The use of acceleration measurements to improve the tracking control of robots

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The Use of Acceleration Measurements to Improve the Tracking Control of Robots

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SUMMARY

The paper discusses the use of acceleration measurements to improve the performance and robustness of controllers for robotic systems. To use acceleration signals there are at least two approaches: direct use of the acceleration in a feedback loop to improve the performance and robustness, and indirect use in an observer to improve the estimates of position and speed of the robot. An evaluation of both approaches is presented, using simulations and experiments on a flexible multi degree-of-freedom XY-table.

Several proposals for the use of the acceleration in the feedback loop, giving slightly modified controllers, are discussed. The design of the controllers is based on a simplified two degree-of-freedom model. The observer is of the predictive type to compensate for the time delay in the implementation, and its design is partially based on Kalman filter theory. The simulation and experimental results enable us to draw some conclusions with respect to the improvement of performance and robustness.

It appeared that both acceleration feedback and an acceleration based observer can improve the performance of the control system, but the robustness did not change significantly. A combination of both approaches did not give any improvement in the experiments, but some in the simulations, because the stability of the controlled system was impaired. Contamination with noise of the acceleration signal (especially motor torque ripple), phase lag introduced by the signal processing equipment, time delay caused by the discrete time implementation of the controller and observer, and the non co-locatedness of the position and acceleration sensors are believed to be limitations for the usefulness of the acceleration signal. An improvement by a factor of 1.5 seems to be possible in practice, so the use of acceleration measurements in a feedback loop or an observer is recommended.

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INTRODUCTION

The use of acceleration measurements may improve the tracking performance of controlled mechanical systems. We distinguish between at least two approaches for the use of acceleration signals in robotic control systems. A *direct* approach, where the acceleration signal is used directly in some kind of feedback loop to improve the robust performance, and an *indirect* approach, where the signal is used indirectly in an observer for the estimation of the manipulator degrees-of-freedom and their derivatives, to improve the estimates of position and speed, *i.e.*, reduce the contamination with noise by filtering the measurements, or raise the bandwidth of the measurements [1]. Other benefits of using acceleration measurements are

1. the acceleration measurement can replace more expensive "no structure mounted" measurements
2. the acceleration sensor can be attached to the structure easily
3. it has low costs [2].

Our use of acceleration measurements aims at improving both the performance, *i.e.*, smaller tracking errors, and the robustness for model errors of robotic control systems.

The principal theme of the paper is an assessment and discussion of the usefulness of acceleration measurements in the robust control of robotic systems.

This theme has already been discussed by several authors. In [3,4] the acceleration is used to counteract the effects of uncertainty in the robot inertia matrix. Other types of model errors are not assessed. They modify a standard computed torque controller and compare several proposals for selecting some weight factors in this modification. Their results indicate that optimal selected factors give the smallest tracking errors, also compared with a standard computed torque controller. Slotine [5] hints at the use of an additional acceleration error feedback and gives an expression for the reduction of the tracking error in the presence of measurement errors. He adds a term proportionally with the first and second derivative of the tracking error to the control input signal of a standard adaptive computed torque like controller, later discussed in [6], and claims a reduction of the influence of parametric uncertainty on performance. This reduction is bounded by the influence of measurement noise. Heeren [7] proposes to use the acceleration to reduce the equation error, a measure for the model uncertainties. Here, the controller output is a linear combination, with suitable chosen factor, of the output of a lower level controller and the acceleration, then the equation error is reduced, proportionally, with this factor. His modification only decreases the equation error in the presence of model errors, and not otherwise. For certain types of lower level controllers, this modification also gives a proportional reduction of the tracking error. Still another approach, and an alternative for model-based control, is to use a simple linear PDD controller based on position measurement only [8]. Here, the acceleration is obtained by numeric differentiation. This gives only good results due to the very high sample rate of ≈ 5 [kHz]. Also the quantization error of the position measurement has to be quite small. Experimental results of the use of acceleration feedback are presented by, *e.g.*, [1,2,9-13].

The use of acceleration signals to improve the estimates of position and velocity, by filtering the signals to reduce the contamination with noise, or by raising the bandwidth of the signals, has also been proposed earlier, see, *e.g.*, [1].

A comparison of several of these proposals and an assessment of their relative merits, *i.e.*, potential benefits and limitations, is the aim of this research.

The next section gives a more thorough description of the control schemes investigated, Next we discus the experimental system and its design and simulation model, followed by a discussion of the setup of the evaluation. The following section presents and discusses the simulation and the experimental results. Finally, the last section contains the conclusions and recommendations.

CONTROL SCHEMES

This section contains an overview of several of the control schemes studied. Some schemes are based on an adaptive computed torque like controller proposed by Slotine and Li [6]. One of the schemes does not use acceleration feedback and is used as reference. Main emphasis is on a scheme that uses the acceleration according to the proposal of Heeren [7].

The system to be controlled is modeled by the following set of nonlinear equations in the m degrees-of-freedom q

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

where $M(q,\theta)$ is the $m \times m$ positive definite inertia matrix with model parameters θ, $C(q,\dot{q},\theta)\dot{q}$ is the m vector of Coriolis and centripetal forces, $g(q,\dot{q},\theta)$ the m vector of gravitational forces, Coulomb, and viscous friction, and f the m vector of generalized control forces. In this model each degree-of-freedom has its own motor. Here, we neglect the dynamics of the motors and amplifiers, and the influence of stiction, backlash, and flexibility of the joints and links.

The control scheme of Slotine and Li consists of a feed forward component, based on an estimate of the manipulator dynamics, and a PD component, resulting in

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

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, $\dot{q}_r = \dot{q}_d + \Lambda\tilde{q}$ a virtual reference trajectory, $s = \dot{\tilde{q}} + \Lambda\tilde{q}$ a measure of tracking accuracy, $\tilde{q} = q_d - q$ the tracking error, and $q_d(t), \dot{q}_d(t), \ddot{q}_d(t)$ the desired trajectory. The control parameters are K_v and Λ.

The component $K_v s$ is a genuine PD control, because it is equal to $K_v(\dot{\tilde{q}} + \Lambda\tilde{q}) = K_v\dot{\tilde{q}} + K_p\tilde{q}$ with $K_p = K_v\Lambda$. Putting the PD component in this form makes it easy to extend the class of controllers for the tracking error from PD to, *e.g.*, sliding motion controllers, based on the sign of s. The measure of tracking accuracy s is used also in the adaptation part of the controller.

The adaptation law proposed by Slotine and Li is not used in this work, to enable a more lucid view and interpretation of the results, when using acceleration signals.

The modification proposed in [5] is to add a term $\alpha\dot{s}$ to the control input signal of (2). A reduction of the influence of parametric uncertainty on performance by a factor $1 + \alpha/\beta$, with β the gain margin, is claimed. So a large α is desired to improve the tracking performance. However, the influence of noise $n_{\ddot{q}}$ on the acceleration measurement will diminish this improvement. A relative error Δ_r in this measurement is claimed to have the same influence on tracking performance as a disturbance signal of relative size $\frac{\alpha}{\alpha\beta+1}\Delta_r$. For small α this influence is negligible ($\approx \alpha\Delta_r$), but for large α it is proportional with Δ_r/β. So, a good conditioning of the acceleration signal, by using filters, and an accurate sensor are necessary.

The modification proposed by [4] modifies the standard computed torque control

$$f = \hat{M}(q)(\nu + \ddot{q}_d) + \hat{C}(q,\dot{q})\dot{q} + \hat{g}(q,\dot{q}) \qquad (3)$$

where ν is the output of a linear, *e.g.*, PD, controller to

$$f = \hat{M}(q)(\alpha I(\nu + \ddot{q}_d) - \beta I\ddot{q}) + \hat{C}(q,\dot{q})\dot{q} + \hat{g}(q,\dot{q}) \qquad (4)$$

When $\hat{M}$ is chosen so the relative uncertainty in the mass matrix $\gamma = \max_{q,\theta} \|M^{-1}\hat{M} - I\| < 1$ and β is chosen to satisfy some stability requirement, they argue that the following choice for α is optimal

$$\alpha = 2\left(\frac{1+\gamma}{1+\beta(1+\gamma)} + \frac{1-\gamma}{1+\beta(1-\gamma)}\right)^{-1} \qquad (5)$$

in the sense that it gives the largest reduction of the influence of errors in the mass matrix $\hat{M}$ on the closed loop system equations. A simpler alternative is to choose $\alpha = \beta + 1$.

The acceleration can give an indication of the equation error, simply by filling in the measurements in the model equation; the resulting residue is an indication of the equation error and there are several ways to reduce it, using acceleration feedback, as will be discussed in the following. Define the equation error for (1) as

$$e = M(q_m, \hat{\theta})\ddot{q}_m + C(q_m, \dot{q}_m, \hat{\theta})\dot{q}_m + g(q_m, \dot{q}_m, \hat{\theta}) - f_m$$

where q_m, $\dot{q}_m$, $\ddot{q}_m$, and f_m are measurements that can be associated with q, $\dot{q}$, $\ddot{q}$, and f.

A simple method to reduce the equation error is using the acceleration as an additional input to the controller. If the new controller output is a linear combination, with suitable chosen factor, of the output of the original controller and the acceleration, the equation error can be reduced. The control force $f = f(q, \dot{q}, t)$, *e.g.*, (2), can be extended to $f^* = f^*(q, \dot{q}, \ddot{q}, t)$ when acceleration measurements are available. As shown by [7], when the acceleration enters in the feedback law as

$$f^*(q, \dot{q}, \ddot{q}, t) = (1 + \alpha)f(q, \dot{q}, t) - \\ - \alpha\left(\hat{M}(q)\ddot{q} + \hat{C}(q, \dot{q})\dot{q} + \hat{g}(q, \dot{q})\right) \quad (6)$$

it is possible to reduce the equation error e to

$$\frac{e}{1 + \alpha}. \quad (7)$$

A large α may reduce the equation error considerably. A limitation is the fact that the acceleration signal is contaminated with noise, see [5], and is fed back with some time delay. This limits the choice of α, *e.g.*, $\alpha < 2/3$. Also relation (7) does not hold exactly, because it assumes that the unmodified equation error e does not change when using another feedback law. This assumption is not valid, because the system proceeds along a slightly modified trajectory q.

For controllers of the type (2) the equation error e appears as the only driving term in the tracking error dynamics, and its influence is reduced by the same factor $1 + \alpha$, giving a reduction of the tracking error for $\alpha > 0$. For other controllers, *e.g.*, a PD control law, there are more driving terms in the tracking error dynamics. Here a more complex relation between α and the tracking error exists.

Based on the available literature, there is presently no readily available recipe to design the acceleration feedback gain, let alone some guidelines for the use of acceleration in a more complex control scheme than a simple feedback loop (besides using it in a state estimator). In the following we will only present results obtained with the controller modification proposed by [7].

For the other approach investigated, the use of an acceleration based observer, a presentation of the observer for a general mechanical system (1) is not the purpose of this paper. A presentation is therefore deferred and we only comment that the design of the observer is based on a linear model, so standard techniques to design the gain, based on Kalman filter theory, could be used, the only complication is the direct feed-through of the input torque in the acceleration measurements, but for this problem a standard solution is available. Because the standard assumptions used in Kalman filter theory are not satisfied, *i.e.*, the system and measurement noise are not white and Gaussian, the filter gain matrix needs some tuning to be useful in practice.

SYSTEM AND MODELS

The system studied is an 2D Cartesian manipulator, see Fig. 1, acting in the horizontal plane. The control system configuration is presented in Fig. 2. The acceleration measurement system is not included in this drawing and the laser based end-effector position measurement system [14] was not used in our experiments. The table consists of three prismatic joints, where two of the joints move parallel to each other and are coupled by a torsion spring. The spring can easily be replaced, and that is done to change the stiffness of this link. A complicated model of the XY-table [15], the evaluation model, has been used for the simulations. It will not be elaborated here, but it is a three degrees-of-freedom model, including provisions for motor torque ripple, sensor quantization, discrete time implementation of the controller, and also Coulomb, viscous, and position dependent or periodic friction [16].

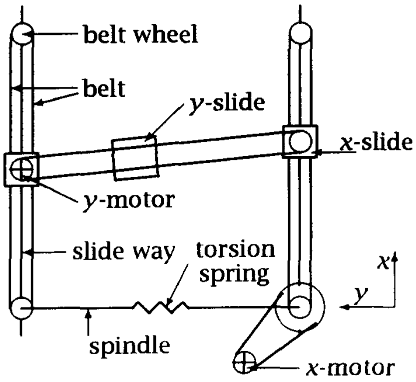

Figure 1: Schematic drawing of XY-table

It consists of three prismatic joints, where two of the joints move parallel

For the design computations and in the model based controller a simple model of the XY-table has been used. The equations for this model are

$$\theta_1\ddot{x} + \theta_3 \operatorname{sgn}\dot{x} = f_x$$
$$\theta_2\ddot{y} + \theta_4 \operatorname{sgn}\dot{y} = f_y$$

where x and y, the coordinates of the y-slide, are the degrees-of-freedom q, f_x and f_y the control forces in x

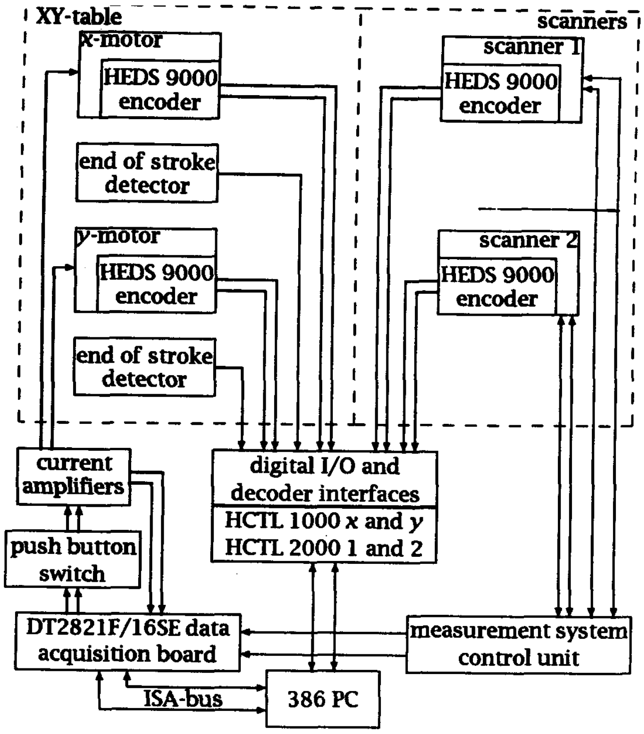

Figure 2: Control system of XY-table

and y direction, and $\theta_i, i = 1, \ldots, 4$, the model parameters: θ_1 and θ_2 are the equivalent masses in x and y direction, θ_3 and θ_4 are the coefficients of the Coulomb friction in x and y direction. The other effects, mentioned above, are not taken into account. Coriolis and centrifugal forces are absent, because there is almost no coupling between movements in x and y direction. Also gravitational forces are absent because the manipulator moves in the horizontal plane.

For the nominal parameter values used in the design computations see Table 1.

Table 1: NOMINAL PARAMETERS OF THE XY-TABLE DESIGN MODEL

Parameter	Value	Unit
θ_1	46.5	kg
θ_2	4.3	kg
θ_3	50.0	N
θ_4	15.0	N

EVALUATION SETUP

Both approaches are evaluated, using simulations and experiments on a multi degree-of-freedom XY-table, containing several sources for unmodeled dynamics that can be manipulated by the experimenter. The design of the controllers and observer is based on the simplified two degree-of-freedom model. The use of such a simplified model, compared with the more complex real system, enables us to draw conclusions with respect to the improvement of robustness of the control system. The controller used is a non-adaptive version of an adaptive nonlinear controller proposed by [6] with, additionally, several types of acceleration feedback loops and an observer for the estimation of the position and velocity. A simple friction compensation term has also been added, see [16]. Because the controller is implemented in discrete time, the observer is of the predictive type, predicting the states one sample ahead of the latest measurement available, to compensate for the computational time delay of the implementation. The simulation model used is just a plug in replacement for the experimental system. The controller implementation for the simulations and the experiments is therefore essentially the same.

RESULTS AND DISCUSSION

Acceleration feedback

It appeared that acceleration feedback, as proposed by [7] can improve the performance of the control system, but the robustness did not change significantly. This is evident from Figs. 3-4, showing the influence of parameter errors in the end-effector mass on tracking error performance for several values of α. The tracking error is reduced, but its relative increase for changes in the mass does not change significantly. Both simulation and experimental results are presented and the control task was the tracking of a circle. The measure of tracking accuracy used is the mean absolute tracking error (MATE) over the last complete circle, so initial transient effects are not included.

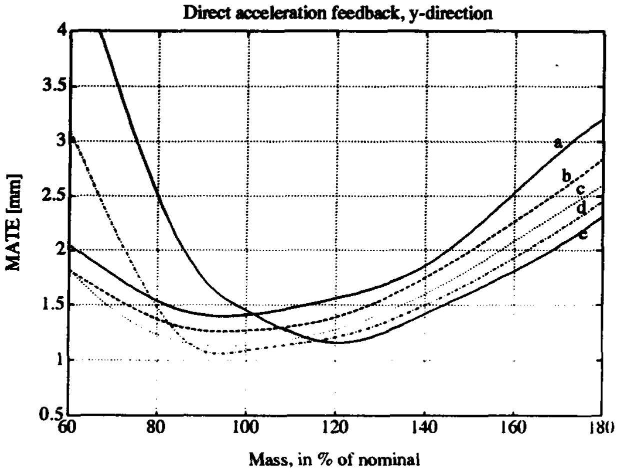

Figure 3: Tracking error in y-direction, simulation, a: $\alpha = 0$, b: $\alpha = 0.2$, c: $\alpha = 0.4$, d: $\alpha = 0.6$, e: $\alpha = 0.8$

The influence of the torsion spring stiffness, *e.g.*, a change in the unmodeled dynamics, is shown in Fig. 5. The MATE is given both as a function of closed loop

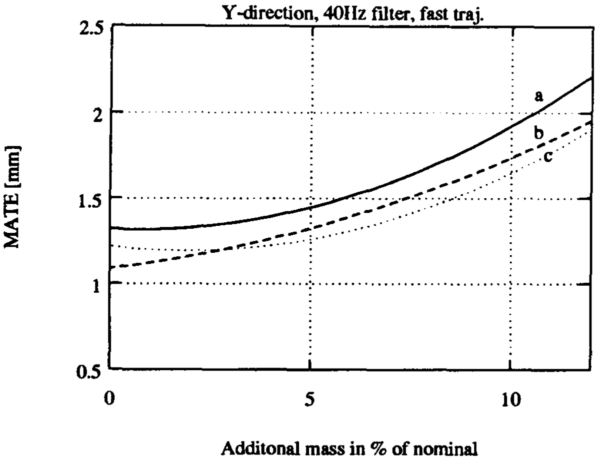

Figure 4: Tracking error in y-direction, experiment, a: $\alpha = 0$, b: $\alpha = 0.3$, c: $\alpha = 0.4$

design frequency and α. Here, the usefulness of acceleration feedback is not evident. The performance measure is quite insensitive for acceleration feedback when the spring is flexible, but the stability is impaired for larger design frequencies and larger α.

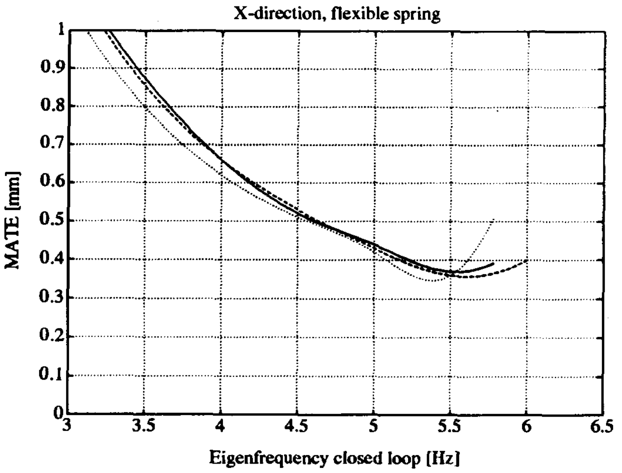

Figure 5: Tracking error in x-direction, experiment, — : $\alpha = 0$, - -: $\alpha = 0.4$, · · ·: $\alpha = 0.6$

In principle, the performance increase depends, by a fraction like function, on the acceleration feedback gains. The feedback gains can, however, not be increased too much. Contamination with noise of the acceleration signal, torque ripple, time delays in the feedback and observer, non co-located position and measurement sensors (the position encoder is mounted on the motor shaft and the acceleration sensor on the end-effector) are the main limitations for high gains in the acceleration feedback loop, and therefore the main limitations for its use. To eliminate noise and increase the signal-to-noise ratio, it was necessary to, quite elaborately, filter the measured acceleration with low pass filters. Several filters have been used, *e.g.*, Butterworth filters with cut-of-frequencies of 1 [kHz] and 10 [Hz], and a first order filter with 10 [Hz]. The Butterworth filter is incorporated in the signal amplifier and the first order filer was inserted between the amplifier and the AD conversion.

Acceleration based observer

The use of the acceleration signal in an observer makes it possible to obtain a more accurate estimate of, especially, the velocities. Also the bandwidth of the velocity signal estimate improves. This results in an improvement of the tracking error, for both simulations and experiments, see Figs. 6-7. This improvement was of the same order as obtained with acceleration feedback. The improvement of the robustness was not sig-

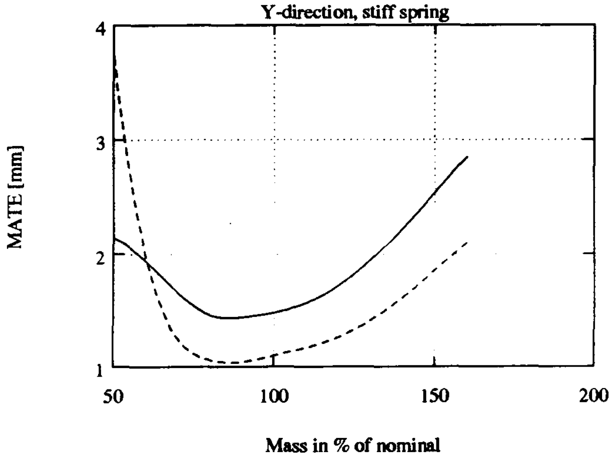

Figure 6: Tracking error in y-direction, simulation, — : without, - -: with using acceleration

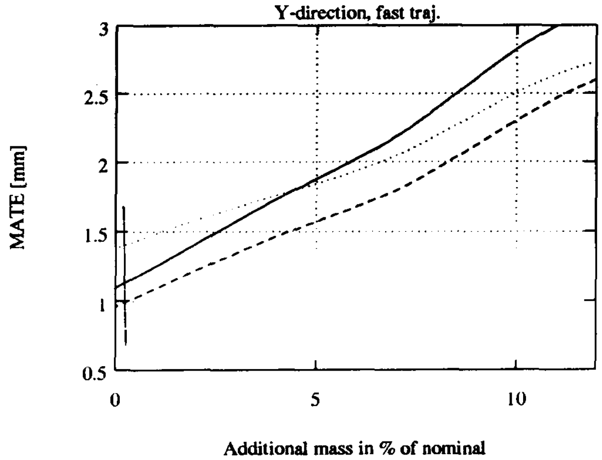

Figure 7: Tracking error in y-direction, experiment, —: without using acceleration, - -: with acceleration filtered at 40 [Hz], · · ·: with acceleration filtered at 10 [Hz]

nificant, also just like in the acceleration feedback approach, and for the same reasons. The same situation occurs for the influence of the flexibility of the torsion spring.

Acceleration feedback and observer combined

The combined use of the acceleration for both a feedback loop and an observer did show to be profitable in simulations but not in practice due to impaired stability that made a lower controller bandwidth necessary. Because in our case the separation theorem is not valid, due to the nonlinearity of the system and the unmodeled dynamics, this is not unexpected. The stability problem is accounted to the frequency contents of the input signal, in our case the torque commands to the drives. When both approaches are used this signal contains fairly large high frequency components that excite unmodeled dynamics. An additional filtering of the input signal, except for the friction compensation part, could not eliminate this phenomena, due to the causality of the filter and the corresponding additional phase shift.

CONCLUSIONS AND RECOMMENDATIONS

In general, the trend to avoid, at all costs, the use of acceleration measurements (*e.g.*, evident in the adaptive control of robots, where it is stated to be an advantage not to use the acceleration explicitly in the control scheme) does not seem to be appropriate, especially because it can improve the tracking performance, and also because the acceleration is relatively easy and straight forward to measure, and the measurement can be performed by structure mounted devices. An increase in tracking accuracy by a factor of 1.5 seems to be possible in practice. We therefore recommend to use acceleration feedback, or acceleration based observers to replace velocity signals measured by low bandwidth tacho's. Based on our experience we do not recommend to use the two approaches together, but this may be due to our specific system. A clean acceleration signal is paramount for its usefulness, so a high fidelity sensor is necessary and some filters should be used to increase the signal-to-noise ratio, without adding to much phase shift.

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