END-POINT CONTROL OF A FAST AND PRECISE MACRO/MICRO-MANIPULATOR

Agathe Hodac
Institute of Robotics, Swiss Federal Institute of Technology Zürich, Switzerland,
hodac@ifr.mavt.ethz.ch

Roland Siegwart
Institute of Robotic Systems, Swiss Federal Institute of Technology Lausanne, Switzerland,
roland.siegwart@epfl.ch

ABSTRACT

This paper presents a high performance macro/micro-manipulator architecture for rapid and precise positioning operations. The control approach is based on end-point position measurements in a limited range. Since the macro-manipulator can't be controlled precisely at high speed, due to structure and joint flexibility, the micro-manipulator is controlled to correct possible misalignments between the end-point relative to the target and also to compensate for the vibrations occurring at end-point, thus improving the accuracy and decreasing the cycle time.

First, the paper presents the design and the performance of the voice-coil micro-manipulator that we have developed. The system achieves an accuracy of 1 µm and a settling time of 15 ms. Secondly, an end-point position control strategy for the macro/micro-manipulator that compensates for the oscillations measured at end-point is presented. In particular, the controller of the micro-manipulator accounts for the interaction with the macro-manipulator. Finally, experimental results demonstrating the efficiency of the method are presented.

KEYWORDS

Macro/micro-manipulator, end-point sensing, local actuation, vibration compensation

1. INTRODUCTION

In recent years, there is an increasing demand in manufacturing industry for fast robot systems which can perform accurate positioning tasks at a target position that might be different at each cycle. An important consideration, when designing such a high performance robot, is the sensor location. An end-point sensor might be the optimal solution to achieve the highest possible accuracy and repeatability. However, for classical robots, the end-point sensor is not collocated with the actuators located at the base of the links. Complex control strategies are therefore required to overcome the structural flexibility and the non-linearities in the system. This difficulty can be avoided by mounting a micro-manipulator at the tip of the large manipulator. Proposed by Sharon [6], the two-stage manipulator, called macro/micro-manipulator, has the advantage to combine the workspace of a large manipulator and the accuracy and acceleration of a micro-manipulator.

The objective of the research presented in this paper is to compensate with the micro-manipulator for position errors due to a misalignment of the end-effector relative to the target (offset), thus improving the system's accuracy and repeatability. Moreover, since the rapid motion of the flexible macro-manipulator excites the system's resonance modes, a further objective of this research is to compensate for the oscillations at end-point in order to reduce the cycle time and/or to improve the accuracy. An important contribution of the paper lies in the location of sensors and actuators that can be both operative in a limited workspace.

The idea of using a micro-manipulator mounted at the tip of a large and elastic arm for vibration control has been reported in the literature mainly in the field of space robotics. Lew [3] and Cannon [2] have considered active damping of the macro-manipulator with the micro-manipulator using a flexible motion compensator based on measurements of the macro-manipulator's flexibility. Yim [8] has proposed a nonlinear inverse and predictive end-point control of a flexible macro/micro-manipulator. The control algorithm of this research is based on a system model.

The paper is organized as follows. First, in Section 2, we describe the design of the micro-manipulator since it constitutes an essential element to the overall system improvements. The control strategy for the macro/micro-manipulator, including the end-point control of the micro-manipulator, is presented in Section 3. Finally the experimental results in Section 4 show the effective performance improvements.

2. DESIGN OF THE MICRO-MANIPULATOR

The micro-manipulator is depicted in Figure 1. It has a single translational degree of freedom.

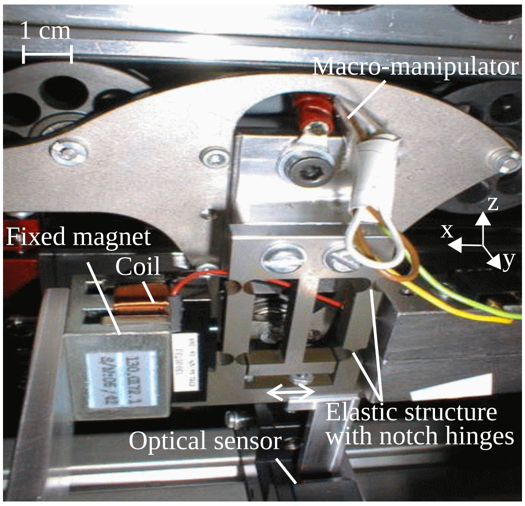

FIGURE 1: Voice-coil micro-manipulator (1 dof)

The micro-manipulator has been designed to meet high specifications of dynamics and precision. The requirements can be listed as follows:

- *Minimum weight (<150 g)* so not to load the macro-manipulator adversely.
- *Working range of 1 mm* in order to correct the maximum misalignment.
- *High acceleration capability* to achieve fast positioning.
- *Micrometer accuracy* to perform precise displacements.

We have selected the voice-coil principle to realize the actuation. It provides high precision (limited only by the sensor resolution) and high dynamic response (limited by the amplifier performance). A working range of 1 mm can be easily achieved. Furthermore, since the manipulator performs repetitive tasks, the magnet can be mounted fixed in the goal area, thus lightening the micro-manipulator that is mounted at the tip of the macro-manipulator. The relationship between force F_m and current i is given in Eq. (1):

$$F_m = k_m B(x_e) \cdot i \tag{1}$$

where k_m is the thrust constant. The magnetic field B is a function of the end-effector position x_e because the coil is plunged into the magnet only in the area of the goal position.

The coil is attached to a flexible structure formed by a parallel spring stage with four notch hinges [4]. The mobile platform moves parallel with respect to the base, which provides one translational degree of freedom. The maximum deflection is mechanically limited to ± 0.5 mm. The stiffness in x direction has been selected to be low (1.7 N/mm) whereas the stage is rigid in z direction (890e3 N/mm) and in torsion about z axis (8450 Nm/rad). Buckling effects are limited on the structure due to the flexure thickness of 4 mm.

The performance of the micro-manipulator is shown in Table 1.

TABLE 1: Micro-manipulator's characteristics

Characteristics	Values
Overall dimensions	5x60x40 mm^3
Total mass	120 g
Moving mass	12 g
Nominal inductance	15.2 mH
Coil resistance	19.7 Ω
Max. magnetic force	6 N
Peak acceleration	5 g
settling time	15 ms
Position accuracy	< 1 µm

Within a workspace of 1 mm, the micro-manipulator achieves fine positioning with an accuracy of 1 µm and a settling time of 15 ms.

3. CONTROL STRATEGY

3.1. End-Point Control

A straightforward way to increase the precision for positioning tasks is to measure the end-point position directly. The fine positioning with the voice-coil actuator at the tip provides a good collocation between the end-point sensor and the actuator. It eliminates the control problem which results from having actuators at the base of flexible links. Moreover, the dynamic response can be

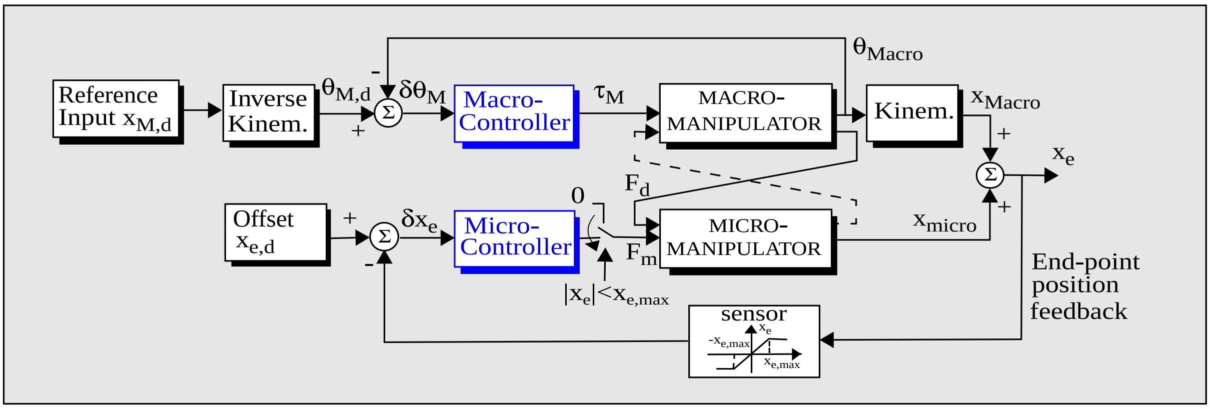

FIGURE 2: Controller strategy with local end-point sensing

improved because only a small mass of the robotic system is moved to achieve fine position corrections. Additionally, the end-point controller can achieve a higher bandwidth without needing a dynamic model of the system. In the case of the control of elastic manipulators, it is commonly said that the bandwidth is limited to one half of the lowest resonance frequency. Here, the end-point closed-loop controller achieves a bandwidth much larger than the dominant structural mode of the macro-manipulator.

Our approach presents the interesting features of local sensing and local actuation:

- The end-position is only *sensed in a limited workspace* corresponding to the goal area where the accuracy is required. The sensor can achieve a good working range/accuracy ratio and a high dynamic. Indeed a camera might allow accurate absolute position measurements but may not provide sufficient dynamic to be used in feedback control.
- The voice-coil actuator is only *enabled in the goal area* where the moving coil is in the magnetic field generated by the stationary magnet.

Figure 2 shows the block diagram of the controller consisting of two separate loops for the macro- and the micro-manipulators.

The macro-manipulator is position controlled to follow a repetitive trajectory ($x_{M,d}$) defined by a sixth-order polynomial profile. The smooth trajectory command produces a reduced acceleration ($\ddot{x}_{M,d}$) at the end of motion.

In the goal area, the end-point position information is fed back to the micro-manipulator which compensates for oscillations and corrects position errors δx_M due to the macro-manipulator's inaccuracy. The controller of the micro-manipulator is detailed in Section 3.3.

3.2. Interaction Issues

Mounting a micro-manipulator at the tip of a flexible manipulator results in a dynamically coupled system [1][7].

The coupling effect of the micro-manipulator on the macro-manipulator is negligible, first because the high flexibility of the micro-manipulator suspension reduces the reaction force at the tip and secondly because the inertia of the macro-manipulator is much greater than the inertia of the micro-manipulator.

The effect of the macro-manipulator on the micro-manipulator is represented by a disturbance force F_d. Therefore, the controller of the micro-manipulator must have a good disturbance rejection. As already mentioned, the controller of the voice-coil micro-manipulator is only enabled in the goal area. Therefore, it simplifies the control problem because the acceleration of the macro-manipulator is considerably reduced within this limited range.

By exploiting the dominant one-way coupling, the control design becomes a partitioned approach: the macro-manipulator is controlled to bring the micro-manipulator to the goal area, then the micro-manipulator is end-point controlled to reach the goal position precisely.

3.3. Design of the Feedback Control

Next we study the end-point controller of the micro-manipulator. The PD control law is of the form:

$$F_m = -P \cdot \delta x_e - D \cdot \delta \dot{x}_e \qquad (2)$$

First an analysis in the physical domain gives interesting insight how the controller of the micro-manipulator can compensate for the vibrations of the macro-manipulator. As proposed by Sharon [5], the manipulator can be modeled by a number of masses (M_i) connected in series by springs (k_i) and dampers (c_i). We have considered a simplified model of the macro/micro-manipulator based of three masses. The macro-manipulator is actuated by the force F_M at the base. Its joint dynamics are lumped into c_a and M_1 and its structural dynamics are lumped into k_{12}, c_{12} and M_2. The micro-manipulator is characterized by the structural dynamics k_{23}, c_{23} and M_3. The force of the voice-coil actuator is acting between M_3 and the ground. As the voice-coil actuator and the end-point sensor act on the same point, the following equivalencies of control elements can be considered in the physical domain:

- The *negative position feedback* corresponds to a spring action
- The *negative velocity feedback* is equivalent to a damping action

The macro/micro-manipulator can be modeled as shown in Figure 3. The end-point position controller (PD type) is also represented.

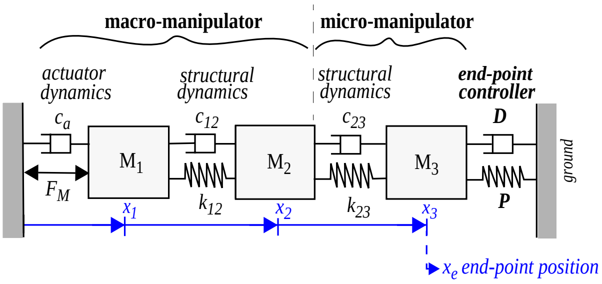

FIGURE 3: Model of the macro/micro-manipulator with absolute position and velocity feedback

The proportional term P of the controller provides high effective stiffness relative to ground. The micro-manipulator is relatively flexible such as $k_{23} << P$. Therefore the oscillations of the mass M_2 (tip of the macro-manipulator) are not transmitted to the mass M_3 (mobile platform of the micro-manipulator). Even if the tip of the macro-manipulator oscillates due to structure and joint flexibility, the end-effector of the two-stage system stays fixed relative to the ground and therefore the positioning task can be accomplished.

The end-point velocity feedback increases the damping and improves the stability of the system.

Examination of the Bode plots confirms the vibration compensation by only using end-point control of the micro-manipulator. The Figure 4 shows the PD control block diagram of the micro-manipulator. The absolute end-point position x_e is fed back and the reference input $x_{e,d}$ is set to zero (no oscillation desired at end-point). The micro-manipulator can treat the macro-manipulator as an external disturbance (F_d). Therefore the control objective is to maintain the desired end-point position in presence of the disturbance F_d.

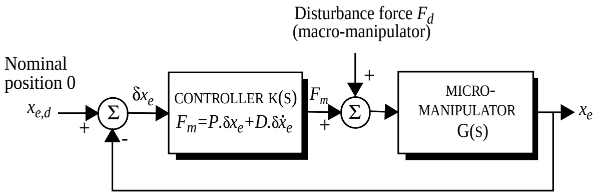

FIGURE 4: Control block diagram of the micro-manipulator

The controller design objective amounts to selecting the parameters to maintain a minimum error due to the disturbance. With G(s) the plant transfer function, the closed-loop output $x_e(s)$ due to the two inputs $x_{e,d}(s)$ and $F_d(s)$ is given as:

$$x_e(s) = \underbrace{\frac{K(s)G(s)}{1 + K(s)G(s)}}_{T_r(s)} x_{e,d}(s) + \underbrace{\frac{G(s)}{1 + K(s)G(s)}}_{T_d(s)} F_d(s) \quad (3)$$

The Bode plot[1] corresponding to the transfer function $T_r(s)$ from reference position $x_{e,d}$ to output absolute end-position x_e is given in Figure 5. The closed-loop bandwidth of the position control is about 500 Hz.

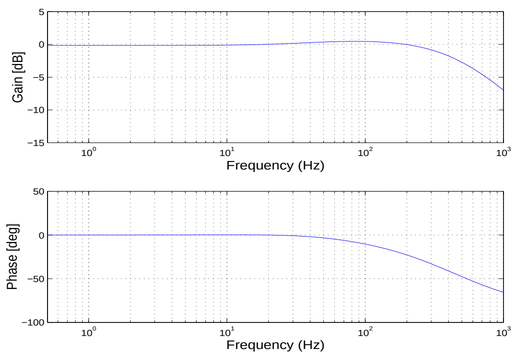

FIGURE 5: Transfer function $T_r(s)$ from reference position $x_{e,d}$ to absolute end-point position x_e

The Bode plot corresponding to the transfer function $T_d(s)$ from disturbance force F_d to output absolute end-position x_e is given in Figure 6.

1. The parameter values used for the Bode plots characterize the micro-manipulator described in Section 2.

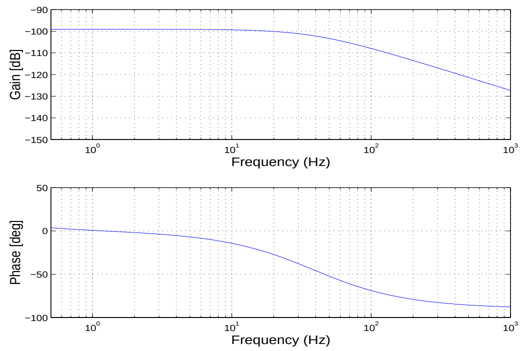

FIGURE 6: Transfer function $T_d(s)$ from disturbance force F_d to absolute end-point position x_e

Examining Eq. (3), we note that a large gain P of the controller K(s) will reduce the effect of the disturbance $F_d(s)$. The disturbance will be rejected over the frequency range where |K(s)| >> 1 and |K(s)G(s)| >> 1.

4. EXPERIMENTAL RESULTS

Experiments have been pursued to test the validity of our approach. The experimental system is composed of a flexible macro-manipulator combined with the voice-coil micro-manipulator described in Section 2. The main resonance frequency of the macro-manipulator is measured to be about 120 Hz. The macro-manipulator is driven by a DC motor and an encoder is mounted on the motor to measure the position at the base. An optical sensor (with a working range of 1 mm and an accuracy of 0.6 µm) has been placed at the end of the motion range to measure the absolute end-point position. The micro-manipulator is only controlled using end-point position measurements. The setup is controlled with a dSpace system at sampling rates up to 8 kHz. Figure 7 gives a schematic view of the experimental system.

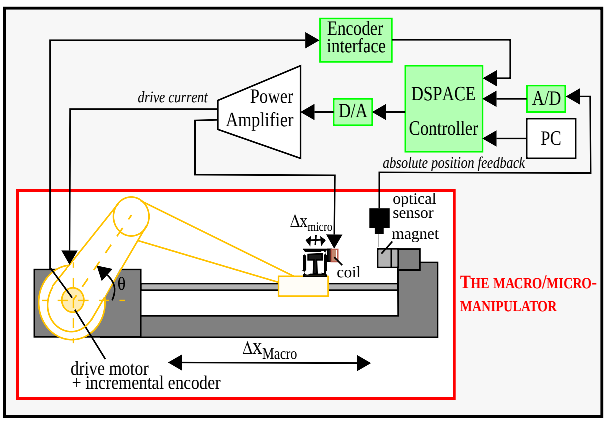

FIGURE 7: Schematic view of the experimental setup

The system's performance measured at end-point is presented in Table 2. For the macro-manipulator alone, measurements correspond to a single goal position command (called 0) whereas, for the macro/micro-manipulator, position commands are in the range of ± 0.5 mm around the position 0.

TABLE 2: Experimental system performance (measured at end-point at final time): comparison between macro-manipulator and macro/micro-manipulator

PERFORMANCE (AT END-POINT AT FINAL TIME)	MACRO ALONE	MACRO/ MICRO
CYCLE TIME MACRO/MICRO	0.24 s	0.24 s
ABSOLUTE ACCURACY	~ 30 µm	**~ 1 µm**
REPEATABILITY	10.5 µm	**1 µm**
AMPLITUDE OF VIBRATIONS	± 20 µm	< ± 1 µm
MAIN FREQUENCY OF VIBRATIONS	120 Hz	~120 Hz

For example, Figure 8 shows the position measurements at the end-point of the macro-manipulator and the macro/micro-manipulator for the goal position 0.

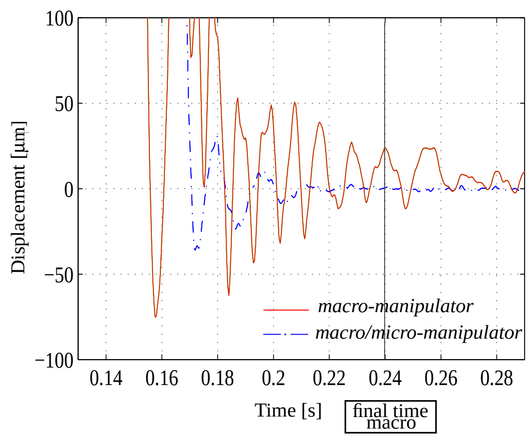

FIGURE 8: Experimental end-point position (for goal position 0): comparison between macro-manipulator and macro/micro-manipulator

These results show that the macro/micro-manipulator demonstrates significant superior performance of accuracy and repeatability than the macro-manipulator alone.

Figure 9 shows the measurements of the end-point position for several offset corrections in the range of 1 mm.

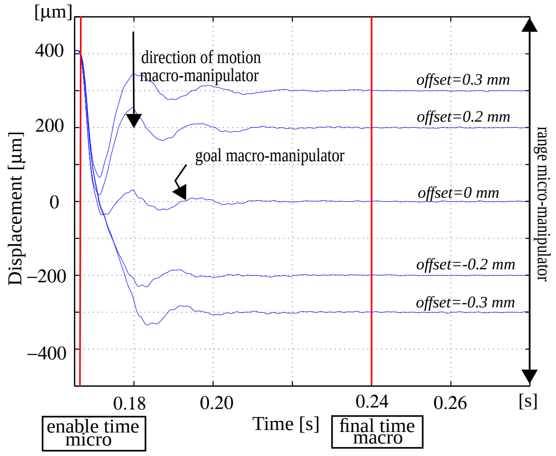

FIGURE 9: Experimental end-point position (at tip of the micro-manipulator) for different offset corrections

Oscillations visible in Figure 9 result from the simultaneous displacements of the macro-manipulator and the micro-manipulator.

The macro/micro-manipulator can reach the goal position nearly without oscillations. The micro-manipulator reaches the target position quickly and keeps it while the macro-manipulator is still moving. For higher performance, the controller can be enabled as soon as the coil enters the magnet. It leads to a better damping of the structural oscillations.

5. CONCLUSION

The paper has presented an effective method for controlling the macro/micro-manipulator to realize pick and place operations quickly without residual oscillations, thus decreasing the cycle time.

Local end-point sensing and local actuation constitute a successful approach to achieve high performance control without needing a system model.

Experimental results have demonstrated the performance improvements due to the end-point control of the macro/micro-manipulator.

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