CIS II Paper Review

Author:

Tianyu Wang

Paper:

A Simple Active Damping Control for Compliant Base Manipulators

J. Y. Lew and S.- Moon, “A simple active damping control for compliant base manipulators,” IEEE/ASME Transactions on Mechatronics, vol. 6, no. 3, pp. 305–310, Sep. 2001, doi: 10.1109/3516.951368.

Paper Selection Reason:

1. The paper discusses the reduction of mechanical vibration in order to increase end-effector accuracy, this could also be a key question that concerns our own project mechanical design
2. This paper illustrates the mathematical assumptions and models of an robotic manipulator mounted on to a mobile platform, which is also similar with our intended mechanical structure.
3. This paper introduces novel active damping feedback loop independent from the control loop of the robotic manipulator, thus decreasing the cost it takes for us to adapt such control strategy to our design in the future.

CIS II Project Summary:

This project originates from the need to design a robot to recognize key ICU equipment, operate them, and project key information from such equipment straight back to the operator. Thus, reducing the time, protection gear, and exposure risk cost that an ICU team member faces when entering an ICU room during a COVID-19 pandemic.

Our team targets the end-effector design and the user interface of this tele-operable robotics system. More specifically, we want to build an effective end effector based on an cartesian robots that is able to interact accurately with different modalities (knob, buttons, sliders etc.) of medical equipments in the ICU, and can be operate on a functional GUI.
Furthermore, additional object recognition algorithm will be developed alongside the above robot to provide the robot with the information of its relative location to the target equipment based on camera input.

Paper Abstract:

Problem: Mechanical vibration of the base for compliant based robotic manipulator (i.e robotic manipulator mounted on a mobile platform), present 6 DOF vibration that hinders the accuracy of the end effector.

Goal: To present a novel active damping control strategy using one-time torque information and acceleration of the robotic joint angles.

This paper introduces and evaluates a novel robust control strategy that reduces overall mechanical vibration and enables better end-effector tip positioning of an end effector mounted on a mobile robot. More specifically, it models a moving mobile platform and its oscillation as compliant based manipulator and proposed a control algorithm that utilizes acceleration feedback to actively compensate for overall mechanical vibration of the system.

Background:

When a robotic manipulator is mounted to a crane, boom or mobile platform, it loses its accuracy and speed due to the compliance of the base. More Specifically, such loss in accuracy and speed is a result of 6 DOF vibration due to the mechanical nature of the mobile platform. Such vibration conducts serially through the robotic manipulator onto the end-effector and is often amplified due to the lever principle. Therefore, we need a method to reduce overall mechanical vibration to increase end-effector accuracy by actively compensating for it.

Competitive methods:
There are many methods introduces that targets similar problem of maintaining accuracy of local end-effector movement, some approach this monitoring tip position to compensate, others use linear model to achieve a robust and simple feedback loop. Here are some more representative methods the author mentioned and their pros and cons.

Methods	Pros	Cons	Cite
Tip dynamic tracking control for a micro/macro manipulator	Accurate local end-effector movement & versatile mobile platform movement	Ignored internal dynamic stability	T. Yoshikawa, H. Kensuke, and A. Matsunomo, “Hybrid position/force control of flexible-macro/rigid-micro manipulator systems,” IEEE Trans. Robot. Automat., pp. 633–640, 1996.
Damping Controller based on linear model	Robust and simple to calculate	Only applicable to linear model	A. Sharon, “The Macro/Micro Manipulator: An Improved Architecture for Robot Control,” Ph.D. dissertation, MIT, Cambridge, MA, 1988.
a two-time scale model of micro/macro manipulators	Accurate	Configuration Specific	S. Lee and W. J. Book, “Robot vibration control using inertial damping forces,” presented at the VIII CISM-IFTOMM Symp. Theory and Practice of Robots and Manipulators, Cracow, Poland, July 1990

Paper Significance

Approach: The control strategy utilizes modeling to decouple the effect of control input on compliant base and on linear robotic manipulator. By finding the optimum control input using feedback loop, the strategy accounts for nonlinear and uncertain base oscillation by using acceleration of joint angle and one-time delay torque input to achieve faster damping time of the oscillation and therefore reaches higher accuracy in end-effector positioning.

Result: The simulation and experimental study demonstrated the improvement of the overall system performance over large configuration change

Assumptions

To model the behavior of this system, we make the following assumption:

1. Compliant base can be modeled as paralleled spring and damper system with 6 DOF.
2. Robotic manipulator can be evaluated independently as an fix-based linked robotic arm.
3. Their overall dynamic can be modelled by combining them serially.

Shown below is an illustration of how such system can be broken down to a lumped mass model and a robotic manipulator with fixed base.

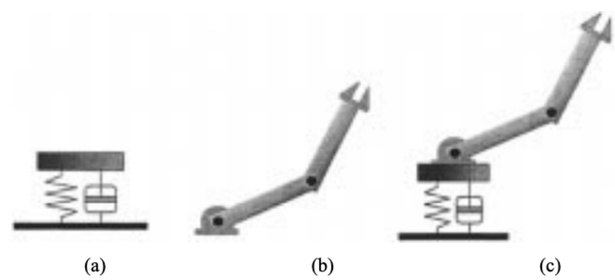

Fig. 2. (a) Lumped mass model of compliant base, (b) robotic manipulator with fixed base; and (c) robotic manipulator with compliant base.

Modeling

Based on previous assumptions, we model the system using the following dynamic equations

$$\mathbf{M}_b \ddot{X}_b + \mathbf{C}_b \dot{X}_b + \mathbf{K}_b X_b = 0$$

Compliant Base: We establish the dynamic equation using inertial, damping and stiffness component of the base, and monitor its oscillatory movement, speed and acceleration.

$$\mathbf{M}_r(q)\ddot{q} + C_r(\dot{q}, q) = \tau$$

Robotic Manipulator: for the linked robotic manipulator dynamic is modeled using a nonlinear term including centrifugal, Coriolis, joint friction and gravitational force. The input is Tao.

$$\begin{bmatrix} \mathbf{M}_b + \mathbf{M}_{b/r} & \mathbf{M}_{br}(q) \\ \mathbf{M}_{br}^{\mathrm{T}}(q) & \mathbf{M}_r(q) \end{bmatrix} \begin{Bmatrix} \ddot{X}_b \\ \ddot{q} \end{Bmatrix} + \begin{Bmatrix} \mathbf{C}_b \dot{X}_b + C_{br}(\dot{q}, q) \\ C_r(\dot{q}, q) \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_b & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} X_b \\ q \end{Bmatrix} = \begin{Bmatrix} 0 \\ \tau \end{Bmatrix}. \quad (4)$$

Overall System

Combining the above two equation serially, we have the equation for the unified system shown above. Note that this equation assumes only translational movement on the base and rotational movement is assumed to be very small.

Index of the equation :

- M: Inertia Matrix
- C: Damping Matrix
- K: Stiffness Matrix
- X_b : 6x1 vector of 6 DOF oscillation motion
- q: Joint coordinate vector
- Tao: input control

Control Scheme

The control objective is to determine the input control such that the base oscillation damps out as quickly as possible while the joint angle follows the desired path. This is a difficult control problem because: (1) one control input, has to control two variables and (2) an exact model of an inertia matrix and nonlinear terms is not available, and they vary as the configuration changes. A special damping controller is necessary to meet such a goal.

Finding Tao (Input Control)

To find Tao, we first introduce an uncertainty term as shown here. We mentioned before that we need to estimate the inertial term of linked robotic manipulator and measure the joint acceleration. Thus we manipulate the above full system equation and get this following uncertainty term.

$$\begin{aligned} N(\ddot{X}, \dot{X}, X) &= (\mathbf{M}_r(q) - \hat{\mathbf{M}}_r)\ddot{q} + \mathbf{M}_{br}^{\mathrm{T}}(q)\ddot{X}_b + C_r(\dot{q}, q) \\ &= \tau_p - \hat{\mathbf{M}}_r \ddot{q}. \end{aligned} \quad (6)$$

Notice here we used one-sample previous actuator torque T_p = Tao and utilized motor encoder to measure the acceleration of q. The uncertainty term can be computed from the acceleration measurement and one-sample delayed torque, and it is used as a feedforward term to linearize the system dynamics. Note that U term is input for feedback control. Notice how manipulator motion is now decoupled from base motion.

$$\tau = \tau_p - \hat{\mathbf{M}}_r \ddot{q} + u.$$

$$\begin{bmatrix} \mathbf{M}_b + \mathbf{M}_{b/r} & \mathbf{M}_{br}(q) \\ 0 & \hat{\mathbf{M}}_r \end{bmatrix} \begin{Bmatrix} \ddot{X}_b \\ \ddot{q} \end{Bmatrix} + \begin{Bmatrix} \mathbf{C}_b \dot{X}_b + C_{br}(\dot{q}, q) \\ 0 \end{Bmatrix} + \begin{bmatrix} \mathbf{K}_b & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} X_b \\ q \end{Bmatrix} = \begin{Bmatrix} 0 \\ u \end{Bmatrix} \quad (8)$$

$$\left\{ \ddot{X}_b + \mathbf{H}_{11} \mathbf{C}_b \dot{X}_b \right\} + \mathbf{H}_{11} \mathbf{K}_b X_b + \mathbf{H}_{11} C_{br}(\dot{q}, q) = \mathbf{H}_{12}(q) u \quad (10)$$

$$\hat{\mathbf{M}}_r \ddot{q} = u. \quad (11)$$

Show cased above is the derived optimized solution for Tao. As stated above, we see that the only variable we need to change is U, using this, we rewrite the whole system equation into equation 8, and separate them into two independent equations controlled by U. From equation 10 and 11 we observe that equation 10 illustrate how U influences the base damping and 11illustrate how we can use U to control only the linear robotic manipulator.

Finding U

Now our objective is to find U such that we optimize damping for the entire system while keeping q on trajectory. To find U, a composite controller is proposed based on decoupled model. Our goal now is to find U such that both equations shown above is stabilized.

$$u = u_{\text{fast}}(q) + u_{\text{slow}}(X_b).$$

This equation utilizes the two -time scale theory in which we design a fast controller for trajectory and a slow controller for controlling the base. More specifically, these two controller have the following characteristics.

- U_fast utilize linear tracking controller with high gain to differentiate from low natural frequency of the base
- U_slow utilizes derivative feedback of the base oscillation with gain to increase natural damping.
- In the actual implementation, the damping gain was increased gradually until maximum damping is obtained without violating the assumption that two-time scale separation exists in the closed loop system and that the base oscillation changes slowly.

$$u_{\text{fast}} = \mathbf{K}_p \tilde{q} + \mathbf{K}_d \dot{\tilde{q}} + \hat{\mathbf{M}}_r \ddot{q}_d$$

$$u_{\text{slow}} = -\mathbf{H}_{12}^{-1}(q_d) \mathbf{K}_{bd} \dot{X}_b$$

$$\ddot{X}_b + (\mathbf{K}_{bd} + \mathbf{H}_{11} \mathbf{C}_b) \dot{X}_b + \mathbf{H}_{11} \mathbf{K}_b X_b = -\mathbf{H}_{11} C_{br}(\dot{q}_d, q_d) + \mathbf{H}_{12} \hat{\mathbf{M}}_r \ddot{q}_d.$$

The three equations above showcases U_fast, U_slow and the combined composite controller dynamics. To make sure the system is stable, we contrict H_12 to be non-singular and H_11K_b, and H_11C_b are PD. With this, as long as we choose K_bd, the gain of the dynamic system, as a PD, the system will be stable. And as we increase K_bd, damping time decrease. Then lastly, bringing U back into Tao, we get this.

$$\tau = \tau_p - \hat{\mathbf{M}}_r \ddot{q} + \mathbf{K}_p \tilde{q} + \mathbf{K}_d \dot{\tilde{q}} + \hat{\mathbf{M}}_r \ddot{q}_d - \mathbf{H}_{12}^{-1}(q)\mathbf{K}_{bd} \dot{X}_b.$$

Test and Evaluation of Approach

Two set of test are conducted, one is simulation study with mathematical model. Then author also conducted experimental to demonstrate the effectiveness of the proposed active damping control scheme in a physical test bed. Test bed structure shown here.

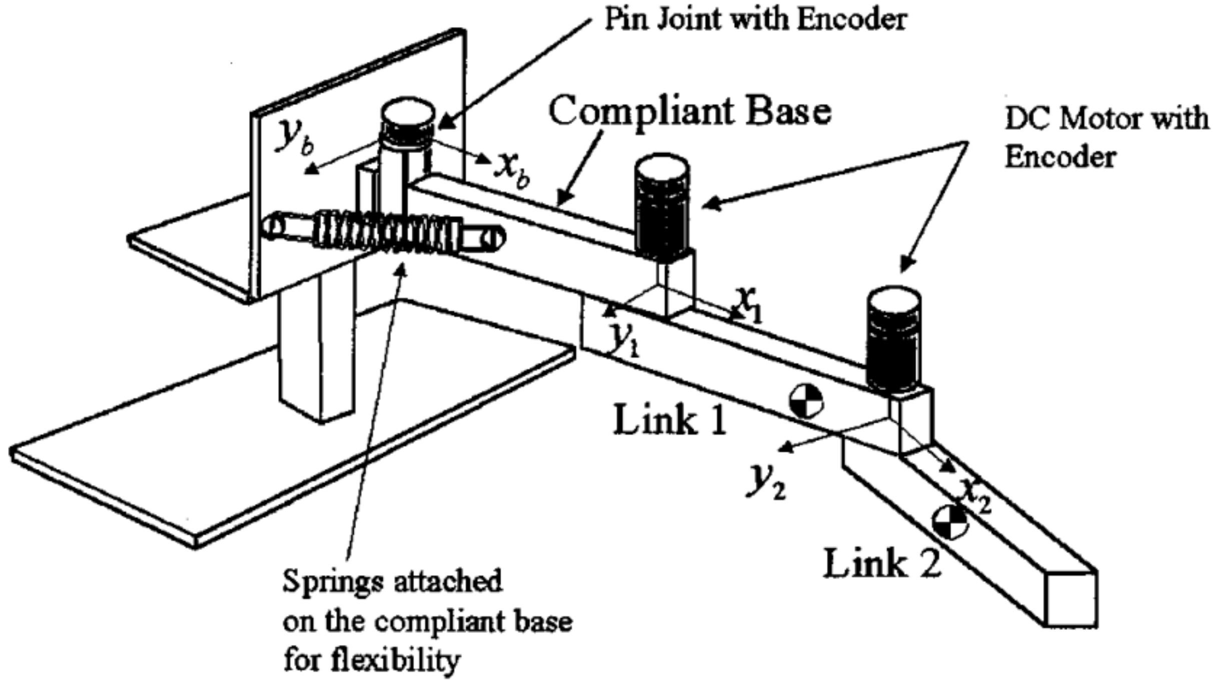

Fig. 3. Ohio University test bed.

It has a two-link rigid manipulator and a compliant base. The rotational joint with linear springs emulates the compliance of various supporting structures. And base compliance can be adjusted by adding a different set of linear springs

Result

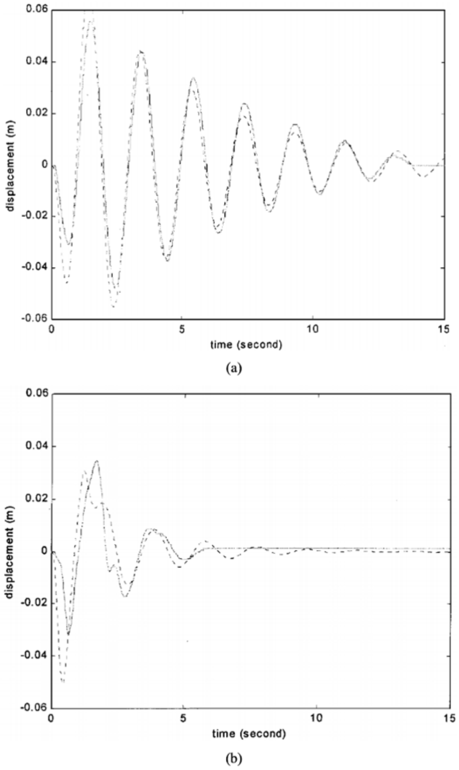

Fig. 4. Base motion for third order polynomial desired path (solid line: experiment result, dashed line: simulation result).(a) With PD control. (b) With active damping control.

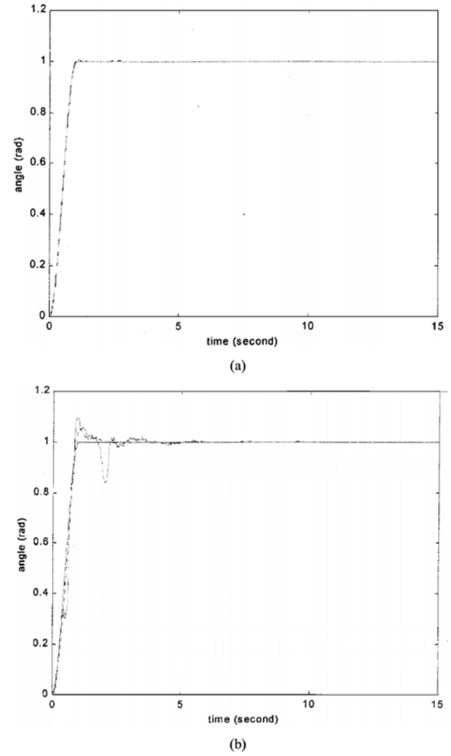

Fig. 5. Joint 2 motion for third order polynomial desired path (solid line: experiment result, dashed line: simulation result).(a) With PD control. (b) With active damping control.

The result of the paper is shown below, we have dashlines as experimental result and solid line for simulation. We can observe that for the top graphs, which is no active damping system, we see relatively accurate joint angle movement but long damping time with oscillation magnitude up to 0.06 m. However, it is obvious that with both simulation and experiment result, once the active damping control strategy is implemented, we observe an almost 50 % decrease in damping time and a significant decrease in oscillation magnitude from the start , showcasing the effectiveness of the strategy. Although we did also observe some disturbance in joint angle when doing experimental test, it soon falls back to stability after about 5 s. which is a reasonable trade off.

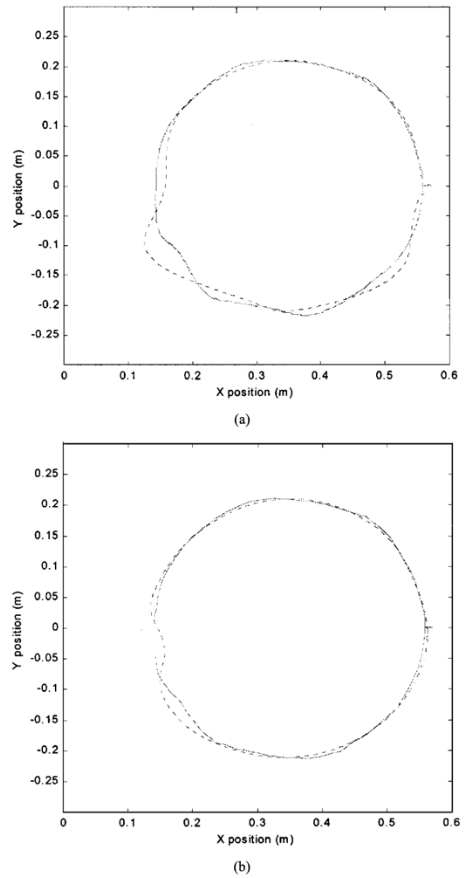

Fig. 6. Tip position for circular desired path (solid line: experiment result, dashed line: simulation result). (a) With PD control. (b) With active damping control.

Further test is conducted by asking the end effector to draw a circle. We see that the accuracy significantly increases with experimental result where the circle has no significant extrusion or disturbance in its trajectory.

What this paper did well

1. The author did a good job breaking down the complex system into series of simple models and conducted a novel decoupling method to separate the effect of input parameter Tao on base and on linear robotic manipulator.
2. The author defines clearly all the assumption made during his methodology and clearly indicated their purpose.
3. The approach to actively damp the oscillation generated by the base utilizes minimum parameter that can be easily gathered in real life and made this model open-ended such that we can apply to other configuration with some slight adjustment.
4. The active damping control strategy is made independent from the linear control loop such that this can be modularly added to other systems.

Comments

1. Author keep emphasizing on the active feedback loop of the control input and the feedforward loop to estimate inertia, but does not provide a diagram to clearly illustrate the relative relationship and interaction between passive estimation and active feedback.
2. This paper simplifies the 6 DOF by only considering derivation related to linear translation movement and did not consider rotational movement.
3. The proposed solution only offers damping control on relatively ideal situation and is based on many assumptions, whereas in reality, some assumptions may be violated leading to the system solution not able to converge.

Conclusion

- An active damping controller for a manipulator mounted on a compliant base is proposed in this paper.
- Under the assumption of two-time scale, its stability and design procedures are presented for a multiple link manipulator with multiple dimensional oscillation.
- It does not require the exact information of the model.
- The controller cancels out nonlinear and uncertain dynamics by acceleration feedback and adds more damping by base motion feedback.
- The simulation and experimental study demonstrated the improvement of the overall system performance over large configuration change.

Application to Project

- Design and analysis of mathematical model that decouples the movement of linear model with moving mobile platform.
- Method of evaluation for end effector accuracy by comparing input order with actual output trajectory.
- Design of controller and filter to smooth out end-effector movement.