

Analysis and Experiments of a Haptic Telemanipulation Environment for a Microrobot Driven by Centripetal Forces

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This paper presents the analytical and experimental results on a new haptic telemanipulation environment for microrobot control. The proposed environment is comprised of a 5DOF force feedback mechanism, acting as the master, and a 2DOF microrobot, acting as the slave. The fact that the slave microrobot is driven by two centripetal force vibration micromotors makes the presented telemanipulation environment exceptional and challenging. The unique characteristics and challenges that arise during the haptic micromanipulation of the specific device are described and analyzed. The developed solutions are presented and discussed. Several experiments show that, regardless of the disparity between the master and slave, the proposed environment facilitates functional and simple microrobot control during micromanipulation operations.

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1 Introduction

Recently, research in the area of robotic manipulation in the micro- and nanoworlds has gained a lot of interest and importance. The research activity focuses on areas, such as microsurgery, direct medical procedures on cells, biomechanics, micro-manufacturing, and micro-assembly, where tele-operated microrobotic devices can be used. It is well known now that not only the visual but also the haptic feedback can be helpful for a successful tele-operated micromanipulation procedure [1]. Therefore, some of the master manipulators are haptic devices, able to drive the microrobots and at the same time to transmit torques and forces to the operator.

A haptic tele-operation system, for use in microsurgery, was presented by Salcudean and Yan [2] and by Salcudean et al. [3]. Their system consists of two magnetically levitated and kinematically identical wrists, acting as a macromaster and a microslave, and a conventional manipulator that transports them. A telerobotics system using an atomic force microscope (AFM), as the nanorobot, has been proposed by Sitti and Hashimoto [4]. The system provides a 1DOF force feedback device for haptic sensing, using a linear scaling approach. A microsurgical telerobot is presented, which consists of a 6DOF parallel micromanipulator attached to a macromotion industrial robot and a 6DOF haptic master device [5]. The system provides a disturbance observer to enhance the operator's perception.

A microtele-operation system for tasks, such as micro-assembly or micromanufacturing, was developed by Ando et al. [6]. The haptic master is a 6DOF serial link mechanism, and the slave is a parallel link mechanism. Alternatively the Phantom, a commercial haptic interface, can be used as a master device [7]. The Phantom was used as a haptic master by Menciassi et al. [8] where a micro-instrument for microsurgery or minimally invasive surgery was tested. Sitti et al. [9] used the same haptic interface to tele-operate a piezoresistive atomic force microscope probe used as a slave manipulator and force sensor. A biomicromanipulation system for biological objects, such as embryos, cells, or oocytes, was pre-

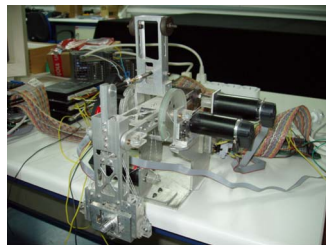
sented in Ref. [10]. The system uses the Phantom to provide an augmented virtual haptic feedback during cell injection. A similar system for microinjection of embryonic stem cells into blastocysts is described in Ref. [11], although the system has no haptic feedback. The mechanical design of a haptic device integrated into a mobile nanohandling station is presented in Ref. [12]. The Delta haptic device was proposed as a nanomanipulator in Ref. [13]. The device is also interfaced to an AFM.

The scaling problem in macro-micro bilateral manipulation has been discussed by Colgate [14], where a condition for the robust stability of an operator/bilateral manipulator/environment system is derived using the structured singular value. Goldfarb [15] addressed the issue of dynamic similarity and intensive property invariance in scaled bilateral manipulation. Using dimensional analysis methods yields a force-scaling factor that minimizes the intensive distortion of the environment. A force feedback control system for micro-assembly focusing on the issues of force transmission and control was presented [16]. Park and Khatib [17] presented a tele-operation approach using a virtual spring and a local contact force control on the slave robot. Faulring et al. [18] developed an algorithm that enables the haptic display of constrained dynamic systems via admittance displays.

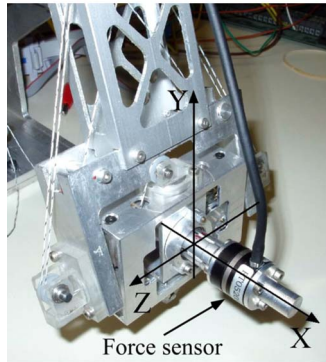
For a successful coordination between the master and slave, an appropriate telemanipulation environment is required, especially when the two have a disparate structure. This may happen in cases in which we need to manipulate different slave devices with the same master haptic mechanism, as for example in microsurgery, in micro-assembly, or in micromanipulation. Obviously, this has economic benefits too. In this paper the master and slave mechanisms are not only structurally disparate, but in addition, they function at a different scale. These characteristics make the telemanipulation, as described above, a particularly challenging issue.

In the proposed haptic environment, the commanding master device is a 5DOF force feedback mechanism, while the executing slave is a 2DOF microrobot with special behavior and is driven by two centripetal force actuators. Although the haptic master employed is a haptic mechanism designed for the human hand, and therefore shares characteristics with other such devices, to the knowledge of the authors, it is the first time that a vibration driven micro-robotic device is considered as the slave. This slave mechanism has a number of advantages relative to other microrobotic devices; namely, it is characterized by a low cost, complexity, and

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(a)



(b)

Fig. 1 The haptic master (a) and its force sensor-equipped spherical joint (b)

79 power consumption. The special characteristics and challenges
 80 that arise due to the unique design of the microrobotic device
 81 during haptic micromanipulation are described and analyzed. This
 82 design has implications not only the device's motion, but also on
 83 the forces that appear during micromanipulation. Note here that
 84 the particular design of the microrobot rules out any consideration
 85 of designing a special haptic master dedicated to the particular
 86 slave microrobot. The developed solutions are presented and dis-
 87 cussed. Two communication channels are identified and their in-
 88 tegrated input modes and force phases are described in detail. The
 89 use of the proposed haptic telemanipulation environment is illus-
 90 trated by several experiments. These show that, regardless of the
 91 disparity between master and slave, the proposed environment
 92 facilitates functional and simple to the user microrobot control
 93 during micromanipulation operations.

94 The proposed environment represents a first step in developing
 95 a unified framework for the manipulation of devices with dispar-
 96 ate structure and scale using haptic technologies. These devices
 97 can be robotic mechanisms of any degrees of freedom (DOF),
 98 holonomic or nonholonomic vehicles, or linear or nonlinear sys-

tems. They can follow a path or interact with their environment 99
 and must be commanded through a haptic interface. The reason 100
 for this can be the size of the manipulation device (too big for 101
 human capabilities), the distance between the human and the de- 102
 vice (control of an exploration rover), the scale of the manipu- 103
 lation environment (a microrobotic device for tissue inspection), the 104
 potential risk for the human or the device, (a mobile platform in a 105
 nuclear facility), or the physical nature of the manipulated device 106
 (for example, a simulated virtual environment). 107

2 Master and Slave Brief Description 108

The developed haptic telemanipulation environment employs 109
 an existing 5DOF haptic mechanism as the master and a 2DOF 110
 microrobotic platform driven by two centripetal force actuators as 111
 the slave. A brief description of the master and slave is given next. 112

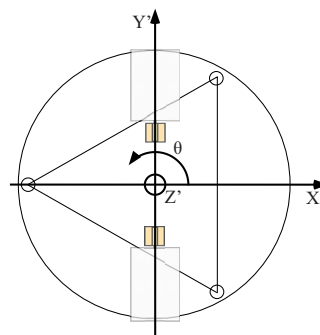
2.1 Master Haptic Device. The master device is the haptic 113
 mechanism shown in Fig. 1. It consists of a 2DOF five-bar linkage 114
 and a 3DOF spherical joint. All DOF are active. To reduce the 115
 mechanism moving the mass and inertia, all actuators are placed 116
 at the base. The transmission system is implemented using tendon 117
 drives with capstans. The device is thoroughly described, includ- 118
 ing kinematics and dynamics, in Ref. [19]. Although this haptic 119
 device was not developed for micromanipulation, it is suitable 120
 since it was designed optimally to exhibit maximum transparency, 121
 as seen from the operator side [20]. Fig. 1(b) shows the macro- 122
 world coordination system, i.e., the master haptic device system. 123
 The mechanism can translate in the X and Y axes by 10 cm and 124
 rotate about the X axis by ± 180 deg and about the Y and Z axes 125
 by ± 30 deg maintaining at the same time its good functionality. 126

2.2 Slave Microrobotic Platform. The slave device, shown 127
 in Fig. 2(a), is a microrobotic platform employing two vibration 128
 micro-actuators. This novel motion mechanism exploits the cen- 129
 tripetal forces generated by eccentric masses that are rotated by 130
 motors mounted on a platform. The angular speed of these motors 131
 is controlled, so that the generated centripetal forces induce to the 132
 platform a desirable motion. The interaction of centripetal forces 133
 with frictional forces developed at contact points yields a stepwise 134
 motion of the platform. The magnitude of the net displacement per 135
 step is controlled by the rotational speed of the eccentric load and 136
 can be made arbitrarily small. This way micromotion can easily be 137
 achieved. The concept was inspired by observing the motion of 138
 devices that vibrate, such as cellular phones or unbalanced wash- 139
 ing machines. The platform is described in detail, including the 140
 design, kinematics, dynamics, and control, in Ref. [21]. It is a 141
 novel totally enclosed design with applications in the areas of 142
 micro-assembly, biomechanics, microsurgery, etc. 143

The platform can perform translational and rotational sliding 144
 with submicrometer positioning accuracy and velocities of up to 145
 1.5 mm/s. All the components of the mechanism, including its 146



(a)



(b)

Fig. 2 The slave microrobotic platform (a) and the microworld coordination system (b)

147 driving units, are of low cost and are readily available. The total
 148 cost of the platform does not exceed 50 euros. In Fig. 2(b), the
 149 microworld coordination system is shown. The platform translates
 150 along the X' axis and rotates about the Z' axis by an angle θ .

151 3 Haptic Telemanipulation System Features and Re- 152 quirements

153 **3.1 Slave Microrobot Features.** The design and special fea-
 154 tures of the slave microrobotic platform (microrobot) introduce a
 155 number of challenges that need to be tackled by the telemanipu-
 156 lation environment design. These are presented next.

- AQ: #1 157 1. The microrobot is enabled for coarse and fine motions. It is
 158 a mobile platform designed to perform fine tasks, such as
 159 assembling parts at the microscale in cooperation with other
 160 similar microrobots. Furthermore, to avoid the need to be
 161 transported by an additional macrorobotic mechanism, it is
 162 designed with the capability for coarse high-speed motions
 163 during large displacements toward a target. Its translational
 164 sliding velocity is up to 1.5 mm/s.
 165 2. The slave microplatform and the master haptic device are
 166 kinematical dissimilar. The former is a 2DOF mobile plat-
 167 form and the latter is a 5DOF robotic mechanism.
 168 3. The inverse kinematics of the nonlinear microrobot is not
 169 available in real time. In addition, the microrobot exhibits
 170 complex nonholonomic characteristics.
 171 4. The vibration actuators must operate within a specific speed
 172 range (rpm). The theoretical upper limit depends on the type
 173 of the ground and results in the maximum translational ve-
 174 locity. When this limit is exceeded, the microrobot exhibits
 175 an additional undesirable vertical vibration. The practical
 176 upper limit is taken to be about 80–90% of the theoretical
 177 limit. A low rpm limit also exists and is due to the need to
 178 overcome the support frictional forces, so that net motion
 179 may result.
 180 5. To achieve sub micrometer positioning accuracy, the mi-
 181 crorobot has the option to drive alternatively the two vibra-
 182 tion micro-actuators.
 183 6. The forces applied on the microtargets can be smooth or, due
 184 to the vibrating nature of the actuation, can be in the form of
 185 impacts.

AQ: #2 186 **3.2 Master Haptic Device Requirements.** The above slave
 187 microrobot features dictate the following requirements for the
 188 master haptic device.

- 189 1. The master haptic device has to drive the microplatform (a)
 190 toward the target in coarse motion and (b) during microma-
 191 nipulation in fine motion. During the coarse motion phase, a
 192 high speed and low positioning accuracy is needed, while
 193 the opposite is true during fine motion.
 194 2. To resolve the kinematical dissimilarity between the master
 195 and the slave, taking into account that an inverse kinematics
 196 relationship is unavailable in real time, a mapping from the
 197 master haptic device Cartesian space to the microrobot ac-
 198 tuator space has to be developed.
 199 3. The master must send independent commands to each actua-
 200 tor. In addition, the ability to drive each micro-actuator al-
 201 ternatively is needed. In general, capabilities for (a) pure
 202 translation, (b) pure rotation, and (c) combined planar mo-
 203 tion must be available.
 204 4. A suitable micro/macro force mapping has to be defined.
 205 The force feedback mechanism should transfer the microen-
 206 vironment forces to the macro-environment operator forces
 207 according to an appropriate function. This function must be
 208 able to handle not only smooth forces, but impact forces as
 209 well.

210 Next, the implementation of the above requirements to the hap-
 211 tic telemanipulation environment is described.

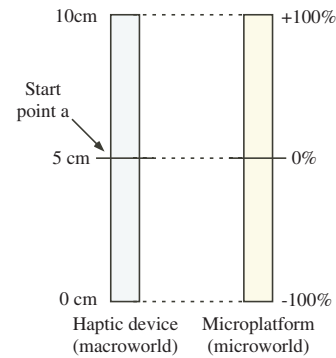


Fig. 3 The MaIM input scheme

4 Haptic Telemanipulation Environment Analysis 212

In the haptic telemanipulation environment, the master haptic 213
 device and the slave microplatform communicate bilaterally. The 214
 first communication channel transmits motion commands from the 215
 haptic mechanism to the microrobot. PWM circuits drive the mi- 216 AQ:
 croplatform actuators, according to the percentage (0–100%) of 217 #3
 their duty cycle. As a result, actuator angular velocities are set and 218
 produce microrobot translations and rotations. Consequently the 219
 output of the master haptic device should be the percentage (0– 220
 100%) of the PWM duty cycle. The input to the haptic mechanism 221
 is the command given by the operator's hand. 222

The second communication channel transmits forces from the 223
 microrobot to the haptic mechanism. Its input is the microforces 224
 sensed by the microrobot during manipulation. The output of this 225
 channel is the force that the haptic device applies to the operator. 226
 Next, the communication channels are analyzed further. 227

4.1 First Communication Channel. In order to realize the 228
 first communication channel, the following three mutually exclu- 229
 sive input modes are defined. The first is the macroscopic input 230
 mode (MaIM), the second is the macroscopic rotation input mode 231
 (MRIM), and the third is the microscopic input mode (MiIM). The 232
 operator can choose and control the modes from the appropriate 233
 software. Our goal in the first two input modes is to achieve 234
 coarse motion of the platform, while in the third mode, it is to 235
 achieve fine micromanipulation. 236

4.1.1 The Macroscopic Input Mode. The master haptic ma- 237
 nipulator uses this mode in order to drive the microrobotic plat- 238
 form toward the microtarget in linear or curved coarse motion. In 239
 this mode the positive/negative translation of the master haptic 240
 device end-effector in the X axis results in an increase in the 241
 positive/negative rotational speed of *both* microrobot vibration 242
 micro-actuators and therefore results in microrobot translation 243
 along the X axis. 244

To obtain a curved translation, a difference in the micro- 245
 actuator rotational velocities must exist. This is achieved by rotat- 246
 ing the haptic device end-effector about the Y axis. A positive/ 247
 negative rotation about this axis results in an increase in the 248
 rotational speed of the first/second micro-actuator. 249

As mentioned earlier, the haptic device end-effector can trans- 250
 late in the X axis by 10 cm and rotate about the Y axis by about 251
 ± 30 deg. Therefore, the start point of the end-effector is taken at 252
 the middle of its possible displacement, see Fig. 3, point *a*. A 253
 translation of the haptic device end-effector from start point *a* 254
 results in a percentage command of the micro-actuator speeds q 255
 according to 256

$$q = 20(p - 5) \quad (\%) \quad (1) \quad 257$$

where p (cm) is the haptic device end-effector position. 258

Table 1 Haptic telemanipulation environment input modes

	MaIM		MRIM		MaIM	
In X positive	+	+	+	-	+	+
In X negative	-	-	-	+	-	-
About Y positive	↑	0	↑	0	1	0
About Y negative	0	↑	0	↑	0	1
	Microat. A	Microat. B	Microat. A	Microat. B	Microat. A	Microat. B

259 Additionally, for each degree (deg) of end-effector rotation
 260 about the Y axis, the corresponding micro-actuator speed is in-
 261 creased by 1%.

262 **4.1.2 The Macroscopic Rotation Input Mode.** The master haptic
 263 device uses this mode to rotate the microrobot without trans-
 264 lation, again in coarse motion. This mode is useful in changing
 265 fast the direction of microplatform motion, and can be achieved
 266 by rotating the micro-actuators in equal and opposite speeds. To
 267 this end, the master operator translates the end-effector along the
 268 X axis resulting in an increase in the rotational speed of both
 269 micro-actuators, but this time with an opposite speed direction.

270 **4.1.3 The Microscopic Input Mode.** The master haptic device
 271 uses this mode during micromanipulation. This mode is useful
 272 after the microplatform has reached the microtarget and is starting
 273 micromanipulations. Two alternative ways were examined for this
 274 mode. The first is to function the haptic device in MaIM, such as
 275 in the macroscopic case, but with low actuator velocities. The
 276 second is to drive the micro-actuators one at a time.

277 Sometimes, because of anisotropies in the behavior of the mi-
 278 croplatform translation when both micro-actuators are function-
 279 ing, see Ref. [21], for smooth and fine motion, the micro-actuators
 280 have to function one at a time. To produce such a motion, the
 281 operator of the master device translates the end-effector in the
 282 positive or negative direction in the X axis indicating the rotation
 283 velocity and direction of the micro-actuators and at the same time
 284 rotates the end-effector about the Y axis to indicate which micro-
 285 actuator should function.

286 Table 1 illustrates the presented input modes above. The “+”/
 287 “-” symbols denote a positive/negative rotational micro-actuator
 288 speed, the “↑” symbol denotes a micro-actuator speed increase,
 289 while “0” denotes that the corresponding micro-actuator is not
 290 influenced. During the MiIM phase, “1” denotes that the corre-
 291 sponding micro-actuator is functioning and “0” denotes that the
 292 micro-actuator is not functioning.

293 **4.2 Second Communication Channel.** In order to realize the
 294 second communication channel from the microrobot to the haptic
 295 mechanism, we define the following control phases. (a) The macro-
 296 scopic control phase (MaCP), during which the haptic mecha-
 297 nism operator drives the microplatform toward the microtarget, in
 298 a coarse motion, and (b) the microscopic control phase (MiCP), in
 299 which the micromanipulation of the microtarget occurs in fine
 300 motion. Next, both phases are presented in detail. Again, the con-
 301 trol phases can be selected from the software.

302 **4.2.1 The Macroscopic Control Phase.** During this control
 303 phase, no micromanipulation forces exist, and therefore, normally
 304 the haptic device would not apply forces to the operator. However,
 305 as discussed earlier, above a critical micro-actuator speed, the mi-
 306 crobot vibrates vertically and may even tip over. To indicate the
 307 limits of the permissible actuation speed, a spring force propor-
 308 tional to the haptic end-effector translation (and micro-actuator
 309 speed) is applied to the operator, see Fig. 4. This force is given by
 310

311
$$f_{sp} = k(p - 5) \quad (2)$$

312 where p is the haptic device end-effector translation, see Fig. 3,
 313 and k is a variable spring constant. By experimentation, it was

found that tipping occurs at about 85% of the maximum micro-
 actuator speed, depending on the ground type or platform mass.
 To signal this limit, a spring constant three times harder than
 before is employed above 85% of the maximum speed. To achieve
 a smooth transition, the spring constant changes according to an
 exponential function. The maximum force applied to the operator
 is set to be 5 N. This value is slightly under 15% of 35.5 N, which
 is the average maximum controllable force a female can produce
 with her wrist according to Tan et al. [22]. Measurements in Ref.
 [23] showed that humans exert forces of up to 15% of their maxi-
 mum ability, without fatigue for a long period of time. Conse-
 quently, the chosen spring constant, k , is defined as follows:

$$k = \begin{cases} 0.33, & |p - 5| \leq 4.25 \\ e^{0.68(|p-5|-4.25)} - 0.66, & 5.0 \geq |p - 5| > 4.25 \\ 1, & |p - 5| > 5.0 \end{cases} \quad (3)$$

4.2.2 The Microscopic Control Phase. During this control
 phase, forces resulting from the micromanipulation are applied to
 the operator by the haptic device. As seen in Fig. 5, the microplat-
 form following the operator commands comes into contact with
 the environment, e.g., pushes a micro-object. The developed force
 is measured, filtered, and fed by the haptic device, according to a
 suitable scaling function, to the operator’s hand. The scaling fac-
 tor depends (a) on the maximum force applied by the microrobot,
 (b) on the maximum force that the haptic mechanism can apply,
 and (c) on the maximum force that the operator can exert without
 fatigue for a long period of time (5 N). Although the haptic
 mechanism can apply larger forces, it is designed for applications
 that need a maximum force of this magnitude, see Ref. [19]. Fur-
 thermore, experiments in Ref. [24] showed that the maximum
 force that the microrobot exerts is not greater than 0.05 N, thus

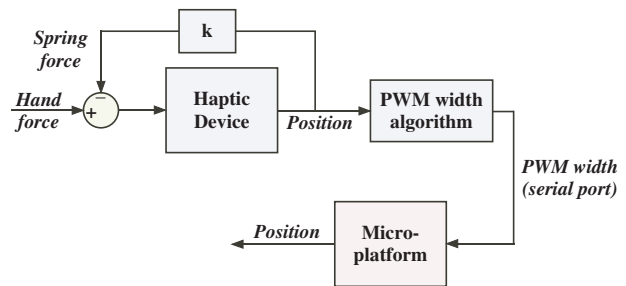


Fig. 4 The macroscopic control phase force loop

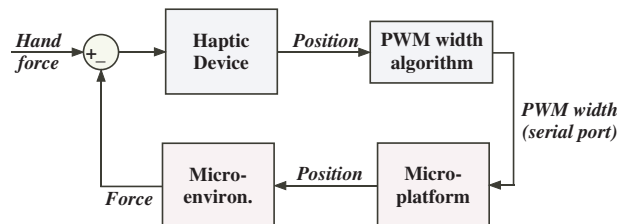


Fig. 5 The microscopic control phase force loop

Table 2 Function of the haptic telemanipulation environment modes and phases regarding the type of motion

	Coarse motion	Fine motion
1st communication channel	MaIM, MRIM	MiIM
2nd communication channel	MaCP	MiCP

the selected scaling factor is 100. Oversampling at 1 kHz and the average calculation of successive samples before scaling was the filtering method employed.

In general, interaction forces are smooth. However, depending on the microrobot-environment springiness and damping, the generated forces can be in the form of impacts, [21]. In this case, a simple force magnification does not provide useful haptic information, while it may be potentially dangerous for both the operator and the haptic device. To overcome this situation, the impact forces are filtered and the resulting smooth signal is magnified and applied to the operator. As mentioned earlier, oversampling at 1 kHz and average calculation of successive samples were used. Although the magnitude of the impact forces can reach 0.3 N, the average value is about 20 times smaller, see Ref. [24] and the experimental results in Sec. 6.2.4. Hence, the same scale factor (100) was used.

Table 2 illustrates the function of the above modes and phases of the two communication channels regarding the type of motion (coarse or fine).

375
376

$$\frac{X_m(s)}{F(s)} = \frac{k_h}{m_h m_m s^4 + (m_h b_m + b_h m_m) s^3 + (m_h(k + k_h) + b_h b_m + k_h m_m) s^2 + (b_h(k + k_h) + k_h b_m) s + k_h k} \quad (4)$$

377
378
379
380

During the simulation the operator's hand mass m_h is 1.46 kg, the hand damping b_h is 3.6 N s/m, and the hand stiffness k_h is 200 N/m. These represent average values taken from the relevant literature [25,26]. The haptic mechanism apparent mass m_m in the X axis is about 0.27 kg and the mechanism damping b_m is about

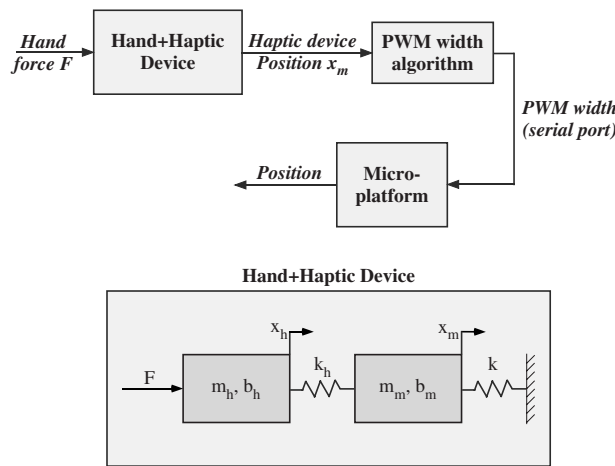


Fig. 6 The model of the haptic telemanipulation system including the user hand during the MaCP force loop (no interaction with the microenvironment)

Table 3 Definition of the symbols in Fig. 6 and Eq. (3)

Symbol	Definition
F	Operator's hand force
m_h	Operator's hand mass
b_h	Operator's hand damping
x_h	Operator's hand position
k_h	Operator's hand stiffness
m_m	Haptic mechanism mass
b_m	Haptic mechanism damping
x_m	Haptic mechanism position
k	Virtual spring constant

5 Haptic Telemanipulation Environment Simulation 361

Next, a 1-dof model system in macroscopic mode, with no interaction with the microenvironment, is defined. It consists of (a) the operator's hand, (b) the haptic mechanism, and (c) the micro-robotic system, see Fig. 6(a). The operator's hand is modeled as a mass-spring-damper system, attached to the haptic mechanism, which is modeled as a mass-damper system, see Fig. 6(b). We do not present the model of the microplatform used here, since it is described in detail in Ref. [21]. Note that during the macroscopic control phase, the haptic device is connected with a virtual spring defined by Eq. (2), with spring constant k .

The transfer function of the "Hand+Haptic Device" system in Fig. 6 is described by Eq. (4), and the related symbols are defined in Table 3.

5 N s/m. These values are found through experimentation with the haptic mechanism, see Ref. [19]. The input to the system is a step of about 0.18 N of the operator's hand force F . The virtual spring value k is 4 N/m. The simulated period is 20 s.

Figure 7 shows the result of the simulated try in MiIM under (MaCP). The operator's hand step force results in the translation of the haptic mechanism end-effector of about 0.045 m and the duty cycle command shown in Fig. 7 (first schema), as explained in Sec. 4.1.1. Consequently, when friction and inertia forces are

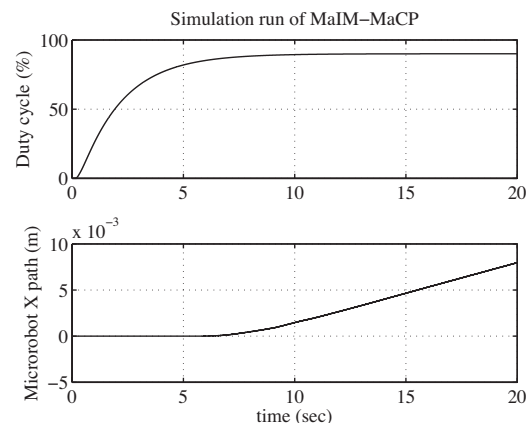


Fig. 7 The simulation result

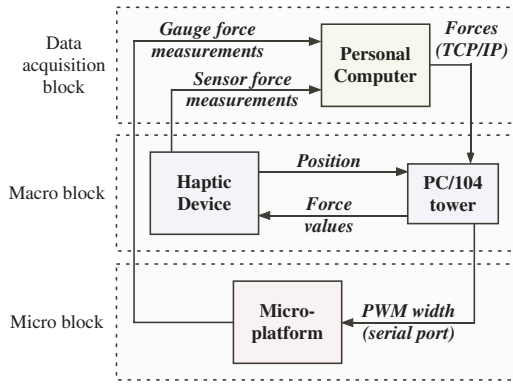


Fig. 8 The experimental setup

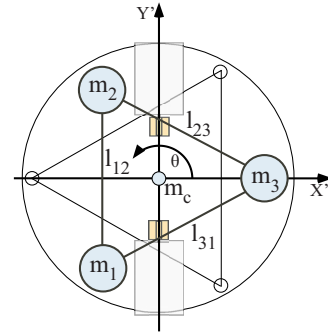


Fig. 9 Schematic view of the microrobot top with the white marks

395 exceeded (sixth second in Fig. 7), the microrobot starts to move,
 396 see the second schema in Fig. 7. Note here that after friction and
 397 inertia forces are exceeded, the microrobot can be driven with less
 398 speed.

399 6 Haptic Telemanipulation Environment Experiments

400 **6.1 Experimental Setup.** The experimental setup consists of
 401 three blocks, see Fig. 8. The first is the *Macroblock*, where the
 402 operator moves the haptic device end-effector along the X axis
 403 and rotates it about the Y axis. The end-effector position and the
 404 angle are captured by encoders attached on the haptic device ac-
 405 tuators (Maxon dc motors), and transmitted to a PC/104 tower.
 406 This tower is the control unit, that runs the algorithm that trans-
 407 lates the operator input into the microrobot input according to Eq.
 408 (1).

409 The *Microblock* consists of the microplatform, a 1 DOF strain
 410 gauge force sensor attached to it, and the PWM circuits. The input
 411 to the PWMs is transmitted from the PC/104 tower through a
 412 serial port. When the microrobot is about to perform a microma-
 413 nipulation (e.g., the microrobot's end-effector is under a micro-
 414 scope's field of view) the operator changes the software operation
 415 to MiCP. In this case if the microrobot manipulates a micro-
 416 object, the strain gauge captures the produced microforces and
 417 transmits them to a PC in the *data acquisition block*. From there,
 418 these forces are passed to the PC/104 tower, and after suitable
 419 scaling and smoothing, the necessary commands are sent to the
 420 haptic device actuators by the PC/104 I/O card. The applied
 421 forces to the operator are measured by an ATI nano17 6DOF force
 422 sensor attached to the haptic device end-effector. These measure-
 423 ments are also passed to the data acquisition block.

424 In order to record the obtained microplatform trajectory during
 425 the experiments, we recorded a video the microplatform motion.
 426 To improve the results, white round marks were placed on the top
 427 surface of the microrobot. Figure 9 shows a schematic view of the
 428 microrobot top with the white marks, m_1 , m_2 , and m_3 , and the
 429 platform center m_c .

430 The obtained video file is processed using Matlab's *image pro-
 431 cessing toolbox* routines to yield the coordinate trajectories of the
 432 white marks. Assuming these are placed on the three vertices of an
 433 isosceles triangle, we can calculate the angle θ according to

$$434 \quad q = \left(\arcsin \frac{m_{1,y} - m_{3,y}}{\sqrt{(m_{1,x} - m_{3,x})^2 + (m_{1,y} - m_{3,y})^2}} \right) - 30 \text{ deg} \quad (5)$$

435 and the coordinates of the microrobot center, $m_{c,x}$, $m_{c,y}$, according
 436 to

$$437 \quad m_{c,x} = m_{1,x} + l_{m1c} \cos(30 \text{ deg} + q)$$

$$m_{c,y} = m_{1,y} - l_{m1c} \sin(30 \text{ deg} + q) \quad (6) \quad 438$$

439 where $m_{i,x}$ and $m_{i,y}$ are the coordinates of mark m_i ($i=1,2,3$) and
 440 l_{m1c} is the distance between mark m_1 and the center m_c , according
 441 to

$$l_{m1c} = \frac{\sqrt{(m_{1,x} - m_{2,x})^2 + (m_{1,y} - m_{2,y})^2}}{2 \cos(30 \text{ deg})} \quad (7) \quad 442$$

443 The output of the processing is the trajectory of the microro-
 444 botic platform frame by frame. With a frame rate of 60 fps, a
 445 resolution of 1.7 pixels is achieved. In this case, where a 115.2
 446 $\times 92.16 \text{ mm}^2$ surface is covered by a frame of 720×576 pixels,
 447 the resolution is 0.3 mm, which is acceptable for the macroscopic
 448 mode. Note here that only two points (m_1 and m_3) are used in Eq.
 449 (5). Nevertheless, the third one is necessary in case of a rotation
 450 greater than 180 deg.

451 **6.2 Experimental Results.** We have executed five different
 452 experiments. The first four aimed at studying the behavior of the
 453 haptic telemanipulation environment during the three different in-
 454 put modes. The last one studies the forces applied to the operator
 455 by the haptic device during the contact between the microrobot
 456 and a rigid obstacle.

457 **6.2.1 MaIM Experiment.** Two experiments are executed in the
 458 MaIM input mode. In the first one, the master haptic device oper-
 459 ator drives the microplatform in a straight line. The result is
 460 shown in Fig. 10. The left plot shows the output of the image
 461 processing algorithm. The right plots display the x , y , and θ
 462 coordinates of the microplatform's geometric center. We can see from
 463 the third plot at the right side of Fig. 10 that the operator has to
 464 make several correctional moves by rotating the microrobot. This
 465 is expected since the same command to the micro-actuators results
 466 in different rotational velocities due to several platform anisotropies,
 467 see Ref. [21]. The haptic command was between 65% and
 468 75% of the maximum speed. In order to correct the translation,
 469 a $\pm 20\%$ difference between the two micro-actuator speeds was
 470 initiated.

471 In the second experiment, the master haptic device operator
 472 drives the microrobot along a curved path, see Fig. 11. This is
 473 achieved by rotating the haptic device end-effector by 25 deg
 474 about the Y axis, hence setting a 25% difference between the two
 475 micro-actuator speeds.

476 **6.2.2 MRIM Experiment.** In the MRIM experiment, equal but
 477 opposite micro-actuator speeds were set. The plus and minus ar-
 478 rows in Fig. 12 show the direction change, which is also visible on
 479 the plot of the angle θ of the microrobot at the right side. Observ-
 480 ing the third plot on the right in Fig. 12, we observe that the
 481 microrobot rotates as commanded. The small translation that oc-
 482 curs is due to small differences between micro-actuator rotational
 483 speeds.

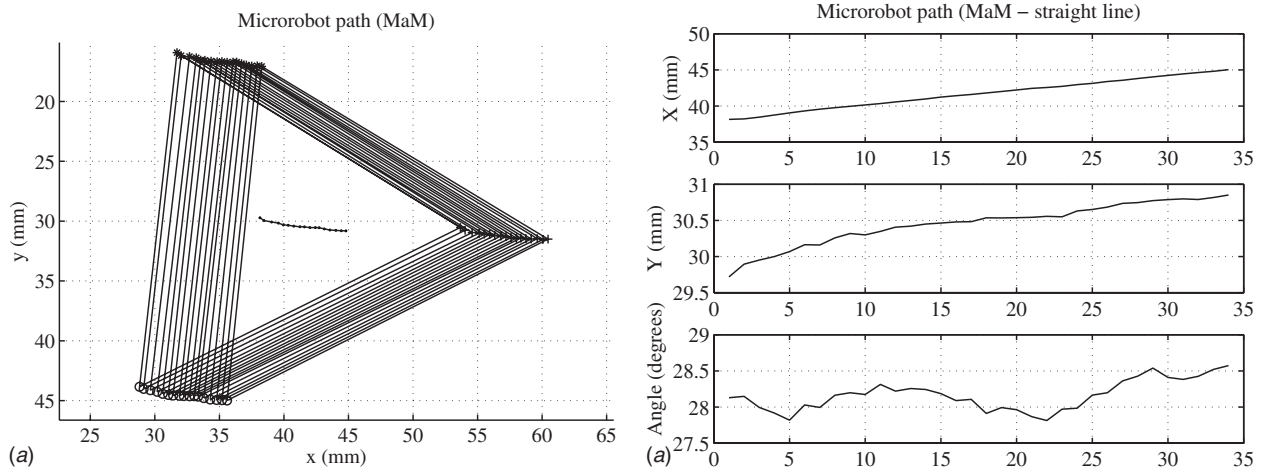


Fig. 10 The microrobot path during a MaM experiment in a straight line

484 6.2.3 *MiIM Experiment*. The next two experiments study the
 485 microrobot motion in the MiIM mode. During the first try, the
 486 microplatform is driven at a low velocity and commanded by the
 487 master haptic device to move across the microscope's field of
 488 view. In Fig. 13 we see the tip of a needle attached on the mi-
 489 crorobot. During this experiment, the command to both micro-

actuators was about 55% of the maximum velocity. 490

During the second try, the micro-actuators are driven one at a 491
 time. Note here that in order to start the motion, the command to 492
 the micro-actuators should exceed 70–75% for a very short period 493
 because of frictional forces. This is addressed by a software routine, 494
 which when it is called, initiates such a command for a very 495

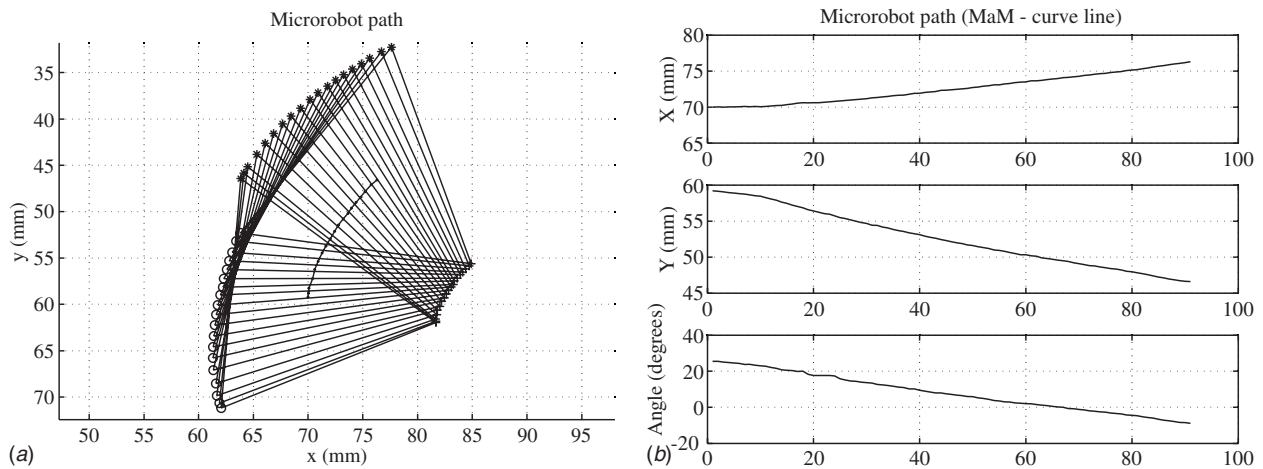


Fig. 11 The microrobot path during a MaM experiment in a curved line

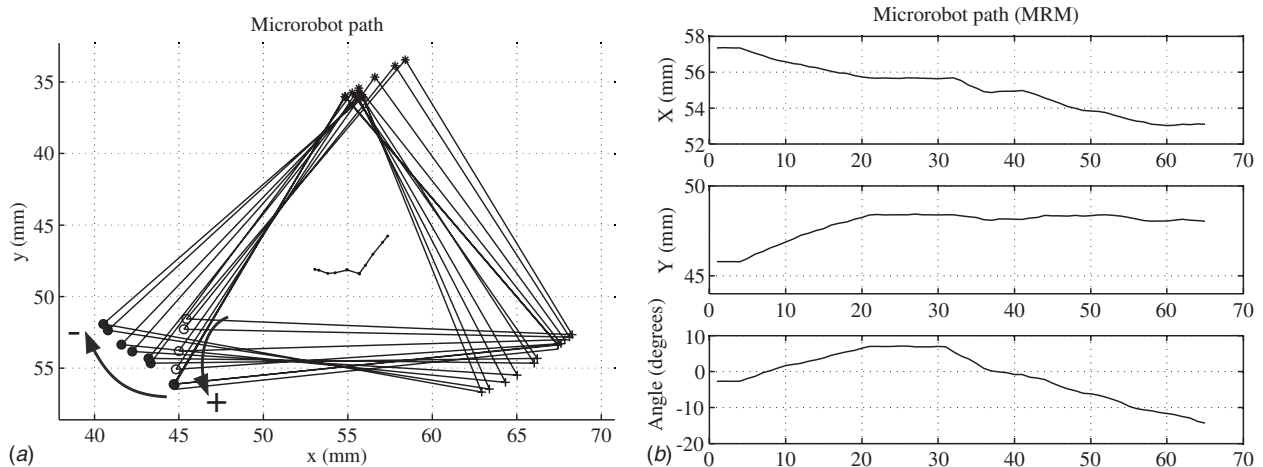


Fig. 12 The microrobot path during a MRIM experiment

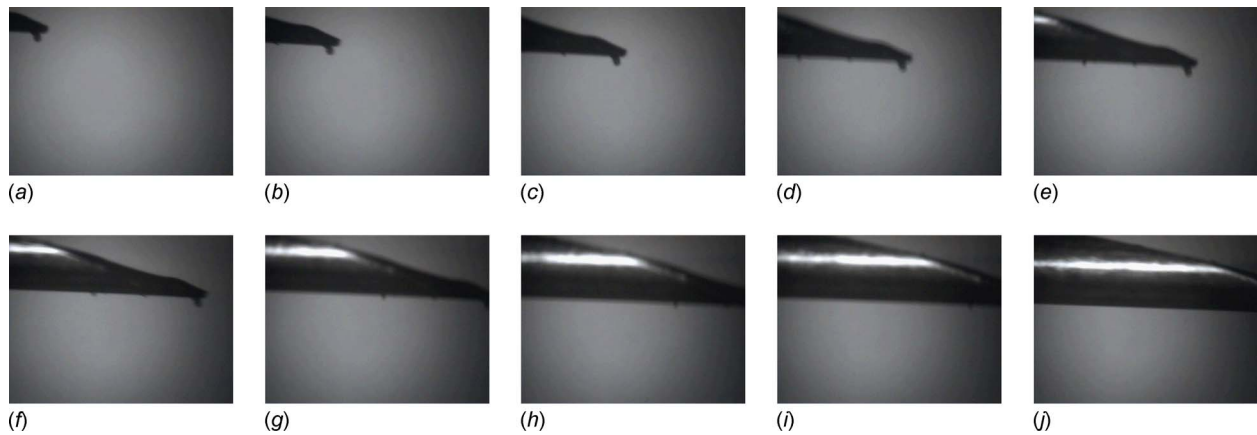


Fig. 13 Microrobot motion across the microscope field of view during a MiM experiment (both actuators at a low speed)

496 short period and then returns to 50% of the maximum velocity.
 497 The result is shown in Fig. 14, where we can see the “slalom”
 498 motion of the platform. Both ways result in good behavior. How-
 499 ever, the second one shows a smoother and finer motion.
 500 The experiments showed that the operator should not decrease
 501 the command below 45% of the maximum speed because the
 502 micro-actuators stop due to friction. As before, to avoid platform
 503 tipping, the command should not exceed the 85–90%. The ideal
 504 operation space is between 55% and 85% depending on the input
 505 mode. These values depend on many environmental parameters,
 506 such as the type and the situation of the ground or the mass of the
 507 platform. However, these can be determined easily.

508 **6.2.4 Force Experiments.** The experiments described here
 509 study the forces applied to the operator by the haptic device dur-
 510 ing contact between the microrobot and a rigid obstacle. In the
 511 first experiment, the microrobot was always in contact and no
 512 impacts occur. The experiment was conducted with 70% and 80%
 513 of the maximum micro-actuator speeds and cover smooth and
 514 impact forces. Figure 15(a) shows the forces measured by a force
 515 sensor during micromanipulation before and after filtering and
 516 scaling.

517 In the second experiment because of the high stiffness of the
 AQ: 518 obstacle, the measured forces are in the form of impacts, see Fig.
 #7 519 15(b). The top right plot shows in detail the impacts. By smooth-
 520 ing the signal and using the scaling factor defined in Sec. 3, the
 521 forces illustrated in Fig. 15(b) are obtained. Despite the impacts,
 522 the forces applied to the operator are smooth and meaningful,

facilitating the force application to the obstacle. 523

Note that, in general, the stability of the system is an important 524
 issue, especially for the master haptic device. However in our 525
 case, the interaction forces are in general low and smooth as they 526
 correspond to a soft environment, due to the microrobot- 527
 environment springiness and damping [24]. Even in the case of 528
 mild impact forces, these are filtered and the resulting smooth 529
 signal is magnified and applied to the operator. The filtering itself 530
 does not introduce a significant delay and therefore it does not 531
 destabilize the system, see Fig. 15. 532

7 Conclusions 533

The analysis and several experimental results of a new haptic 534
 telemanipulation environment are presented in this paper. The pro- 535
 posed environment combines and controls a 5DOF force feedback 536
 mechanism, acting as the master, and a 2DOF microrobot, acting 537
 as the slave. Regardless of the disparity between the master and 538
 slave and the fact that the slave microrobot is driven by two cen- 539
 tripetal force vibration micromotors, the environment gives to the 540
 operator the ability to drive and control the microplatform in a 541
 functional and simple manner. 542

The proposed environment manages to solve with success prob- 543
 lems that arise during the haptic micromanipulation of the specific 544
 device, such as the fact that the slave microplatform and the mas- 545
 ter haptic device are kinematically dissimilar, that the vibration 546
 actuators must operate within a specific speed range (rpm) and at 547
 the same time achieve a high speed in macroscopic motion and 548

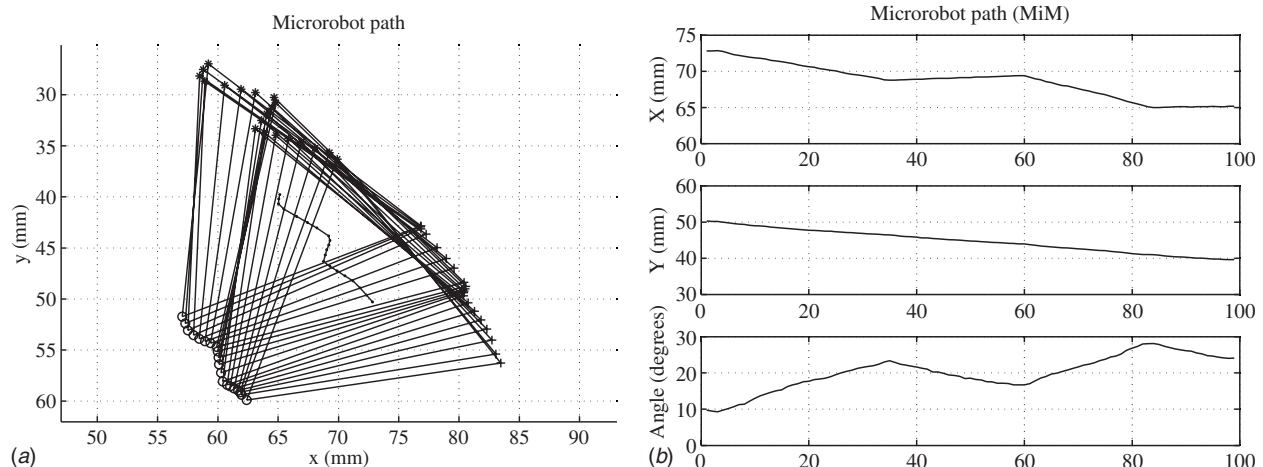


Fig. 14 The microrobot path during a MiM experiment (actuators one at a time)

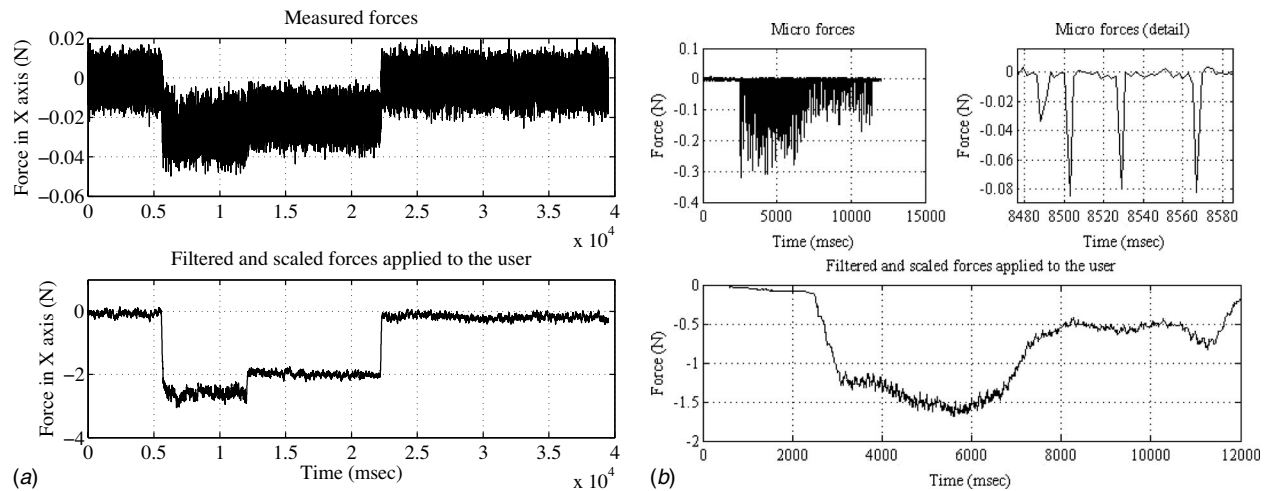


Fig. 15 The smooth (a) and impact (b) forces applied to the operator with and without filtering and scaling

549 submicrometer positioning accuracy in microscopic motion. In addition, even though the microforces measured by the microrobot can be in the form of impacts, the forces applied to the operator are smooth and meaningful, facilitating the force application to the obstacle.

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