A Handheld Master Device for 3D Remote Micro-Manipulation

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Haptic Remote Control Interface for Robotic Micro-Assembly at Low Frequency

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Abstract— **Microassembly of submillimetric objects is still a manual process in most industries. Manufacture of MOEMS (Micro-Optical-Electrical-Mechanical System) based sensors, or watchmaking and even micro-surgery relies very heavily on the motor skills of an operator handling specialized tools. We propose here a preliminary work on bilateral coupling between a macro-tweezers and a micro-tweezers using a user interface for a microrobotic system which ambitions to combine the precision of the robot with the expertise of the craftsman. It strives to hide the scale-change between the microcomponents and the user's workbench, by providing a scaled-up tabletop image of the robot's sample-holder, co-located with a hand-held tool. This active tweezers mimics the traditional tool in form and function, albeit augmented with feedback. Its motions are tracked to drive the microgripper. Users may hence directly pick-up a micro-object from the image, while feeling the grasp of the microgripper on their fingers.**

I. INTRODUCTION

Precision manipulation of millimeter-range components is an intricate task, still mostly done manually. For example in watchmaking, the know-how and dexterity of craftsmen and their experience are unique assets. As in most cases in surgery, full-automation without operator intervention is currently unreachable. However, the requirements of self-discipline and long training make new operators difficult to recruit. Moreover, novel MOEMS components (Micro-Optical-Electrical-Mechanical System) appear with dimensions below the human capabilities. Consequently, robotic solutions are called for assist the operator and push down the dimensions of assemblies.

Teleoperation is a robotic technique first proposed for macroscale industrial applications [1]. Coupled with haptic feedback, an operator can achieve the task better and faster, or intervene in remote, and potentially hostile environments while taking advantage of his learned motor skills [2]. This strategy is particularly adapted to mentioned applications. However, the idea of combining the skills of the operator to the dexterity of a robotic system in teleoperation does not always hold, especially in the case of micromanipulation. The user interface generally consists of 2D screens, of input

devices like a mouse, joystick, buttons, and eventually of a generic haptic device [3], [4]. A skilled technician considers unconsciously their tools as an extension of themselves and it has an important impact on the workflow [5]. Teleoperation interfaces hence imply a fundamentally different workflow from manual manipulation and do not translate well, especially in the case of a senior technician. This human-machine interface issue is also at the heart of a general problem of insertion of robotics in microassembly workshops or in medical applications.

Consequently, the problem has been investigated in the literature form different angles. A simple approach is to equip a grounded haptic device with an 'active gripping extension' instrumenting the two-finger pinch, as in some commercially available interfaces [6] or in prototypes designed as a part of complete teleoperation chain [7]. However, grounded devices are quite cumbersome and do not sit well on a microassembly workbench. Other solutions like wearable devices [8], [9] or gloves [10] are proposed to feedback the gripping force to human hand. These approaches strive to emulate the hand grasping directly as the remote object, whereas precision manipulation uses tools. In addition, a tool can be easily put down momentarily, whereas it is more tedious to take off a wearable device. Hand-held solutions have hence a particular allure.

Some works adopt well-known designs such an augmented joystick or a gamepad, hence they are solely used as remote controllers [11]. On the other hand, traditional tools of the precision work, tweezers or forceps, are among humanity's oldest instrument. Nowadays, they still retained their function and form. There are very few changes between modern specimens and the ones found by archaeologists in Egyptian pyramids or in Mesopotamia [12]. A robotic evolution of this design would tackle the acceptability issue while retaining the operator's expertise. A prototype based on real tweezers augmented with a voice-coil actuator is proposed. However, it is designed as an extension to a grounded haptic device [13]. Tweezers with voice-coils are also explored [14], [15] but this particular actuation exhibits some limitations, especially in heat dissipation.

Lately, we have developed compact hand-held active tweezers designed from the ground for microassembly [16], [17]. This device offers a good compromise between force output, power requirements and thermal behavior by the mechatronic choices. It is designed to be used either as a replacement of classical tweezers with assisted force control on gripping or as a master device for remote operation with a microassembly robot. This manuscript focuses on this
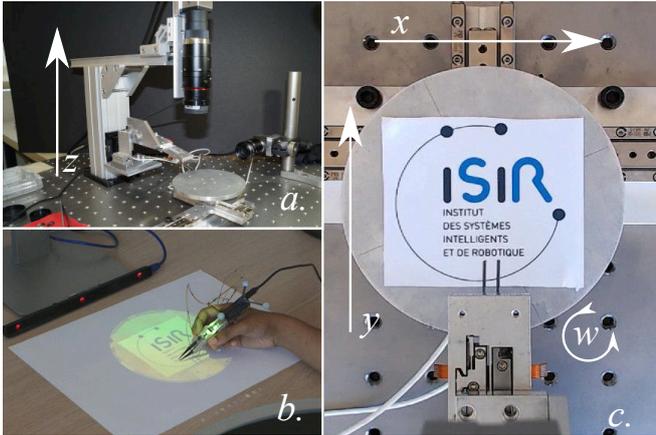
Fig. 1. Experimental setup: *a.* Microassembly station; *b.* Active tweezers as master device; *c.* Microgripper and the sample-holder. The assembly station provides the vertical motion of the microgripper and the sample-holder 3 planar DoF. User operates on top of a real-time projected and enlarged image of the sample-holder where its motion is compensated.

latter usage. The setup including the master device and the slave microassembly robot are presented next. A particular coupling strategy is crafted to work around the limitations of the communication layer and is then implemented. A grasping operation demonstrates the proposed teleoperation chain.

II. MICROASSEMBLY STATION

Fig. 1 depicts the different components of the micro-teleoperation setup used in this paper. The master tool is a hand-held active tweezers. The slave system is a microassembly station[1] with 4 DoF and an instrumented microgripper.

A. Hand-Held Active Tweezers as Master Tool

The master device is a tweezers-shaped ungrounded interface which measures $14.5cm$ and weights $51.2g$ (Fig. 2). It has a single active degree of freedom which corresponds to the grasping, driven by a coreless motor (DCX10L, Maxon Motor) coupled through a backlash-free mechanism. This motion is reversible, letting the user operate the tweezers
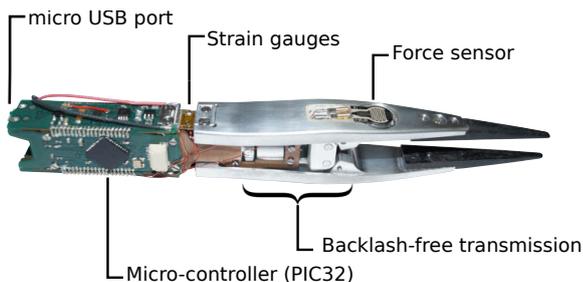
[1] http://www.percipio-robotics.com

Fig. 2. The active tweezers used as the master device. A DC motor actuates the gripping in both ways through a perfectly reversible mechanism. Several sensors collect crucial information (not shown in the picture: Accelerometer, Hall sensor, motor encoder).
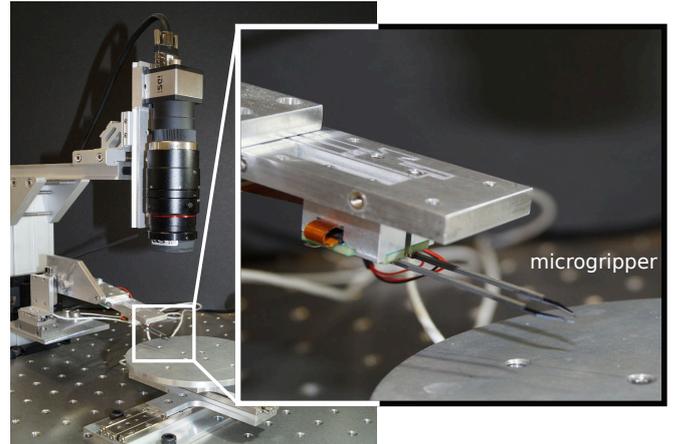

Fig. 3. The microassembly station is equipped with a microgripper. Its composed of two piezeoceramic beams carrying strain gauges at their base.

as a traditional one, with a possible haptic assistance from the motor.

All electronic boards are embedded. It includes a wide range of sensors: strain gauges at the clamped end of the tweezers' branches allow for opening and contact detection. A force sensor under the fingertip collects the force applied by the user.

Device position and orientation are tracked externally by vision. In that respect, 2 infra-red cameras (*Prime 13W, Optitrack*) are placed at approximately $2m$ from the working space on both sides and a 3D-printed marker is mounted on the tweezers (Fig. 1.b). The tracking uses the constructor's own closed source software and occurs at $120Hz$ and has a precision of $0.1mm$ [16].

B. 4 DoF microManipulator as Slave Device

The microassembly station is a 4 DoF robot composed of a sample-holder mounted on 3 piezoelectric stick-slip stages (2 translations $x-y$ and 1 rotation ω). The microgripper is mounted on a vertical piezoelectric stick-slip stage z. Translations have a resolution around $100nm$ while rotation exhibits a resolution of $500\mu°$. Furthermore, it is possible to change manually the orientation of the gripper around x axis. In the future it could be considered to add the two other rotations to get a 6 Dof micro-manipulator and reach the dexterity of a craftsman.

Two cameras (top and side views) provide visual feedback (IDS UI-3590CP,18 Mpx 21fps).

The microgripper is composed of 2 fingers consisting in piezoelectric beams with 2 strain gauges on the bottom and outer faces at their clamped end (fig.5). The grasp is controlled by the voltage applied to both fingers. The gripping force f_mu and the contact with the substrate are measured thanks to four gauges. The output of those sensors is not linear and presents a hysteresis as depicted in Fig.4.
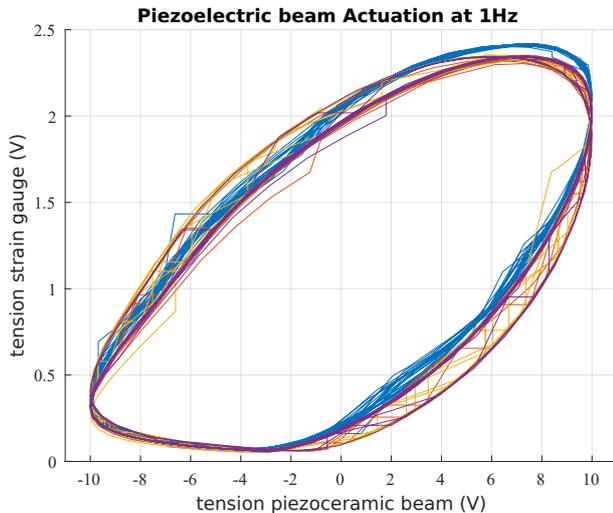
Piezoelectric beam Actuation at 1Hz

Fig. 4. Characterization of the microgripper. Piezoceramic actuation and strain gauge's output exhibit a predictable hysteresis.

C. High-Level Control interface of the Microassembly Station

The microassembly station relies on a main controller unit and appropriate APIs to communicate and control individual entities of the system. Typically, all stick-slip actuators can be controlled, as well as microgripper input voltage. It feeds back the position as reported by internal encoders and the tension measured by a strain gauge at the microgripper.

Although quite straightforward to the interface, this controller does not allow for low-level functionalities and is limited by a frequency below $50Hz$ to communicate. We have also observed random jitter affecting the communication frequency by 40% in some conditions. Moreover, the microgripper input and output are measured in Volts. Those are not straightforward to convert to Newtons because of the hysteresis and lack of proper knowledge of physical parameters and low-level access.

III. TRAJECTORY CONTROL

The motion of the gripper, excluding the grasp, is controlled with the motion of the master device. An overhead projector projects the top-view camera in front of the user on his workbench, considerably enlarging the image (fig.1.b). Side-view is shown on the monitor in front of the user.

The position of the master tool's tip is obtained from Optitrack system. A short calibration using 3 pre-defined points on the workbench gives the homothecy between the user's workspace and the robot's.

For motion control, the operator's position with respect to the sample holder is extracted. The microgripper is brought to this position using the robot's internal controllers. Only the rotation around the vertical axis is respected. Note that actually the movement is executed solely by the sample-holder, but its motion is compensated in the video feed before being displayed to the user, so from his point of view only the microgripper moves.

The only feedback during the process is visual, from top and side-view cameras. To alleviate the burden of controlling the 3 spatial translations simultaneously, the vertical axis is constrained. The microgripper is kept a few centimeters above the substrate so it can easily be positioned above the sample without risking a collision. The vertical motion is controlled explicitly when the operator requires it, with the master tool, or from the classical user interface. A single DoF haptic device is planned for this motion, relying on the vertical force sensing of the microgripper [18].

This remote control strategy, as well as an alternative rate-mode coupling, are explained in detail in [19].

IV. HAPTIC COUPLING OF MICROGRIPPING

The system is composed of the *microgripper* described previously and used as the slave device whereas *active tweezers* operate as the master. The objective is to couple the gripping of microscale objects with the master tool to take advantage of the user's motor skills for force control of the grasp. Furthermore, in order to evaluate the impact of haptic feedback, two different modes of operation are compared:

1) The first one only relies on visual feedback. The opening of the microgripper controls the opening of the active tweezers with appropriate scaling.
2) The second one provides the user with force feedback from the microgripper. It is thus necessary to propose a controller to achieve force rendering on the master side.

A. Low Rate Communication Issue

Haptic devices for teleoperated gripping has already been explored [20], [7], [4], [21], [9]. Bilateral haptic coupling can be modeled as a two-port system and is prone to instabilities when passivity criteria is not met [22]. Additionally, a sampling frequency close to 1 kHz is expected for better results [23], [24].

This requirement poses a serious issue with the current slave system, whose communication protocol is not designed for such use. The latency and bandwidth are well below mentioned values and initial measurements indicate that the average frequency is around 40Hz. This low bandwidth issue has been widely studied in the field of teleoperated systems [25]. Although some approaches exist to teleoperate at these frequencies, their trade-off is of a considerable complexity with a degraded perception because of the added damping.

We propose here an alternative approach to enable force feedback manipulation at low rate communication. The challenge is to render physical interactions at the master's side based on minimal data exchange. The proposed solution is to locally compute force feedback in the active tweezers loop as soon as contact detection is triggered at the slave's side. This clearly relies on minimal information exchange since only binary [contact / non-contact] information is required.

However, despite its apparent simplicity, several issues still need to be addressed. The first one is to detect the grasp in real-time from the slave's side. The second one is to
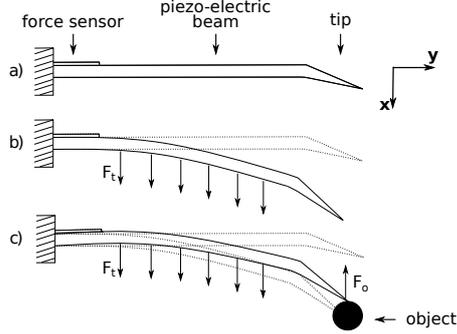
Fig. 5. Different stage of the piezoelectric beam deformation according to conditions at the tip. a) piezoelectric beam not actuated. - b) piezoelectric actuated: it bends as a beam recessed/free - c) piezoelectric beam closing until an object: behavior can be approximate to a beam recessed/simply supported.

make force rendering as most realistic as possible on the active tweezers. Naturally, a transparent rendering cannot be achieved because information like forces and positions are not shared in real-time.

We assume that providing binary grasp information through a predefined stiffness variation would provide sufficient additional stimuli for better user efficiency [26].

B. Grasp Detection

The microgripper is controlled with an integrated proprietary microcontroller. It handles the tension applied to each arm and collects the strain gauges information through a Wheatstone bridge. It communicates with on-demand TCP packets via ethernet and keeps the command voltage constant between requests. This protocol is not adapted to real-time control as it does not care to minimize the latency nor to keep the periodicity. The approach proposed is to estimate the state [grasping / not-grasping] of the gripper by observing the output signal with respect to the input set-point.

The input voltage is roughly proportional to the microgripper's opening, f_c. The output signal, stemming from the strain gauges, gives the deformation torque at the clamped end. When the beam is activated, its behavior is of a clamped-free cantilever. While in contact with an object, considering a perfect symmetry, the system is akin to a clamped-pinned beam. For the same load, this results in a higher strain and the clamped end as depicted in fig. 5.

Observing the variation of the difference of output signal f_{mu} and input f_c, it's been pointed out its time-derivative drops sharply at contact. On the opposite direction, a sharp increase occurs. A threshold t_g value is empirically determined and grasp state is set accordingly:

$$\text{if} \quad \frac{d}{dt}(f_c - f_{mu}) < -t_g \quad \rightarrow \quad \text{grasp} \quad (1)$$
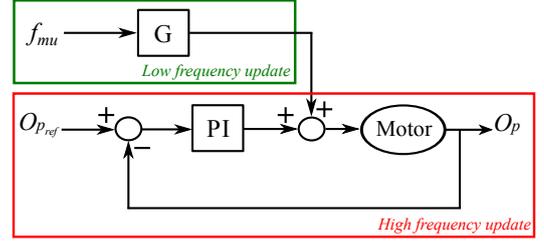$$\frac{d}{dt}(f_c - f_{mu}) > t_g \quad \rightarrow \quad \text{release} \quad (2)$$

Fig. 6. Control scheme to regulate the active tweezers stiffness.

C. Stiffness Variation on Active Tweezers

Haptic perception of contact is interpreted as a change in the stiffness [27]. Additionally, during fine manipulation with tweezers, Human's motor control loop is referenced on force, rather their fingers opening. At contact, a clamped-free to clamped-pinned transition occurs resulting in a rise of the apparent stiffness of the tweezers.

This behavior can be reproduced using the actuator of the master tweezers. Writing the contribution of natural stiffness of the device as $k_n \times \theta$ (with θ the opening angle), the actuator can be controlled to provide a desired apparent overall stiffness k_d such as :

$$(k_n + k_a) \times \theta \quad \text{with} \quad k_d = k_a + k_n$$
$$\implies W_a = k_a \times \theta$$

with W_a the motor torque and k_a a parameter which can be positive or negative. This simple torque control is quite straightforward to implement. Note that choosing a negative k_a between $-k_n$ and 0 gives a lower apparent stiffness.

However, it is necessary to modify the apparent stiffness of the gripper without causing a discontinuity on the force rendered to the user. Assuming that in no-grasp state only the natural stiffness of the mater tweezers is felt and at grasp the apparent stiffness switches to k_c, an offset value W_{off} has to be set in order to keep torque $W_a(\theta_c)$ at the same value, with θ_c the contact position.

$$W_a(\theta_c) \quad = \quad k_n \times \theta_c = k_c \times \theta_c + W_{off} \quad (3)$$
$$\implies W_{off} \quad = \quad (k_n - k_c) \times \theta_c \quad (4)$$

D. Coupling of grasping

Fig. 6 shows the scheme implemented to control the opening of the microgripper through the master tweezers and to modify its stiffness at contact. It relies on a *Proportional-Integral* controller that aims to regulate the opening of the active tweezers. The opening O_p is monitored and compared to $O_{p_{ref}}$ which denotes the initial opening of the active tweezers. The *PI* controller prevents the user to completely close the gripper by modifying the stiffness of the active tweezers. It tends to maintain constant the opening and, as a consequence, increases the force feedback. The gains define the dynamical change of the stiffness.

Remarkably, the control scheme in Fig. 6 does not rely on continuous data exchange. More precisely, it does not require continuous force measurement at the slave's side. However,
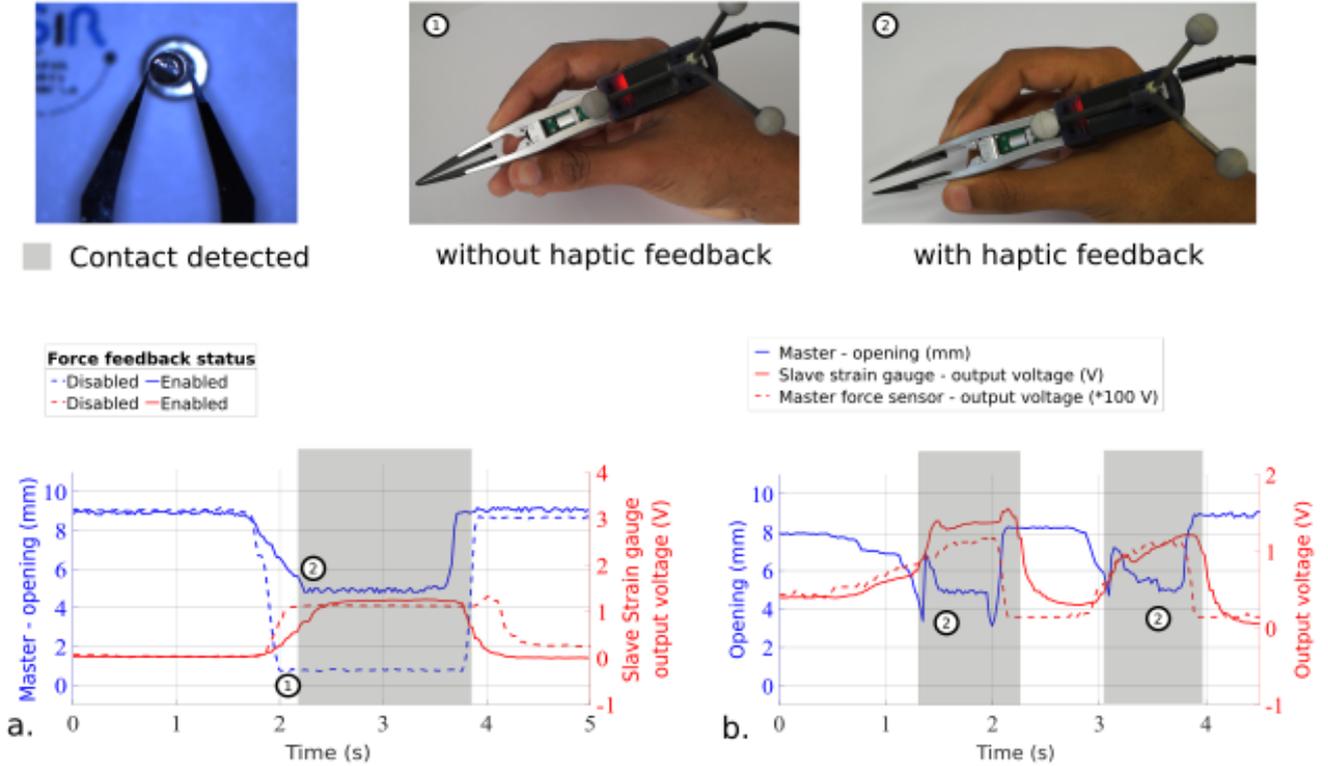
Fig. 7. Three trials to grasp a screw with the master and the slave devices. Without feedback, the user closes the tweezer at its maximum, exerting unnecessary load on the microgripper.

the output voltage f_{mu} of the force sensor located on the piezoelectric beam is added to the motor's input through a gain G. This signal is used to settle between the forces arising at microscale and those applied to the user. Moreover, the reference used to close the gripper is also updated at the same low frequency to drive the microgripper tracking the master tool.

To summarize, the stiffness is controlled in real-time and at high frequency (around $3kHz$) with the *PI* controller on the master side. Meanwhile, the forces arising between the microgripper and the object is added at a lower frequency (around $40Hz$) to render effects that occur at microscale. The current master opening O_p is sent to the microgripper as an input command.

E. Experimental Results

The experiment consists in grasping a screw with a $1.4mm$ radius. The active tweezers is controlled with the control scheme presented in Fig. 6.

In a first experiment, force feedback is disabled and the user grasps the screw and releases it. The results are presented in Fig. 7-a (dashed lines). Without the change in the apparent stiffness, hence without sensing the contact, the operator closes the master tool to its maximum, where he gets, at last, a stimulus by the touching of both branches. Meanwhile, the microgripper is pushed to its maximum

power, exerting unnecessarily excessive force on the gripped object.

In a second trial, the feedback controller is used. Measurements are plotted with continuous lines in Fig. 7-a. When the contact is detected, based on the derivative value of the output's strain gauge, force feedback is enabled and the reference opening $O_{p_{ref}}$ is recorded. As expected, the opening is controlled with respect to $O_{p_{ref}}$ and the controller limits its value by modifying the stiffness of the active tweezers.

In a third trial following immediately the second, the user quickly re-grips the object without moving it. The results are presented in Fig. 7-b. The same data are plotted as well as the output voltage of the master force sensor (dashed line). With the structure proposed in Fig. 6, we cannot expect that the forces measured at microscale correspond to those applied on the user (including a gain for the scale factor). Remarkably, the shapes of the signals that represent the forces (slave strain gauges and master force sensor) are very similar. It means that, despite its particular structure, the coupling proposed throughout this paper is suitable to render forces measured with the microgripper. The main difference is when the user intends to release the object. The signal of the master force sensor quickly decreases and a delay is observed before the output voltage of the strain gauge also decreases. This is mainly due to the low frequency update of the reference of the microgripper as well as its inner controller. Nevertheless,

this latency goes mostly unnoticed by the user who relies on the haptic feedback on his fingers.

In Fig. 7-b, some disturbances appear on the opening of the active tweezers. This phenomenon, which was not observed in Fig. 7-a, seems to indicate that the user is closing the active tweezers too fast. These peaks suggest that the transient state while switching force feedback on or off needs to be better controlled.

Those experiments show that force-feedback is successfully enabled even if information is exchanged at a low rate. The stiffness of the master device is virtually changed with the controller and the opening is controlled to provide the user with forces.

V. DISCUSSION

This paper presents a haptic remote control interface for an industrial microassembly robot using an innovative master tool. The ambition here is to provide a "cockpit" very much like the traditional workbench of a manual microassembly technicians, as in watchmaking or jewelry. The objective is the uttermost transparency of the robotization, as to let the operator draw advantageously from their learned motor skills.

The interface provides a tabletop display of a microassembly robot's work area, enlarged to the user's scale thanks to the projection. They operate directly on the projected scene using the active tweezers, which mimics successfully classic tweezers in form and function.

The position of the master's tip is assumed by the microgripper, co-locating both scale-spaces. A previous work on motion control using optical tracking has shown that position control was more precise but with a combination of both position and speed, it might be possible to be more efficient [16].

Here, the haptic control of the grasping is detailed. Dealing with low frequency communication due to the microassembly robot's API, a strategy has been developed. It has been proven that the grasp detection between the micro-object and the tweezers was robust. It is computed based on the behavior of the microgripper's strain gauges. Then, results revealed that despite the low frequency of the communication, rendering a stiffness change without destabilizing the user nor the system is possible.

Note that the proposed coupling has some "sloppiness": the microgripper is poorly characterized, and no calibration has been sought to tie the input and output tensions to physical quantities. The hysteresis is observed but is not compensated by signal processing. Moreover, the strain gauges, by their positions on the beams do not provide realistically the force applied by the branches, which depends if an object is grasped (clamped-pinned) or not (clamped-free). Furthermore, the control scheme was tested only on hard objects and not soft. Future works would have to explore the manipulation of different kind of objects.

However, handing the control to Human, and providing them with sensory input, off-loads all these shortcomings to their motor control skills. They are instinctively capable of dealing with hysteresis, and of evaluating successfully the amount of their mechanical action.

This strategy seems to pay off, and its confirmation is underway in a user-evaluation campaign with operators specialized in manual microassembly. For the comparison's sake, a state-of-art large-bandwidth coupling will be implemented by gaining low-level access to microgripper. The overall interface will also be run against a traditional screen-and-joystick setup, eventually extended with an Omega.7 type haptics device.

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