A Simple Active Damping Control for Compliant Base Manipulators

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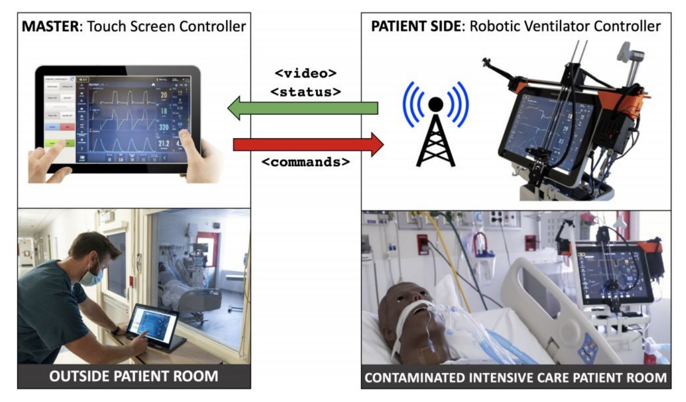
J. Y. Lew and S.- Moon, “A simple active damping control for compliant base manipulators,” *IEEE/ASME Transactions on Mechatronics*, vol. 6, no. 3, pp. 305–310, Sep. 2001, doi: 10.1109/3516.951368.

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.**

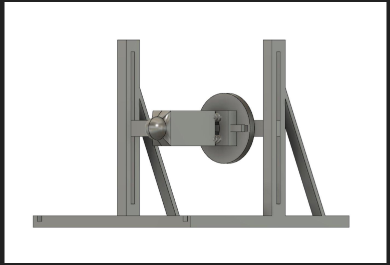


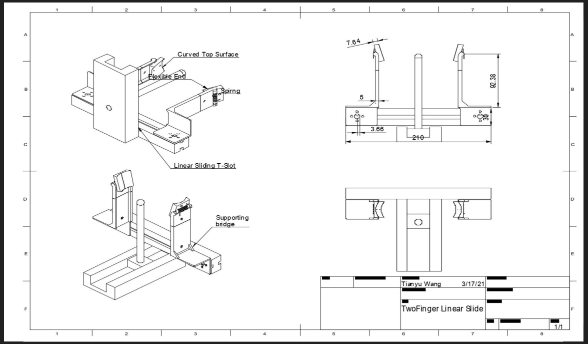
B. P. Vagvolgyi *et al.*, “Telerobotic Operation of Intensive Care Unit Ventilators,” *arXiv:2010.05247 [cs]*, Oct. 2020, Accessed: Apr. 12, 2021. [Online]. Available: http://arxiv.org/abs/2010.05247.

Our Goal

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

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.

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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 oscillation** 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.

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Competitive Methods

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	Requires measurement of tip position	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

“A Simple Active Damping Control for Compliant Base Manipulators”

- Relevance to project:
  - Mechanical vibration modeling using acceleration and one-sample previous torque
  - Independent damping control strategy that can be easily added to existing position control mechanism
- Summary and Key Results:
  - 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: propose a simple robust control strategy that will reduce mechanical vibrations and enable better tip positioning
  - 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

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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.

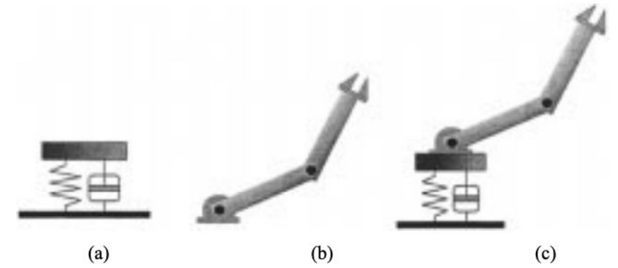

Fig. 2. (a) Lumped mass model of compliant base, (b) robotic manipulator with fixed base; and (c) robotic manipulator with compliant base.

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Modeling

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

1. Compliant Base

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

2. Robotic Manipulator

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

3. Overall System

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

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

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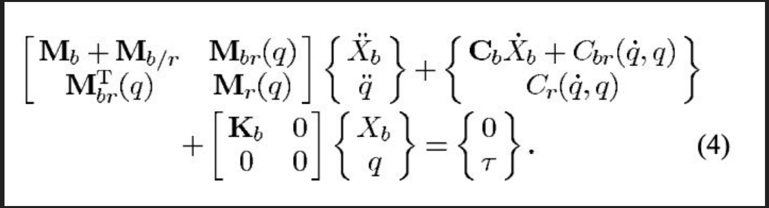
Control Scheme Design

Objective: To determine the input control such that the base oscillation damps out as quickly as possible while the joint angle follows the desired path.

Challenges:

- Tao has to control two variable q and X_b
- Exact inertial matrix and nonlinear term unknown



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

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Finding Tao

- Introduce uncertainty term N

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

  - Use one-sample previous actuator torque T_p
  - Use motor encoder to measure and smooth q, then compute 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.

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

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

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

$$\hat{\mathbf{M}}_r\ddot{q} = u. \tag{11}$$

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Finding U

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

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

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.

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

U_fast and U_slow :

- Chosen in different time scale
- Slow scale affect base motion and fast scale affects joint angle movements
- 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.

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

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

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

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Test and Evaluation of Approach

1. Simulation study with mathematical model
2. Experimental study is carried out to demonstrate the effectiveness of the proposed active damping control scheme in a physical test bed
    a. Two-link rigid manipulator and a compliant base
    b. The rotational joint with linear springs emulates the compliance of various supporting structures.
    c. Base compliance can be adjusted by adding a different set of linear springs

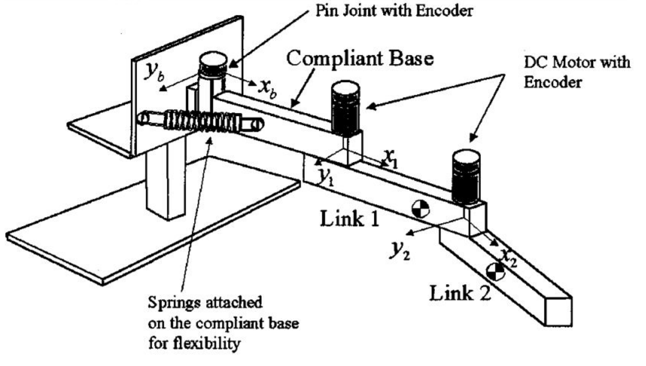

Fig. 3. Ohio University test bed.

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Result

- Solid Line: Simulation
- Dash Line: Experiment
- Top: PD Controller
- Bottom: with active damping
- 40% Decrease when active damping is used for base.

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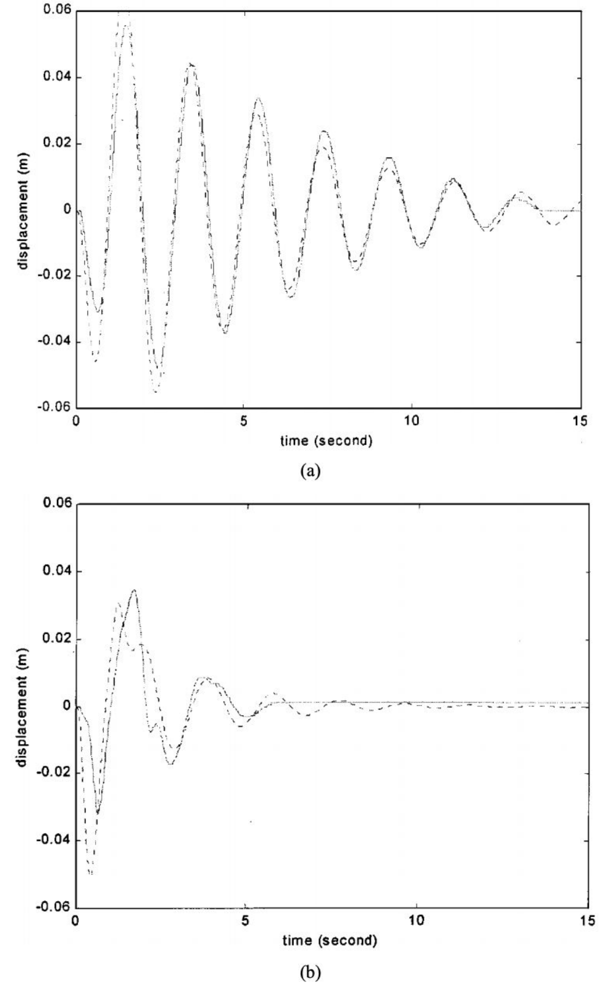


Fig. 4. Base motion for third order polynomial desired path (solid line: experiment result, dashed line: simulation result).(a) With PD control. (b) With active damping control.

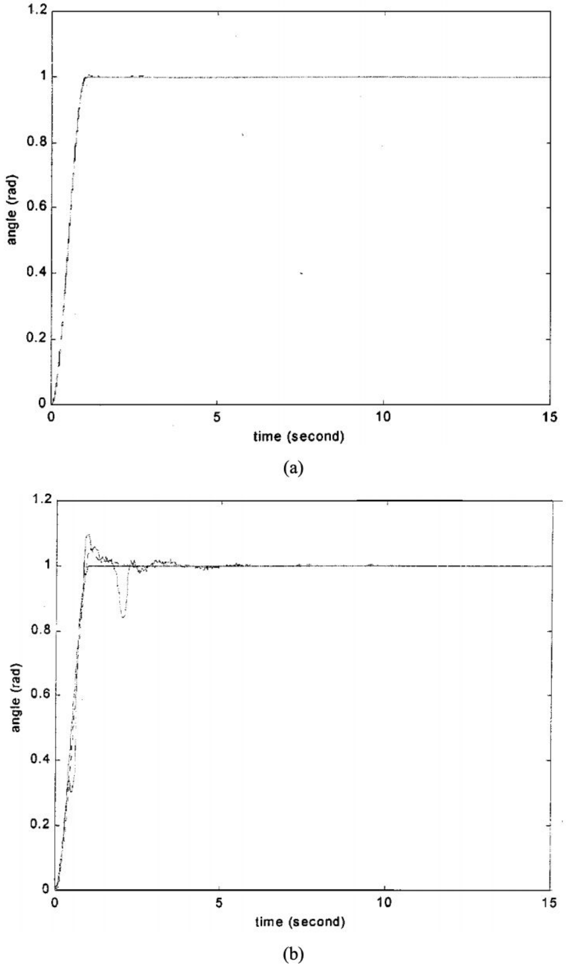


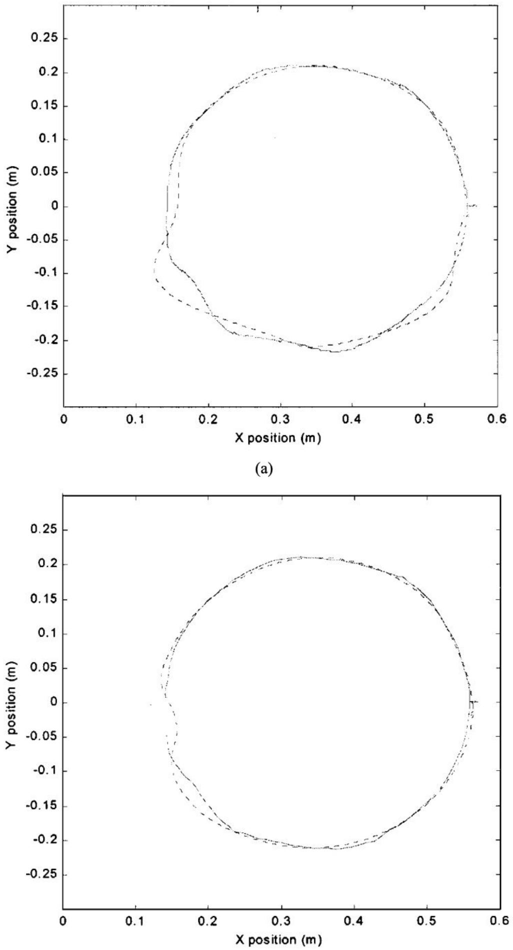
Fig. 5. Joint 2 motion for third order polynomial desired path (solid line: experiment result, dashed line: simulation result).(a) With PD control. (b) With active damping control.

Result (cont.)

Top: Pure PD Control

Bottom: With active damping control

Note: an additional 4Hz butterworth filter was added to ensure smooth acceleration calculation



(a)

(b)

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.

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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.

Critiques

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.

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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.