Design of the \(\mu\)MAZE Platform and Microrobots for Independent Control and Micromanipulation Tasks

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Abstract— We present the \(\mu\)MAZE (\(\mu\)(Micro) Magnetic Actuation Zone control Environment) platform for independent control of multiple magnetic microrobots for performing individual and collaborative micromanipulation tasks. We present a new local magnetic field generating coil system design, microrobot design, actuation scheme, and orientation control for actuating multiple magnetic microrobots independently. The new designs are validated and experiments showcasing their abilities are presented. The demonstrations include closed-loop independent and simultaneous control of four microrobots and a sample micromanipulation task involving two microrobots pushing micro-parts into a prescribed formation.

I. INTRODUCTION

Untethered agents at the microscale (footprint less than 1 \(\text{mm}\)) are crucial in manipulating single cells for arranging tissue scaffolds, drug delivery, and manipulation of microcomponents for low-cost additive manufacturing tasks. Mobile microrobots are agents with such capabilities that can interact with objects in this scale. Independent control of multiple microrobots can improve the speed and throughput of executing these tasks. The main challenges of designing such microrobots is in ensuring sufficient power storage, locomotion capabilities, and independent control of such agents at this scale. In the past decade, several solutions have emerged to the design and development of such microrobots using optical energy, magnetic fields, and physiological energy [1].

Electromagnetic actuation is a widely used method due to its ability to penetrate most materials and suitability to actuate objects remotely [2]. Several systems have provided promising results to date [3]. The possibility to control position and orientation independently using magnetic field strength for torque (orientation) and field gradient strength for force (position) has led to the development of several commercial actuation systems [4] and applications in biology [5]. The microrobots used with these systems are made of permanent magnetic, ferromagnetic, or paramagnetic materials that respond to the field generated in the workspace using external electromagnetic coils. However, the fields generated by such coils are not limited to the desired microrobot itself, but can extend to other areas in the workspace. When multiple microrobots are present in the workspace, they will respond to the stray magnetic fields generated by the coils, restricting independent actuation to a single microrobot at a time. Collective control of swarms of microrobots for manipulation tasks has been demonstrated in [6], [7], [8] but the collective behavior of such systems is restricted to performing a single task at a time.

Recently, heterogeneous microrobots with varying magnetic properties were independently controlled using these global gradient fields [9], [10], [11] and rotational fields [12], [13], [14]. However, their motions are still coupled and hence do not easily scale to handle larger numbers of robots (> 2 microrobots). Sorting of larger number of microrobots were achieved using rotating magnetic fields [15], however, the independent control of each agent was limited. In [16], parallel operation of multiple MEMS microrobots was demonstrated using a global magnetic field along with an interdigitated electrode grid on the workspace where the microrobots operate. The motion of the robots are still coupled here and require high voltages to clamp the robot for position and orientation control. Another approach is to use oscillating external magnetic field to generate vibrations in the robots to move them in the planar workspace [17]. Although these robots are capable of moving in dry and wet surfaces, multi-agent control is again challenging due to the global nature of the oscillating field.

Thus, instead of using coils that generate global fields, coils that generate local fields have been an alternative for independent actuation of multiple microrobots. These systems are typically designed on printed circuit boards for accurate positioning of the planar coils and ease of handling. Magnetic mm-scaled robots have been actuated precisely with a serpentine shaped array of traces on a printed circuit board in [18], and applied successfully in microbiological environments in [19]. These robots are partially levitated to avoid frictional forces that dominate actuation forces in dry conditions. However, the size of these robots (5 × 5 array of 1.4 \(\text{mm}\) magnets) restricts the presence of these robots in a small workspace for micromanipulation tasks. These systems also lack independent control of orientation of the microrobots, where specialized zones are required to rotate the microrobot.

In our previous work [20], planar spiral coils were designed into a Printed Circuit Board (PCB) to control robots which were 3 \(\text{mm}\) diameter and 0.5 \(\text{mm}\) thick N52 disc magnets. The vias in this configuration were placed far apart as a prospective design to scale down the design to actuate...
micromagnets. However, these coils require advanced modeling and control to achieve simple motion tasks [21]. The design of local field generating coils resulted in lower current magnitudes that requires use of stronger neodymium magnets for generating sufficient actuation force. These magnets have inherent interactions between each other which restricts how close they can approach each other in the same workspace. Hence independent control of each robot is only possible in a specific zone which is sized at the minimum interaction distance. In [22], the microcoils were designed into a PCB to generate local magnetic field in an area of $1 \text{ mm} \times 1 \text{ mm}$ for a $1 \text{ mm}$ diameter, $0.50 \text{ mm}$ thick neodymium N52 disc robot. However, the required spacing between the vias that was manufacturable by advanced PCB manufacturing techniques restricted scaling down the size and spacing of the coils to enable actuation of smaller robots.

In this work, we present the design, development and analysis of μMAZE ($\mu$MICRO Magnetic Actuation Zone control Environment) that is capable of simultaneous, independent control of multiple magnetic microrobots. In Sec. II, the design of a new magnetic coil system, which resembles in operation that of a stepper motor, is discussed. The design of $750 \mu \text{m} \times 500 \mu \text{m} \times 300 \mu \text{m}$ microrobot to be actuated with the coil system is then presented. The implementation and validation tests for the new coil system and microrobot designs are presented in Sec. III. The capabilities of the system are showcased in Sec. IV through independent closed-loop control tests with four microrobots and a demonstration of a sample micromanipulation task that involves pushing 3D printed micro-parts. Finally, the results from these experiments are discussed, along with conclusions, in Sec. V.

II. ACTUATION SYSTEM AND MICROROBOT CO-DESIGN

The design of the new actuation system and microrobots are discussed in this section. The goal is to design a magnetic coil system that is able to actuate a sufficiently small neodymium magnet ($250 \mu \text{m}$ cube) (which has sufficient magnetization for actuation at this scale) for use as a component of a new mobile microrobot design. The new mobile microrobot must be designed in a way that both position and orientation control are possible in the workspace using the magnetic coil system. Finally, the interaction between the new microrobots designs must be investigated for the practical aspects of using these microrobots to perform simultaneous independent tasks in the workspace.

A. Coil Design

The PCB traces that form the coil are laid out to attract a $250 \mu \text{m}$ cube magnet into a stable local equilibrium area. This area is formed at the intersection of a pair of orthogonal serpentine shaped planar coils (Fig. 1(a)(top)). For a configuration of current directions, the coils generate net magnetic moments in the out-of-plane direction. However, the moments generated by a simple pair of these coils do not overlap and hence won’t allow for motion of the robot in the 2D plane at any given configuration of currents. By adding another set of orthogonal traces circuits laid at the interval of the previous pair, intermediate stable equilibrium areas can be generated to obtain motion of the robot in the plane. The traces are spaced to ensure that a $250 \mu \text{m}$ cube magnet fit inside the equilibrium zone. The gap between the centers of two adjacent traces of a single serpentine coil is $16 \text{ mils} (\approx 406 \mu \text{m})$, so that the gap between the inner edges of the traces would be equal to $250 \mu \text{m}$ to fit the magnet. The width of the trace is set at $152.4 \mu \text{m}$ to ensure that the magnet microrobot is over the width of a trace at all times in the workspace.

B. Actuation Scheme

The design of the coil system resembles those developed at SRI for the actuation of larger milli-scale robots made of an array of magnets using diamagnetic levitation [18]. However, several challenges exist for this design to actuate single magnets at the microscale. This includes the lower peak actuation force due to the reduced magnetic volume and the effect of the earth’s magnetic field on a single microscale robot in the workspace. The actuation scheme used here to control a microrobot along each axis is shown in Fig. 1(a)(top). The actuation is similar to the operation of a two-phase bipolar stepper motor for motion along each axis. The steps for moving along each axis are shown in Fig. 1(a), where four steps are shown to move the microrobot to a new equilibrium position. The set of coils that move the robot along the X-axis and Y-axis are named $\text{Coil X}$ and $\text{Coil Y}$, respectively. (The -1 and -2 labels correspond to different layer locations in the PCB). Since the four coils are on different planes, the currents to the four coils are computed to generate equal fields in the workspace. The currents used in this actuation scheme is uniquely defined based on the step number, based on the total number of steps using a sine-cosine microstepping approach [23]. The currents in $\text{Coil X}$ are given by

$$\phi = \frac{2\pi}{\# \text{ of steps}}$$

$$I_1 = I_{1\text{max}} \cos \phi$$

$$I_2 = I_{2\text{max}} \sin \phi$$

where $\phi$ is the step angle in radians and $I_1$ and $I_2$ are the currents to $\text{Coil X}$ based on the step value with respect to the maximum current $I_{1\text{max}}$ and $I_{2\text{max}}$ which provides the same magnetic field to the robot. Similarly, for $\text{Coil Y}$, $I_3$ and $I_4$ can be determined. The minimum count of steps is four, but the system can also be configured in microstepping mode to generate additional steps for the same segment of the coil by generating mixed signals on the two circuits based on the equations above. To enable independent control of multiple robots in the workspace, the serpentine coils are laid in four separate quadrants (Q0-Q3) where four robots can be independently actuated (Fig.1(a)(bottom)). Four quadrants were chosen here due to manufacturing constraints that restrict the placing of the coils and to simplify the proposed control method for independent actuation of multiple microrobots.
The layout of the coils are designed so that the robots can transition from one quadrant to another by ensuring the gaps between the quadrants are identical as the gap between the traces within each quadrant.

C. Microrobot Design

The 250 µm cube magnet is the driver of the robot. For successful actuation of the robot, the magnet’s poles must be oriented such that its magnetization \( \vec{M} \) is out of the plane of the surface of the workspace, as shown in Fig. 1(b)(i). However, in the absence of field in the workspace, these tiny magnets tip over to align with the earth’s magnetic field. This is prevented by providing sufficient side support structure for the magnet, as shown in Fig. 1(b)(ii).

To enable orientation control, the center of mass of the robot has to be offset from the magnetic center [22]. This can be achieved by adding a tail segment at the back of the robot (Fig. 1(b)(ii)). To achieve these objectives, while keeping the size of the robot under 1 mm, a 3D printed part (Projet MJP2500, 3D Systems, Inc., USA) is designed to be attached to the 250 µm cube magnet as shown in Fig. 1(b)(iv). The side walls provide support to prevent tipping when the robots are not being actuated by the coils. The tail section shifts the center of mass of the robot to enable preferred orientation control. The tops of the robot are painted with blue and red colors, as shown in Fig. 1(b)(iii), to aid in feedback of position and orientation of the robot during actuation.

To calculate the position and orientation of a microrobot from an overhead camera image, the position of the robot \( \vec{r}_{pos} = x_{pos}\hat{i} + y_{pos}\hat{j} \) is assumed to be the location of centroid of the 250 µm magnet and the orientation (\( \theta_{pos} \)) is calculated as the angle of the vector joining the centroid of the blue contour and the position of the magnet. The position of the robot is estimated using the tracked centroids of the red \( \left( \vec{r}_{red} = x_{red}\hat{i} + y_{red}\hat{j} \right) \) and blue \( \left( \vec{r}_{blue} = x_{blue}\hat{i} + y_{blue}\hat{j} \right) \) regions, as shown in Fig. 1(b)(v)), using following equation:

\[
\vec{r}_{pos} = \vec{r}_{blue} + |\vec{r}_{red} - \vec{r}_{blue}|(\cos\theta_{pos}\hat{i} + \sin\theta_{pos}\hat{j}) \tag{4}
\]

\( \theta_{pos} \) is estimated using the angle of the vector formed by the centroids of the red and blue segments and the fixed angle \( \theta_0 \) (Fig. 1(vi)) with:

\[
\theta_{pos} = \theta_{rb} + \theta_0 \tag{5}
\]

D. Multi-robot Interaction

The permanent magnetic nature of the microrobots introduce interactive forces between multiple robots in the workspace. To ensure that these robots do not collapse into each other during actuation, the magnetization vector of all robots are maintained in the same direction which introduces repulsive forces between the robots. However, this restricts how close they can come together in the workspace due to these repulsive forces overcoming the actuation force. On evaluating the repulsive forces between similar magnets, 250 µm cube magnets experience far less interaction forces compared to 500 µm cube magnets or the 1.00 mm magnets used in [22], as shown in Fig. 1(c), calculated using the analytical model in [24]. Due to the scaling down of the size of actuator magnet, the forces experienced by the smaller robots are also significantly reduced. By using a reduction factor \( k \),
the scale reduction divides the magnetic actuation force $F_{\text{act}}$ by $k^3$ ($F'_{\text{act}} = F_{\text{act}}/k^3$), while the scale reduction divides the interaction force $F_{\text{int}}$ by $k^2$ ($F'_{\text{int}} = F_{\text{int}}/k^2$) [25]. However, the magnetic actuation force on the robot can be improved by increasing the current density of the coil. This is achieved using a smaller trace width and trace thickness for the same magnitude of current. However, the current density should be carefully controlled to ensure only the generation of the minimum actuation forces for motion of the robot in the workspace due to increased Joule heating effects in the coils related to the increased current density in the coil.

III. IMPLEMENTATION AND VALIDATION

A. µMAZE Platform

The µMAZE platform is shown in Fig. 2(a). The platform consists of the workspace where the serpentine coils are fixed, an overhead camera-lens system for image feedback of the workspace, a coil controller board to control the current in the coils, and an Arduino microcontroller that is capable of communicating between the coil controller board and the computer that processes the feedback images.

The workspace consists of two flexible PCBs, each containing two layers of coils capable of moving a robot along a single axis (Coil X or Coil Y). Two-layer flexible PCBs were chosen due to their low thickness (100 µm for a 2-layer board) which maximizes the magnetic field generated by lower coils at the surface of the workspace. Each PCB has eight inputs for current for the two sets of coils in each quadrant. The PCBs are aligned and attached with double sided tape (89 µm thick, 3M 665) at an orthogonal angle to allow motion in both the X and Y axes. This ensures that the surfaces do not move, and that working fluid doesn’t get in between the two PCBs during actuation.

The position and orientation feedback is achieved through images captured by an overhead camera-lens system shown in Fig. 2(a). The camera (Point Grey FL3-U3-13E4C-C) is used to capture the overall workspace of 13.38 mm × 13.38 mm (Fig. 2(b)) while using a wide-angle lens (Tamron C-Mount 4-13mm Manual Iris Varifocal Lens) at a resolution of 750 × 750 pixels. For improved resolution of the motion and feedback images, a zoom lens (VZM™ 450i Zoom Imaging Lens, Edmund Optics) is used to observe a smaller segment of the workspace of size 9.38 mm × 8.33 mm covered by a portion of all four quadrants (Fig. 2(c)) at a resolution of 1280 × 1024 pixels.

The currents in the serpentine coils are controlled using a current control board used in our previous work [22] [20]. The current control board can power up to 16 coils, which is enough for all the coils in the workspace (4 coils in each quadrant). The current control board is accessible through an I2C interface that allows the control of all the coils using an Arduino microcontroller. Commands are sent from the computer (Intel® Core™ i7-4790 CPU @ 3.60GHz processor, 16.0GB RAM) to the arduino using serial communication through a virtual studio program. The currents are generated through an external power supply (Mean Well RSP-320-2.5) that can supply up to 60 A of current at 2.50 V. This allows for sufficient current to be supplied to the 16 serpentine coils at the same time. However, to eliminate excessive heat generation, the peak value of current is restricted to 0.65 A.

B. Workspace Preparation

Peak dry friction forces on glass cover-slips are in the range of 0.1 mN [26]. Since this is higher than the actuation forces of the magnetic coils, the microrobots are actuated in silicone oil medium to reduce the friction force. The microcoil workspace is prepared for actuation by setting up a 22 mm × 22 mm No.0 (Thermofisher Scientific Gold Seal Cover Glass #3206) glass coverslip on top of the cleaned workspace. About 250 µL of silicone oil (A12728 (40 cSt), Alfa Aesar) is added to the middle of the coverslip and allowed to spread. This forms an uniform layer of the fluid that is thick enough to submerge the microrobot. The absence of walls prevent wall effects that may affect the movement of the robots.

C. Microstepping

The motion of the microrobots are controlled by regulating the currents in the four layers of coils as shown in Fig. 3(a). The motion in the X-axis is controlled using the Coil X vertical traces that use currents $I_1$ and $I_2$. Similarly, motion in the Y-axis is controlled using the Coil Y horizontal traces that use currents $I_3$ and $I_4$. The computed maximum currents for all the layers to ensure equally generated magnetic field are shown in Table. I where the highest current is applied to the lowest layer coil. Since high currents can generate heat in the workspace, just the minimum current required to actuate the microrobot is used. For example, the highest continuous current value of 0.5 A can lead to a temperature rise of ≈ 30 °C (IPC-2152 [27]) for a coil of trace width of 150 µm and 17.5 µm thickness. While we only use short bursts of continuous currents, the silicon oil remains stable in this temperature range.

For four steps, the currents can be regulated as shown in Fig. 3(b) for moving the robot to the respective stable equilibrium points as shown in Fig. 3(d). The path of the robot in each axis is shown in Fig. 3(c) where the
TABLE I
μMAZE PLATFORM CURRENTS.

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Coil Current</th>
<th>Force Direction</th>
<th>Height from surface (µm)</th>
<th>Max Current $I_{\text{max}}$(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$I_1$</td>
<td>X</td>
<td>113</td>
<td>0.08</td>
</tr>
<tr>
<td>2</td>
<td>$I_2$</td>
<td>X</td>
<td>158</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>$I_3$</td>
<td>Y</td>
<td>246</td>
<td>0.50</td>
</tr>
<tr>
<td>4</td>
<td>$I_4$</td>
<td>Y</td>
<td>291</td>
<td>0.30</td>
</tr>
</tbody>
</table>

The motion of a robot can be independently controlled in each quadrant. The quadrant for each Coil X and Coil Y are shown in Fig. 3(e). The quadrants for each Coil X and Coil Y are aligned to not overlap each other to prevent a uncontrollable dead zone at the center. To ensure that the microrobots can transition from one quadrant to another, each Coil X and Coil Y workspace is divided in to several zones as shown in Fig. 3(f). Zones 0-3 require coils from a single quadrant to actuate the microrobot. Zones 5 and 6 require the adjacent quadrants to be in sync to ensure that the transition areas between the quadrants have the correct resultant field to ensure smooth motion between the quadrants. For this, when the microrobot enters zone 5 or 6, the step number of the quadrant in which the robot lies is equated to the adjacent quadrant. Zone 7 is a dead zone in the workspace for motion in each axis. Only a small (300 µm x 300 µm) area in the workspace is a partial dead zone for both axes. However, in case a microrobot accidentally enters this zone, it can be moved out using all the four coils surrounding this dead zone.

Fig. 3. Implementation and Validation: (a) Coil X and Coil Y dimensions and coil current variables. (b) Sine-cosine microstepping current values for four steps and sixteen steps cases. (c) Microrobot position for all Coil X steps. (d) Validation experiment of microrobot moving through steps in Coil X and Coil Y. (e) Coil X and Coil Y divisions. (f) Coil X and Coil Y zones for closed loop control for use in algorithm shown in Fig. 4.

D. Multi-robot Interaction

The peak force that can be applied to the drive magnet by a coil is estimated to be $\approx 0.02$ mN for a current of $0.08$ A at a depth of $\approx 113$ µm underneath the magnet. The peak magnetic field is $\approx 0.15$ mT and peak field gradient is $\approx 1.2$ T/m, at the center of the coil. Hence, according to Fig. 1(c), the microrobots should be maintained at distances greater than 2 mm to ensure unaffected motion through the workspace from the other microrobots.
Fig. 4. Algorithm to determine the currents in the serpentine coils in the workspace (Note that T and F are “True” and “False” respectively.)

This interaction between multiple robots was tested by actuating two robots to approach each other in both the X and Y axes. The interaction distance was experimentally estimated as the distance at which one of the robots cannot repeatedly go to the next step during its motion. The interaction distance for the X-axis motion was found to be 2.65 mm and 3.58 mm for the y-axis motion, as shown in Fig. 3(h). The higher distance for the y-axis motion is attributed to the lower position of the coils in layer 3 and 4 where the actuation force was observed to be less in spite of higher current settings.

E. Closed Loop Control

Closed loop control is achieved by maintaining the step count for X and Y axes on each quadrant of the μMAZE platform. Each step has a combination of currents in the underlying coil that allow the robot reach the required equilibrium point. The algorithm to estimate how the steps change to move the robot from the current position, \( \vec{r}_{pos} \), to \( \vec{r}_{des} \), is shown in Fig. 4. The strategy is to adjust the step count based on the error in position while making sure that the microrobots can cross across quadrants and prevent effects from stray fields. Delay time, \( t \), is the time between steps and hence, it determines the speed of the microrobot.

IV. EXPERIMENTAL RESULTS

A. Multi-robot Independent Motion

The ability of the μMAZE platform to simultaneously control multiple robots independently has been achieved. Four microrobots are placed on the four quadrants of the 9.33 mm × 8.38 mm workspace. Five waypoints are defined for each microrobot (Fig. 5(a)). The coils are configured for microstepping with 16 steps and feedback was processed at 10 Hz using algorithm shown in Fig. 4. The waypoints were updated only when all the robots reached their respective goal locations. The robots successfully traverse the workspace to reach the waypoints along the direction specified by the arrows (Fig. 5(b)) and can also be viewed in the supplemental video. The motion of the robot is restricted to just X or Y axis at one time in this experiment. The path of these robots were controlled independently in their respective zones, and a tracked points representing the letters “PUWL”.

B. Manipulation Tasks

The ability of these robots to work together to assemble parts at the microscale is demonstrated here. Two robots are used to assemble five parts (approx. dimensions of 1 mm × 1 mm) moved from various areas of the workspace to form the letter “P” as shown in Fig. 5(c). The robots are able to operate independently when placed in separate quadrants. This task was achieved by using feedback control to move the robot from one area of the workspace to other using prescribed waypoints that force the robot to push the parts. In some cases, manual control of the robot was used to push the parts to increase the delay time needed to achieve sufficient force for successful manipulation.

The main challenges of manipulation was the variability in force required to push different parts, which is attributed to surface finish of the 3D printed parts. Also, the coils in lower layers that generate motion of the microrobot in the Y axis were observed to not be powerful enough at times to complete the pushing task in the first attempt and hence cycles through the steps were required to ensure that the waypoint is reached. In some instances, manually controlled pushes were implemented to limit the number of cycles executed by increasing the delay time to ensure that robots reached the desired step. Another aspect is the tight workspace required for the image resolution needed needed for closed loop controls restricts the workspace for the robots to move in. A higher resolution camera and a wider field of view lens will enable the use of the entire workspace for fine motion control for micromanipulation tasks, and allow additional robots to work in the same workspace.

C. Orientation Control

The offset between the center of mass of the robot and center of the magnets generates force-moment couple that orients the robot in the direction of motion. This is useful to push objects in the workspace in a desired orientation. The 3D printed tail of the robot offsets the center of mass of the robot from the center of the magnet. However, due to the large difference in the density of the magnet and the 3D printed material, this offset is low and hence the torque generated is low. The torque generated can be improved by increasing the velocity of motion of the robot which generates continuous force in the direction specified. This method is effective only through long paths and requires additional path planning to ensure correct orientation during manipulation tasks. The torque generated is highest when the force is orthogonal to the orientation of the robot. By dividing the workspace into a higher step count, forces in orthogonal directions can be generated. An example of such a task done manually is shown in Fig. 5(e) and the supplemental video. The mean position of the robot is maintained while the position of the magnet follows the orthogonal force generated in the coils. Also, slower motion of the robot doesn’t produce as much torque and maintains...
Fig. 5. Experimental Results: (a) Four microrobots and waypoints defined for each robot along the arrows. (b) Tracked path of the five robots to form the letters "PUWL". (c) Manipulation tasks setup with two microrobots and four 3D printed parts numbered 1-5. (d) Final assembled "P" structure formed by pushing the parts from their initial to final position using two microrobots. (e) Orientation control of a microrobot by manually adjusting the steps to orient the robot in increments of $\frac{\pi}{4}$ radians.

the orientation which is useful in making small adjustments in position without changing the orientation.

V. CONCLUSIONS AND DISCUSSIONS

We have presented the design and analysis of the $\mu$MAZE platform that is capable of simultaneous independent control of up to 4 microrobots. The main driver of each robot is a neodymium 250 $\mu$m N50 cube magnet which is attached to a 3D printed part for stability and orientation control. The overall robot is sized 1 mm $\times$ 1 mm in size and is painted to get feedback of its position and orientation for closed loop control. The motion of the robot using the coils resembled that of a stepper motor which enabled the use of sine-cosine functions to specify currents in the coils for smooth motion of the microrobot in the workspace. These robots were tested to move as fast as 3 mm/s during feedback control and rotate manually at 22.5°/s, which can be improved when automated. The experiments demonstrated the capability of the microrobot and platform to simultaneously actuate up to four robots independently and successfully perform manipulation tasks. The ability to control the orientation of the microrobot is also demonstrated that has improved ability to perform manipulation tasks. The smaller size of the magnet has reduced the interaction distance greatly, from $\approx 7$ mm to $\approx 3$ mm. This has allowed the independent control of up to four microrobots in a comparable workspace. Another major improvement is the independent orientation control of each magnet by using the smaller step size and faster movements to achieve orientation control while staying in the same approximate position instead of the requirement to move long distances to orient the microrobot in a preferred direction.

This $\mu$MAZE platform has several advantages over our previous design that could do orientation control for sub-mm microrobots [22]. The similarly shaped serpentine coils in [18] were used to manipulate larger robots in different surfaces [28]. However, the rotation of the robot could be achieved only through a variety of configurations in the substrate design and fixtures on the workspace [29]. This due to the mm-scale robot design consisting of an array of magnets. The $\mu$MAZE platform is able to control both position and orientation of smaller robots (sub-mm) at finer resolutions through a clever robot design and without the need for specific mechanical constraints in the workspace. The global nature of the actuation fields in [17] makes independent orientation control of multiple microrobots difficult. These issues are solved here by the use of localized magnetic fields and zones which enable independent position and orientation control.

This new coil system is somewhat restricted in the force generated for pushing and manipulation tasks. This can be improved by using stronger magnets of the same size. The current 250 $\mu$m magnet on the robot provides sufficient area for the microrobot design to expand around the magnet to up to the sub-mm size. To use larger magnets, the spacing between the coils have to be adjusted. However, larger magnets would have significantly higher mutual interactions that restrict the motion of the robot. Similarly, for smaller drive magnets, the coil spacing will also need to be adjusted to be smaller. However, this be will limited due to the existing PCB manufacturing methods.

The size of the microrobot can also be decreased by using...
optimized designs that enable efficient shifting of the center of mass while offering side support to prevent accidental tipping. These robots can also be designed with capabilities such as force sensing or active grippers to further enhance their role in manipulation tasks. Study of the motion of the microrobots using this system in water/biological media can also expand the applications of these microrobots for future in vitro experiments. The limitations due to the interaction forces can be alleviated by designing an end-effector attachment that extends away from the drive magnet that can be used to manipulate objects in the workspace. These end-effectors, which can come closer than the actual drive magnets, will have the capability to perform collaborative tasks without being affected by the interaction forces. The existing four quadrants can be expanded using advanced manufacturing techniques to enable independent control of even more microrobots, as desired. There is also a possibility to model the interaction forces between the microrobots to improve the independent control of the robots when in close proximity to each other [21], [30]. Feedback control would also include closed loop orientation control, which is currently only done manually or through moving long distances through the workspace. More sophisticated path planning techniques can also be used to consider the zones that the robots operate to ensure successful transitions from one quadrant to another, which is an area of future work.

REFERENCES
