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DESIGN AND CONTROL OF A FAST AND PRECISE MACRO/MICRO-MANIPULATOR

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ABSTRACT

Coarse/fine position systems have been proposed, analyzed and used as a mean of enhancing the performance in manufacturing tasks [1]. The objective of the research is to combine a micro-manipulator (µM) to a general task manipulator (MM) to realize both accurate and fast manipulation.

This paper presents first the design of an electromagnetic micro-manipulator and its performance. The system achieves an accuracy better than 1 µm within a range of 1 mm.

Secondly the paper presents the overall experimental setup which consists of a micro-manipulator (for fine positioning) mounted on a macro-manipulator (for large movement). Simulations have proven the capability of the micro-manipulator to improve the endpoint accuracy of the whole system.

1. INTRODUCTION

In many assembly tasks, the required levels of precision and speed point out the limitation of classical industrial robots. Previous work, in particular by Sharon [1], have shown the improvements achieved by a 2-stage approach, i. e. a specific micro-positioner mounted at the tip of an available robot as shown on Fig. 1. This architecture preserves both, the workspace of the conventional robot and the accuracy and speed of the micro-positioner. Dynamic response is increased because of a low moving mass and accuracy is improved due to the collocation actuator-sensor.

The overall performance improvements depend much on the design of the micro-manipulator. Important realizations of fine positioners are the fine-motion magnetically levitated robot wrist ('Magic Wrist') [2] or the Suspension and Propulsion Unit (SPU) acting as linear active magnetic bearings [3]. Nevertheless whereas those solutions satisfy high accuracy requirements, their response time is insufficient for most high speed assembly operations. Our work is thus motivated by the actual limits of manipulators in combining speed and precision.

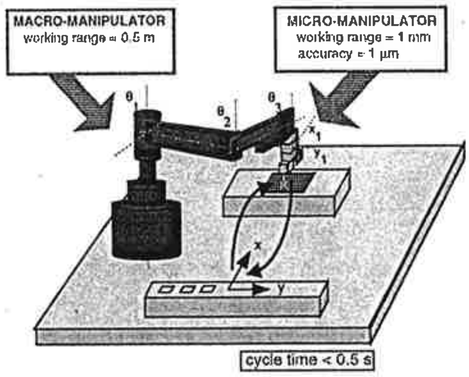

Fig. 1 Macro/micro-manipulator system

This paper deals with design aspects of the micro-manipulator whose challenge has been to integrate suspension, actuators and sensors in a compact and light structure. We decided to concentrate initially on a 1-dof-structure. Using a non linear compensation, a prototype has been built and controlled successfully. Furthermore a preliminary study of the macro/micro-manipulator approach is presented and simulation results, which shows enhanced performances due to this 2-stage architecture, are discussed.

2. Micro-manipulator

2.1. Micro-manipulator design

The following principal criteria for the design of the micro-manipulator have been defined:

- an accuracy of 1 µm
- a light weight so to avoid loading the macro-manipulator (<150 g)
- a working range of 1 mm in order to correct the maximal misalignment
- a high acceleration capacity to reduce the cycle time

The micro-manipulator shown on Fig. 2 meets the requirements. The following sections describe in some detail the compact micro-positioner components: actuators, suspension and sensors.

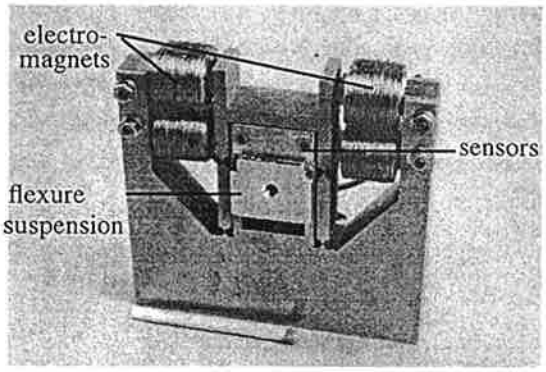

Fig. 2 Micro-manipulator (1 dof)

2.2. Actuators

Reluctance actuation has been selected as an appropriate principle to realize fast and precise positioning. Indeed, magnetic actuators provide high precision (limited by the sensor resolution) and high dynamic response (limited by the amplifier performances). Moreover, it is possible to control several degrees of freedom with a single non active moving element and therefore to extend the micro-positioner to more degrees of freedom.

Figure 4 shows the layout of this reluctance actuator:

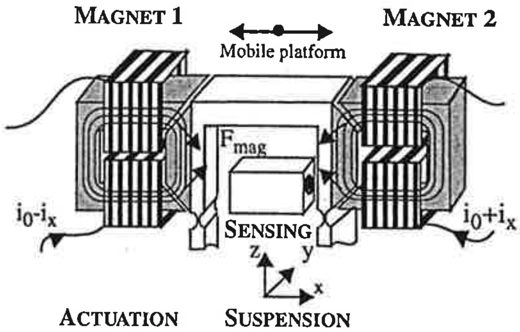

Fig. 3 Reluctance actuator schema

The electromagnets are carefully designed so that the ratio force/weight is maximized. The nominal gap is given by the specified working range. The cross section of the electromagnet cores are chosen to avoid saturation effects and the coils are dimensioned to prevent overheating [4]. In order to reduce eddy-current losses prejudicial for the dynamic response, the cores are made of Si-Fe laminated pole pieces.

Table 1 Micro-manipulator characteristics

Characteristics	Values
Nominal air gap	0.6 mm
Overall dimensions	10x60x60 mm^3
Moving mass	12 g
Nominal coil inductance	24.5 mH
Coil resistance	11.6 Ω
Max. current (per coil)	0.4 A
Max. magnetic force (middle position)	7.8 N

Similar to the magnetic bearing principle, actuation is realized by two electromagnets placed opposite to each other. The electromagnets are driven in differential mode by the sum (respective the difference) of the constant pre-magnetizing current i_0 (generally around half of the maximum current) and the actual control current i_x respectively. The force-current-displacement relationship for this differential scheme (the magnetization of the iron, hysteresis effects are neglected) is given eq. (1) [4]:

$$F_x = K_m\left[\frac{(i_0-i_x)^2}{(s_0-x)^2}-\frac{(i_0+i_x)^2}{(s_0+x)^2}\right] \quad (1)$$

$$K_m = \frac{1}{4}\mu_0 N^2 A_k \quad (2)$$

μ_0 = vacuum permeability

s_0 = nominal air gap

N = number of windings per electromagnet

A_k = cross section of the air gap

If this equation is linearized with respect to $x << s_0$, the magnetic force will behave linearly:

$$F_x = 4K_m\frac{i_0^2}{s_0^3}x + 4K_m\frac{i_0}{s_0^2}i_x = K_s x + K_i i_x \quad (3)$$

K_i = force-current factor

K_s = force-displacement factor (or bearing stiffness)

2.3. Flexure suspension

Slide or ball bearings are traditionally used to suspend moving parts, but problems of backlash, friction and wear are unacceptable for applications with micrometer precision. Thus, our approach consists in using flexible structures with notch hinges. We selected a stage with four necked down flexures presented on Fig. 4. Each notch acts as a rotary bearing. The upper platform moves parallel with respect to the base, which provides one translational degree of freedom.

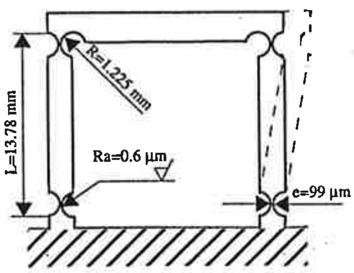

Fig. 4 Parallel spring stage with four necked down flexures

The monolithic stage has been manufactured in spring steel (DIN60SiCr7) by wire electro-discharge machining with notch sections having a thickness of 99 µm. The stiffness in x direction results is measured to be 5.4 N/mm, whereas the stage is rigid in z direction (2.2E4 N/mm) and in torsion about z axis (25 Nm/ rad). Buckling effects are limited on this structure due to the flexure thickness of 2.5 mm.

We show that the flexure rigidity can be chosen optimally to minimize the size and therefore the weight of the micro-manipulator. If we consider the motion from one extreme position to the other, the electromagnetic actuators get benefit of forces from the flexure suspension in the first half of the workrange and then must operate against them in the second half. The flexure stiffness K_{fl} is chosen to be equal to the negative bearing stiffness K_s in order to optimize the actuation force.

This effect is shown on the Fig. 5, which displays the flexure force, the maximum magnetic force of one coil and their sum, i.e. the force available to accelerate the moving part in the working range.

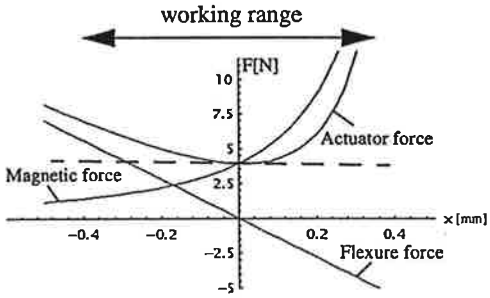

Fig. 5 Maximal actuator force versus displacement

Magnetic bearings have to be actively controlled due to their unstable nature. The measurement of the rotor position with a gap sensor is used in a closed loop controller to stabilize the moving element. It generates appropriate current commands in the power amplifiers that drive the currents through the electromagnets, in such a way that the mobile platform moves to the desired position.

2.4. Sensor integration

Magnetic bearing systems require sensors with good resolution to achieve precise positioning. Moreover, these sensors must be able to sense the total dynamic range of motion (typically twice the air gap). Eddy current sensors are appropriate to this task at reasonable price and volume. The sensor non linearity can measured with a high precision sensor then compensated within the digital controller. Experiments have shown that eddy-current sensors achieve the best performances on a highly conductive but non magnetic target. Operation in differential mode eliminates the influence of temperature variations. The resolution of these sensors, limited to the signal noise, is better than 1 µm.

2.5. Control strategy

Over a few years, non linear control algorithms have been studied because of the non linear magnetic attractive force especially for large variations of air gap and external disturbances like vibrations [5].

We highlight a simple method to compensate for the non-linearity of the electromagnets [6]. It is applicable with a PD controller. By multiplying the command signals with the air gap, we obtain a proportional relationship between the controller signal and the force acting on the moving platform even if the air gap varies. The relation between force F_x and control signal c_x becomes:

$$F_x = K_m \left[\frac{((s_0 - \cancel{x}) \cdot (C_0 + C_x))^2}{(s_0 - \cancel{x})^2} - \frac{((s_{\cancel{0}} + x) \cdot (C_0 - C_x))^2}{(s_{\cancel{0}} + x)^2} \right]$$

$$F_x = 2K_m i_0 C_x \qquad (4)$$

Eq. (4) shows that he magnetic force is then a linear function of the control signal. It means that the closed-loop behavior of the system is independent of the air gap.

In many cases, a good solution shown on Eq. (6) is to multiply the command signal with the input signal x_s rather than with the signal x_r of the gap sensors. Indeed, the input signal is about equivalent to the air gap and comports the advantage to be free of noise.

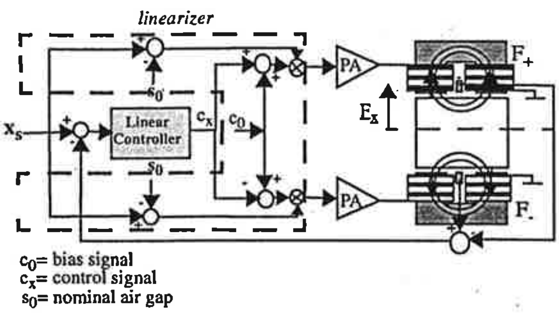

Fig. 6 Feedforward linearization controller

We will further explore model-depending controllers to improve dynamic performances.

2.6. Experimental setup

In our experimental setup, we have controlled the micromanipulator with a dSPACE system. It consists of a floating point processor board with a signal processor TMS320C40, 16 A/D and 6 D/A converters. DSPACE also provides a controller prototyping development environment. The system achieves a sampling rate up to 20 kHz for this setup.

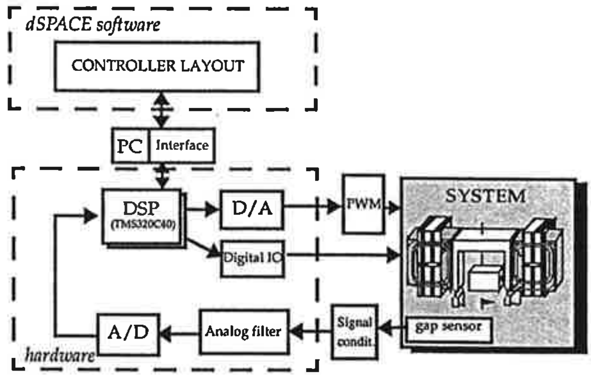

Fig. 7 Block diagram of the experimental setup

System's performance are presented in Table 2. An important characteristic is the closed-loop bandwith since it determines how fast the system can react against disturbances.

Table 2 System performances

Performances	Values
Controller sampling rate	15 kHz
Cut-off frequency	300 Hz
Settling time	15 ms
Position stability (triangulation sensors)	50 nm
Position accuracy (eddy current sensors)	< 1 µm

Fig. 8 shows the response behavior to a step of 0.1 mm for several eccentric positions.

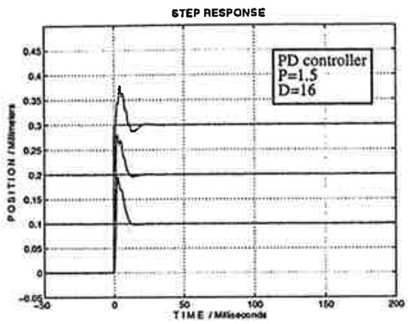

Fig. 8 Step response of the micro-manipulator

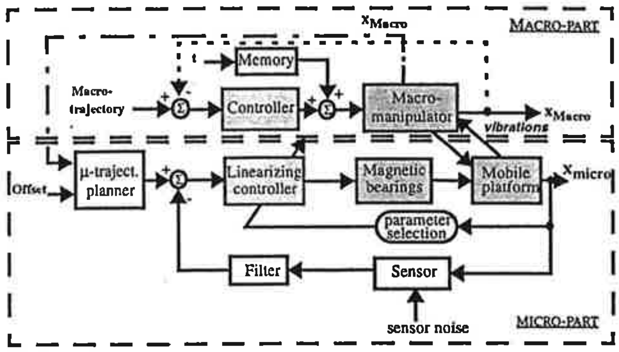

Fig. 9 Macro/micro-controller strategy

The system is well-damped and reaches the final position with an accuracy of 1 μm and a settling time of 15 ms.

3. MACRO/MICRO-MANIPULATION

3.1. Controller design

For pick&place operations, the target position often varies at each cycle. Most manipulators are not able to realize fine movements and thus to reach the target position with an accuracy of 1 μm. It results a misalignment of the end-effector relative to the target. This limitation can be overpassed by providing at the tip a fine manipulator whose task is to correct this misalignment.

It stands out the problem of position measurement. An absolute endpoint measurement (absolute sensing) is recommended but not always available. In many cases, an endpoint measurement relative to the target, limited in a reduced range, is sufficient to achieve the accuracy.

We adopt a different approach which consists in splitting the movement in two phases: first the macro-manipulator is required to come always to the same position, so it can be designed and controlled optimally for this trajectory. Secondly the micro-manipulator (whose working range is equal to the maximal misalignment) corrects the misalignment. Only preliminary calibration and the position measurement of the micro-manipulator platform (local sensing) relative to its base are required.

A block diagram of the system control strategy is shown on Fig. 9.

The macro-manipulator is controlled to follow an acceleration profile whose maximum exceeds 10 g. On the other hand, the micro-manipulator is controlled to cope with the high acceleration during the large travel of the macro-manipulator and to finally realize the desired endpoint position within a short time (here 15 ms).

3.2. Compensation of vibrations

For fast and accurate positioning, it is particularly important to reduce vibrations due to the macro-manipulator movement. An approach consists in smoothing the control signal so that the macro-manipulator is not excited at its resonance frequencies. An interesting method called learning control realizes this input shape optimization effectively [7]. Through a preliminary learning process, the unknown dynamics are identified for a given trajectory.

The complementary approach is to implement a feedback control algorithm so that the micro-manipulator is moved to counteract the vibrations.

In presence of vibrations, local sensing is not sufficient because those vibrations are not visible to the micro-manipulator. On the other hand, if an absolute measurement is available, the micro-manipulator, due to its high dynamics, can compensate for the vibrations with an adequate motion of its mobile platform. As a result, the tip stays fixed relative to the absolute frame.

3.3. Simulation results

A lumped parameter model [1] of the overall system has been developed to get more insights of the dynamics of the system. The system is characterized by structural dynamic parameters c_i, k_i, M_i and the actuator forces are noted F.

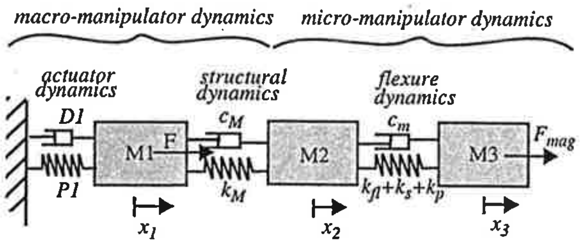

Fig. 10 Model of the macro/micro-manipulator

This model has been used for simulations to demonstrate the performances of the proposed control algorithm.

If local sensing (x3-x2) is used, Figure 10 shows that the vibrations at the macro-manipulator's tip are transmitted to the micro-manipulator, which limits the endpoint accuracy.

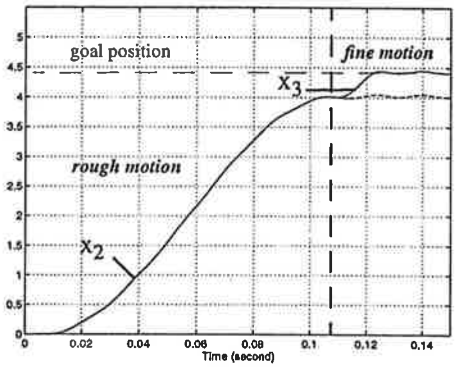

Fig. 11 Simulation results: Vibrations at endpoint - local sensing (x_3-x_2)

On the other hand, if absolute sensing (x3) of the endpoint position is used, we can see on Fig. 12 that the mini-manipulator is able to compensate for vibrations. The complete system reaches the goal position with an accuracy of 1 μm and within 15 ms.

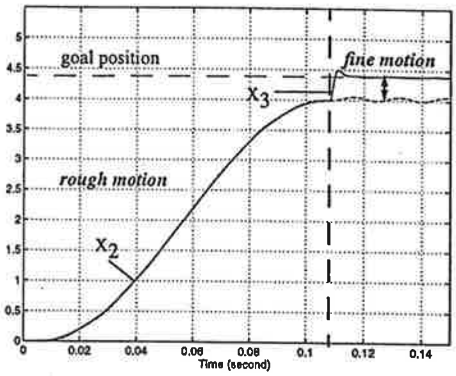

Fig. 12 Simulation results: Compensation of vibrations by the micro-manipulator - Absolute sensing (x_3)

4. Conclusion

We have described the design of a magnetically-actuated micro-manipulator. The combination with a general task manipulator allows to reach an accuracy of 1 μm. The micro-manipulator realizes two operations simultaneously: one is to compensate vibrations and the other is to correct the offset to the goal position.

5. Extension

A prototype including the macro/micro-manipulator is currently installed and first experiments have started. We will pursue experimentations to verify the simulation results. Future works include also the development of a micro-positioner with more degrees of freedom.

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