Towards Functional Mobile Microrobotic Systems

Sagar Chowdhury\textsuperscript{1,\$}, Wuming Jing\textsuperscript{2,\$}, Maria Guix\textsuperscript{1,\$}, Benjamin V. Johnson\textsuperscript{1}, Chenghao Bi\textsuperscript{1} and David Cappelleri\textsuperscript{1,†}

\textit{Abstract}—This paper will present our work over the last decade in developing functional mobile microrobotic systems. We will discuss our work on the design, fabrication, and testing of a number of different mobile microrobot designs, including the microscale magnetostrictive asymmetric bimorph micro-robot (\(\mu\)MAB), the microscale tumbling magnetic microrobot (\(\mu\)TUM), and the micro-force sensing magnetic microrobot (\(\mu\)FSMM). Additionally, we will present our latest results on using local magnetic field actuation for independent control of multiple magnetic microrobots in the same workspace for microassembly tasks.

\section*{I. INTRODUCTION}

With the advent of numerous microfabrication techniques the prospect for microscale robots have greatly increased over last decade. A fully autonomous fleet of microrobots can potentially revolutionize both in vitro and in vivo cell manipulation/sensing techniques for the biomedical field, assembly operations of heterogeneous microscale objects in the manufacturing field, and targeted drug delivery operation in the medical field. Miniaturization of the robot footprint by taking advantage of modern fabrication techniques comes with the challenge of accommodating on-board power, sensors, communication, and control. Often time, to carry these accessories the robot footprint needs to be scaled up which makes them unsuitable for lot of aforementioned applications.

Our current research is driven by answering the question: can we outsource all the auxiliary components (e.g. power, sensor, communication and control) to an off-board system and still be able to operate a fully autonomous fleet of microrobots?

Over the years, researchers have proposed the following different actuation techniques to actuate the microrobots: electrostatic \cite{1}, magnetic \cite{2,3,4}, optical \cite{5,6,7}, microfluidics \cite{8}, bacteria \cite{9,10}, chemical\cite{11}. Of them, magnetic, optical, and microfluidics are non-contact in nature making them suitable to for off-board operations. Magnetic actuation has garnered lots of attention in last decade because of the large range of force it can provide \cite{12}, the ease in ability to make customizable systems \cite{13}, cost effectiveness, ability to be integrated with many medical instruments, e.g. MRI \cite{14}. However, the global nature of actuation is a discouraging factor in designing a fully autonomous fleet of magnetic microrobots. That brings up the next question we want to address: How can you make magnetic microrobots to be actuated independently of each other?

Typically, robots need to be equipped with sensors/end effectors to perform certain tasks or sense the surrounding world. Our microrobots are fabricated with functional components that are suitable for a particular task, e.g. end-effectors for manipulation, elastic components to indirectly sense force, etc. A fully autonomous functional microrobot must sense the world for feedback. The most popular means of collecting information from an on-board sensing element is through passive sensing (e.g. using optical imaging, MR imaging, etc.). Optical imaging with an overhead camera is suitable for in vitro applications as well as microassembly operations. However, for in vivo operation, MR or ultrasound imaging are the only available options. The challenge here is to make the functional components within the limited footprint of the robot that are sensitive enough to be operated with the passive sensing elements that can be observed by an imaging system.

Our microrobots are designed to be operated in an environment with multiple dynamic obstacles. In a multirobot operation, each robot is treated as an obstacle with respect to the other. The robots communicate with each other and synchronize their movements with each other through a centralized system. The planning and control for multiple microrobots become challenging since it has to take care of randomly moving obstacles as well as to synchronize the individual robot path with the other robot paths. The planner also needs to take care of any uncertainty that can arise from the sensing or actuation in the system.

In this paper, we will discuss three microrobot designs in the light of the challenges and issues mentioned above. We will also discuss our independent robot swarm platform to address the challenge of planning and control. The rest of the paper is organized as follows: Section II outlines the different experimental setups we have used for actuating both single and multiple robots; Section III explains the design, actuation, and application of three robots actuated by a global magnetic coil system; Section IV discusses our approach to actuate and autonomous control of multiple microrobots, three generations of our microcoil array system and the experimental demonstrations. We conclude our paper
in Section V with a discussion of the importance of different microrobots we have developed over the years in the light of the challenges that we have laid out in the above.

II. MAGNETIC MANIPULATION SYSTEM

In order to power the variously designed magnetic microrobots, an electromagnetic coil manipulation system has been built with multiple customized solenoid coils. Side coils were designed to generate horizontal magnetic fields and the top/bottom coils were designed to provide field control in the vertical direction. There has been two versions of the magnetic manipulation systems developed with different merits. One version is the adjustable lab version (Fig. 1 (a)), whose coils can be easily adjusted in and away from the workspace. It is built for the convenience of testing a large variety of magnetic microrobot prototypes. The coils of the lab version were made of more turns and with conducting wires of lower gauge, when compared to the portable compact version shown in Fig. 1(b). The compact version, with less than a 6" × 6" footprint, also consists of coils generating both horizontal and vertical fields. Its portability allowed us to demonstrate our microrobots globally and compete in the international Mobile Microrobot Challenge [15] in various years.

Our experimental setup (Fig. 2) for the independent control of multiple robots (Section IV) consists of an overhead camera for sensing the state of the robot, a control electronics box for selectively activating the microcoil, a power supply unit, and a substrate with an embedded microcoil array. With selective actuation of the microcoils, thus generating local magnetic fields, our system can actuate each robot in the workspace independently.

III. MAGNETIC MICOROBOT DESIGNS

A. Magnetic Bimorph Microrobot (µMAB)

Our microrobot exploration started with addressing the mobility challenges present at the microscale. Aimed to the 2010 Mobile Microrobot Challenge, the first microrobot design was a micro-scale Magnetostrictive Asymmetric thin film Bimorph (µMAB) microrobot [16], [17] (Fig. 3). Similar as the piezoelectric phenomenon, magnetostrictive material generates strain in the presence of an external magnetic field. The µMAB design binds a magnetic layer on top of a non-magnetic layer. This bimorph structure will bend due to the magnetostrictive strain. Thus, pulsing a magnetic field on and off will alternately bend and straighten the microrobot body. The deflection of the layered structure was simulated using a piezoelectric FEM model, translated from magnetostrictive parameters. When the design geometry is asymmetric at both ends, the blocking force due to bending will also be uneven. Therefore, the resulting differential of blocking force from the rear and front ends will translate the microrobot body across the substrate in a step-wise fashion.

The µMAB microrobot was prototyped with surface microfabrication methods. The non-magnetic layer was patterned with SU-8 photoresist using a photolithography process. The magnetic layer was deposited through a Physical Vapor Deposition (PVD) method. The challenge on fabrication was to have magnetic layer with sufficient magnetostrictive property and thickness. Most of the magnetic materials demonstrate magnetostrictive property, but only few composite materials, such as Terfenol-D, have demonstrated significant magnetostriction. Unfortunately, Terfenol-D has not been validated for the PVD deposition process. Therefore, instead, we deposited a nickel magnetic layer via PVD. Even for the readily deposited nickel layer, it is still difficult to reach the ideal µm-level thickness due
to the limitations posed by the PVD process typical of only producing nm-level thicknesses. Given the magnetic layer with suboptimal magnetostrictive property, the μMAB microrobot prototype was actuated on a dry substrate by a pulsing magnetic field signal. It turned out that only a portion of the trials showed the expected vibrating step-wise motion. It was also observed that the robot translation is significantly influenced by the local substrate condition.

Given these imperfections, our first μMAB magnetic microrobot still demonstrated mobility on a dry substrate, which is the critical requirement for the microrobot to work in the realistic working environments. At present, the mobility on complex surfaces is still one of the major challenges for microrobots. For this reason, we have investigated another magnetic microrobot design with enhanced mobility capabilities, as detailed in the following section.

**B. Microscale Tumbling Magnetic Microrobot (μTUM)**

Our second mobile magnetic microrobot design was a micro-scale tumbling magnetic microrobot [18], [19], [20] (μTUM, Fig. 4). It addressed the mobility challenge on the complex dry substrate with the novel tumbling mechanism. The previous μMAB design utilized the blocking force differential to generate stepwise motion. However, it required relative motion between the robot body and substrate, which is a major challenge for the microrobot’s mobility. Still utilizing the blocking force against the surface, the μTUM microrobot investigated a novel tumbling locomotion mechanism in order to overcome complex working terrains.

The μTUM design is a composite magnetic structure in dumb-bell shape on the submillimeter scale. The non-magnetic bridge component connects two magnetic bell ends with opposite polarity directions (Fig. 4(a)). The tumbling locomotion mechanism, that utilizes an alternating magnetic field, is recapped in Fig. 4(b). When a vertical magnetic field turns on, one magnetic bell part will be repelled up away from the surface while the other magnetic bell is attracted to the surface. Next, the vertical field is turned off and a horizontal field is turned on. This signal sequence will tumble the microrobot forward naturally to fulfill a locomotion cycle. Experimental tests have demonstrated reliable mobility on various surfaces through tumbling locomotion. Different from the μMAB and other representative microrobot designs [3], [4] working on dry substrates, this tumbling locomotion cycle does not need relative motion against the surface. Therefore, the tumbling locomotion mechanism significantly advanced the adaptive mobility in complex (non-even) working terrains.

The fabrication of μTUM prototype was carried out only using photolithography processes. All the sections of the robot were made from SU-8 photoresist. The magnetic parts were made by mixing neodymium (NdFeB) permanent magnetic powder into the SU-8. The opposite polarization was realized by exerting opposite external magnetic fields when soft baking the sample during photolithography process. Thereafter, the magnetic particles were aligned by the external fields and fixed. Although the orientation of external magnetic field is barely uniform across the whole silicon wafer, the majority of the fabricated μTUM prototypes did exhibit successful tumbling locomotion.

A second generation of the μTUM capable of locomoting in both complex wet and dry environments using rotating magnetic fields was recently demonstrated [21]. Although the dumb-bell shape geometry with its ends containing magnetic particles resembles the first μTUM generation, in this particular case the magnetic particles embedded in both ends are aligned in the same direction. Once a continuously rotating magnetic field along a rotation axis parallel to the horizontal plane is applied, a magnetic torque causes the robot to rotate about the same axis (Fig. 5). Depending on the particles alignment, two different tumbling motions are observed: lengthwise tumble (LT) or sideways tumble (ST). Interestingly, such μTUMs were able to traverse complex terrains (i.e. knurled, cylindrical bump, honeycomb) and climb incline surfaces in dry conditions, where increased attractive forces represent a challenge for the microrobots motion when compared to wet environments.

**C. Micro Force Sensing Magnetic Microrobot (μFSMM)**

Further than addressing the substantial mobility challenge for microscale robots, we also investigated adding a sensing module to our wireless mobile microrobots. The full potential of mobile microrobots can only be realized through the addition of on-board sensing and closed-loop control. Towards this end, we have incorporated a vision-based micro-force sensor into a magnetic microrobot. The resulting micro-force sensing mobile microrobot (μFSMM) is believed to be the first submillimeter scale wireless microrobot with real-time, on-board micro-force sensing capabilities [22], [23], [24], [25], [26], [27], [28]. It has promising applications for performing micro-scale automated biomechanization tasks with real-time force sensing feedback and to apply known μN-level forces to cells/tissue for mechanobiology studies.

The μFSMM microrobot design consists of two function modules (Fig. 6 (a)): the magnetic body part for mobility, and
Fig. 5: Second generation micro-scale tumbling magnetic microrobot \(\mu\text{TUM}\) [21]. The tumbling working mechanism and snapshots of one cycle of tumbling locomotion. (a) The \(\mu\text{TUM}\) consists of a polymeric body with two rectangular shaped ends with integrated and aligned magnetic particles; (b)(c) Depending on the particle alignment, the \(\mu\text{TUM}\) exhibits sideways tumbling (ST) or a lengthwise tumbling (LT) under the presence of a rotational magnetic field. \(\mu\text{TUM}\)s are able to climb inclined rough surfaces (d)) and traverse complex terrains in wet or dry conditions, like the dry knurled terrain in (e).

Fig. 6: Micro-force sensing mobile microrobot \(\mu\text{FSMM}\) [22], [23], [24], [25], [26], [27], [28]. (a) The design schematic and a \(\mu\text{FSMM}\) prototype on a U.S. penny. (b) The evolution of the \(\mu\text{FSMM}\) microrobot designs. The compliant structure for vision based micro-force sensing. Both parts are constructed onto a silicon frame. The magnetic part not only dictates the mobility of the whole microrobot, but it also determines the manipulation force magnitude that the microrobot can exert and sense. According to Hooke’s Law, the acting force can be sensed through visually detected deformation of the micro-force sensor. Thus, the force sensing range and resolution essentially depend on the stiffness of the compliant force sensing structure. Both of the magnetic power and the stiffness of micro-force sensing structure have been theoretically evaluated and experimentally tested.

The fabrication of \(\mu\text{FSMM}\) microrobot had been carried out through multiple microfabrication steps. The compliant micro-force sensing structure was first molded in the silicon wafer and then filled with Polydimethylsiloxane (PDMS) polymer. After curing and planing of the PDMS, the silicon frame was etched out aligned with the micro-force sensing section. The composite structure was then released with a back-side etching process. At last, a chemically etched nickel piece, serving as magnetic body, is individually assembled to the released structure. The total assembly (Fig. 6(a)) performs consistently as our \(\mu\text{FSMM}\) micro-force sensing mobile microrobot.

As shown in Fig. 6 (b), our \(\mu\text{FSMM}\) microrobot has evolved over three generations based on improving microfabrication capacity and image processing techniques. The footprint of \(\mu\text{FSMM}\) has been sized down on the micron-scale and the micro-force sensing resolution has reached low \(\mu\text{N}\) level. The calibrated \(\mu\text{FSMM}\) prototypes can readily detect single digit \(\mu\text{N}\)-level forces with sub \(\mu\text{N}\)-resolution at speeds of 20 Hz when manipulating cell analog micro-objects. The manipulation force is also correlated with ramped system input current. Further with planned motion paths, our \(\mu\text{FSMM}\) microrobot has demonstrated the capability to accomplish automated biomanipulation with a prescribed maximum allowable applied force constraint (Fig. 7).

IV. INDEPENDENTLY CONTROLLABLE MICROSWARMS

One of the biggest limitations of magnetic actuation is its global influence on the workspace which limits the independent control of multiple microrobots. Over the years researchers have proposed different approaches to get around this limitation. Diller et al. [31] proposed to use electrostatic anchoring of a robot while another robot is actuated by the global magnetic field to prevent undesired movement. Another popular approach is to utilize the heterogeneity among different microrobots effected by the same global magnetic field. Frutiger et al. [33] have utilized the non-uniformity of the robots to control them individually with the global magnetic field in a pushing based manipulation operation. DeVon and Bretl [34] have developed a controller for these microrobots with carefully introduced heterogeneity that is able to
move the robots in different speeds to the desired directions with same global input. Wong et al. [35] came up with an individual magnetic field region for the robots where they can be controlled independently. However, their approach suffers from occasional singularity and faces difficulty in fine control of the robot.

The approaches presented above either suffer from undesired coupling or singularities that limits their ability to scale up in terms of the number of microrobots as well as greatly limits the manipulation capability of the robots. Our research is motivated by alleviating the robots from any constraint that might arise from the nature of actuation. We have developed a substrate with an array of embedded microcoils that can be switched on and off independently, actuating the microrobots only in the vicinity of that particular microcoil. Due to the limited influence zone, the microcoil array can be utilized to independently control multiple microrobots independently. Table I shows the evolution of our microcoil array platforms in terms of size and manipulation capability. Our first generation platform consists 64 microcoils arranged in a $8 \times 8$ array. Each coil can generate forces that either push a microrobot outward or pull it inward to the center of the coil. Hence, to provide directionality to the actuation multiple microcoils need to be sequentially activated based on the position of the robot in the workspace. We have developed a heuristic based planning algorithm that not only computes the desired paths for the robots to the respective goal locations but also determines the coils that need to be activated along with the required current and the polarity [29]. We have demonstrated autonomous navigation of two mm-scale robots moving independently towards their respective goal locations with activating the selective number of coils that influence only the motion of the robot in their vicinity (Figure 8).

To reduce the platform and robot size we can independently control we have replaced the microcoil with copper strip in our second generation system ($\mu$m generation 1 on Table I). Each strip can be activated independently with the current. We have demonstrated independent actuation of multiple microrobots less than a milimeter in size with our second generation system [30]. However, due to the
monolithic arrangement of the microstrips, the actuation force is higher in X-direction relative to the Y-direction. Our heuristic planning algorithm models this disparity in actuation force as action uncertainty and computes paths that have higher actuation force in reaching the goals. We have demonstrated independent actuation of two microrobots with our first generation µm system (Figure 9).

Our most recent platform addresses the disparity in actuation force in X and Y directions by introducing another layer of microstrips in an orthogonal direction (µm generation 2 on Table I). With the new array of microstrips we can generate uniform actuation force in both X and Y directions. We can use the same planning algorithm to compute the path as well as determining the current and polarity of the coils to generate desired actuation forces.

V. Conclusion

Microrobots with functional components are needed for accomplishing various manipulation as well as sensing tasks in the microenvironment. Magnetic fields can be used for remote actuation of microrobots. We have demonstrated three different designs of magnetic microrobots capable of navigating in different challenging terrains as well as measuring forces by interacting with the environment. Actuation with global magnetic fields can significantly limit the use of multiple microrobots in the workspace. We have developed microcoil array that can be selectively activated to generate local magnetic field for actuating multiple microrobots independently. Our systems equipped with the heuristic based planning algorithms are capable of moving multiple microrobots to the desired goal locations independently of each other while avoiding obstacles in the workspace. Microrobots with these unique capabilities have use in medical fields, biology, as well as manufacturing industries.

References


