The Limitations of Independent Controller Design for a Multiple-link Flexible Macro-manipulator Carrying a Rigid Mini-manipulator

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Abstract

The combination of a long reach macro-manipulator and a short reach mini-manipulator enables fast, precise manipulation through a large workspace. When the macro-manipulator contains low frequency vibration modes, the control system design must account for the effects of these flexible modes. Because the mini-manipulator rides on the macro-manipulator, the mini-manipulator control torques will couple to the macro-manipulator. The most straight forward method of designing the control system is to develop independent controllers for the macro-manipulator and mini-manipulator subsystems and form a control architecture where the reference input for the mini is the difference between the desired tip position and the macro-manipulator end-point position. Thus the performance objective of positioning the tip quickly and precisely is achieved. In this paper, we show that such a control architecture creates a feedback loop between the two subsystems that results in two-way coupling between the macro and mini subsystems. This control architecture is then applied to the model of the Stanford University Two-Link Flexible Manipulator and the effects of the coupling are discussed. This analysis shows that designing independent controllers for the macro and mini subsystems can result in system instability, even though the subsystems are stable, and that to achieve desirable performance and assure system stability, the system model and the control system design must include this two-way coupling.

1 Introduction

Many applications require robotic manipulators which have a large workspace and are capable of fast, precise motion throughout the workspace such as that offered by a macro/mini (or macro/micro) robotic system. The long reach, or macro, manipulator is characterized by a "slow" response due to it's size. In contrast, the short reach, or mini, manipulator is characterized by a small work volume with fast, precise manipulation capability over that work volume. Combining the two such that the mini-manipulator rides on the end of the macro-manipulator offers an approach to the requirement of fast, precise manipulation over a large workspace [1].

In some application domains, the control system design for macro/mini-manipulators is complicated by flexibility in the links of the macro-manipulator. In space, for example, the cost of boosting mass into orbit requires the minimization of the robotic system mass while maintaining a

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large work volume. In hazardous waste cleanup, the narrow access of storage tank entries constrains the cross sectional area of the manipulator system. A long reach manipulator with either minimum mass or minimum cross sectional area has low vibration frequencies, typically within or near the desired bandwidth of the control system. To maintain stability and ensure desired performance, the control system design must account for these low-frequency vibration modes.

The simplest method for designing the control system is to assume there is no coupling between the subsystems and to partition the control design into two pieces: a macro-manipulator controller and a mini-manipulator controller. The macro controller is designed to control the macro-manipulator in the global frame, and the mini controller is designed to control the mini-manipulator in the mini frame in response to a reference input. Because the mini rides on the macro, there will be coupling from the mini control torques to the macro. This one-way dynamic coupling leads to interactions that degrade performance but, when the mini reference input is static (i.e. independent of the macro end-point position), do not cause instability.

The performance objective for the macro/mini system is to position the **tip** of the manipulator system quickly and precisely. This objective naturally suggests a control architecture where the reference input for the mini is the difference between the desired tip position and the macro end-point position, since the high bandwidth mini can compensate for overall positioning errors. The mini dynamic reference input creates a feedback loop between the two subsystems resulting in two-way coupling which must be properly included in the system model and control system design to achieve desirable performance and system stability.

2 Background

The concept of using a fast, short reach manipulator mounted on a slower, long reach manipulator, also called a Macro/Micro or Macro/Mini manipulator, was first introduced by Sharon and Hogan [1]. They conclude that independent macro and mini controllers are appropriate because the dynamics of the macro are slower than those of the mini.

Ballhaus developed independent controllers for a macro/mini system where the macro is a two-link flexible manipulator. He describes an undesirable interaction between the macro and mini manipulators when the gains on the mini controller are too large [2], resulting in performance limitations on the overall system.

Lew [3] uses the mini as a proof mass actuator to control the macro vibrations. Lew's work only examines the applicability of using the mini control torques to damp the macro vibration and ignores system performance issues. Sharf [4] addresses the use of the mini to damp the vibrations of the macro throughout the portion of the maneuver when the task is outside the workspace of the mini. Sharf's simulations illuminate the shortcomings of partitioning the control. Once the task enters the workspace of the mini, the mini not only discontinues damping the vibration modes, but allows the energy previously removed from the macro to return to the macro subsystem. The performance of the system can be quite poor. Sharf's research also recognizes the effects of the mini control torques on the macro subsystem, but does not address system performance.

3 Experimental System

The Stanford University Two-Link Flexible Manipulator System was constructed for research in the control of manipulators exhibiting link flexibility. The particular hardware system, shown in Figure 1, has been designed to enhance the issues associated with inherent structural flexibility in a multiple-link manipulator.

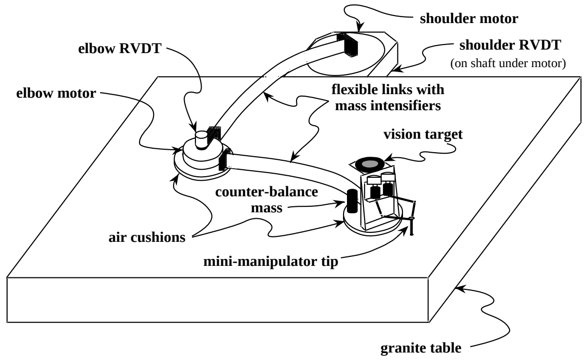

Figure 1: **Experimental Hardware Schematic**

The two-link flexible manipulator with a mini-manipulator mounted at its end-point.

The two-link, flexible main arm operates on air cushions in the horizontal plane of a granite table. The flexible links, which are 0.52m in length, exhibit significant bending in the horizontal plane due to their narrow cross section and orientation. Both the shoulder and elbow actuators are direct-drive, DC limited-angle torquers. Rotary variable differential transformers (RVDT's) are located at each of the motor shafts and provide joint angle measurements. A vision sensor provides end-point position and orientation measurements at 60 Hz.

A two degree of freedom mini-manipulator is mounted at the end-point of the two-link flexible main arm. The mini-manipulator consists of a five-link, closed-kinematic chain which operates in the horizontal plane. To allow for quick, precise motion of the tip, the four moving links are made of hollow tubes and are actuated by two small DC electric motors located at the base of the mini-manipulator. Rotary encoders mounted on top of the motors provide angular position and velocity information.

4 Modeling the Experimental System

To understand the effects of the mini control torques on the macro subsystem, a model of the full system is developed using a finite element approach [5] and model concatenation [6]. The model is linearized about the nominal configuration and includes the relevant sensor dynamics, the most notable of which is a 2 sample delay in the vision sensor used to determine the macromanipulator end-point position and orientation.

The model is verified by comparing frequency responses of the model and the experimental system. Experimental frequency response data were obtained from sine sweep tests, where a low-gain proportional-derivative controller was used at each joint to keep the manipulator near the desired configuration. The system model includes 8 flexible modes and the 4 rigid body modes.

Figure 2 shows the magnitude of four representative transfer functions. The solid line is the experimental data and the dashed line is the model. The upper left plot shows a collocated transfer function, the lower left shows a noncollocated transfer function, the upper right plot shows the coupling from mini control torques to the macro-manipulator, and the lower right plots validates the modeling of the mini-manipulator as a tip mass with linear actuators. Note that the transfer functions with mini control inputs show the effects of unmodeled friction and of the low-gain PD controller used for data collection. These results validate the model and demonstrate the coupling between the mini control torques and the macro subsystem.

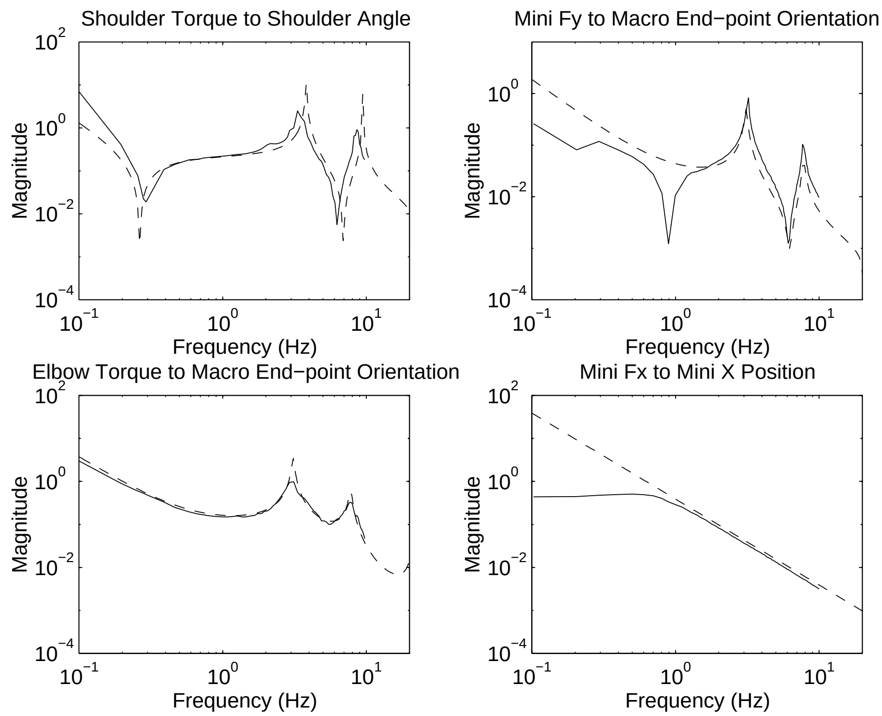

Figure 2: **Model and Experimental Transfer Functions**

Comparing the modeled transfer functions, the dashed line, and the experimental data, the solid line, shows excellent agreement between the two. The model accurately represents the dynamics of the experimental system. The experimental transfer functions with mini-Manipulator inputs show both unmodeled friction and the low-gain PD controller.

5 Combined Subsystem Controller

Typically, independently designed subsystem controllers are connected to form a Combined Subsystem Controller [1][2], as shown in Figure 3. The mini controller is designed to respond very quickly to a reference input while the macro controller is designed to position the macro end-point, which is assumed to be a rigid body, as quickly as possible. When $\alpha = 0$, referred to as the the static mini reference input, the desired mini position is determined before a maneuver and is not changed. When $\alpha = 1$, referred to as the mini dynamic reference input, the desired mini position is the difference between the desired tip position and the current macro end-point position.

Combining the two subsystems independently involves assigning a macro desired position and a mini desired position, shown in Figure 3 when $\alpha = 0$. In this case, the subsystems react with their independent closed loop dynamics. Although there is interaction from the mini control inputs to the macro, the mini response is fast compared to the macro and it achieves the desired set point relatively quickly, so the period of interaction is short. However, this combination does not take full advantage of the high-bandwidth nature of the mini as the mini reference input is based on a static value and the mini can not compensate for steady-state positioning errors in the macro subsystem, which dominate the performance.

Combining the subsystems such that the reference input for the mini is the difference between the macro end-point position and the desired tip position, shown in Figure 3 with $\alpha = 1$, allows the system to position the **tip** much faster by capitalizing on the full capabilities of the mini-manipulator

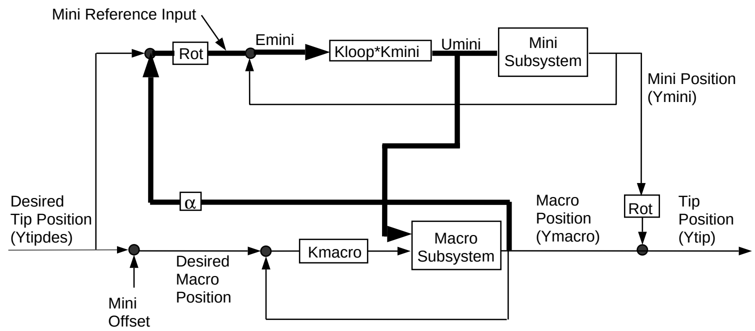

Figure 3: **Combined Subsystem Controller Topology**

The macro and mini controllers are designed independently. In the case $\alpha = 0$ the subsystems function independently and the system performance is limited by the macro-manipulator dynamic response. In the case $\alpha = 1$ the mini-manipulator reference input is the difference between the macro end-point position and the desired tip position. A new feedback loop is closed creating an interaction between the subsystems.

to compensate for small macro errors. Examination of the block diagram shows that there is now a **system** feedback loop that dynamically couples the subsystems. Previous researchers using the mini dynamic reference input note undesirable performance and instability with high gain mini controllers [2]. The system feedback loop, closed with the mini dynamic reference input, creates the dynamic coupling between the two subsystems that degrades performance and can cause instability.

6 Interaction Analysis

Analyzing this combination of macro and mini subsystems introduced with the mini dynamic reference input shows that the subsystems are now dynamically coupled and the system dynamics are not the same as the dynamics of the two independent subsystems.

Examination of the block diagram, Figure 3, for the case $\alpha = 1$ shows a feedback loop from macro position, Y^G_{macro}, through K_{mini} to U_{mini} and back to the macro. Defining $E^M_{mini}(\alpha)$ as the difference between the mini reference input and the actual mini position in the Mini frame, it is easily shown that:

$$E^M_{mini}(\alpha) = R^M_G \left[Y^G_{tipdes} - \alpha Y^G_{macro}\right] - Y^M_{mini} \tag{1}$$

$$Y^G_{tip} = Y^G_{macro} + R^G_M Y^M_{mini} \tag{2}$$

$$E^M_{mini}(\alpha) = R^M_G \left[Y^G_{tipdes} - Y^G_{tip}\right] \tag{3}$$

Where R^M_G is the rotation from global to mini coordinates, and R^G_M is the rotation from mini to global coordinates. The superscript G indicates a quantity in the Global frame and a superscript M indicates a quantity in the Mini frame.

Equation 3 shows that the effect of the mini dynamic reference input, when $\alpha = 1$, is to essentially drive the mini with the difference between the actual and desired tip position. However, it is clear from Figure 1 that the tip position is a function of the dynamics of both the macro and mini subsystems. The mini control system, designed as if the mini were on a fixed base, ends up trying to control the entire system.

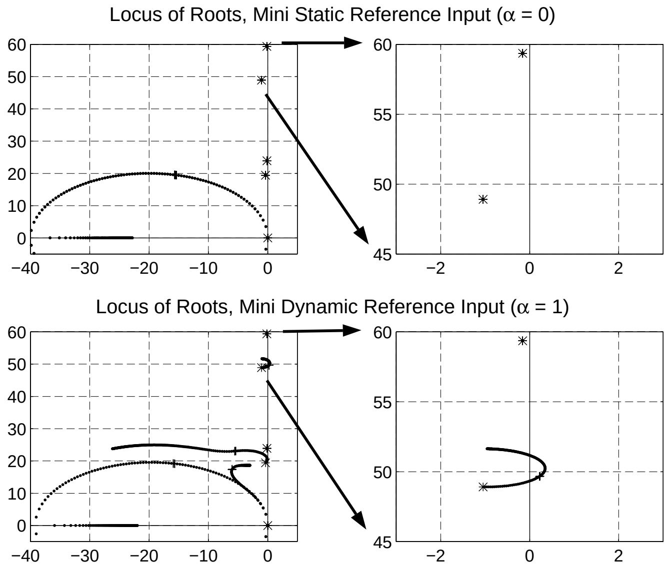

Figure 4: **Locus of Roots vs. mini loop gain** K_{loop}

The system roots are evaluated as a function of the mini-manipulator loop gain. The upper plots show the response when $\alpha = 0$. The upper right hand plot shows that no interaction between the subsystems is evident. In the lower plots, where $\alpha = 1$, the reference input of the mini-manipulator is the difference between the desired tip position and the actual mini base position. The lower right hand plot shows that the mini control subsystem changes the effective dynamics of the macro. The closed loop performance is degraded and instability can result.

The effects of the independent controllers acting in the system can be examined using the system model developed for the experimental apparatus. Examination of the system dynamics as a function of mini control gain demonstrates the effects of the mini dynamic reference input. For purposes of this analysis, the macro is operating open loop, i.e. $K_{macro} = 0$. However, these results are general in that the macro controller typically adds damping to the flexible modes of interest.

Closing the mini loop with a variable gain K_{loop}, the system dynamics are:

$$A_{cl} \quad = \quad A_{ol} + [B_2]\, K_{loop} K_{mini} E^{M}_{mini}(\alpha) \tag{4}$$

A locus of system roots vs. the mini control gain, K_{loop}, shown in Figure 4, demonstrates the strong interaction between the mini and macro subsystems. In the upper plots $\alpha = 0$, the rigid body poles of the mini are stabilized as shown in the upper left hand plot and the poles corresponding to the flexible modes are not effected by the mini controller as shown in the upper right hand plot. In the lower plots $\alpha = 1$ and the system feedback loop is closed. As before, the lower left hand plot shows the rigid body poles of the mini are stabilized. The lower right hand plot shows that the mini controller influences the poles corresponding to the flexible modes in the macro subsystem. In the case shown, the subsystem interaction is also affected by the sensor delay which has been included in the model and is included in the macro subsystem controller design. The locus shows a destabilizing interaction between macro and mini subsystems, which is consistent with the behavior observed in the experimental system [2].

This analysis demonstrates the strong interaction of the high gain mini controller with the flexible modes of the macro subsystem. The worst case, similar to that shown above, is that the system will be unstable. More commonly, there will be a degradation in performance due to the fact that the effective dynamics of the macro subsystem, with the mini control loop closed, are significantly different from those of the open loop system. Hence, a macro subsystem controller designed with precise knowledge of the open loop macro subsystem dynamics will not perform as well when the two subsystems are combined.

Developing a system model enables the design and implementation a control system which uses all of the available actuators and knowledge of the system dynamics to achieve the performance objective. In such a system, the mini control torques will be used to damp vibrations in a manner similar to Lew's [3], while the overall performance objective of positioning the tip will be accomplished. In addition, development of a system model incorporating all of the system dynamics, including any sensor dynamics, guarantees stability by automatically accounting for these effects in the control system design.

7 Conclusions

A macro/mini-manipulator enables fast, precise manipulation throughout a large workspace. When the vibration modes of the macro-manipulator are near or within the control bandwidth, the control system must account for these vibration modes.

The dynamic coupling from the mini-manipulator control torques to the macro-manipulator is significant. This one-way coupling leads to interactions that degrade performance but, when the mini reference input is static, do not cause instability.

However, the performance objective for the macro/mini system is to position the tip quickly and precisely. This objective naturally suggests a control architecture where the mini-manipulator reference input is the difference between the desired tip position and the macro end-point position.

The application of this control architecture to the experimental system has shown that this mini dynamic reference input creates a feedback loop between the two subsystems resulting in two-way coupling. Further, the analysis has shown that failure to include the two-way coupling in the control system design degrades performance and can cause instability. Clearly the system model and control system design must account for the effects of this two-way coupling to achieve guaranteed stability and desirable system performance.

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