory for the x and y slide.

4.3 Tracking control

4.3.1 Simulation results

Simulations have been performed to investigate the influence of parameter errors in the inertia, friction, and disturbance torque models. An example is in Fig. 2. Here tracking error results for the y-direction of the XY-table are presented, with and without adaptation, using as starting parameter values 80% of the nominal parameter values.

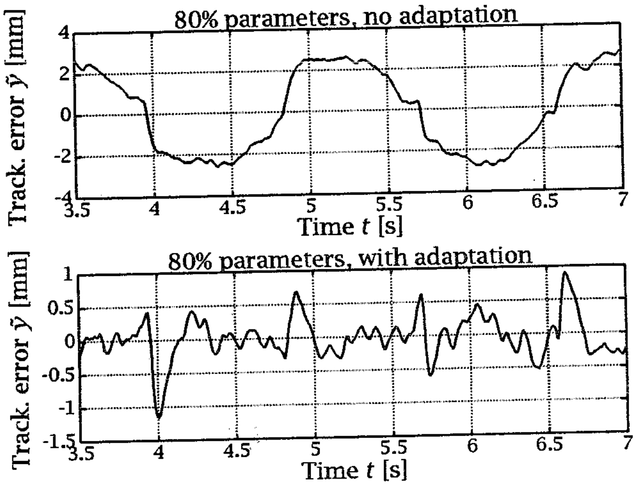

Figure 2: Simulation results with extended model based compensation but approximate parameters

These results shows the effectiveness of the adaptation. The tracking error with adaptation is much smaller as without, although the error in the model parameters θ was only 20%.

4.3.2 Experimental results

Experiments have also been performed. A typical result is in Fig. 3. Again, the tracking error in y-direction is given as a function of time t. The controller parameter settings are the same as for the simulations, so the results should be comparable.

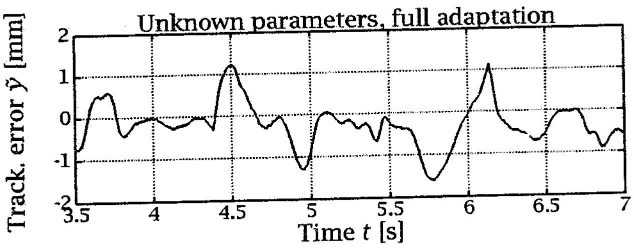

Figure 3: Experimental result with extended model based compensation but unknown parameters

The tracking error $\tilde{y}$ is larger than in the simulations, but in this experiment the parameter estimate is not fully converged yet, because the initial parameter estimates are set to $\hat{\theta}(0) = 0$, so the tracking error will be reduced further. It is also observed that $\tilde{y}$ contains deterministic components, so the models used for torque disturbance and friction compensation can still be improved.

4.4 Failure detection/determination

4.4.1 Simulation results

To show the possibilities for failure detection/determination, a simulation was performed where the Coulomb friction parameter θ_{f_0} in the simulation model was increased at $t = 8$ [s]. This represents the increase of dry friction due to failure of a bearing.

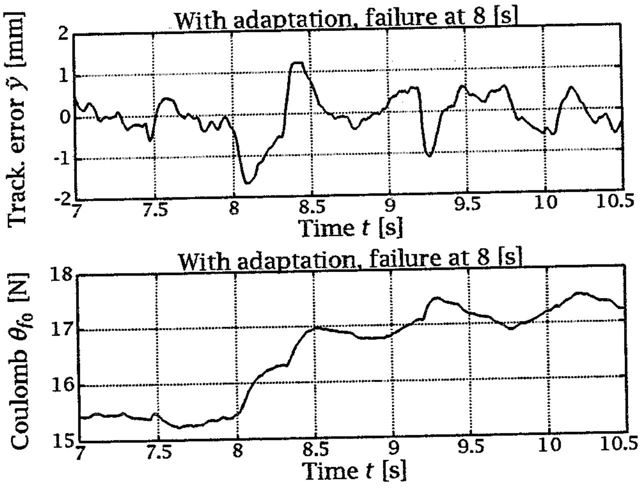

Figure 4: Simulation results with failure at $t = 8$ [s]

The first plot in Fig. 4 shows that this caused a temporary increase of the tracking error. The second plot in Fig. 4 presents the estimated dry friction coefficient $\hat{\theta}_{f_0}$, in this case not direction dependent, and shows the significant increase in the coefficient, that can be used for failure detection/determination purposes.

4.4.2 Experimental results

Experiments that verify the findings of the simulations are in the planning stage. We envisage to introduce failures in the system by

- using a kind of brakes to increase Coulomb friction
- loosening the belts to introduce additional backlash.

Other failure modes are less easy to introduce.

5 CONCLUSIONS

We conclude that by using adaptive disturbance and friction torque compensation

1. the tracking/positioning error is decreased,
2. the robustness for uncertain parameters is increased, especially for the difficult to determine friction parameters,
3. failures and wear can be determined.

However, the evidence for (1) and (2) is stronger than for (3), because (1) and (2) are backed up by experimental results that are still lacking for (3) and a generalization of (3) to other systems is more difficult to justify.

Subjects for further research are the experimental validation of (3) and the development of improved torque disturbance and friction models.

REFERENCES

[1] B. Armstrong, "Friction: Experimental determination, modeling and compensation," in *Proc. of the 1988 IEEE Internat. Conf. on Robotics and Automat.*, vol. 3, (Philadelphia, PA, Apr. 1988), pp. 1422–1427, IEEE, IEEE Computer Society Press, Washington, DC, 1988.

[2] B. Armstrong-Hélouvry, *Control of machines with friction.* Boston: Kluwer Academic Publishers, 1991.

[3] B. de Jager, "Improving the tracking performance of mechanical systems by adaptive extended friction compensation," in *Preprints of the 12th IFAC World Congress*, vol. IX, (Sydney, Australia), pp. 37–42, IFAC, 1993.

[4] B. de Jager, "Improving the tracking performance of mechanical systems by adaptive extended friction compensation," *Control Engrg. Practice*, 1994. To appear.

[5] C. Canudas de Wit, "Experimental results on adaptive friction compensation in robot manipulators: Low velocities," in *Proc. Symp. Experimental Robotics I* (V. Hayward and O. Khatib, eds.), vol. 139 of *Lecture Notes in Control and Information Sciences*, (Montreal, June 1990), pp. 196–214, Springer Verlag, Berlin, 1990.

[6] C. Canudas de Wit, P. Noël, A. Aubin, and B. Brogliato, "Adaptive friction compensation in robot manipulators: Low velocities," *Internat. J. Robotics Res.*, vol. 10, pp. 189–199, June 1991.

[7] J.-J. E. Slotine and W. Li, "Adaptive manipulator control: A case study," *IEEE Trans. Automat. Control*, vol. AC-33, pp. 995–1003, Nov. 1988.

[8] J.-J. E. Slotine and W. Li, *Applied Nonlinear Control.* Englewood Cliffs, New Jersey: Prentice-Hall, Inc., 1991.

[9] R. Ortega and M. W. Spong, "Adaptive motion control of rigid robots: a tutorial," *Automatica—J. IFAC*, vol. 25, pp. 877–888, Nov. 1989.