External Vibration Damping of a Robot Manipulator’s TCP Using Acceleration Feedback

Tobias F. C. Berninger\textsuperscript{1,*} and Daniel J. Rixen\textsuperscript{1}
\textsuperscript{1} TUM Chair of Applied Mechanics, Boltzmannstr. 15, 85748 Garching

There are multiple possible applications, which demand high accuracy from industrial robot arms. The usual approach to improve the path accuracy of these robot manipulators is to make the mechanical design as stiff as possible and to employ high fidelity joint controllers, which compensate path inaccuracies with well-identified models of the manipulator system. These methods are, however, only available to the robot manufactures themselves during their development phase. Companies designing tools for specific high accuracy tasks generally cannot change the design of a given robot manipulator and are bound to its precision. An alternative concept to further increase the path accuracy of a robot manipulator, without making changes to its design itself, might be to employ traditional Active Vibration Damping techniques by adding a supplementary proof-mass actuator to the robots tool center point with collocated acceleration sensor feedback. This paper explores the feasibility of this idea within a multi body simulation of a simple robot manipulator, which consist of rigid links, flexible joints and is actuated by cascaded joint controllers. The performance of an acceleration feedback controller employed on the robots TCP is evaluated by a test trajectory.

1 Introduction

The large impact of the structural dynamics of a robot manipulator on its overall accuracy has spawned a great amount of publications over the last decades [1]. A concise overview on various topics of modeling and control of the structural dynamics of a robot can for example be found in [2]. Most proposed control techniques assume either the joint torque or motor position as the control input and rely on the accurate knowledge of the underlying system dynamics [3, 4]. In practice, a full dynamic model of a robot manipulator is difficult to acquire using measurements and even harder to predict with just simulation data. Measurements of the pose dependent structural dynamics of a robot manipulator are for example shown in [5].

The External Vibration Damping (EVD) approach proposed in this work aims to simplify the control problem by adding a proof-mass actuator near the robot’s TCP, Fig. 1. By moving the actuator, its inertia forces provide an additional control input to directly influence the dynamics of the TCP, which should move as smoothly as possible. A collocated acceleration sensor next to the actuator provides feedback. This setup allows to employ simple active vibration damping control techniques as for example described in [6], by reducing the robot manipulator to a time varying mechanical structure. The external active vibration controller is supposed to work independently of the robot’s joint controllers and without prior knowledge of the underlying system dynamics.

An idea that is closely related to this is the utilization of micro/macror redundancy: A first set of macro degrees of freedom (DOF) provide a large range of motion but without the required accuracy. The second set of micro DOF utilize smaller sized actuators which only have to carry the robot’s tool or payload and provide the required high precision over a larger bandwidth. Book and Lee [7] try to suppress unwanted vibrations of a large flexible manipulator through the inertial forces induced by the joint torques of a small arm located at the TCP of the large robot. The concept is further explored in [8–10] by using the small arm as a two DOF vibration absorber with acceleration feedback.

2 Robot Model and External Vibration Damping

A multi body simulation (MBS) of a 2D robot arm is built to test the viability of external vibration damping at the TCP with a proof-mass actuator and acceleration feedback. The robot model consists of three rigid links which are connected by three rotary joints, Fig. 1. The MBS is coupled to a joint model which uses a linear stiffness $c_J$ to couple the joint angle $\theta_J$ of the MBS to the motor angle $\theta_M$, Fig. 2. Motor inertia $J_M$ and a gear ratio of $N = 100$ also accounted for in the joint model, while the inertia of the links is part of the MBS. Gear friction is modeled as viscous damping $d_J$:

\[
\begin{bmatrix}
J_M & 0 \\
0 & 0
\end{bmatrix}
\begin{bmatrix}
\dot{\theta}_M \\
\dot{\theta}_J
\end{bmatrix} +
\begin{bmatrix}
0 & 0 \\
1 & d_J
\end{bmatrix}
\begin{bmatrix}
\ddot{\theta}_M \\
\ddot{\theta}_J
\end{bmatrix} +
\begin{bmatrix}
c_J & -c_J N \\
-c_J N & c_J N^2
\end{bmatrix}
\begin{bmatrix}
\theta_M \\
\theta_J
\end{bmatrix} =
\begin{bmatrix}
T_M \\
T_J
\end{bmatrix}.
\]

The joint model is driven by the motor torque $T_M$. A model for a typical BLDC motor is used and the motor angle $\theta_M$ is controlled by a cascaded P-PI-PI joint position controller.

\* t.berninger@tum.de
The robot performs a test trajectory from a completely stretched out position to a retracted one with high jerk in the beginning and the end. The resulting path deviation is shown in Fig. 3 (blue line), which shows high levels of vibrations at the end position. To damp out the residual vibrations, a typical acceleration feedback controller is used [6]:

\[
G_c = \frac{f_c}{\omega_{TCP}} = \frac{-g}{s^2 + 2\xi_c\omega_c s + \omega_c^2},
\]

\[
G_c = G_{c1}(g_1, \xi_{c1}, \omega_{c1}) + G_{c2}(g_2, \xi_{c2}, \omega_{c2}).
\]

The controller replicates a tuned-mass damper and is tuned to the first two structural eigenfrequencies of the robot in its end position \(\omega_{c1}, \omega_{c2}\). The damping factors are \(\eta_{c1}/c_2 = 0.5\) and appropriate gains \(g_{c1}/c_2\) are chosen. Results obtained when controlling one or two modes are shown in Fig. 3, which shows a large improvement of the dynamic accuracy of the system.

3 Conclusions

The analysis of this simple but realistic example shows good potential for the external vibration damping approach at the TCP of a robot. A simple controller can easily be tuned to greatly improve the dynamic performance of the system at the cost of a reduced payload, since an additional set of proof-mass actuators has to be carried by the robot.

The tuning parameters of the acceleration controller used here are set to the eigenfrequencies of the robot in its end pose, however the structural dynamics of the robot are dependent on its position. This should be taken into account for the controller design and will be part of future work. Furthermore, the MBS will be extended with flexible links and better friction models. Interaction between the external vibration damping controller at the TCP and the robot joint controller is an area of concern and will be investigated in simulation and on a test rig. Finally, a prototype device will be built to be tested on different types of industrial manipulators.

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