Teleoperation of self-propelled microjets with haptic feedback

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I. Contribution

There are several scenarios where microrobots can be beneficial, especially in the field of medicine [1]. The use of microdevices can in fact enable clinicians to perform less invasive diagnostic, therapeutic and surgical interventions, thanks to the fact that these robots can provide new ways of accessing areas of the patient's body that are hard to reach (e.g., deeply-located tumors).

This paper presents an innovative teleoperation system with force reflection for steering self-propelled microjets in 2-dimensional space, shown in Fig. 1. The propulsion of these microjets is based on the catalytic decomposition of hydrogen peroxide by thin layers of platinum, which generates bubbles and leads to the fast forward jet motion of the microtube [2]. The proposed teleoperation system enables the human operator to intuitively and accurately control the motion of a microjet in the remote environment while providing him/her with compelling haptic force feedback.

A novel particle-filter-based visual tracking algorithm tracks at runtime the position of the microjet in the remote environment. A 6-degrees-of-freedom (6-DoF) haptic interface then provides the human operator with haptic feedback about the interaction between the controlled microjet and the environment, as well as enabling the operator to intuitively control the target position of the microjet. Finally, a wireless magnetic control system regulates the orientation of the microjet to reach the target point. Figure 2 shows how the tracking, haptic, and control systems are interconnected.

1) Tracking System: A high-resolution camera is placed above the Petri dish hosting the environment. The camera has an adjustable zoom with a maximum of 24X, and it is mounted on a linear stage to enable precise focusing. Each frame registered by the camera is first filtered by a Laplacian of Gaussian (LoG) filter [3], which is used to find areas of rapid change (edges) in the image. Subsequently, the tracker selects the target object based on shape, size, and temporal consistency, and it then estimates its position. Finally, to robustly track inconsistent shapes (e.g., bubble trails of the microjets) and to effectively reject the presence of other microjets that we do not want to control, we use a particle filter [4]. The tracker uses the estimated position to

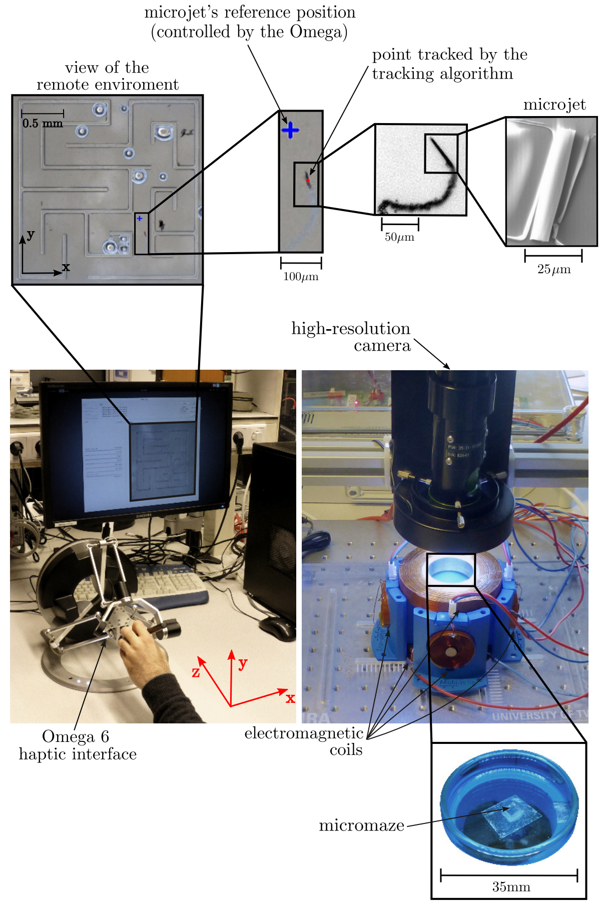

Fig. 1. Teleoperation system. The tracker measures at runtime the position of the microjets in the remote environment. The human operator then set the microjet's reference point by controlling the position of the end-effector of a 6-degrees-of-freedom haptic interface. At the same time, he is also provided with kinesthetic and vibrotactile feedback coming from the remote environment. Finally, the magnetic control system regulates the orientation of the microjet toward the reference point.

weight the particles of the particle filter. After the weighting, the particles are also used for position estimation in the next frame. To do this, the particles are resampled based on their weights and translated based on the measured object velocity. Experiments showed the tracker to be able to track microjets in 2-D with an average precision of 90.4 μm.

2) Haptic System: The haptic feedback system is composed of a 6-DoF Omega haptic interface (Force Dimension, Switzerland). We measured the position of the end-effector of the Omega, controlled by the human operator, to set the reference target position of the microjet. At the same time, through the same end-effector, we provided the operator with force feedback from the remote environment (see Sec. II).

3) Control System: Given the current position of the microjet, as estimated by the tracking algorithm, and the commanded reference position, as controlled by the operator through the haptic interface, the control system controls the

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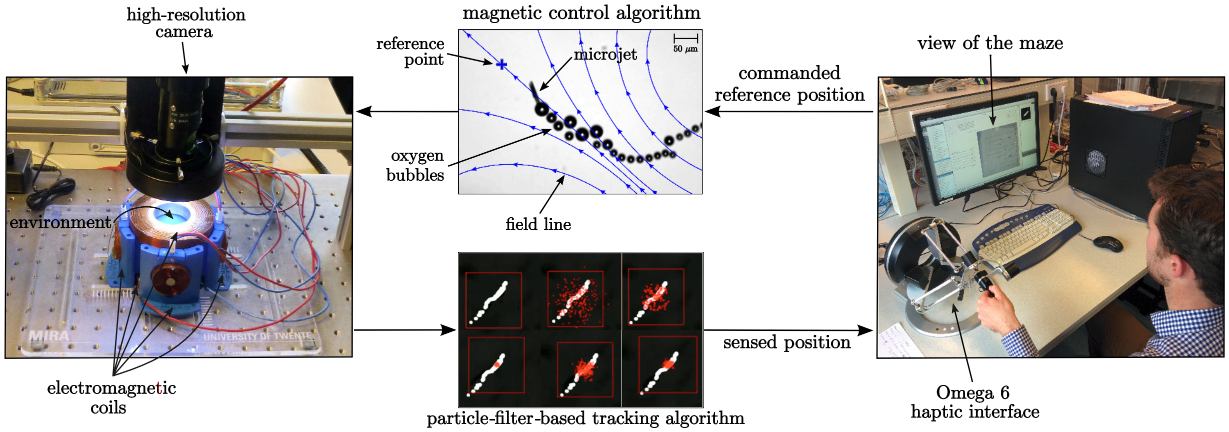

Fig. 2. Scheme of how the tracking, haptic, and control systems are interconnected.

orientation of the microjet through six electromagnetic coils, with the aim of steering it toward the reference point. The orientation of the selected microjet is controlled using external magnetic torque, whereas the forward motion towards the reference position is accomplished by the thrust force generated by the ejecting oxygen bubbles. In particular, we employ a sliding-mode control system [5], owing to its robustness in the presence of parameter uncertainties and unmodeled disturbance forces, such as wall and surface effects, bubbles-microjet interactions, and microjet-microjet interactions. The control system has been proved to position microjets within an average region-of-convergence of 365 μm [6].

II. Steering a microjet in a maze

We evaluated our system in a remote environment composed of a 2.25×2.25 mm maze made of polydimethylsiloxane (PDMS), shown in Fig. 2. The maze was filled with hydrogen peroxide solution with concentration of 5%, along with small amounts of isopropanol and Triton X. A microjet with a length of 50 μm was used.

The task consisted of steering a microjet through the maze shown in Fig. 1, being as fast as possible and trying to avoid collisions with the maze walls. The operator was provided with kinesthetic feedback about the inertia of the controlled microjet and vibrotactile feedback about the collisions with the maze walls.

Vibrotactile force feedback $\mathbf{f_c}(\mathbf{t})$, responsible for rendering collisions of the reference point with the maze walls, is evaluated according to the popular god-object model. The maze walls are modeled as spring-damper systems:

$$\mathbf{f_c}(\mathbf{t}) = k_{c,v}(\mathbf{p_r}(\mathbf{t}) - \mathbf{p_{r,proxy}}(\mathbf{t})) \begin{bmatrix} \sin(2\pi f_h t) \\ \sin(2\pi f_v t) \end{bmatrix}.$$

$k_{c,v} = 200$ N/m is the elastic constant of the spring, $f_h = 200$ Hz and $f_v = 150$ Hz are the frequencies of the vibrations when the collisions happen along the x and y directions, respectively, $\mathbf{p_r}(\mathbf{t}) \in \mathbb{R}^2$ is the current position of the reference point as controlled by the operator through the haptic interface, and $\mathbf{p_{r,proxy}}(\mathbf{t}) \in \mathbb{R}^2$ is the virtual location of the reference point, placed where the haptic interface point would be if the haptic interface and the wall were infinitely stiff (i.e., on the surface of the maze walls in our case). The amplitude of the vibration indicates the magnitude of the penetration inside the maze wall while its frequency indicates the direction of the collision [7], [8].

On the other hand, kinesthetic feedback $\mathbf{f_i}(\mathbf{t})$, responsible for rendering the inertia of the microjet, is evaluated as if a spring-damper system connected the reference point and the microjet:

$$\mathbf{f_i}(\mathbf{t}) = -k_i(\mathbf{p_r}(\mathbf{t}) - \mathbf{p_j}(\mathbf{t})) - b_i\dot{\mathbf{p}}_\mathbf{r}(\mathbf{t}),$$

where $k_i = 100$ N/m is the elastic constant of the spring, $b_i = 5$ Ns/m the damping coefficient, and $\mathbf{p_j}(\mathbf{t}) \in \mathbb{R}^2$ the current position of the microjet as evaluated by the tracker.

The operator thus feels an opposite force when trying to penetrate the maze walls and when moving the reference point far from the microjet (i.e., when the microjet was not fast enough to follow the reference point). Both forces are provided by the Omega 6 haptic interface. A video of the experiment can be downloaded at http://goo.gl/IqBwv8.

Visual feedback on the remote environment is always provided to the operators (see Fig. 2), and the Omega 6 haptic interface is always used to provide the controller with the microjet's reference point.

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