An Ungrounded Master Device for Tele-Microassembly

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Abstract—Micro-assembly is a challenging issue for automation due to particularities of micro-world physics and limitations on sensors. Consequently, most applications are human-operated often with basic joystick-like interfaces. Beside being nonintuitive, these solutions do not provide their users with a meaningful insight into the microworld. This paper proposes a novel intuitive remote handling interface, using a classical hand-held assembly tool as a paradigm. The master device is a portable instrumented tweezers with one active degree of freedom. Its spatial motion, tracked by optical means, controls the slave kinematics while its pinch commands the slave robot’s microgripper and provides haptic feedback. Different coupling strategies using position or speed variables are demonstrated.

I. INTRODUCTION

The Human eye perceives down to a few hundred micrometers, but manipulating at such scale remains quite difficult. Precision fields like jewelry, watchmaking, or experimental biology have been relying on manual manipulation with tweezers for several centuries. With the advent of micro-assembly and micro-technologies, robotized solutions are implemented when sample dimensions are beyond the limits of human dexterity. However, automation at these scales is still a very challenging issue in most cases where working conditions are uncertain and samples unstructured. Automatizing a specific task is a time-consuming operation, often beyond the competencies of the end-user [1]. Also, most tasks require some human know-how as the operator can determine the optimal method or technique considering the case. Hence, manual control of the robot is widely used for the sake of flexibility and to keep the user in the loop. For example, manipulating cells or microorganisms is conducted with simple robots: basically a cartesian kinematic structure fitted with a needle or pipette under an optical microscope, where the operator directly controls each actuator with buttons or a joystick.

The limitation in those cases is the Human-Machine Interface. Many off-the-shelf commercial solutions comprise basic interfaces with buttons, knobs or joysticks, each directly controlling a single actuator and ignoring the overall kinematics of the robot. The only feedback supplied to the user is the vision, through optical magnification with its inherent limitations on perception of depth, noise and discriminating of relative positions of tools, samples and features. These working conditions are inherently different from manual manipulation which the robotic solution aims to replace. Consequently, manual manipulation with tweezers and robotic operation involve both different sets of skills for the operator and it is not straightforward to rely and build on one’s expertise.

Similar issues in classic robotics have been treated using bilateral teleoperation chains, where a master device is handled by the operator to control a slave robot, and to render him/her back force sensor data as haptic information [2]. This approach involves operator’s motor skills and is shown clearly to benefit the precision, task duration, error rate and intuitiveness [3]. Various master devices, namely haptic interfaces, are developed aiming at different tasks or perceptual clues [4]. Naturally, the same approach was proposed for smaller scales, as in surgery [5], [6], or micro-manipulation [7], with the aim to transcribe the user’s know-how into the robotic control loop.

However, working in microscale has drastic limitations on robotic systems, the most prominent being the lack of force sensors. Six-axis force/torque sensors are commonplace for typical industrial robots, whereas there are no microscale equivalents providing multi-axis data on the interaction of the tool with its environment. All commercially available offerings lack effectors fitted with force sensors, except some microgrippers where only the gripping force is available. Also, AFM (Atomic Force Microscopy) based systems can provide up to 2-axis force measurement, but are limited to use the AFM cantilever itself as an end-effector [8]. Integrating force sensing to microscale tools is currently actively investigated [9], [10], but novel products are still to hit the market.

Hence, force reflecting tele-micromanipulation currently lacks full-space information for a proper haptic feedback. Although some partial feedback is demonstrated on AFM based manipulation systems or with custom sensors [8], [11], the use of a 6-DoF haptic interface may be counter-intuitive because it is under-exploited since the user observes the microworld through an optical magnification device which basically flattens the scene to 2D. Virtual reality (VR) and simulation based approaches are then proposed to provide a 3D display of the workspace fitted with virtual sensors [12].

The use of VR made some novel ideas possible for remote handling [13]. In [14], an operator is presented with a virtual scene mimicking the workspace with micro-objects brought to human dimensions, and his/her gestures are interpreted to teleoperate a micromanipulation system. The interface is hence quite intuitive because real-life pick and place gestures are used to control the robot. This solution is still however difficult to extend to a general purpose micromanipulation system.

The approach proposed here builds on these observations that interfaces based on usual tools are most intuitive and

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prone to be easily accepted on one hand, and that the current sensing technology does not provide full-space force information directly exploitabable for haptic feedback on the other hand. We have thus designed a portable ungrounded master device mimicking classical tweezers with a sole active DoF for its pinch. Its spatial motion provides the motion control of the slave robot, and in future works the pinch will be coupled to the microgripper and will feed back the gripping force.

Several studies tried to improve tweezers [15], [16], mainly for assisted surgery, but few introduced an ungrounded device which therefore limits the scope of possible applications. The design proposed for our haptic tweezers is kinematically optimized to function both as a force reflecting interface providing feedback on the gripping force, and as active tweezers assisting the user by for example stabilizing its pinch and grasp.

This manuscript focuses on its use for remotely operating a microassembly robot. The design of the handheld master device is presented next. The external tracking system is then evaluated and different coupling strategies are proposed. Pilot experiments illustrate the remote control of a micromanipulation system and give insight into its intuitiveness.

II. OVERVIEW OF THE MASTER INTERFACE

The objective is to propose a teleoperated micromanipulation system both intuitive for the user and favoring the exploitation of his/her experience. The driving idea is to focus on a master device, which can then be easily coupled with a commercially available system among offerings from different vendors. Tweezers are a commonplace tool for the target audience, and cognitively well connected to the target task. That is why they have been chosen as the baseline for the design. Since the slave system lacks sensor feedback except on the gripper, a portable device is a better fit than a desktop-grounded design, as it can be handled exactly as real tweezers. An external sensing system is used to track its motion. Both components are detailed below.

A. Haptic Tweezers as Master Device

There are some examples of robotic tweezers in the literature. First, note that an instrumented version is already commercialized for surgical applications. It is however not used like tweezers because its opening and closing are controlled with a joystick. No force feedback is possible on such a device, making its applications quite different. Haptic forceps have been proposed by [17], but have to be grounded to a 6-DoF interface. The use case is to reflect forces from a VR simulation for surgery training, so providing full space feedback is relevant. A voice coil actuated design is also presented for neuro-surgery [15]. A similar device is demonstrated in a master and slave configuration where only the gripping is coupled. There are some inherent limitations to these devices because of the actuation, which is bulky and prone to heating, and their lack of sensors.

The design proposed here is driven by a will to produce most compact and lightweight tools. The actuation is provided by a DC coreless motor, integrated into the body of the device and linked to a ball-screw converting the rotational movement into a slider. A preloaded cam/roller mechanism coupled to the slider opens and closes both branches symmetrically (Fig. 1a). This design is mechanically reversible. In consequence, the motor force can be used for both providing haptic feedback and controlling the opening of the branches.

This device is equipped with many sensors (Fig. 1b). A resistive pressure sensor is placed on the upper branch, under the user’s index. A full bridge of strain gauges is placed on flexures located at the base of both branches to give the opening. This distance is additionally obtained by an infrared proximity sensor that measures the motion of the slider. Winding current in the motor is also monitored. A PIC32 microcontroller is embedded to handle the control loop. No external controller is required. This device is plug-and-play as it only requires a USB connection to be powered and to communicate with the slave.

With a mass of only 40 g, it can provide force feedback stimuli up to 5 N, with a bandwidth up to 100 Hz. Its dimensions are consistent with handheld tweezers. The benefit of such a design is to be able to control the actuation to decorrelate the tweezer’s grasping force from the user’s grip. It can hence be used directly as real tweezers providing a gripping aid, or as a haptic device rendering the grasp of a virtual object.

B. Tracking System: OptiTrack

Because the master device is hand-held, a tracking system is required to measure its position and orientation. An embedded Inertial Measurement Unit would hardly provide consistent motion information and an absolute tracking system appears necessary.

Three different solutions are compared: a commercial magnetic tracker, a vision processing with a CCD camera, and a commercial IR motion tracker (OptiTrack, NaturalPoint).

The magnetic system (trackSTAR) is based on the measurement of variations of a magnetic field. A sensing in-
duction coil has to be integrated to the master device which requires an extra cable and its working space is rather limited compared to hand motions. It is also not compatible if one works with ferromagnetic parts, which is a common occurrence in microassembly.

Among optical methods, a CCD camera tracking a feature on the device (a QR code) and IR cameras tracking 3 ball-markers are compared. The second solution gives a higher frame rate at 120 Hz and exhibits much better accuracy and robustness. This solution is implemented by integrating removable markers on the device. Their attachment system ensures a repeatable positioning and fits both left- or right-handed use cases (Fig. 1c).

This tracking system is analyzed in depth in the next section.

C. Validation of the Tracking System

A set of experiments are conducted to investigate the accuracy of the OptiTrack system. The setup uses two Prime 13 W cameras placed on both sides of the user, at nearly 1.7 m each, and 1.25 m above the table (Fig. 4). The included software provides all the necessary tools to perform the spatial calibration and directly outputs positions in a given reference.

1) Static precision: 5 markers were positioned at different locations of a hypothetical working space represented by a parallelepiped (25 cm × 27 cm × 35 cm). The first marker was positioned at the center and others at 4 corners. Markers’ positions were continuously recorded for 10 seconds. The experiment is repeated with interiors lighting on and off, 10 times each.

The relative deviation between the measurement of each marker is calculated. The mean error is below 1% for all 3 directions. Interior lighting does not seem to affect the measurements.

Fig. 2 shows the mean position of marker 1 along to the X-axis as well as its peak values for each trial. All markers and directions give similar results. The precision, in this case, is less than 0.1 mm, which is consistent with official specifications.

2) Dynamic Accuracy and Precision: To evaluate the dynamic precision, 10 horizontal and 10 vertical translations were recorded using calipers with a resolution of 0.1 mm. Fig. 3 shows the real displacement vs OptiTrack measurement. As above the relative deviation was studied: for both horizontal and vertical translations the error is 0.87% and 0.13%, respectively. Hence, the accuracy is above 99%. The precision is in line with previous measurements and well below 0.1 mm. The offset highlighted in Fig. 3 can easily be removed with a numerical correction thus improving the accuracy.

III. SYSTEM DESCRIPTION AND COUPLING

A. Experimental Set-up

A 4-DoF micromanipulation platform is used as a slave robot (Fig. 4). The system is produced by Percipio Robotics, and comes with an open controller allowing low-level access. Two cameras provide top and side views, with adjustable magnification. All actuators are stick-slip piezo inertia drives, with sub-micrometer resolution, and maximum speed around 20 mm s⁻¹.

This system consists of a planar motorized sample-holder, with 80 mm × 100 mm travel range on x and y-axis mounted on an infinite rotation around z with 500 μrad resolution. A microgripper is mounted on an independent axis with vertical 18 mm motion. The gripper orientation can also be adjusted manually around the x-axis. This kinematic architecture keeps the microgripper always in the view of the top camera, as well as the center of the rotation of the sample holder.

All actuators are internally controlled with factory implemented PID controllers. Set-points can be updated at 50 Hz, through serial or ethernet links to allow an external control.

B. Master/Slave Coupling

The master device is tracked to drive the motion of the robot. For the sake of simplicity, only horizontal motions are treated here.

The first step is to get the position of the tip from marker positions. When the tip is fixed, tracked points draw the surface area of an imaginary sphere, where its radius is featured by the size of the tool. Considering rotation matrix and position tracked, the tip position can be found.

Fig. 5a shows the calibration acquisition, where the master device is moved around its tip fixed in space. Fig. 5b shows
the validation, with the measured point cloud (on the top) and the calculated tip position (on the bottom). The tip position is accurate at 5 mm, which can be further improved, if necessary. Two strategies are used to couple the master and slave motions:

1) Position control: The first one maps directly the master device position to the slave, with an appropriate scaling. This factor depends on the operator comfort but also on task dimensions, optical magnification and screen size on the other hand.

2) Speed control: The second strategy is to control the velocity of the slave according to a vector between the center of the workspace and the tip of the master device, akin to joystick control. Again, a scaling factor can be chosen according to the task at hand.

Both strategies are comparatively illustrated next.

IV. EXPERIMENTAL VALIDATION

A. Single-axis Coupling

The first task is to follow a straight line using a single actuator. Ten back and forth motions, approx. 20 mm between two features on the sample holder of the slave device are performed.

In the case of position control, a scaling coefficient of 0.1 is used, i.e., when the user performs 1 cm the slave travels 1 mm.

In the case of the speed control, a scaling coefficient $0.05 \text{s}^{-1}$ is applied to the tweezers position, i.e. 1 cm of master motion generates a speed of $0.5 \text{mm s}^{-1}$.

Operator moves the tip of the microgripper from one mark to the other using solely visual feedback. He/she does not access any other information such as axis positions.

Fig. 6 shows the results for both strategies. To compare each other, the error for reaching the maximal position and the end position is measured for each trial. Then the median of this error is plotted on Fig. 6 for position and velocity control, respectively. Note that the median is preferred in this paper to the average value because the median is not affected by the extremum values which can be due to human careless mistake.

Boxplot representation shows that median errors for both the maximum and the end positions are lower in position control than velocity control. Furthermore, the error distribution is more localized in position control. These indicate that the position control allows being more precise than the velocity control.

The second experiment consists on a sinusoidal motion in position control, with a stronger scaling coefficient in order to study the microscale precision of the slave robot. This
factor is set to $0.005$: when the user performs 5 cm the slave travels 250 µm.

Fig. 7a shows the trajectory performed by the operator and Fig. 7b the slave motion according to the reference. Following error is computed as being the distance between each point along the trajectory. Fig. 7c depicts the errors for each trial in boxplot. This graph shows that the median error ranges from 0.004 mm to 0.01 mm, below 10 µm. Considering the motion range, the error is below 2%.

B. 2D Coupling

A complete path following task is implemented to demonstrate both strategies. Users are asked to follow a path through 7 waypoints: 4 placed on a 5 mm square, then 3 on a quarter-circle 15 mm in radius around the first point. These points are drawn on a graph paper, placed on the sample holder. Fig. 8 shows the results for both couplings. The scaling is 0.15 for position control and 0.05 s$^{-1}$ for speed control. The users are only presented with the camera views during the experiment as feedback.

It is also observed that the position control shows wide shakes and variations on the master side. However, the resulting slave trajectories are much cleaner. As a matter of fact, the slower refresh rate of the slave system acts as a low-pass filter. Also, the maximum velocity of the robot actuators is limited, hence master motions faster than this threshold do not affect the trajectory. Considering the hand motions, precision gestures are low-frequency and slow, while involuntary trembles are faster and higher frequency. Hence, the system architecture itself filters the command to keep the control consistent with a precision move. Furthermore, the human brain is a very capable controller and the operator regulates its hand motions unconsciously while observing the slave trajectory.

In both cases, a naive user manages to handle the slave system quite efficiently. For the position control, a very good accuracy on the target waypoints is achieved. The trajectories are however quite noisy and irregular. On the other hand, the speed control is less accurate, however produces cleaner trajectories.

V. DISCUSSION AND CONCLUSIONS

This paper proposes a remote handling approach for micro-assembly, based on a novel master device: a haptic tweezers paired with a micromanipulation system. The ungrounded approach lacks feedback on spatial motion but may provide feedback on the gripping. This is in line with the available sensors on the slave device and gives much more freedom to the user while at the same time relying on the slave trajectory for each trial.

## Fig. 6
Results of the first experiment: a 20 mm movement imposed to the slave robot on a single axis. Position control on the left and speed control on the right. a) Position reference and displacement of the slave. b) Speed reference and displacement of the slave. c) Median errors in position control. d) Median errors in velocity control.

## Fig. 7
Second experiment: sinusoidal path following. a) Real trajectory performed by the operator. b) Reference and displacement of the slave (with 0.005 as scaling coefficient). c) Median errors between the reference and the slave trajectory for each trial.

## Fig. 8
2D Trajectory control. Position coupling on the left and speed coupling on the right. First line shows the master motion (a - c) and the second the slave’s (b - d).
greatly on his motor skills.

The problematic of haptic coupling between the master device and the microgripper will be treated in a separate dissertation as it encompasses other issues. Two spatial coupling strategies are demonstrated in this manuscript. First qualitative results show that the position control gives much better accuracy, but is maybe tiring and clumsy in transfer phases, while the speed control is less accurate, but gives cleaner trajectories. These findings are consistent with previous works on similar human/machine interfaces comparing, for example, mouse and joystick uses [18].

In that respect, the idea is to combine those two control methods. Fig. 9 is a representation of a projected 2D-working space. At the center, operator will get a precise working space with a high scaling coefficient, similar to the second experiment (position control). The outer area provides wider movements with a velocity control.

Note that in many parts of this work, simple solutions are adopted instead of pushing the precision: for example, the tip position is calculated with 5 mm accuracy, much above the possibilities of the tracking system. The slave’s systems controller is clumsy from a teleoperation point of view, yet it is exploited as it is. Despite those limitations, the small set of experiments conducted with naive users were very well-received. As explained above, this is mostly due to the great adaptation capabilities of the human brain, which in the case of an ungrounded device are greatly put to contribution, even unconsciously. This postulate is of course yet to be proven formally.

Future work will focus on user experiments and on a proper evaluation of the system and its impact on the work comfort of operators. Planned experiments with expert users will allow to further develop and shape hybrid control strategies. Intention detection approaches as in [14] will be explored.

**Fig. 9.** Scheme of a 2D-working space including two different control zones: the inner square area for position control and the border for velocity control.

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