

Force-feedback coupling for micro-handling applications

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Abstract—This paper presents a coupling method in order to establish force-feedback user interaction with a micromanipulator. The presented control scheme design is based on stability considerations and, hence, allows unconditional stable operation independently on the haptic interface, micromanipulator and scaling ratios on force and position. Experimental comparison of proposed coupling with a common force-position coupling is also included.

Keywords: Micromanipulation; haptic interfaces; force-feedback remote handling; unconditional stability.

1. INTRODUCTION

The actual research in micromanipulation focuses generally on application specific cases, such as manipulation of single micro parts, biological applications (cell manipulation, injection) or characterization tasks. As a consequence, a great variety of manipulation techniques exist, depending on the manipulation mode (contact or non-contact), gripper types (tweezers, single cantilevers or pipettes), manipulated objects and the environment [1–5]. This diversity is mainly due to specific physical effects in the environment, such as adhesion, viscous forces in an aqueous environment, or electrostaticity if under a scanning electron microscope.

Hence, the design of micromanipulation systems, in addition to classical miniaturization and precision requirements, also needs the development of adapted control schemes based on the vision or force-sensor data. As a result, most of the existing systems are difficult to use for a non-initiated user. However, user guidance is necessary, as micromanipulation tasks are generally complex and often objects and

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target positions are not predefined. Note also that the end-user of the system is often out of field, as such is the case for biology oriented applications.

A state-of-art solution to enhance this user interaction is to use a force-feedback haptic interface. This approach has already been proposed in some works [6, 7]. Nevertheless, its implementation depends on the architecture of the manipulator and on its functionalities. Usually, between the haptic interface and the micromanipulator there is only a direct homothetic coupling with fixed scaling ratios. In this case, instability is an often occurring problem, especially if it is needed to change these scaling ratios during a manipulation task, or in the case of micromanipulation, where very important scaling ratios are used. For this special case, an enhanced version of ‘force-position’ control has been proposed in some works [8, 9] or, alternatively, a coupling including an additional position loop [10]. As demonstrated below, this kind of control schemes are not unconditionally stable, mainly due to the variant stiffness of the environment [11].

In order to propose a haptic interaction with microscale, we have privileged a passive, hence, robust, approach. It is based on a modular construction and local loops and aims to respect the co-localization principle, closely related to passivity properties. This choice is mainly motivated by the initial work from Anderson [12], based on ‘position–position’ coupling. Some complementary works propose an extended version of this approach [13] which favors the transparency, but in the case of a master interface with weak inertia and low friction, this extended coupling can be neglected if a local force loop is applied on the master [14].

Also, the presented coupling scheme is not based on a prior knowledge of the dynamics of the system or the environment, in contrast to what has been proposed in Refs [8, 13, 15–17] for direct compensation. This approach risks the loss of passivity and unconditional stability, as presented in Ref. [18].

A theoretical and experimental comparison between a direct force-position control and the proposed one is also presented in this paper.

2. EXPERIMENTAL SET-UP

The system on which the proposed force feedback coupling is experimented is an atomic-force-microscopy-based micromanipulator with nanometer and micronnewton accuracy, called *[miu]MAD*. The control and the force feedback are insured by an haptic device.

2.1. AFM-based manipulation

Atomic force microscopy (AFM) is first introduced as a surface topography and micro/nano-scale force measurement system. The principle is to measure the deflection of cantilever (AFM probe) of known dimensions and stiffness, by means of a laser beam or piezoresistivity with nanoscale accuracy on displacements and forces. This particularity has led to the use of the AFM systems for manipulation purposes,

particularly in pushing mode for nanomanipulation [19], or for adhesion based pick-up and release [20]. Compared to other types of grippers such as tweezers, AFM-based systems stand as the only tool with integrated force sensing. Although some tweezers can effectively measure solely the gripping force, single-fingered grippers based on AFM architecture allow to measure the whole object/environment/gripper interaction.

2.2. The micro-manipulator

The micromanipulation system [mü]MAD is built around an active gripper, whose design is based on the adhesion phenomena. This gripper is an AFM piezoresistive tipless cantilever beam coupled to two PZT ceramics, for vertical and horizontal motion. This design allows high dynamical performances, used mainly for the release of microparticles gripped by adhesion, as described in Ref. [20]. The dimensions of the AFM probe are $600 \times 140 \times 10 \mu\text{m}$ and its stiffness has been estimated to $K_{\text{canti}} = 21 \text{ N m}^{-1}$. The relation between the force F_{canti} and the displacement P_{canti} is considered as a linear elasticity:

$$F_{\text{canti}} = K_{\text{canti}} P_{\text{canti}}. \quad (1)$$

The principal natural frequencies of the cantilever are 33.8, 211.7 and 592.6 kHz. These values are experimentally cross-checked constructor values. Although the theoretical precision of this system is well below μN level with a 16-bit ADC, in practical conditions it does not perform better than $\simeq 1 \mu\text{N}$, mainly due to electrical and mechanical noise.

The vertical displacement is provided by two serial actuators: a nanostage with $12 \mu\text{m}$ amplitude and a microstage with sub micrometer resolution over 2.5 cm. Thus, the contact force is controlled by the motion of these actuators. The horizontal motion is produced by two identical microstages. The active gripper is shown in Fig. 1. Figure 2 shows the whole micromanipulator, called [mü]MAD, placed under an optical microscope. A full description of the design of [mü]MAD is given in Ref. [21].

Experimentations of [mü]MAD on pick-up, release (using adhesion forces and dynamical effects) and mechanical characterization tasks have been carried out. Detailed results can be found in Refs [11, 20].

As the force measurements are limited to the vertical axis due to the architecture of the AFM based gripper, only the vertical motions of [mü]MAD present an interest for the force-feedback remote handling. Hereafter, the gripper, the nanostage and the vertical microstage will be referred to as ‘slave’. Table 1 gives an overview of its characteristics.

It is to be noted that there is a kinematic redundancy on the slave if both the nano- and microstages are used. The nanostage allows [mü]MAD’s most precise vertical motion, whereas the microstage compensates the lack of motion range. In order to avoid problems inherent to this redundant architecture, it has been chosen to use

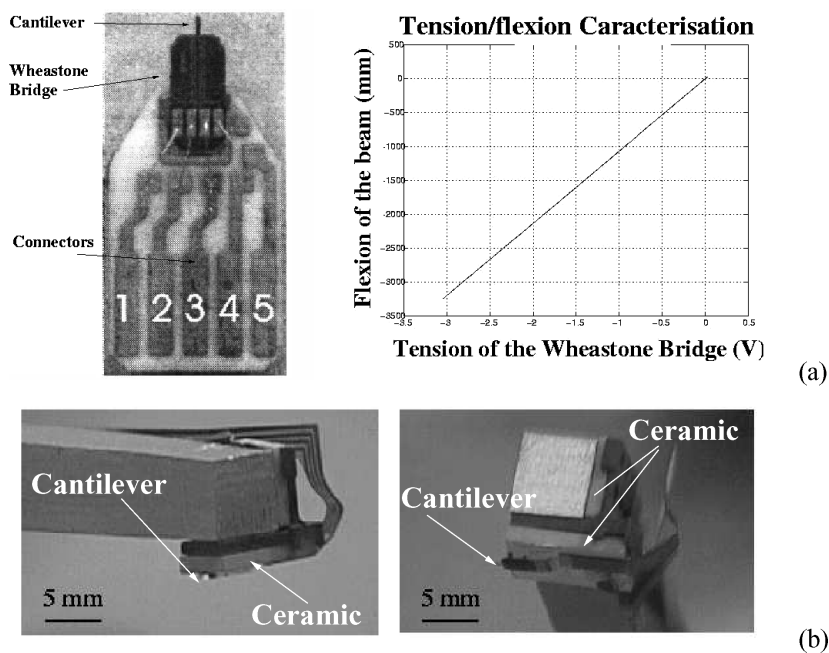


Figure 1. The active gripper for manipulation by adhesion: (a) AFM cantilever, (b) end-effector with piezoceramic actuator.

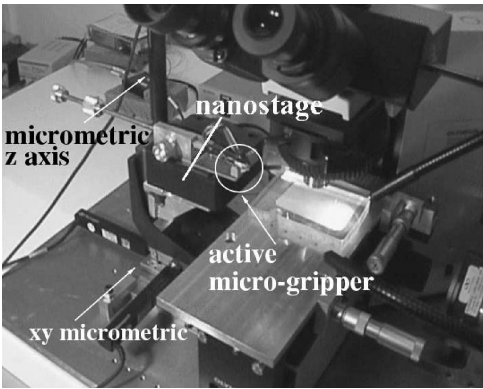


Figure 2. The micromanipulator [mü]MAD.

Table 1.
Mechanical characteristics of the slave

Stiffness of the AFM cantilever	K_{canti}	21 N/m
Max. stroke of the microstage	$C_{\text{micro}}^{\text{max}}$	2.5 cm
Max. stroke of the nanostage	$C_{\text{nano}}^{\text{max}}$	12 μm

only the nanostage for force feedback coupling. The microstage will be used only when nanostage reaches one of its motion bounds. The experimentally identified transfer function of the nanostage is:

$$H_{\text{nano}} = \frac{1321000}{s^2 + 2508s + 1310000}, \quad (2)$$

where s is the Laplace variable.

2.3. Haptic interfaces

Different kinds of haptic interfaces can be used for the micromanipulation. The most appropriate one would be 3D (or 6D) force-feed back arms such as Virtuose 6D and Delta 3D [22], as they allow the control of the overall motions of the manipulator. However, a one degree of freedom interface can be used for specific applications [19] or for test purposes such as presented here. It has been chosen to study the proposed control scheme with a basic 1-DOF interface in the first phase. Then, the same coupling is used with a 6-DOF interface.

2.3.1. One degree of freedom interface. This haptic interface, called ‘Brigit’, has been designed especially to experiment the feasibility of the force-feedback teleoperation (Fig. 3). Since the teleoperated slave has one DOF with force-feedback, the master device can have either a prismatic or a rotational joint. A prismatic joint appears to be more realistic as it reproduces the kinematics of the slave actuator. Despite this consideration, a rotational joint has some advantages over the prismatic one in this first phase of the project, as it has an unlimited range of movement. Thus, the motion between the slave and master can be more freely adjusted.

Brigit is composed of a DC motor equipped with an optical coder and a control wheel. The technical specifications of this device are given in Table 2. The I/O

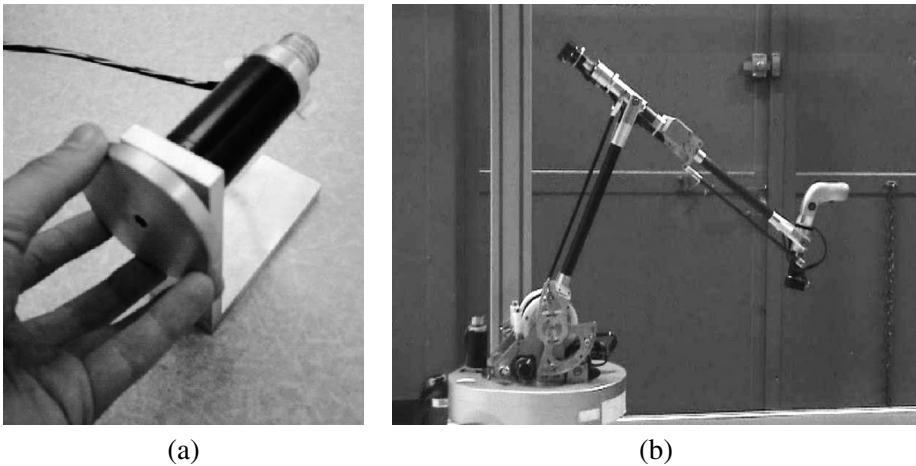


Figure 3. Haptic interfaces Brigit (a) and Virtuose 6D (b).

Table 2.
Specifications of the master device Brigit

Optical coder	
Resolution	2×10^4 pts/tour
Wheel	
Radius R_B	3.5 cm
Inertia	5.82×10^{-5} kgm ²
DC motor	
Nominal voltage	42 V
Maximum current $I_d^{\max}$	1.9 A
Torque constant	52.5×10^{-3} N m/A
Maximum torque $T_B^{\max}$	0.1 N m
Rotor inertia	6.96×10^{-6} kgm ²
Overall	
Friction coefficient μ	6×10^{-6}
Force/current coef. K_t	5.25×10^{-2} N m/A
Total inertia I_B	6.523×10^{-5} kgm ²

Table 3.
Specifications of the master device Virtuose 6D

Geometric characteristics	
Maximal stroke	45 cm
Dynamic characteristics	
Maximum effort $F_{\text{macro}}^{\max}$	35 N
Overall	
Appearing mass M_{Virt}	1 kg
Appearing inertia I_{Virt}	0.03 kgm ²

relation is given by:

$$\begin{bmatrix} V_B \\ \omega_B \end{bmatrix} = \begin{bmatrix} \frac{1}{L_B s + \mu} & \frac{R_B K_t}{I_B s + \mu} \\ \frac{1}{R_B I_B s + R_B \mu} & \frac{K_t}{I_B s + \mu} \end{bmatrix} \begin{bmatrix} F_{\text{op}} \\ I_d \end{bmatrix}, \quad (3)$$

where V_B and ω_B are linear and rotational velocities ($V_B = R_B \times \omega_B$), respectively, F_{op} the force applied by the operator, I_d the injected current and R_B , I_B , K_t , μ the characteristic parameters of Brigit given in Table 2.

2.3.2. Six degrees of freedom interface. In order to control the overall motion of the manipulator, an interface with at least 3 DOF is needed. The chosen one is Virtuose 6D from Haption (www.haption.com). It is a 6-DOF 6R arm with its own computing resources, in order to reduce the CPU load of the workstation. It is internally controlled on force or position, with inertial and mass compensation. This

control also includes inverse geometric and dynamic models; therefore, it can easily be controlled from an external application by sending set-point positions or forces. Note that as the slave has a Cartesian architecture, rotational degrees of freedom of the Virtuoso are not used. Its characteristics are given in Table 3.

2.4. Communication

The micromanipulator and haptic interfaces are controlled through separate PCs, each running RTLinux, an open source real-time OS. Because the software communication protocol is home-built as real-time kernel modules on top of a UDP/IP stack, the time delay is completely neglected when working at $T_e \geq 2 \mu s$ sampling.

3. FORCE-FEEDBACK COUPLING FOR MICRO-TELEOPERATION

In the literature, several coupling methods have been developed for micro-teleoperation systems. When they include force feedback they are called bilateral coupling methods. The most natural and commonly used bilateral coupling method for micro-manipulation applications is a direct homothetic force–position coupling. As it is shown in Section 3.1 it is never passive, it lacks robustness and, therefore, overall the teleoperated system can be unstable.

For general teleoperation applications, a commonly used coupling scheme is the bilateral position–position coupling that guarantees the robustness of the overall system by being passive. Moreover, for micro-teleoperation applications, it offers a modular architecture where both the slave or the master can be easily changed. The proposed scheme presented in Section 3.2 is based on that coupling. Its performances are then compared to the homothetic direct coupling.

3.1. Direct homothetic coupling

In this scheme, the set-point position of the manipulator is position of the haptic interface and the force coupling is achieved using force sensor data of the manipulator as set-point force on the haptic interface, both with linear scaling ratios (Fig. 4).

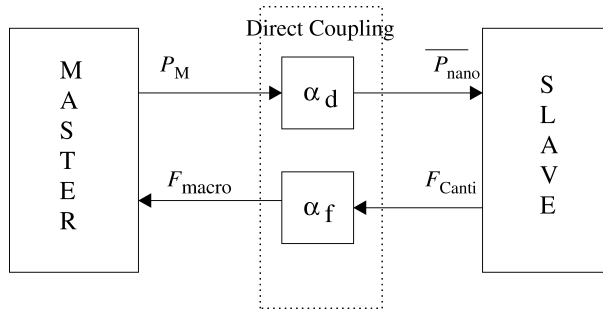


Figure 4. Direct homothetic force–position coupling.

In this case, because of the scale change between micro and macro worlds, very important scaling ratios, generally around 10^4 (for micro-to-macro) are needed. Additionally, adhesion, pull-off and contact forces on the microscale are very different in magnitude. It is then crucial to transmit them to the macroworld with identical scaling ratios. Moreover, for different phases of a micromanipulation operation, one sometimes needs a precise motion (for positioning) or, in contrast, a great travel range for transport. If both tasks are to be controlled through the same haptic interface, it is necessary to adapt the motion scaling. In these case, instability is an often occurring problem as the direct homothetic coupling is clearly very intolerant to changes on the scaling ratios if the condition $a_d = 1/a_f$ is not respected [23]. As this condition is very restrictive, an alternative flexible coupling scheme is needed, whose stability would also be unaffected by variations on the scaling ratios, guaranteeing the stability and robustness.

3.2. Position–position bilateral coupling

The proposed control scheme is called position-position bilateral control and will be hereafter referred to as ‘PPB’. Its design is based on passivity considerations for teleoperated systems [24]. The overall control scheme is split into local control loops. The unconditional stability of the control loop guarantees that in case where the system is coupled with passive components, the overall stability will not be affected [25]. The unconditional stability is verified using Llewellyn’s criteria, described in Section 3.3.

Table 4.
System parameters

P_M, V_M	Measured position/velocity of master
F_{macro}	Force on master
P_{nano}, V_{nano}	Measured position/velocity of nanostage
P_{nano}, V_{nano}	Set-point position/velocity of nanostage
P_{macro}, V_{macro}	Position/velocity of nanostage translated in macroworld
F_{canti}	AFM gripper measured contact force

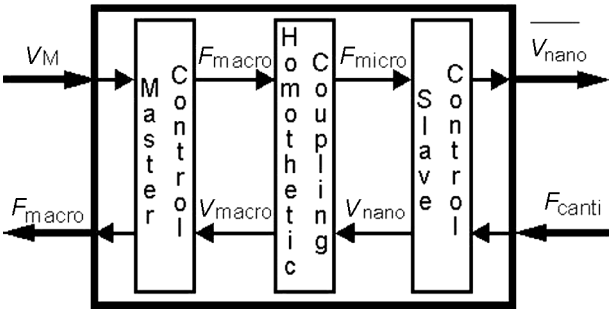


Figure 5. The PPB control scheme decomposition.

In this regard, the chosen architecture for the PPB control is modular. The global control is composed of three modules: the master control block, the homothetic coupling block and the slave control block (Fig. 5). Parameters used in this control are given Table 4.

3.2.1. The homothetic coupling block. The homothetic coupling block is used for macro-to-micro and micro-to-macro conversions, between force F , position P and velocity V data, using force and motion scaling ratios α_f and α_d . Scaling ratios are defined according to the master used for the teleoperation, [mü]MAD, and the desired performances. The motion of micromanipulator will be controlled by the haptic interface, thus the motion scaling is ‘macro to micro’. On the other hand, the force is measured in the microworld and transmitted to the master haptic interface; thus, the force scaling is ‘micro to macro’.

The master is designed for a maximal force $F_{\text{macro}}^{\text{max}}$. Considering that the maximum flexion of the AFM cantilever is $12 \mu\text{m}$, which is the maximum stroke $C_{\text{nano}}^{\text{max}}$ of the nanostage, maximal measurable force is given by:

$$F_{\text{canti}}^{\text{max}} = K_{\text{canti}} C_{\text{nano}}^{\text{max}} = 2.52 \times 10^4 \text{ N.} \quad (4)$$

Thus, the force scaling ratio is given by:

$$\alpha_f = \frac{F_{\text{canti}}^{\text{max}}}{F_{\text{macro}}^{\text{max}}}. \quad (5)$$

For the motion scaling, the maximal vertical stroke C_z^{max} of the master is used. In case of the master’s motion is unlimited, or the master’s bounds are too spaced out, virtual bounds have to be defined in order to limit the master’s stroke $C_{\text{zvirt}}^{\text{max}}$. The bounds will correspond to $C_{\text{nano}}^{\text{max}} = 12 \mu\text{m}$ of the nanostage motion. The motion scaling ratio α_d between the nanostage and the master is, thus, given by:

$$\alpha_d = \frac{C_{\text{zvirt}}^{\text{max}}}{C_{\text{nano}}^{\text{max}}}. \quad (6)$$

Micro and macro homothetic ratios are then defined as follows:

$$P_{\text{macro}} = \alpha_d P_{\text{nano}}, \quad (7)$$

$$V_{\text{macro}} = \alpha_d \overline{V_{\text{nano}}}, \quad (8)$$

$$F_{\text{micro}} = \alpha_f F_{\text{macro}}. \quad (9)$$

3.2.2. The master control block. The master control block allows to compute the set-point force on the master F_{macro} , which is also used in the slave control block after using the force scaling ratio. It is a proportional-derivative control of the error on the master position with respect to the slave position converted into macroworld.

In a two-port model it has the velocity of the nanostage translated to macroworld V_{macro} and the velocity of the master V_M as inputs.

$$F_{\text{macro}} = K_p(P_M - P_{\text{macro}}) + K_d(V_M - V_{\text{macro}}) \quad (10)$$

with control parameters K_p and K_d chosen in accordance to the sampling period T_e . Considering the differential equation in P_M obtained with zero as reference position:

$$\frac{I_M}{K_p} \ddot{P}_M + \frac{K_d}{K_p} \dot{P}_M + P_M = 0. \quad (11)$$

The cut-off frequency ω_0 is then given by:

$$\omega_0 = \sqrt{\frac{K_p}{I_M}}. \quad (12)$$

With $T_e = 2$ ms, the sampling frequency is $f_e = 500$ Hz. The bandwidth ω_{BP} is given by:

$$\omega_{\text{BP}} = \frac{2\pi f_e}{10} = 314 \text{ rad s}^{-1}. \quad (13)$$

Necessarily, $\omega_0 < \omega_{\text{BP}}$. Therefore, we have chosen $\omega_0 = 100 \text{ rad s}^{-1}$. Accordingly, K_p is computed as follows:

$$K_p = I_M \omega_0^2. \quad (14)$$

Choosing the damping ratio $\zeta = 1$ in order to limit the over-shooting, K_d is then given by:

$$\frac{2\zeta}{\omega_0} = \frac{K_d}{K_p} \implies K_d = \frac{2\zeta K_p}{\omega_0}. \quad (15)$$

3.2.3. The slave control block. The slave control block allows to compute the set-point velocity $\overline{V_{\text{nano}}}$ of the nanostage, which is also sent back to the homothetic coupling block to be used in the master control. The calculation of $\overline{V_{\text{nano}}}$ is based on the comparison of the master force translated in the microworld F_{micro} , and the cantilever contact force F_{canti} (16). As the nanostage is controlled on position, $\overline{P_{\text{nano}}}$ is computed by integrating $\overline{V_{\text{nano}}}$ with saturation levels at 0 and 12×10^{-6} m, travel limits of the nanostage (Table 1).

$$\overline{V_{\text{nano}}} = K(F_{\text{micro}} + F_{\text{canti}}), \quad (16)$$

where K is the enslaving gain of the force loop. Actually, the gain K must be small to insure the unconditional stability of the overall system and a good time response under the human reflex time, which is about 10 ms. Simulations using the parametric model obtained with the given transfer functions in Sections 2 and 3.2 have shown those performances are achieved with $K = 3$.

3.2.4. Algebraic loop. As stated above, $\overline{V_{\text{nano}}}$ is used both for position control of the nanostage in slave control and for position control of the master device in the master control block. This approach causes an algebraic loop in the expression of $\overline{V_{\text{nano}}}$ when converted from time continuous to sampled representation.

$$V_{c_k+1} = \delta_1 V_{c_k} + \delta_2 V_{M_k} + \delta_3 I_{nt_k} - K F_{\text{canti}_k}, \quad (17)$$

where $I_{nt_k} = P_{M_k} - P_{\text{macro}_k}$, $\delta_1 = -K \times K_d \alpha_f \alpha_d$, $\delta_2 = K_d \alpha_f$ and $\delta_3 = K \times K_p \alpha_f$.

When working with real time sampling, if $|\delta_1| > 1$, this loop is unstable. In this case, it is possible to overcome this algebraic loop without changing the performances of the control (i.e., without changing parameters K , K_d , α_f , or α_d), by considering that $V_{c_{k+1}} = V_{c_k}$ in (17), which becomes:

$$V_{c_{k+1}} = \delta_1 V_{c_{k+1}} + \delta_2 V_{M_k} + \delta_3 I_{nt_k} - K F_{\text{canti}_k}, \quad (18)$$

$$V_{c_{k+1}} = \frac{K K_d \alpha_f}{1 + K K_d \alpha_f \alpha_d} V_{M_k} + \frac{K K_p \alpha_f}{1 + K K_d \alpha_f \alpha_d} I_{nt_k} - \frac{K}{1 + K K_d \alpha_f \alpha_d} F_{\text{canti}_k}. \quad (19)$$

3.3. Llewellyn's unconditional stability criteria

It is possible to represent a dynamic system by a two-port model considering velocities V_1 , V_2 and forces F_1 , F_2 as inputs and outputs.

According to the choice of inputs and outputs, three representations can be defined: impedance Z (20), admittance Y (21) or hybrid H (22).

$$\begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}, \quad (20)$$

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \end{bmatrix}, \quad (21)$$

$$\begin{bmatrix} F_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ F_2 \end{bmatrix}. \quad (22)$$

The unconditional stability of the system can thus be verified using the Llewellyn's criteria. The two-port system is passive, and unconditional stability is ensured if all three following criteria are true:

$$Re(Q_{11}) \geq 0, \quad (23)$$

$$Re(Q_{22}) \geq 0, \quad (24)$$

$$2Re(Q_{11})Re(Q_{22}) - |Q_{12}Q_{12}| + Re(Q_{12}Q_{12}) \geq 0, \quad (25)$$

where $Q = Z, Y$ or H in accordance with the considered two-port system. These three criteria will be used to qualify and compare the proposed control scheme.

4. FORCE-FEEDBACK HUMAN OPERATED MANIPULATION EXPERIMENTS

4.1. One degree-of-freedom haptic interface: Brigit

First, the haptic interface Brigit is used to compare both force position and PPB controls.

4.1.1. Definition of parameters. The haptic interface Brigit has been designed for a maximal torque $T_B^{\max} = 0.1$ N m (Table 2). This value ensures a good ‘hand held feeling’ for the user. The corresponding maximal tangential effort $F_M^{\max}$ is given by: $F_M^{\max} T_B^{\max} / R_B = 2.8$ N.

Thus, the force scaling ratio given by (5) is $\alpha_f = 8.8 \times 10^{-5}$.

For the motion scaling, it is necessary to define virtual bounds, as the master’s motion is rotational, hence, unlimited. Choosing $C_B^{rd\max} = 2$ rad, approximatively the maximum rotation of a human wrist, ensures that the operator does not need to release it while manipulating. Then, the equivalent translation is: $C_M^{\max} = C_B^{\max} R_B = 0.07$ m.

The motion scaling ratio α_d between the nanostage and the Brigit as given by (5) is $\alpha_d = 5833$.

Note that as $\alpha_d \times \alpha_f \neq 1$, direct homothetic coupling for this case is inherently not passive.

Parameters K_p and K_d are also functions of the haptic device. According to Table 2 and equations (14) and (15) they are: $K_p = 0.652$ and $K_d = 0.013$.

4.1.2. Comparison of both controls. First, the Llewellyn’s criteria for both systems are computed (20):

$$F_1 = F_{op}, \quad F_2 = F_{canti}, \quad V_1 = V_B \quad \text{and} \quad V_2 = V_{canti}.$$

By inserting the dynamics equations of each of the blocks in (20), the two-port equation of the overall system can be computed in both cases. The obtained two-port model equation for the homothetic coupling is given by (26), and for the PPB it is given by (27) coupling. The chosen frequency range is 0–50 Hz (0–300 rad s⁻¹), according to the bandwidth ω_{BP} given in (13). Each criterion is plotted in Fig. 6, with, for each graph first row: $Re(Y_{11})$, second row: $Re(Y_{22})$ and third row: $2Re(Y_{11})Re(Y_{22}) - |Y_{12}Y_{21}| - Re(Y_{12}Y_{21})$.

$$\begin{bmatrix} V_B \\ V_{canti} \end{bmatrix} = \begin{bmatrix} \frac{1321000R_B^2}{\alpha_f(d_3s^3 + d_2s^2 + d_1s + d_0)} & -\frac{1321000R_B^2}{d_3s^3 + d_2s^2 + d_1s + d_0} \\ \frac{R_B^2}{\alpha_f(I_Bs + \mu)} & -\frac{R_B^2}{I_Bs + \mu} \end{bmatrix} \begin{bmatrix} F_{op} \\ -F_{canti} \end{bmatrix}, \quad (26)$$

where:

- $d_3 = I_B\alpha_d$, $d_2 = 2508I_B\alpha_d + \mu\alpha_d$,

- $d_1 = 1310000I_B\alpha_d + 2508\mu\alpha_d$, $d_0 = 1310000\mu\alpha_d$,

$$\begin{bmatrix} V_B \\ V_{\text{canti}} \end{bmatrix} = \begin{bmatrix} \frac{R_B^2}{I_B s + \mu - R_B T_2} & \frac{R_B T_1}{I_B s + \mu - R_B T_2} \\ \frac{R_B^2 V_{\text{micro2}} H_{\text{nano}}}{I_B s + \mu - R_B T_2} & V_{\text{micro1}} H_{\text{nano}} + \frac{R_B V_{\text{micro2}} T_1 H_{\text{nano}}}{I_B s + \mu - R_B T_2} \end{bmatrix} \begin{bmatrix} F_{\text{op}} \\ -F_{\text{canti}} \end{bmatrix}, \quad (27)$$

where:

- $V_{\text{micro1}} = \frac{K_t R_B K}{K_t R_B + K \alpha_f B}$, $V_{\text{micro2}} = \frac{K_t \alpha_f K}{K_t R_B + K \alpha_f B}$,
- $T_1 = B V_{\text{micro1}}$, $T_2 = A + B V_{\text{micro2}}$,
- $A = \frac{K_{\text{canti}}}{K_t R_B s} + \frac{K_d}{K_t R_B}$, $B = -\alpha_d A$.

Figure 6a shows that the force-position direct homothetic coupling does not imply unconditional stability and passivity, as all three conditions are not always satisfied and criteria have negative values. Moreover, $Re(Y_{22}) = -R_B^2/\mu + I_B^2\omega^2$ can never be positive in the given frequency range. On the other hand, Fig. 6b shows that for the considered frequency domain the coupling with the proposed PPB control always verifies the three Llewellyn's conditions: they are all positive, and the coupling is then passive. Thus, it is unconditionally stable. Moreover, analytical expressions of the three criteria show that the stability is not be affected, even if scaling ratios α_f and α_d are changed.

Using $[m\ddot{u}]$ MAD, the experimental behavior and performances are then studied, first with the above chosen force scaling ratio (5), and second when scaling ratios are changed. The force scaling ratio is divided by 10: $\alpha'_f = 8.8 \times 10^{-6}$; thus, the contact force feeling is amplified on the master (9).

In the first case, both controls have a stable behavior and results are almost identical. However, the force feeling on the master is weak; for example the pull-off phenomena is nearly unnoticed (Fig. 7). Typically in such cases, the operator may require an amplification of the force feeling. The results for the modified scaling ratio α'_f are shown in Fig. 8 for the control scheme. For the PPB control, as seen clearly in the motion plots, the feeling of force is firm and well transmitted even in case of the weak pull-off force, and the system is perfectly stable. On the other hand, Fig. 8a shows that for the force-position control instability occurs as soon as the measured forces are non-zero and the change of the scaling ratio is consequently not possible.

An other issue to discuss is the transparency. In the case of the PPB control, the system is not transparent by design, as the force felt by the operator is proportional to the position error between the master and the slave, on contrary of the direct homothetic coupling which reproduces solely the force measured by the AFM probe. Although it seems to be a drawback, this particularity brings

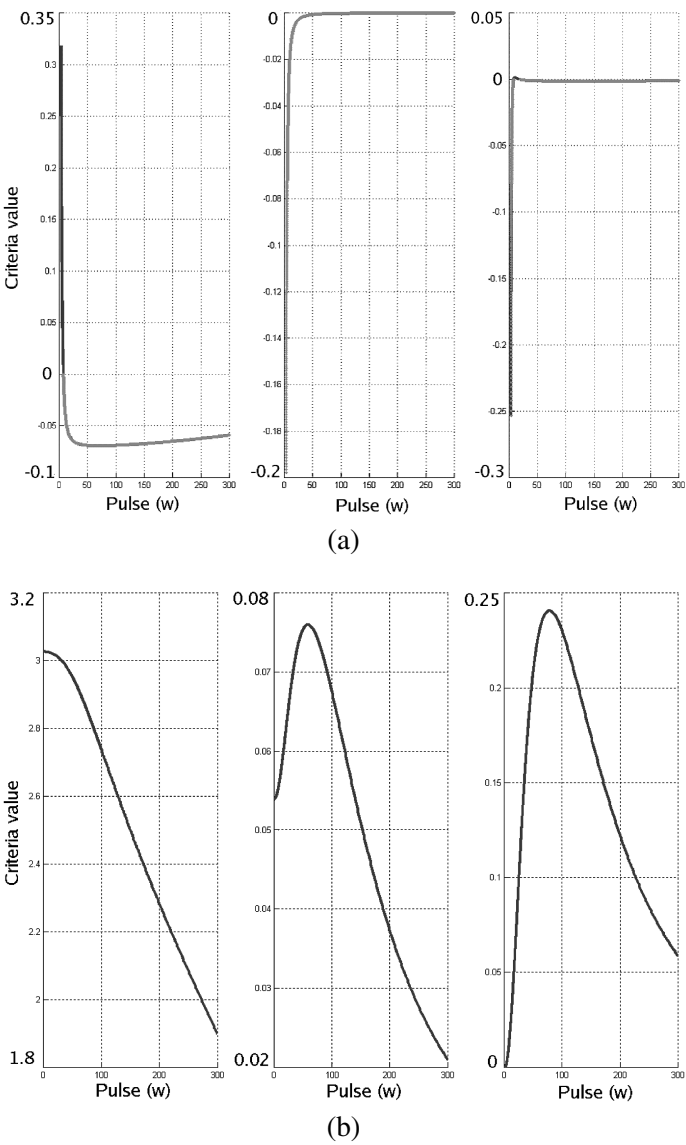


Figure 6. Llewellyn’s criteria for the force-position control (a) and Llewellyn’s criteria for the PPB control (b).

some considerable advantages. In direct homothetic coupling, all external factors influencing the motion of the slave without producing any effect on the force sensor are unnoticed by the user. In PPB coupling the user, feels the following error and can adapt his motion for a better grip in the manipulation task. A good example of this case is when the nanostage reaches its bounds, which is completely unfelt in direct homothetic case, but clearly apparent in PPB control (Fig. 7). Moreover, as the microscale physical phenomena are quite different from classical

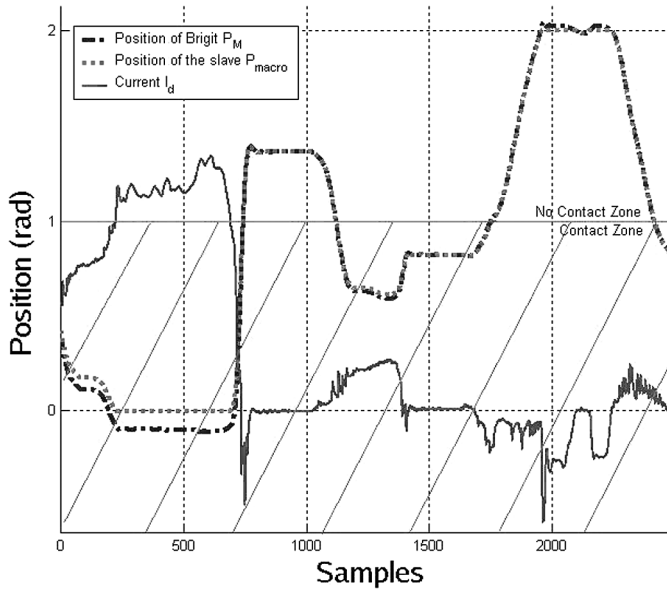


Figure 7. Position and current (proportional to force feedback) for the PPB control for an arbitrary trajectory with ($P_M < 1$ rad) and without ($P_M > 1$ rad) contact of the slave.

macroscale manipulations due to the predominance of the surface forces, this loss of transparency is rather welcome as it isolates the user from unexpected phenomena and smooths its operation.

4.2. Six degrees of freedom haptic interface: *Virtuose 6D*

The three translational degrees of freedom of *Virtuose 6D* allow coupling both vertical and horizontal motions in order to use all the motion possibilities of the micromanipulator [mü]MAD. Rotational DOFs are not used.

4.2.1. Definition of parameters. The *Virtuose 6D* has limited motion range (Table 3). Thus, if the whole stroke of the master is used, the motion scaling ratio given by (5) is $\alpha_d = 37\,500$.

Nevertheless, the use of virtual bounds can be of interest, particularly to take advantage of the kinematic redundancy. In this case, it is sufficient to define a new stroke $C_M^{\max}$ smaller than the maximum stroke. For example for the coupling of the nanostage and the microstage the stroke used to control the nanostage is 2.5 cm; thus, $\alpha_d = 20\,833$.

In accordance to Table 3 and (5), the force scaling ratio is given by: $\alpha_f = 7.2 \times 10^{-6}$.

Parameters K_p (15) and K_d (14) are also functions of the haptic device. According to Table 3, (14) and (15) they are: $K_p = 300$ and $K_d = 6$.

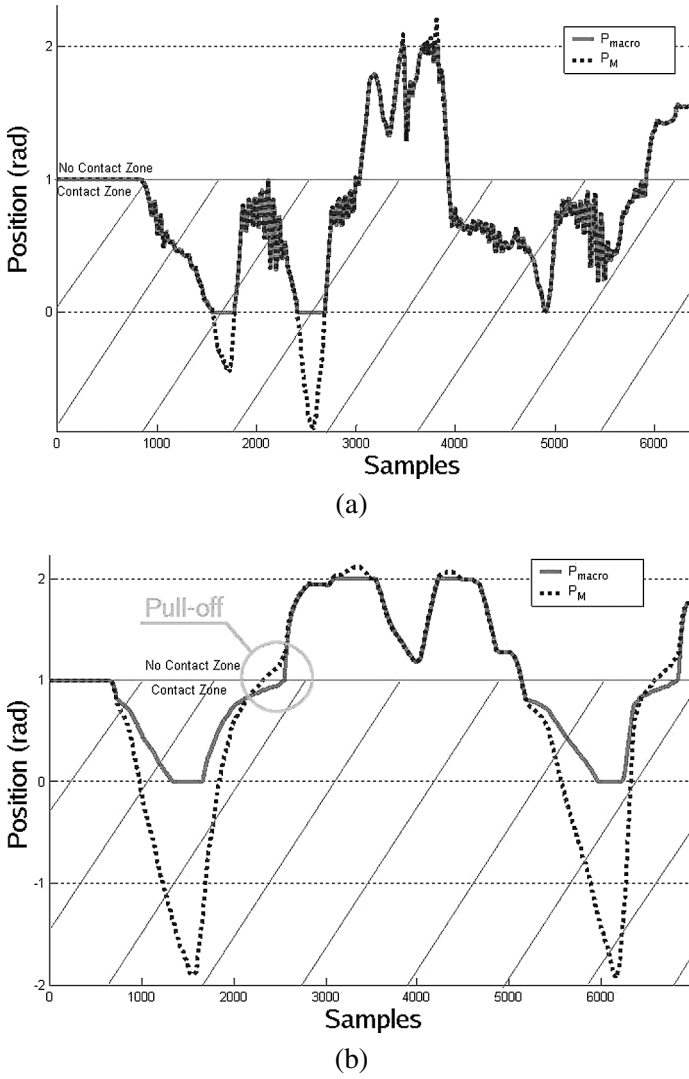


Figure 8. Influence of the force scaling ratio α_f on both controls. (a) For the force-position control instability occurs when the slave is in contact ($P_M < 1$). (b) The PPB control can be used to amplify the feeling of the pull-off forces that occur when contact is broken.

4.2.2. Horizontal microstages control. There is no measured contact force on the horizontal plane. We will then define a slaving control between the set-point velocity of the actuators V_μ and the position of the master C_d in the considered direction d where $d = x$ or y . The ratio between macro-position and micro set-point velocity can be computed as follows: $\alpha_{\mu d} V_\mu^{\max} / C_d^{\max} = 227$.

The set-point velocity is then given by: $V_{\mu d} = \alpha_{\mu d} C_d$.

4.2.3. Vertical microstage and nanostage coupling. As there is redundant actuation on the vertical axis with two actuators, the chosen solution is to couple the controls of both actuators using this same vertical DOF, and to use the measured contact force F_{micro} and the reaching of nanostage bounds to switch between the actuators.

If there is contact, or if the nanostage has not reached one of its bounds, then the nanostage is controlled by the PPB control with virtual bounds.

If there is no contact ($F_{\text{canti}} < 10^{-6}$ N) or if the nanostage has reached a bound ($P_{\text{micro}} = 0$ or 12×10^{-6} μm), the control switches to microstage: its speed is enslaved with the position of the master P_M , as in horizontal microstage control. The motion of the master to control the microstage is then the range between the virtual bound and the real bound of the master, for example, 10 cm on each side. The scaling ratio is then computed with: $\alpha_{\mu z} V_{\mu}^{\text{max}} / C_z^{\text{max}} - C_{z\text{Virt}}^{\text{max}} = 1250$.

4.2.4. Experimental results. The defined control is implemented on the experimental system. Virtuouse 6D is used to control the micromanipulator. Adhesion gripping and release by rolling tasks are successfully accomplished, giving similar results to the 1-DOF interface. Figure 9 shows the position of the nanostage converted in the macroworld, the set point speed of the microstage in the macroworld and the position of the master during such a task. The control switch between the nano- and macrostages allows at the same time both large vertical motion and nanometric precision when in contact. When a force greater than a few microNewtons is sensed by the AFM probe, the system switches back to PPB control, so the stability is ensured as described previously. Note that in this hybrid case the lower bound of the nanostage is artificially brought higher, so the nanostage will not be blocked in its lowest position when user touches an object when lowering down the gripper. This explains the offset between the position curves of Fig. 9.

5. CONCLUSIONS

We have presented the remote handling of a micromanipulator using adhesion forces. This manipulator is based on an AFM probe active gripper and has microNewton force resolution. It has 3 degrees of freedom with redundant vertical actuation in order to combine the large travel range and nanometric precision. The force-feedback coupling between the manipulator and a haptic interface allows a user to interact intuitively with the micro-objects. The proposed control scheme is based on passivity considerations for two port systems. This control provides more robustness than common force-position control, as it is unconditionally stable. It also allows to increase the performances such as the feeling of the contact and pull-off. Moreover, it is even possible to change the scaling ratios on the fly, as the stability of the system is unaffected. It is then possible to adapt the coupling to a given phase of the manipulation task which would need more or less precision or travel range using the same haptic interface.

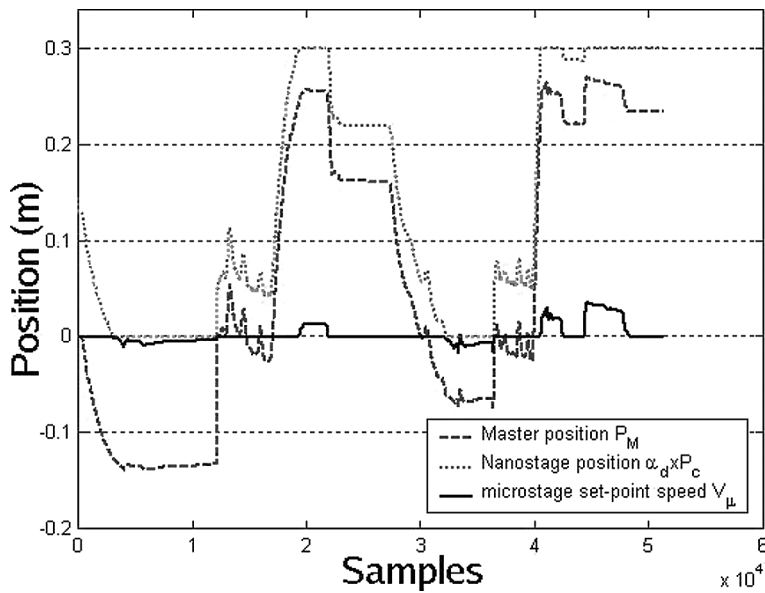


Figure 9. Results using the Virtuoso 6D as master: both microstage and nanostage are controlled.

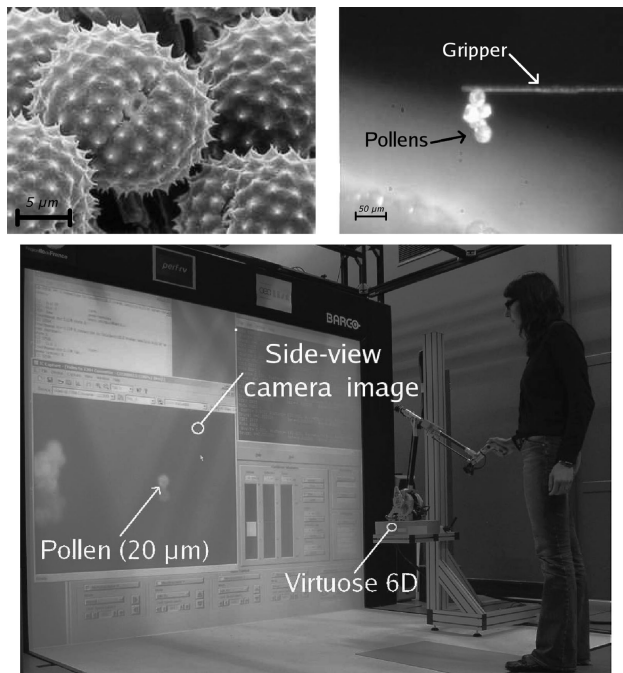


Figure 10. Remote manipulation of ragweed pollens.

The experimental results have been obtained on our experimental system with one and 3-DOF haptic devices for master. Users have been asked to pick-up an isolated

ragweed pollen (diameter = 20 μm) and then to release it on a glass substrate by rolling (Fig. 10). This release mode can only be successfully achieved if the contact force is properly controlled, in order to switch between rolling and sliding. All the first time users (around 20) participating in the experiment have succeeded in the operation in less than few minutes. Several scaling ratios were used as they were modified on demand of the users. Note that the change of the scaling ratios should be made off-line, i.e., when slave and master are not moving and the measured force is null. The success of this test bed leads to conclude that the force feedback supplies sufficient information for intuitive remote handling for this class of objects. As the force and motion scaling parameters can be easily modified, one can expect similar results for other classes. As for the loss of transparency discussed above, according to users' feedback, it has proved not to be an issue and rather an enhancement.

Note that the completion of the same task without the force-feedback is impossible. Moving the fragile AFM probe, remotely handled by a human operator through a joystick or a similar device, would obviously damage the probe as the contact goes unnoticed. It would be necessary to develop additional local control loops to limit the motion of the slave depending on the force measurement or more complex criteria.

The proposed coupling can be very easily applied to any micromanipulator and haptic interface. For microscale applications requiring user intervention, it would permit fast implementation and promote the switch from manual handling to robotic systems in numerous fields; for example, in biology oriented applications.

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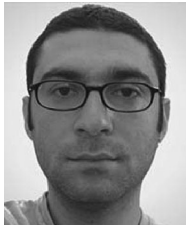
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