Design of an Electromagnetic Setup for Independent Three-Dimensional Control of Pairs of Identical and Nonidentical Microrobots

Federico Ongaro, Stefano Pane, Stefano Scheggi, and Sarthak Misra, Member, IEEE

Abstract—Independent control of microrobots is a cardinal challenge for manipulation at micro/nano scale. In this paper, we design and assemble an electromagnetic setup to overcome some of the major obstacles in the independent control of microrobots. The demanding magnetic requirements are met by the presented experimental testbed that is able to produce magnetic fields and gradients of, respectively, $160 \text{ mT}$ and $3.6 \text{ T/m}$ at the center of the workspace. Through the design process of this testbed, we analyze the importance of design parameters and derive a quantitative analysis of the requirements for the dissipation of the generated heat. Further, we present and develop the model and software infrastructure, capable of running at 25 Hz, necessary for independent control of multiple microrobots. We also introduce two novel techniques for current-minimizing mapping of the desired forces into currents at the electromagnet. Finally, the capabilities of the setup are demonstrated through independent control of two, both identical and nonidentical, soft-magnetic microspheres in three-dimensional space—with average root mean square errors of $102 \mu\text{m}$ and peak velocities of up to $331 \mu\text{m/s}$.

Index Terms—Medical robotics, motion control, multi-robot systems.

I. INTRODUCTION

In recent years, microrobotic devices have drawn a lot of interest, mainly due to their great potential to enhance the functionality of micromanipulation in medical, biological, chemical, and industrial environments. Being small and untethered, microrobots have the potential to drastically improve the effectiveness of various tasks, such as targeted drug delivery, particle separation, mixing, pumping, assembly, manipulation, microsurgery, and chemical analysis [1]–[5].

However, constrained by their small size, these robots are often bound to rather simple and passively actuated structures [6], [7]. Thus, their ability to exert strong forces and perform complex tasks is typically limited. Endowing microrobots with the ability to cooperate, would therefore, allow these robots to overcome this major drawback—without requiring any cumbersome additional structure. Microrobots could maintain the agility and flexibility provided by their microscopic size, while also being able to perform elaborate tasks, with high strength requirements, in hard-to-reach environments. Effectively, cooperative microrobots might open the way to a whole new set of challenges and tasks, such as swarm manipulation of large objects that are currently precluded from robotics at the microscale.

Manuscript received May 30, 2018; revised July 13, 2018; accepted October 1, 2018. Date of publication November 6, 2018; date of current version February 4, 2019. This paper was recommended for publication by Associate Editor Jake Abbott and Editor Pierre Dupont upon evaluation of the reviewers’ comments. This work was supported by the European Research Council under the European Union’s Horizon 2020 Research and Innovation programme under Grant #638428—project ROBOTAR: Robot-Assisted Flexible Needle Steering for Targeted Delivery of Magnetic Agents. (Corresponding author: Federico Ongaro.)

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This paper has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the author.

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Digital Object Identifier 10.1109/TRO.2018.2875393
Given the major significance of such breakthrough, numerous studies have discussed viable techniques for its realization. In particular, acoustic tweezers have drawn attention for such application [8]. Nonetheless, this method demands establishing standing-wave-based pressure traps, which are challenging to achieve in in-vivo environments. Conversely, optical tweezers (high-intensity laser beams) do not suffer from this limitation, and have been widely used for control of microrobots [9]–[11]. However, high-intensity lasers are pernicious to human cells and, due to their high-frequency, cannot penetrate the opaque human body. Contrasting humans are transparent to quasi-static magnetic fields. Additionally, human exposure to magnetic fields has been proven safe even at high intensities [12]. Thus, such fields are a widely diffused choice for motion control of magnetic microrobots.

Even so, independent magnetic control of microrobots still presents relevant challenges [13]. Arguably, the major of these is that all the manipulated robots receive the same control inputs. Further, the coupling of these control inputs is nonlinear with respect to both space and magnitude of the inputs. Three main strategies have emerged to address these issues, which are as follows.

1) The use of microrobots that differ in shape or magnetic properties. Due to this difference, the robots (or their components) behave differently when exposed to a homogeneous magnetic field [14]–[17].

2) The use of specialized substrates, such as electrostatic braking pads or arrays of microcoils, that selectively activate/deactivate robots in specific areas [18], [19].

3) Exploitation of the magnetic field and gradient inhomogeneity for independent control [20]–[22]. Each one of these techniques has its following advantages and limitations.

1) Specifically, the first technique provides a reliable control of up to eight-degrees of freedom (DOF). However, it requires precise modeling and prevents the control of robots exhibiting comparable magnetic response. Moreover, this technique is often based on the average of several control inputs over a period of time, effectively limiting the control bandwidth.

2) On the other hand, the second technique offers very high control frequencies, complete decoupling of the inputs, and numerous DOF. Yet, this technique relies on the proximity of the robots to a large and tethered substrate, hindering its application in hard-to-reach or three-dimensional (3-D) environments.

3) Finally, the third technique allows to steer both identical and nonidentical microrobots with virtually no constraint on the number of DOF. Nonetheless, this technique revolves around the solution of a nondeterministic polynomial-time (NP) nonconvex problem, and thus requires a significant computational effort. Moreover, this technique has so far only been successfully implemented in two-dimensional (2-D) gravity-neglecting environments.

This 2-D-space limitation is not only due to the NP complexity, but also due to the technical requirements. A micro-robot constrained along its gravitational axis, and moving in a flow-less 2-D environment, is essentially inert. Therefore, even minuscule forces generated by weak magnetic fields result in its motion. Conversely, in the 3-D-space, gravity has to be continuously compensated, requiring a constant, significant, force output. During magnetic control, this force has to be generated by strong magnetic fields and gradients. Furthermore, the strength of these fields increases significantly when appreciably different fields in distinct point of the workspace are requested (such as during independent control). Consequently, a magnetic setup capable of generating such fields and gradients, without incurring in magnetic saturation or overheating, is required.

For reasons of control and safety, these strong fields are commonly generated using electromagnetic coils. As effective as electromagnets may be, they require high currents for such activation. In turn, high currents result in significant Joule heating, compromising performance, and, possibly, even stability. For these reasons, efficient techniques for current minimization and thermal management of the coils are fundamental for the safe operation of microrobots.

In this study, we present and experimentally validate a newly designed system capable of independently controlling identical and nonidentical microrobots in the 3-D-space. This is achieved by exploiting the inhomogeneity of the strong fields the system can generate. Moreover, we present a thermal management solution to prevent the overheating of the electromagnetic coils. Finally, the performance of the overall setup is experimentally evaluated during independent six-DOF control. The significant contributions of the paper can be summarized as follows:

1) Analysis, design, and assembly of an electromagnetic setup for the independent control of (identical and nonidentical) robots in the 3-D-space (see Section II).

2) Design and analysis of a thermal management strategy for the electromagnets (see Section II-B).

3) Modeling and singularity analysis of the electromagnetic setup and of the used microrobots (see Section III-B, Appendix B).

4) Development of a control strategy and 3-D-space state-reconstruction procedures for independent six-DOF control of microrobots (see Section III-A).

5) Development and comparison of several techniques for force-to-current mapping with minimal current request (see Section III-D).
force, and hence of the magnetic gradient. At a given position \((p \in \mathbb{R}^3)\), this change is represented by the third-order tensor \((E(p) \in \mathbb{R}^{3 \times 3 \times 3})\) collecting the Hessian matrices of each component of the field. However, due to the quantized nature of FE, we found the estimation of \(E\) to be unreliable. Furthermore, it is challenging to correlate the independent control requirements to optimal values of each element of \(E\).

Alternatively, we first design a specimen electromagnet that respects the requirements in Table I. Successively, we maximize the field and gradient output of such electromagnetic coil (see Fig. 3), as these values are in scalar relation with the Hessian values. In order to address the higher order inverse dependence of the Hessian terms on the distance, the considered values are corrected dividing them by the distance from the coil (gradients) and its square (field). Finally, the arrangement of the coils is fixed to spherical, to guarantee the accessibility requirement, and an optimization routine (MATLAB, Mathworks, Natick, USA) is used to determine the optimal position and number of coils. This optimization aims at minimizing total power consumption during the exertion of 7800 pairs of forces with varying intensity, direction, and exertion points. Three constraints are enforced in this optimization routine: the maximum and minimum current between electromagnets (to avoid overlapping), and the minimum distance between electromagnets and cameras (which are assumed to be positioned on two planar sides, as in the current setup, as well as on top). It is worth noting how the high-order dependence of \(E\) on the distance from the coils, leads to better multiagent performance with systems with closely grouped electromagnets. This distance sensitivity is decreased in systems designed for force-controlled steering, and even further reduced in system for torque-based control only.

The final design (BatMag) consists of nine electromagnetic coils positioned as shown in Figs. 1 and 2. The parameters of these metal-core electromagnets are presented in Table II. Additionally, Fig. 2 shows how the requirements on workspace size and accessibility have been addressed. All actuators, including the electromagnets, are controlled using third-party servo drives (Elmo Motion Control, Petach-Tikva, Israel). In the workspace center, BatMag is capable of generating magnetic fields and gradients of upto 160 mT and 3.6 T/m, respectively, for the configuration used in the presented experiments (see Table III).

### A. Design Choices and Final Design

Guided by the requirements provided in Table I, several designs are developed and evaluated using finite element (FE) analysis software (COMSOL Multiphysics, COMSOL Inc., Stockholm, Sweden). Safety requirements lead us to choose electromagnetic coils over permanent magnets, as the former are inert when shut down in case of emergency. The power requirements for actuation of paramagnetic microscopic robots using air-core electromagnets render them unusable from a thermal point of view. Therefore, Vacoflux-core coils are used in the setup.

Further, it should be noted that not only does the control of multiple microrobots require strong magnetic fields and magnetic field gradients (for magnetization and force exertion), but it also requires swift spatial changes of the magnetic

![Image](image.png)

**Fig. 2.** Computer assisted rendering showing the variable workspace accessibility of the setup. Coils 1 and 3 are set at minimum distance to offer increased accessibility (workspace accessibility: a sphere of diameter 160 mm). Coils 2 and 4 are set at maximum distance which offer the strongest operational fields (workspace accessibility: a sphere of diameter 50 mm). The coils can move in steps of 5 mm, and are fixed to the frame using the holes and slots shown in 5. Finally, a rectangular groove 6 ensures precise alignment. For improved clarity coils, 2 and 4 are rendered using a transparency option. The overall setup can be enclosed in a 300 × 300 × 290 mm³ cuboid.

### II. HARDWARE DESIGN

This section presents the key design points that allowed the setup to perform independent control of two microrobots in the 3-D-space. The design process aims at satisfying a set of minimal requirements. These are listed and discussed in Table I. The final testbed is shown in Figs. 1 and 2.

### B. Thermal Management

Hitherto, only a few studies discuss and quantitatively analyze the thermal management of electromagnetic coils. Yet, this is a crucial aspect for the reliable operation of such

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Wire Diameter</td>
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</tr>
<tr>
<td>Number of Turns</td>
<td>1274</td>
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<tr>
<td>Maximum Coil Length</td>
<td>50 mm</td>
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<tr>
<td>Coil Inner Diameter</td>
<td>20 mm</td>
</tr>
<tr>
<td>Coil Outer Diameter</td>
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</tr>
<tr>
<td>Resistance (20 °C)</td>
<td>8.4 Ω</td>
</tr>
<tr>
<td>Core Diameter</td>
<td>20 mm</td>
</tr>
<tr>
<td>Core Length</td>
<td>100 mm</td>
</tr>
</tbody>
</table>

**Table II**

**Specifications of the Final Coil Design**
Fig. 3. Plots depicting the theoretical electromagnetic force exerted by a single coil on a paramagnetic dipole positioned along the coil’s axis. The distance value represents the normal distance from the metal core, while the paramagnetic dipole has unitary magnetic constant (\( k_{mag} \)) (10). A single parameter is varied throughout the simulation, while the other ones are consistent with Table II. The power input of the simulated coil is set 40 W. (a) Effects of core size are depicted. For accessibility requirements the maximum diameter of the coil is set to 41 mm. Thus, in this plot the thickness of the coil—and consequently the number of turns—decreases as the core diameter increases. (b) Force dependency on the length of the coil is represented. Also, here a tradeoff is present. In fact of point, a longer coil—at equal current—exerts a stronger magnetic field. Yet, this comes at the cost of a longer copper wire and, therefore, higher resistance and lower current for equal power input. (c) Electromagnetic force with respect to the length of the electromagnetic core; the distance between the core and the center of the workspace is maintained constant. Here, a longer core shows (incrementally smaller) force increases over shorter ones. However, the increase in field comes with an increased mass, which requires an oversized frame, and a decrease in the bandwidth of the electromagnet due to the increase in the magnetic energy stored in it.

### TABLE III

<table>
<thead>
<tr>
<th></th>
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<th></th>
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<tbody>
<tr>
<td>Workspace</td>
<td>35x35x35 mm³</td>
<td>Ø25 mm semi-sphere</td>
<td>Ø20 cm sphere</td>
<td>20x20x20 mm³</td>
<td>18x18 mm²</td>
<td>Ø20 mm sphere</td>
</tr>
<tr>
<td>Maximum Workspace</td>
<td>Ø160 mm sphere</td>
<td>[Ø90 mm as reported]</td>
<td>Ø130 mm semi-sphere</td>
<td>cylinder of over Ø20x∞ cm³</td>
<td>120x120x120 mm³</td>
<td>40x40 mm²</td>
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<tr>
<td>Accessibility</td>
<td>160</td>
<td>15</td>
<td>400 vertical</td>
<td>100 horizontal</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Maximum field flux at the center (mT)</td>
<td>3575</td>
<td>200</td>
<td>3000</td>
<td>100</td>
<td>60</td>
<td>250</td>
</tr>
<tr>
<td>Number of electromagnets</td>
<td>9</td>
<td>8</td>
<td>18</td>
<td>8</td>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>

**Note:** BatMag shows improvements of up to an order of magnitude in the intensity of the generated electromagnetic field and gradient. Furthermore, fields are achieved in a workspace volume of up to five times larger than previous literature. The fields and gradients of BatMag are reported with the configuration used to perform the presented experiments, offering a workspace accessibility of a Ø60 mm sphere. Data reproduced from [23].

Electromagnets. In point of fact, during operation a single electromagnetic coil can reach a power of consumption of 450 W. Only a very limited amount of this power is converted in kinetic/potential energy of the controlled microrobots. Part of the transformed energy goes into generating the electromagnetic field and magnetizing the electromagnetic core (see Appendix A). However, at steady state, the majority of the provided energy is dissipated in the form of Joule losses. Due to the low heat capacity of copper (0.385 J/g·°C) and to the limited (external) surface/volume ratio of the coils, the electromagnets—if not cooled—can reach extreme temperatures, posing a risk to the users and the overall electrical system.

Therefore, guided by the FE model, we design a water cooling system to transport the heat from the coils to an aluminum radiator (see Fig. 4). Silicone hoses are clamped against the coils for this purpose. Additionally, the frame is designed in aluminum (205 W/m·K) to act as passive heat-sink. Watercooling is preferred over oil-cooling for its superior performance and increased ease of sterilization in clinically relevant applications.

The nondissipated heat increases the temperature of the coils and, consequently, their resistance. This increase can be estimated using the linear approximation of the steady-state resistivity dependence on temperature

\[
R(T) = R_0[1 + \alpha(T - T_0)]
\]

where \( T \in \mathbb{R} \) is the temperature of the coil, \( R_0 \in \mathbb{R} \) (8.4 Ω) is the resistance of the coil at room temperature \( T_0 \in \mathbb{R} \) (23.7 ± 0.1 °C), and \( \alpha \in \mathbb{R} \) the temperature coefficient of resistivity (0.0039 °C⁻¹ for copper). Substituting (1) in Ohm’s law (\( V = RI \)), we obtain

\[
T = \frac{V - IR_0}{IR_0\alpha + T_0}
\]

where \( I \) is the applied current and \( V \) the measured voltage. Consequently, substituting in (2), the voltage and current output of the power supplier, we are able to indirectly measure the temperature of the coil during operation at several continuous currents—which correspond to root mean square (RMS) ratings in noncontinuous operation. In particular, these experimentally...
estimated temperatures at steady state are 36 ± 3 °C, 53 ± 3 °C, and 82 ± 3 °C for current values of 1.5 A, 2 A, and 2.5 A, respectively. The heating process takes about 12 min to reach 63.2% of its final value. Conversely, after powering down the coils, the cooling system is able to reduce their temperature from 84 to 30 °C in 7:30 min. Remarkably, at just 1.5 A current rating, without cooling, the electromagnet has an experimentally estimated steady-state temperature of 125 ± 3 °C (5 °C above the insulation safety limit), while at 2 A the coil reaches 117 ± 3 °C in 12 min, hence compromising further continuous operation at this rating.

A maximum of about 1.5 A per coil is required to levitate a 1 mm iron sphere. Therefore, also the requirements regarding heat-dissipation are considered satisfied. Furthermore, throughout the experiments, we present (see Section IV) the coils never reached the safety limit of 120 °C.

III. SOFTWARE IMPLEMENTATION

This section presents the software infrastructure, we developed to perform independent six-DOF control of microrobots. The custom software receives the position and desired trajectory, and outputs the currents at the electromagnets required for actuation (see Fig. 5).

A. Camera Calibration and Tracking

For imaging and tracking purposes, two Grasshopper three cameras (FLIR, Wilsonville, USA) are attached to an equal number of orthogonally oriented zoom modules with adjustable magnification (Qioptiq, St Asaph, U.K.). Using this imaging setup, we develop an algorithm capable of tracking the microrobot in a time window suitable for the control frequency (20 ms for the processing of both the images of size 2028 × 2048 pixels each). The simple—yet effective—technique, we used is depicted in Fig. 5. The procedure outputs two points on the two cameras image plane. A linear triangulation of the two points is then performed [27]. This results in the 3-D-space coordinates of the tracked microwhitevice.

B. Modeling and Control

The obtained position can then be used in the developed model. In particular, the motion of a magnetic microrobot can be modeled according to

\begin{align}
F_{\text{em}} + F_d + F_g + F_r + F_b &= 0 \quad (3) \\
I_0 + T_{\text{em}} + T_d &= 0 \quad (4)
\end{align}

where \(F_{\text{em}} \in \mathbb{R}^3\) are the electromagnetic forces, \(F_d \in \mathbb{R}^3\) are the drag forces, \(F_g \in \mathbb{R}^3\) are the gravitational forces, \(F_r \in \mathbb{R}^3\) are the other inertial forces, \(F_b \in \mathbb{R}^3\) are the buoyancy forces, \(I \in \mathbb{R}^{3 \times 3}\) is the moment of inertia, \(\alpha \in \mathbb{R}^3\) is the angular acceleration, \(T_{\text{em}} \in \mathbb{R}^3\) is the electromagnetic torque, and \(T_d \in \mathbb{R}^3\) is the rotational drag.

In this study, the microrobot move in silicon oil with dynamic viscosity of 0.001 m²/s. Therefore, for submillimeter velocities, their Reynolds number will not be above 0.01 [28]. In this low-Reynolds number environment, the forces acting on the microrobots (3) are as follows:

\begin{align}
F_i &= Ma \quad (5) \\
F_g &= Mg \quad (6) \\
F_b &= -gV\rho_m \quad (7) \\
F_d &= -\frac{1}{2}\rho_m C_D Av \quad (8) \\
F_{\text{em}} &= \nabla(B \cdot m) \quad (9)
\end{align}

where \(a \in \mathbb{R}^3\) is the acceleration of the structure and \(M \in \mathbb{R}\) is its mass, \(g \in \mathbb{R}^3\) is the gravitational acceleration, \(V \in \mathbb{R}\) is the volume of the microrobot, and \(\rho_m \in \mathbb{R}\) is the density of medium that surrounds it (970 kg/m³). Further, \(v \in \mathbb{R}^3\) is the speed of the microrobot relative to the fluid, \(A \in \mathbb{R}\) is its cross sectional area, \(C_D \in \mathbb{R}\) is the drag coefficient (0.5 for our microrobots [29]). Finally, \(m \in \mathbb{R}^3\) is the magnetic dipole moment of the microrobot.

The microrobots used in this study are submillimeter microspheres. Being constructed of soft magnetic material, the remnant magnetization of the microsphere is negligible when compared to the magnetization due to the external magnetic field. This, combined with the extremely low time response of magnetization [30], [31], results in

\begin{align}
m = \iiint_V M dV &= \frac{4}{3}\pi r^3 \left(\left|\mathbf{M}_e\right| + \frac{\chi}{\mu_0 (1 + \frac{\chi}{2})} \mathbf{B}_s\right) \\
&\approx k_{\text{mag}} \mathbf{B}_s
\end{align}

where \(r \in \mathbb{R}\) is the radius of the sphere, \(\mathbf{B}_s \in \mathbb{R}^3\) is the magnetic field density at the surface of the sphere (assumed to be constant), and \(\mathbf{B}_s = \frac{2}{3}\mathbf{B}_0\) is the magnetic field density inside the sphere—reduced by the demagnetizing H-field inside the microsphere [32]. Moreover, \(\mathbf{M}_e \in \mathbb{R}^3\) is the remnant magne-
Fig. 5. Flowchart depicting the software structure of the developed setup. For tracking purposes, the cameras image the motion of the microspheres. These images are converted to hue-saturation-value (HSV) colorspace for better contrast among channels. During the tracking procedure, the HSV image is then thresholded using experimentally determined values, and the center of the largest blob is selected as the position of the microsphere in the camera. Finally, the two camera positions are triangulated as described in Section III-A. The variable $e(t)$ represents the error between the observed position and the prescribed reference. $K_p$, $K_i$, and $K_d$ are the feedback proportional, integral, and derivative gains, respectively; $K_v$, and $K_a$ are the feedforward gains on velocity and acceleration, respectively.

(9) $F_{em}(I) = \nabla (B(I) \cdot m(I)) = \nabla (B(I)^T k_{mag} B(I)) = k_{mag} \nabla (I^T B^T B I)$. (11)

This set of equations has to be inverted to obtain the force-to-current map, required for the conversion of the control output. Yet, the nonlinearity—with respect to both position and currents—and nonconvexity (see Appendix C) of these functions renders it particularly arduous to find an analytic solution to this problem.

D. Numerical Solution

Alternatively, we investigate two numerical approaches to obtain the force-to-current map, which are as follows.

1) Nonlinear Optimization: The first approach uses the interior-point method (IPM) to solve a nonconvex quadratically constrained quadratic optimization [35]:

C. Force to Current Map

In order to reach actuation, the computed forces need to be mapped into currents at the electromagnets. The first step of this process is to develop a model of the field generated by the electromagnets. Consequently, we validate the FE results using a calibrated three-axis teslameter (Senis AG, Zug, Switzerland). The validation is performed along a grid of $10 \times 10 \times 10$ points spaced through the $35 \times 35 \times 35$ mm$^3$ workspace. In line with previous literature, we find the measured and simulated field values to be congruous with the exception of a scaling factor [24], [26].

The corrected FE data is then used to compute the function $(B \in \mathbb{R}^{3 \times 9})$ mapping the currents at the electromagnets to the electromagnetic field $(B \in \mathbb{R}^3)$ in the workspace. A polynomial function was used for this purpose and computed using a least square minimization algorithm with an empirical weight to minimize the changes in convexity of the mapping function. Further, the said function is constrained to have null divergence and curl, according to Maxwell’s equations. Finally, the order of the polynomial function was empirically chosen as five, as it offered the lowest errors while still preserving limited higher-order derivatives. This function allows us to map currents into fields at a given position in the workspace. Furthermore, computing the gradient of this function, we are able to map currents into magnetic gradients in the workspace and verify the presence of possible singularities (see Appendix B).
where $I \in \mathbb{R}^9$ is the current at the electromagnets, $I_{\text{max}} \in \mathbb{R}^9$ is the maximum current at the electromagnets, $k_{\text{mag}, j} \in \mathbb{R}$ is the magnetic constant of the $j$-th microrobot, $p_j \in \mathbb{R}^3$ is its position, $F_j \in \mathbb{R}^3$ is the desired force, and $B(p_j) \in \mathbb{R}^{3 \times 9}$ is the position-dependent matrix mapping the currents to the electromagnetic field.

2) Semidefinite Approximation (SDA): The second approach aims at solving the following SDA with nuclear norm minimization (SDANM) of the problem:

**Input:** $p_j \in \mathbb{R}^3$, $F_j \in \mathbb{R}^3$; for $j \in \{1, 2\}$

**Result:** $J \in \mathbb{S}^9$

**Objective function:**

$$\min \| F \|_I$$

subject to:

$$\begin{align*}
F_{i,j} &= k_{\text{mag}, j} \nabla (I^T \tilde{B}(p_j)J^T \tilde{B}(p_j)I) \\
I &< I_{\text{max}} \\
I &> -I_{\text{max}}
\end{align*}$$

for $i \in \{x, y, z\}$, where

$$\tilde{B}_i(p_j) = \frac{\partial}{\partial p_{ji}} \tilde{B}(p_j)$$

(12)

where $p_{ji} \in \mathbb{R}$ is the $i$th component of the position of the $j$th microrobot, and $F_{i,j} \in \mathbb{R}$ is the $i$th component of the force on the $j$th microrobot. Further, $J = I^T$, $\text{tr}(\cdot)$ indicates the trace operator, $\|J\|$, is the nuclear norm of $J$, $w \in \mathbb{R}$ is an empirically determined weight, and $\mathbb{S}^9$ is the set of all $9 \times 9$ real-symmetric matrices. Additionally, $J \succeq 0$ indicates $J$ has to be positive semidefinite. Finally, $I$ is extracted as the eigenvector associated with the largest eigenvalue.

This optimization drops the nonconvex constraint of rank($J$) = 1. However, a convex relaxation of the rank minimization is introduced adding a weighted term for the minimization of the nuclear norm of $J$ in the cost function [36]. Moreover, in order to address for electromagnetic saturation, if the resulting solution exceeds the currents limits it is scaled according to

$$\Gamma = \frac{I}{\alpha I_{\text{max}}}, \quad \text{where} \quad \alpha = \max_k \frac{|I_k|}{I_{\text{max}, k}}$$

(13)

for $k \in \{1, \ldots, 9\}$, where $\Gamma \in \mathbb{R}^9$ is the scaled solution, $I_k$ and $I_{\text{max}, k}$ are the $k$th elements of $I$ and $I_{\text{max}}$, respectively. The scaling in (13) maintains the direction of the force while decreasing its magnitude below saturation.

2) Discussion: The performance of the optimizations are compared on the same 1000 random combinations of points and forces in the workspace. All combinations are selected to have solutions below $I_{\text{max}}$. Additionally, for comparison purposes, also the SDA proposed in [22] is implemented.

As shown by the results (see Table IV) IPM outperformed the SDA (both with and without the nuclear norm term) in terms of average run-time, as well as average and maximum error; therefore, it is used in our experiments. Nonetheless, the hereby presented SDANM offers the state-of-the-art alternative among algorithms with polynomial complexity. This renders it preferable for implementation in hard real-time systems or environments with a high number of controlled variables. Finally, it should be noted that the average runtimes are reduced of about an order of magnitude when computing continuous trajectories in which the previous current is provided as initial solution of the optimization routine.

Particularly, in this study, the average IPM runtime is 7 ms, and its execution time is bound to a maximum of 20 ms. This would results in peak control frequencies of above 40 Hz. However, to ensure a constant bandwidth, the six-DOF control loop is constrained at 25 Hz. The software executes on a computer running Robot Operating System “Lunar Loggerhead” [37].

### IV. EXPERIMENTAL EVALUATION

In order to validate the novel design and techniques, we perform three experiments using both identical and nonidentical microspheres. In all the experiments, the magnetic microspheres are submerged in silicone oil, inside a $22 \times 22 \times 22$ mm$^3$ cube of hydrolytic class one borosilicate glass (170 $\mu$m thick) (see Fig. 1). Please, refer to the accompanying video for the visualization of characteristic examples of the following experiments. Please, also note that errors are reported in the form Root Mean Square ± Standard Deviation (RMS ± SD).

In the first experiment, two microspheres with radii of 350 $\mu$m move along two great circles, sections of an imaginary sphere (see Fig. 6). This imaginary sphere has a radius of 3 mm and is concentric with the workspace. The two paths are chosen on planes perpendicular both to each other, and to the optical axes of the cameras. In the five performed trials, the microrobots are able navigate the prescribed trajectory with error and average velocities of 97 $\pm$ 47 $\mu$m and 209 $\mu$m/s, respectively.

In the second experiment, two microspheres with radii of 350 $\mu$m are used. The first microsphere is maintained still in the center of the workspace, while the second microrobot inscribes it in a vortex-like trajectory (see Fig. 6). In the five performed
trials, we find the still microrobot to maintain its prescribed position with an average error of 82 ± 40 μm, while the moving one performs its trajectory with error and average velocity of 77 ± 32 μm and 122 μm/s, respectively.

In the third experiment, we demonstrate the capability of the system to manipulate nonidentical microrobots. Consequently, we use two microspheres of different radii (250 and 350 μm) to trace U-shaped and T-shaped trajectories (see Fig. 6). Sinusoidal velocities are used as reference along the straight segments in the trajectory. Three trials are performed, in which the error and average velocities of the microrobots are found to be, respectively, 71 ± 41 μm and 171 μm/s—for the 250 μm microsphere—and 112 ± 52 μm and 208 μm/s—for the 350 μm microsphere.

Finally, it is worth noticing that despite the theoretically perfect isotropy of the microsphere—that should result in its almost immediate remagnetization, with no consequent electromagnetic torque exertion—some rare, but sudden, rotation are observed. We hypothesize that these are due to crystal anisotropy, to physical inhomogeneity and to the drag acting on the dye of the microsphere. Yet, these rotations did not seem to affect the motion, as positioning error remained in line with the rest of the trial.

V. CONCLUSION

In this study, we design, simulate, develop, and experimentally validate an electromagnetic setup for independent 3-D control of microrobots. Throughout the design process, we determine the most relevant parameters for the generation of strong electromagnetic fields, and for the dissipation of the generated heat. Exploiting this analysis, we build a setup capable of generating magnetic fields and gradients of, respectively, 160 mT and 3.6 T/m. These values are made more notable by their combination with a workspace of $35 \times 35 \times 35$ mm$^3$, with maximum workspace accessibility of 160 mm. Moreover, a thermal management technique is developed and quantitatively analyzed to prevent overheating during continuous operation. Furthermore, two novel techniques—with deterministic and NP complexities—for force-to-current mapping are presented and evaluated. The performance of such setup is not only tested and evaluated for the six-DOF independent navigation of identical microrobots (with peak velocities of 0.4 body-lengths/s), but also for the independent six-DOF control of nonidentical ones (with RMS errors lower than 0.15 body-lengths). The demonstrated capabilities suggest that these techniques might be used for precise collaborative tasks in the microscopic world, with potential applications in fields such as minimally invasive surgery, microassembly, micromanipulation, tissue engineering, and lab-on-a-chip applications.

Future work will investigate the use of these techniques for tasks of micromanipulation and microassembly. Further, control algorithms regulating more DOF and aimed at current-minimization will be studied. Moreover, more efficient tracking algorithms, possibly exploiting the epipolar nature of the cameras, will be investigated. Finally, we will study the development of similar techniques for the control of swarms, as well as the use of clinically compatible imaging systems (such as ultrasound [38]).

APPENDIX A

ENERGY STORED IN THE MAGNETIC FIELD AND ELECTROMAGNETIC CORE

The following amount of energy is necessary for generating the electromagnetic field ($W_F$) and magnetizing the electromagnetic core ($W_M$):

$$dW_F = \iiint_{V_E} (\mathbf{H} \cdot d\mathbf{B}) dV_E$$

$$dW_M = \mu_0 \iiint_{V_E} (\mathbf{H} \cdot d\mathbf{M}) dV_E.$$  \((14)\)

where $\mathbf{H} \in \mathbb{R}^3$ and $\mathbf{B} \in \mathbb{R}^3$ are the magnetic H-field and the magnetic flux density, respectively, $V_E$ is the volume surrounding the coil, $\mathbf{M} \in \mathbb{R}^3$ is the magnetization, and $\mu_0 \in \mathbb{R}$ is the magnetic permeability of vacuum.

APPENDIX B

SINGULARITY ANALYSIS OF THE ACTUATION SYSTEM

To identify the possible singularities in our actuation system, we analyze the Jacobian ($\mathbf{J} \in \mathbb{R}^{6 \times 9}$) of the electromagnetic...
force with respect to the current

\[
J = \begin{bmatrix}
\frac{\delta}{\delta I_1} F_{em,1}^x(p_1) & \cdots & \frac{\delta}{\delta I_1} F_{em,1}^z(p_1) \\
\frac{\delta}{\delta I_2} F_{em,1}^x(p_1) & \cdots & \frac{\delta}{\delta I_2} F_{em,1}^z(p_1) \\
\frac{\delta}{\delta I_3} F_{em,1}^x(p_1) & \cdots & \frac{\delta}{\delta I_3} F_{em,1}^z(p_1) \\
\frac{\delta}{\delta I_1} F_{em,2}^x(p_2) & \cdots & \frac{\delta}{\delta I_1} F_{em,2}^z(p_2) \\
\frac{\delta}{\delta I_2} F_{em,2}^x(p_2) & \cdots & \frac{\delta}{\delta I_2} F_{em,2}^z(p_2) \\
\frac{\delta}{\delta I_3} F_{em,2}^x(p_2) & \cdots & \frac{\delta}{\delta I_3} F_{em,2}^z(p_2)
\end{bmatrix}
\]

where \( I_q \in \mathbb{R}^9 \) is the current at the \( q \)-th electromagnet and \( F_{em,j}^i(p_j) \) is the \( i \)-th component of the electromagnetic force on the \( j \)-th microrobot at position \( p_j \in \mathbb{R}^3 \), with \( i \in \{x, y, z\} \), \( j = \{1, 2\} \), \( q \in \{1, \ldots, 9\} \) and \( p_1 \neq p_2 \).

The critical points of the system can be identified as the points in which \( J \) is rank deficient. At such critical points, the system loses DOF, compromising its independent actuation. These singularities might be due to the position of the microrobots, to the current at the electromagnets, or to a combination of the two.

In our case, we analytically find no current-independent critical point, meaning that no combination of positions of the microrobots alone affects the rank of \( J \). Yet, we found current dependent and current-and-position dependent critical points. These points correspond to singularities related to the physical expression of the electromagnetic force. Even though the resulting analytic solution is somewhat too intricate and extensive for intuitive understanding (due to the numerous coefficients of the polynomial function), the nature of these critical points becomes evident analyzing the following formulation of the electromagnetic force for \( \mathbf{m} = m_{mag} \mathbf{B} \) [39]:

\[
\mathbf{F} = k_{mag} \mathbf{B} \begin{bmatrix}
\frac{\delta B_x}{\delta x} B_x + \frac{\delta B_y}{\delta y} B_y + \frac{\delta B_z}{\delta z} B_z \\
\frac{\delta B_y}{\delta y} B_x + \frac{\delta B_z}{\delta z} B_y + \frac{\delta B_x}{\delta x} B_z \\
\frac{\delta B_z}{\delta z} B_x + \frac{\delta B_x}{\delta x} B_y - \left( \frac{\delta B_y}{\delta x} + \frac{\delta B_x}{\delta y} \right) B_z
\end{bmatrix}
\]

\[
(17)
\]

For instance, singularities can be noticed when the field in the considered point is zero (e.g., if all currents are zero) or when actuation along a component is not possible (e.g., if \( \mathbf{m} \) is aligned with \( z \) but \( \frac{\delta B_z}{\delta z} = 0 \), then no force can be exerted along the \( x \)-axis).

Despite these singularities, we could not find any numerical set of positions and forces in the workspace, that only had solutions that rendered \( J \) rank deficient. Further, it should be noted that these singularities are intuitively avoided by the optimization in Section III, even when the respective inequalities are not included in the constraints of the optimization, as they would require infinite power for actuation.

\section*{Appendix C}

\section*{Nonconvexity of the Quadratically Constrained Quadratic Optimization}

Let us consider the general formulation of quadratically constrained quadratic programs:

\begin{align*}
\text{Input:} & \quad Q_0, Q_i, \mathbf{q}_i \in \mathbb{R}^{n \times n}, b_i, b_f \in \mathbb{R}, \mathbf{q}_i, \mathbf{q}_f \in \mathbb{R}^n, l, u \in \mathbb{R}^n, \mathcal{T} \cup \mathcal{E} = \{1, \ldots, m\} \\
\text{Output:} & \quad \mathbf{x} \in \mathbb{R}^n \\
\text{Objective function:} & \quad \min \mathbf{x}^T Q_0 \mathbf{x} + \mathbf{q}_0^T \mathbf{x} \\
\text{subject to:} & \quad \mathbf{x}^T Q_i \mathbf{x} + \mathbf{q}_i^T \mathbf{x} \leq b_i, \quad i \in \mathcal{T} \\
& \quad \mathbf{x}^T Q_f \mathbf{x} + \mathbf{q}_f^T \mathbf{x} = b_f, \quad l \in \mathcal{E} \\
\end{align*}

\text{end}

In our case, \( m = 3 \) and \( Q_i = \frac{\delta}{\delta p_i} (\mathbf{B}(p)^T \mathbf{B}(p)) \) with \( p_i \) being the \( i \)-th component of the position of the microrobot. This optimization problem is convex if and only if the matrices \( Q_0, Q_i, Q_f \) are all positive semidefinite or all negative semidefinite [40]. However, such matrices were experimentally found to be indefinite. Further, it should be noted that claiming that any \( Q \) is semidefinite would result in

\[
\mathbf{x}^T Q \mathbf{x} \geq 0, (\leq 0 \text{ for NSD}) \quad \forall \mathbf{x} \neq 0
\]

which would effectively constrain the direction of all forces.


