Abstract—Soft miniaturized untethered grippers can be used to manipulate and transport biological material in unstructured and tortuous environments. Previous studies on control of soft miniaturized grippers employed cameras and optical images as a feedback modality. However, the use of cameras might be unsuitable for localizing miniaturized agents that navigate within the human body. In this paper, we demonstrate the wireless magnetic motion control and planning of soft untethered grippers using feedback extracted from B-mode ultrasound images. Results show that our system employing ultrasound images can be used to control the miniaturized grippers with an average tracking error of 0.4 ± 0.13 mm without payload and 0.3 ± 0.05 mm when the agent performs a transportation task with a payload. The proposed ultrasound feedback magnetic control system demonstrates the ability to control miniaturized grippers in situations where visual feedback cannot be provided via cameras.

I. INTRODUCTION

Miniaturized agents with grasping capabilities provide significant advantages in achieving complex tasks like precise micro-assembly, minimally invasive surgery, cell manipulation, and lab-on-a-chip applications [1]–[7]. Recent studies have demonstrated tracking, closed-loop control and the ability of the grippers to pick-and-place biological material in dynamic environments [8]–[10]. These experiments used optical images acquired by a camera. However, the use of cameras might be unsuitable for localizing miniaturized agents in medical or surgical applications within the human body.

Previous studies used Magnetic Resonance Imaging (MRI) to image and control magnetic drug carriers, nanorobots, and magnetotactic bacteria [11], [12]. However, a major disadvantage in using an MR system for tracking and actuation is the possibility of a time-delay due to communications between the various modules of the interventional platform. This time-delay could cause instability in the closed-loop control system and possibly limit the realization of the control method in real-time. Different from MRI, ultrasound (US) has high frame rates that allows for the realization of real-time control, and is compatible with clinical interventions [13]. Moreover, US scanning is more easily accessible than MRI. It allows dynamic visualization with direct interaction between the clinician and the patient, as well as allowing guided intervention to be performed at the same time. Related studies on US used a high-frequency scanner to evaluate the motion of superparamagnetic iron oxide nanoparticles [14], [15]. The closed-loop position control of paramagnetic microparticles under US guidance has been previously reported in [16]. In addition, Sanchez et al. demonstrated the use of US feedback to track and control self-propelled, fast-moving microrobots [17].

In this study, we demonstrate an integrated system that localizes and controls soft miniaturized grippers to safely reach a target using US images (Fig. 1). This offers the potential to use untethered grippers to autonomously perform advanced manipulation and transportation tasks in clinically relevant scenarios. The system consists of a US tracker which localizes the position of the grippers. A Proportional-Integral-Derivative (PID) magnetic control scheme is used...
to pull the grippers towards the reference position. By using the Linear Quadratic Gaussian Motion Planner (LQG-MP), we show that tracking and motion errors of the gripper can be taken into account during the planning phase, and proper obstacle-free paths can be computed in order to avoid collisions with the environment, e.g., sensitive organs or tissues. Finally, by combining magnetic and temperature control, we demonstrate the capability of soft miniaturized grippers to manipulate a spherical bead and transport it to a target area. To the best of our knowledge, our results represent the first experimental demonstration of the use of a magnetic system coupled with a US probe that simultaneously, (1) detects and tracks miniaturized untethered grippers using US images, (2) successfully controls the grippers along paths performing manipulation and transportation tasks, and (3) robustly controls the grippers along obstacle-free motion plans by taking into account tracking errors and the motion uncertainty of the grippers.

The remainder of this paper is organized as follows: Section II describes the technique used to detect the grippers. Section III shows the electromagnetic system and the control policy. Section IV presents and discusses the experimental results. Finally, Section V concludes and provides directions for future work.

II. TRACKING OF THE SOFT MINIATURIZED UNTETHERED GRIPPERS

In order to perform precise and robust motion control in unstructured environments, an image-guided tracking algorithm is necessary. In what follows, we describe the algorithm used to estimate the pose of the gripper from US images. The US images are acquired using a Siemens 18L6HD transducer (Siemens ACUSON S2000, Siemens Healthcare, Mountain View, USA) operating with a frequency of 16 MHz with an in-plane resolution of approximately 0.09 mm per pixel. Then, we report an extensive validation of the proposed approach, and a comparison with results obtained using a microscopic camera. Let \( p(t) = [x(t), y(t)]^T \in \mathbb{R}^{2\times1} \) be the position of a gripper in 2D space at time \( t \) and \( v(t) = [v_x(t), v_y(t)]^T \in \mathbb{R}^{2\times1} \) its velocity. The state of the gripper is defined as \( \mathbf{x}(t) = [p(t), v(t)] \in \mathbb{R}^{4\times1} \). Let us consider the miniaturized gripper as a second order system controlled by applying suitable force inputs. The tracking algorithm estimates the state \( \mathbf{x}(t) \) of the gripper at runtime (Fig. 2).

In the initial phase, it estimates the position \( \hat{p}(t) = [\hat{x}(t), \hat{y}(t)]^T \) of the gripper. Then, a standard Kalman filter is used to compute the estimated state \( \hat{x}(t) \) from position estimates \( \hat{p}(t) \). The Kalman filter provides an estimation of the current state \( \hat{x}(t) \) as well as a one-step ahead prediction of it \( \hat{x}(t+\Delta t) \), assuming a constant sampling time \( \Delta t \) of the system. The process and measurement noises are obtained from zero mean multivariate Gaussian distributions \( N(0, Q) \) and \( N(0, R) \), respectively, where \( Q \in \mathbb{R}^{4\times4} \) and \( R \in \mathbb{R}^{2\times2} \) are the empirically determined covariance matrices. In order to speed up the detection procedure, temporal continuity is exploited to track the grippers in a sequence of frames. Given the predicted state \( \hat{x}(t+\Delta t) \) of the tracked gripper at time \( t \), in the next frame the image pixels that are within a preset range from that estimation are kept, whereas the remaining pixels are discarded.

The proposed method is evaluated on three different datasets of more than 4000 images. The datasets report the common motion of the miniaturized grippers during manipulation and transportation tasks (Fig. 3). In order to generate ground truth data for the evaluation of the tracker, all the frames are manually labeled. This is a common approach in the relevant literature, since accurate ground truth data for such agents are hard to obtain [18], [19]. The evaluation shows a tracking error of 0.51 ± 0.33 mm, 0.49 ± 0.26 mm, and 0.26 ± 0.13 mm, for the three sequences, respectively. The tracking errors correspond to \( \sim 1.275 \% \), \( \sim 12.25 \% \), and \( \sim 6.5 \% \) of the body length of the miniaturized gripper. By comparing the proposed tracker with the one developed by Pacchierotti et al. for CCD cameras, we observe that the US tracker is less accurate [20]. In fact, by using microscopic cameras images, the average tracking error is about 106 µm (\( \sim 2.5 \% \) of the body length). This is mainly due to the lower resolution of the US images (\( \sim 8 \) times worse than CCD images), and the presence of artifacts and occlusions. The proposed tracker can run at an average frame rate of 100 frame per second on a PC that has an Intel Xeon CPU 3.2 GHz processor and 8 GB of RAM.

III. MODELING OF THE US-BASED MAGNETIC SYSTEM

Wireless control of the soft miniaturized untethered grippers is accomplished using an array of iron-core electromagnets and an US system. The US probe (Siemens ACUSON S2000, Siemens Healthcare, Mountain View, USA) is placed...
The magnetic force-current map is used in the implementation of a closed-loop control system of the soft miniaturized untethered grippers based on feedback obtained by an US device.

In order to fold/unfold the soft miniaturized grippers, we regulate the temperature of the water wherein the grippers are floating using a Peltier element (Fig. 4). The range of temperatures used to fold/unfold the soft miniaturized grippers is between 24° C and 27° C [8]. The Peltier element is placed below the reservoir of water. A closed-loop control is used to regulate the temperature of the Peltier element using the values of water temperature provided by a thermometric probe.

IV. EXPERIMENTAL VALIDATION

In this section, we report three different experiments in order to show the possibility for the soft miniaturized grippers to: (1) follow a pre-defined path, (2) autonomously move in a cluttered environment, and (3) firmly grasp an object and transport it to a target area; please refer to the accompanying video for the visualization of the experiments.

The soft miniaturized grippers used in this work are composed of a stiff SU-8 and thermally responsive pNIPAM-AAc segmented bilayer (Fig. 4). The grippers open and close reversibly due to a lower critical solution temperature (LCST) phase transition and associated swelling or shrinkage in the pNIPAM-AAc layer in response to temperature changes. In order to make the grippers responsive to magnetic fields, the pNIPAM-AAc layer is doped with 3 % (w/w) Fe₂O₃ magnetic nanoparticles. When fully opened, the grippers have an hexagon shape with a tip-to-tip distance of 4 mm. When fully closed, the grippers have the shape of a sphere with a 0.4 mm radius. More details of the fabrication and mechanics modeling of the grippers are described in a previous publication [25].

A. Motion control

In the first scenario, we demonstrate that soft miniaturized untethered grippers can be controlled using US images to follow a pre-defined path. The magnetic force at time instant \( t \) is regulated using a PID controller,

\[
F(p(t)) = K_p (r(t) - \hat{p}(t)) + K_I \int_0^t (r(\tau) - \hat{p}(\tau)) d\tau + K_d (\dot{r}(t) - \dot{\hat{p}}(t)),
\]

where \( p(t) \) is the current position, \( r(t) \) is the desired position, \( \dot{r}(t) \) is the desired velocity, \( \dot{p}(t) \) is the actual velocity, and \( \hat{p}(t) \) is the estimated position. The constants \( K_p, K_I, \) and \( K_d \) are the proportional, integral, and derivative gains, respectively. The magnetic force-current map is used in the implementation of a closed-loop control system of the soft miniaturized untethered grippers based on feedback obtained by an US device.
where $K_p \in \mathbb{R}^{2 \times 2}$, $K_i \in \mathbb{R}^{2 \times 2}$, and $K_d \in \mathbb{R}^{2 \times 2}$ are the controller positive-definite gain matrices. Moreover, $r(t) \in \mathbb{R}^{2 \times 1}$, $\dot{r}(t) \in \mathbb{R}^{2 \times 1}$ are the reference position and its time derivative, while $\hat{p}(t) \in \mathbb{R}^{2 \times 1}$, $\hat{v}(t) \in \mathbb{R}^{2 \times 1}$ are the estimated position and velocity of the gripper (cf. Sect. II). The desired force $F(p)$ is mapped into the currents $I$ using (2).

Two different paths are used: a step path and a sinusoidal path (Figs. 5-6). Motion control using US feedback is achieved by providing waypoints to the control system. The experiment is repeated ten times. We observe that the controlled grippers follow the step trajectory at an average speed of $0.35 \pm 0.13$ mm/s. For the sinusoidal path, the average speed of the grippers is $0.41 \pm 0.14$ mm/s. The average positioning error for the step and the sinusoidal path is $0.32 \pm 0.09$ mm and $0.48 \pm 0.1$ mm, respectively.

B. Motion planning with uncertainty

Results presented in Sect. IV-A show that motion uncertainty, e.g. due to un-modeled external influences on the motion of the soft miniaturized gripper, and imperfect state information due to partial or noisy estimations of the gripper’s state, generate positioning errors. Because safety and accuracy are of critical importance for many medical applications such as targeted drug delivery or biopsies, these uncertainties will have significant influence on determining which path is the best for the task at hand.

In this section, we adapt the Linear Quadratic Gaussian Motion Planner (LQG-MP) to generate a motion plan which minimizes the probability of collisions between the gripper and the environment [26]. LQG-MP is based on the Linear Quadratic Controller (LQG-controller) with Gaussian models of the motion and sensing uncertainty. For the given stochastic model of the gripper dynamics and of the sensor measurements (cf. Sect. II), it is possible to compute in advance (i.e., before execution) the a-priori probability distributions of the states and the control inputs of the agent along a given path. These distributions can be used to compute the probability that collisions will be avoided by the soft miniaturized gripper [27].

We use a sampling-based Rapidly-exploring Random Tree (RRT) planner to generate a set of $N \in \mathbb{R}_{>0}$ obstacle-free motion plans $\Gamma = \{\gamma^i, i = 1, \ldots, N\}$ [28]. Each entry of the motion plan $\gamma^i$ represents a control input $F(p)$ that is applied to the agent after every time interval $\Delta t$. The final plan $\gamma_{best}$ is selected using the LQG-MP by minimizing the probability of collision with the obstacles (Algorithm 1). The planner is customized for the motion planning of soft miniaturized grippers. It is executed offline before starting each experiment, and runs for approximately 3 seconds, generating and evaluating an average of 30 successful motion plans. The experiment is repeated ten times. Among all the trials, the average probability of success of the paths selected using the LQG-MP is 94%. In all the trials the grippers safely reached the target area, avoiding all the obstacles.
present in the environment. Fig. 7 depicts the shortest path (top) and the safest one (bottom) selected using the LQG-MP.

C. Pick-and-place

In the last experimental scenario, we show the ability of the soft miniaturized untethered grippers to grasp a 0.5 mm polyester spherical bead weighing 0.6±0.1 mg, and transport it along a path, until a target area is reached (Fig. 8). This task was chosen in order to resemble real surgical interventions such as deployment of a vascular implant or biopsies [29]. A gripper is positioned in the starting position and it has to reach the bead. The control law (3) proposed in Sect. IV-A is used to move the gripper. Once the bead is reached, the temperature is increased using the Peltier element until the gripper folds and grasps the bead (cf. Sect. III). Therefore, the bead is captured within the soft gripper and can be dragged to the desired target location along a pre-defined path. The experiment is repeated ten times with an average tracking error of 0.36±0.05 mm (~9 % of the body length of the miniaturized gripper). The bead is transported for a distance of 14.5 mm with an average velocity of 0.39 ± 0.06 mm/s.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we demonstrate the tracking, wireless magnetic motion control, and motion planning of soft miniaturized untethered grippers using US feedback. Despite the inevitable motion artifacts obtained in the US images, the grippers are controlled along a path at an average position tracking error of 0.4±0.13 mm without payload. By using a Linear Quadratic Gaussian Motion Planner, we show that obstacle-free paths for the grippers can be computed by taking into account motion errors and imperfect state estimations. Finally, we demonstrate the possibility to pick and move 0.5 mm beads. Manipulation and transportation tasks are completed with an average position tracking error of 0.36 ± 0.05 mm.

As a part of future work, we plan to control the soft miniaturized untethered grippers in 3D space using ultra-fast US images that sweep the spaces, or specialized 3D US probes optimized to acquire/render images in real-time. Moreover, we will consider the use of high-intensity focused US to change the temperature locally and perform manipulation tasks in-vivo. Furthermore, motion control and planning of soft miniaturized grippers will be achieved in fluidic microchannels with time-varying flow rates based on the feedback provided by the US system to enable eventual applicability in-vivo.

REFERENCES

Fig. 8. Representative snapshots of the soft miniaturized gripper during manipulation and transportation of a 0.5 mm bead. The gripper moves from an initial position toward the bead. Once the target is reached, the temperature is increased until the system classifies the gripper as closed. A pre-defined trajectory then guides the gripper to the target area. Temperatures (T) are shown on the top-right corner of each snapshot. Top: Snapshots acquired using an US probe. Bottom: In order to facilitate the reader’s understanding of this experiment, we provided the snapshots acquired with a microscopic camera. Please note that the magnetic controller uses only the feedback provided by the US probe. Please refer to the accompanying video for the visualization of this experiment.


