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RESEARCH PAPER

Controlling multiple microrobots: recent progress and future challenges

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Abstract Robots the size of several microns have numerous application in medicine, biology, and manufacturing. However, simultaneous control of multiple robots at this scale is difficult since the robot itself is too small to carry power, sensors, communication, and control on-board. In this paper, we have summarized different approaches, ranging from specialized robot design and fabrication to specialized ways of actuating robots, with the aim of independent control of a team/swarm of microrobots. We have also discussed the challenges for each approach. In the light of the challenges, we have proposed some directions where the future researchers can focus in order to solve the problem of independent control of a team of microrobots.

Keywords Microrobot · Multiple microrobots · Control · Microrobot teams · Microrobot swarms

1 Introduction

Robots with the ability to navigate into spaces at the microscale and below have applications in medicine, biology, and manufacturing. Robots that can navigate into blood vessels inside the human body can revolutionize targeted drug delivery and non-invasive surgery [1]. Automated in vitro manipulation of biological cells with the help of robots will enable various time-sensitive experiments that can lead to important drug discovery [2]. Robots handling microscale parts can be used to realize low-cost microassembly operations [3]. For the realization and efficient operation of the aforementioned tasks, systems need: (1) the robots to be very small in size, and (2) to handle more than one robot autonomously.

This paper focuses on microrobots to perform the tasks above. However, there is no established definition for a microrobot in the literature. Over the years, researchers have used the following metrics to define a microrobot [4]: (1) the overall size (footprint) of the robot is on the micron scale; (2) the size of at least one feature/component of the robot is in the range of microns; (3) the motion of the robot is no longer dominated by inertial forces (e.g., gravitational force dominates the motion of robots down to the millimeter scale whereas surface related forces, i.e., surface tension, drag, viscous forces, Brownian motion, etc. [5], dominate below this scale). In this survey, we will use the first and third definitions for a microrobot where the robot footprint is less than a millimeter and the motions are dictated by microscale interaction forces.

Microrobots have to overcome two interesting challenges: (1) the size restrictions do not allow for on-board actuation, power, and control and (2) due to the unique interaction forces, the conventional actuation principles utilizing the gravitational forces typically do not work. Due to the size limitation, researchers have proposed different ways to power and actuate microrobots. Figure 1a shows a typical macroscale robot team or swarm where a robot body is equipped with all the hardware and software, i.e., power, computation (CPU) for control, sensors, and communication. However, a microrobotic team (fewer robots) or swarm

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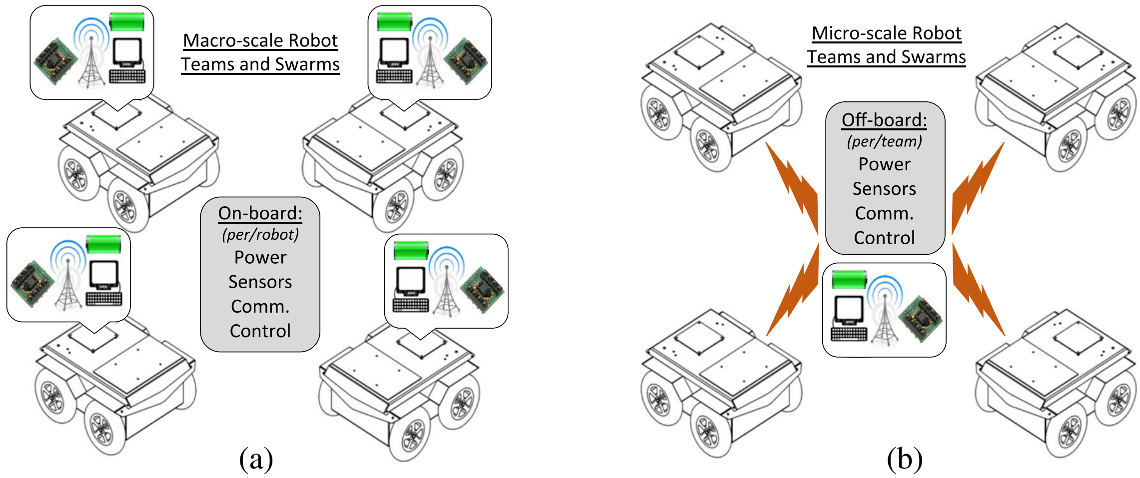


Fig. 1 Robot teams and swarms comparison: Macro-scale robots have on-board power, sensors, communication, and control (**a**). At the micro-scale these systems are typically shared by the entire teams/swarms. This leads to coupled control of micro-scale robots

(many robots) is quite different since a microrobot is typically just a mechanism or a bulk material in the later case. Most of the control and planning of the microrobots are done with off-board computation (Fig. 1b). In terms of actuation, some of them utilize dedicated sources of power and actuation [3, 6, 7] while some other systems rely on off-board global fields for actuation [8–14]. This unique way of actuating and powering microrobots poses a huge challenge in building a microsystem that is capable of controlling a team/swarm of microrobots independently.

Researchers have successfully developed teams and swarms of millimeter scale robots. Seyfried et al. [15] have developed a swarm of milllimeter scale robots each of them equipped with on-board battery pack for power, an insect like walking mechanism for locomotion, ICs for intelligence, and on-board tactile sensing capabilities for manipulation of small objects. Estana et al. [16] developed a swarm of centimeter scale robots with on-board power, communication, and specialized tools to handle biological cells. Rubenstein et al. [17] have a thousand centimeter scale robot (Kilobot) swarm each with onboard power, sensing, and computation capability to study the swarm behavior in nature. Pelrine et al. [18] developed a four layer printed circuit board to generate local magnetic fields for independent control of multiple homogeneous mm-scale robots. Each layer consists of parallel traces of Cu to create a magnetic field in two directions. The current in each trace can be controlled to create a local magnetic field. Thus, the swarm of mm-scale robots can be independently navigated in two dimensions by controlling the local magnetic fields. However, translating this design philosophy to microrobots is very challenging since making the copper tracings (as small as several microns in width) with insulation at multiple layers that will be able to generate enough magnetic forces to drive the robots is not possible with standard printed circuit board (PCB) technology.

Several review and tutorial articles have been published on microrobotics. Abbott et al. [5] were the first one to provide a detailed tutorial article discussing the unique design challenges in developing microrobots. Sitti also provides the manipualtion and mobility challenges of microrobots in [19]. Diller and Sitti [4] have presented a detailed survey on different power and actuation approaches for microrobots.

Many of the survey articles are focused on specific research topics. Sitti [20] has discussed about microrobotic devices that can navigate inside human body. Nelson et al. [21] have delivered a comprehensive survey of medical microrobots that are used for minimally invasive surgery. Martel [22] has compiled the challenges and future directions for nanorobots that are capable of navigating into the vascular networks of human body. Abbott et al. [23] have compared different approaches of propulsion for swimming microrobots actuated by global magnetic fields. Martel [24] provided a survey on nanoparticles used for robotic non-vasive medical procedures using MRI actuation. In another survey article, Martel [25] discussed about the nanorobotic agents used for in-vivo medical drug therapies.

We provide a significantly different perspective from the aforementioned articles by looking at challenges of controlling multiple microrobots independently. This point of view allows us to identify challenges in terms of actuation and control of multiple microrobots that can realize a microsystem capable of performing large number of parallel operations in a cost effective manner. We review the current literature on design, independent actuation, and control of multiple microrobots. Thus, we believe this paper will

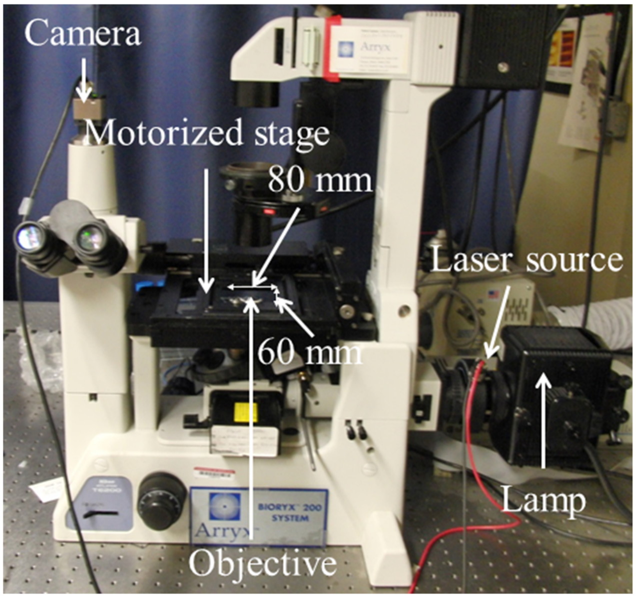


Fig. 2 Multi-microrobot control using optical energy: A high intensity laser beam is focused on the workspace through a high aperture microscope objective to trap a microscale object at the focal point. By moving the laser beam the object can be navigated to a desired location just like a microrobot. A motorized stage is used to change the workspace and camera is used to provide image feedback. The laser beam can be split with the help of a spatial light modulator (SLM) to actuate multiple microrobots.(adapted from [6])

provide important guidelines to future researchers in making microsystems involving multiple microrobotic agents to perform parallel as well as collaborative operations. It will also discuss important challenges that need to be overcome in making such microsystems.

2 Multi-microrobot control using optical energy

High intensity laser beams commonly known as optical tweezers (OT) can be used to trap a particle ranging from 50 nm to 10 μm in size [26]. It is a very common practice among bio-physicists in manipulating biological objects, e.g., cells, DNA, motor proteins [2]. A single beam can be split into multiple beams with the help of scanning mirror or spatial light modulator (SLM) to manipulate multiple of objects simultaneously.

Over the past decade, many roboticists have started to use lasers as an actuator for the microrobots. The overall system consists of a microscope equipped with a CCD camera to get the vision sensing from the workspace, a laser beam controlled with a scanning mirror or SLM and focused through a high-aperture objective lens for the actuation of the robot, and a CPU unit for computing the planning and control feedback (Fig. 2). Various dielectric microspheres or various micro-organisms are regarded as microrobots that are to be manipulated automatically. Banerjee et al. [27] have developed a decision theoretic based planning approach for automatic navigation of silica microspheres actuated by optical tweezers. The authors have demonstrated successful navigation of three microspheres with 2 μm diameters to their respective goal locations in an environment with multiple obstacles. Chowdhury et al. [28] used yeast cells as microrobots by actuating them using optical tweezers. They have developed graph search based algorithms for automated manipulation of multiple yeast cells independently towards their respective goal locations in the presence of external fluid force field inside a microfluidic chamber. The yeast microrobots are capable of avoiding obstacles randomly moving in the workspace during the course of navigation. A number of planning and control approaches to realize automated cell manipulation using optical tweezers have also been developed by [29–31].

However, a high intensity laser is detrimental for cell viability. To protect the cells during manipulation Chowdhury et al. [32] have utilized a single laser beam to be split into multiple to actuate multiple silica microspheres to cooperatively manipulate a single yeast cell. This indirect manipulation prevents the cell from the direct high intensity laser exposure. Similarly, Cheah et al. [33] used multiple laser beams to manipulate a yeast cell indirectly with optically trapped silica microspheres. Arai et al. [34, 35] have developed microtools that can be controlled by OT to manipulate biological objects with minimum laser irradiation.

While optical tweezers allow independent actuation of multiple microrobots (as many as 200), it suffers from a number of limitations: (1) the optical force generated is very low (typically on the order of piconewtons although higher forces can be generated in controlled environments [36]) which limits the size of the microrobot (maximum of 10 μm) that can be actuated; (2) the need to focus the laser with a high aperture objective lens limits the size of workspace to approximately 100 μm $\times$ 100 μm; and (3) the use of laser beam as an actuator limits its use typically to in vitro manipulation on a transparent substrate or in vivo manipulation on a specimen only few microns above the objective lens [37].

Hu et al.[38] utilized optically induced thermocapillary forces to manipulate gas bubbles automatically. The system consists of a laser source along with a computer projector, an objective lens to focus the laser beam, an optically absorbent substrate to convert light into thermal gradients, and gas bubbles as microrobots. By controlling the laser beam focusing on a light absorbent substrate, a thermal gradient is generated which results in fluid flow from the hot side to the cold side of the bubble. The bubble is transported in the desired direction with the fluid flow that can be controlled by controlling the laser focus. Multiple bubbles can

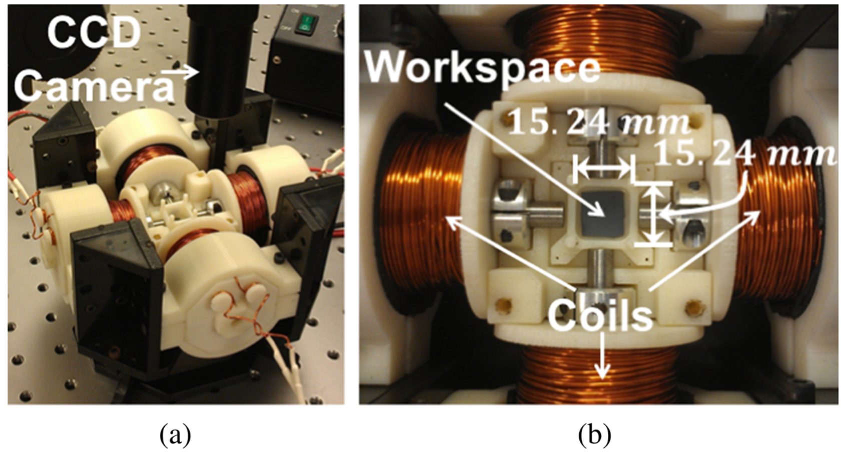


Fig. 3 Multi-microrobot control using external magnetic fields. This is typically done by surrounding the workspace with a coil system: **a** Full view of system with four coils distributed in the plane equipped with an overhead CCD camera; **b** Close-up view of the workspace. (adapted from [40])

be independently controlled by projecting multiple light patterns on the substrate. Bubble microrobots can be utilized to perform microassembly by pushing multiple objects in a pattern. The authors have demonstrated independent control of three bubble microrobots to realize parallel manipulation [39]. However, these bubble microrobots also suffer from limited manipulation force capabilities, thus restricting their applications.

3 Multi-microrobot control using magnetic fields

A magnetic field is a popular actuation method for microrobots due to its high actuation force, compact system size, and low hardware cost (Fig. 3). The microrobots are either made of permanent magnetic, ferromagnetic, or paramagnetic material. Any magnetized robot will experience a torque and a force due to the electromagnetic field that can be controlled as follows:

$$\mathbf{F}_m = V_r(\mathbf{M} \cdot \nabla)\mathbf{B}(x, y, z) \tag{1}$$

$$\mathbf{T}_m = V_r\mathbf{M} \times \mathbf{B}(x, y, z) \tag{2}$$

Where $\mathbf{F}_m$ and $\mathbf{T}_m$ are the force and torque experienced by the robot, V_r is the the volume of the robot, $\mathbf{M}$ is the magnetization of the robot, and $\mathbf{B}$ is the magnetic potential produced by the electromagnetic field. By controlling the magnetic field, the dynamics of the microrobot can be controlled to realize autonomous navigation.

Khalil et al. [41, 42] developed a closed loop control approach to navigate a cluster of micropartilces (100 μm in diameter) with magnetic fields to manipulate another object by pushing it into a desired slot. While the system is able to manipulate multiple objects, individual control of microparticles cannot be achieved due to the global effect of the magnetic field.

Sylvain et al. [43] have developed a nanorobotic platform for in-vivo navigation of untethered devices to a target region in the blood vessel that are too narrow to be reached by catheterization. The platform is based on a Magnetic Resonance Imaging (MRI) system that is an essential instrument for medical diagnosis [44]. The three imaging gradient coils of the MRI system is utilized to provide actuation force for the ferromagnetic microrobots [45]. In some cases, It is very difficult to navigate nanometer scale robots as a group to precisely reach a particular region with magnetic gradients generated by a MRI instrument. The researches proposed three additional special gradient coils that can be installed along with the existing gradient coils to provide enough actuation to reach to the target region. Although this system is capable of navigating a swarm of magnetic carriers towards a region inside a body, it cannot provide individual control to the microrobots. MRI has been embraced by different research groups as an actuation method to provide targeted drug delivery and noninvasive therapy. A survey on MRI guided nanorobotics can be found in [46].

Researchers have long been trying to control multiple microrobots independently using global magnetic fields. Pawashe et al. [47] have developed a magnetic actuation system which consists of six orthogonal magnetic coils. The magnetic field in each coil can be precisely controlled by controlling the amount of current and the corresponding polarity. The work-space is located at the intersection of the axes of all the coils. The microrobots in the workspace respond to the magnetic force generated by the magnetic coils and navigate towards the direction of resultant force. In a separate work [48] they developed a surface with electrostatic pads that can be selectively activated to control multiple microrobots with the influence of a global magnetic field. The motion of a microrobot under the influence of a global field can be selectively stalled by activating the electrostatic pad underneath it. The authors have demonstrated independent control of two microrobots with the hybrid actuation with magnetic coils and the electrostatic surfaces. However, the motions of the microrobots are somewhat coupled since they cannot be navigated in arbitrary directions. The independent motions are mostly dominated by the arrangement of the electrostatic pads. Diller et al. [49] introduced heterogeneity in the microrobots so that they can respond differently to the same magnetic field. By utilizing their heterogeneity the authors independently navigated three microrobots to their respective goal locations.

Frutiger et al. [50] took a similar approach where the authors relied on the design non-uniformity between microrobots for independent control of the microrobot. Each "Magmite" microrobot has a compliant mechanism that can be oscillated by providing an oscillating magnetic field. By introducing non-uniformity in their design, multiple microrobots can have a different resonance frequency resulting in a variation in their motions. The direction of their motions can be altered by providing a rotating magnetic field. The authors have demonstrated limited independent control of two microrobots with a single global input. DeVon and Bretl [51] have developed a controller that is capable of moving multiple heterogenous Magmites towards a specific direction with different speeds.

Cheang et al. [52] developed a team of microswimmers made of magnetic microparticles that are geometrically similar but magnetically different so that they exhibit different swimming behaviors to the same global rotating magnetic field. By utilizing the difference in swimming behaviors the authors have controlled the team of swimmers independently with a single control input to achieve effective drug delivery.

However, dependence on heterogeneity of the microrobot or a selective surface limit the motion of the microrobots to simple trajectories as well as the scalability of the system. The microrobots cannot exhibit complex motion, i.e. cooperative motion or obstacle avoidance.

Wong et al. [53] have analyzed the spatial representation of magnetic fields generated by magnetic coils and the interaction among the magnets to define a region where multiple homogeneous microrobots can be controlled independently. Although the model does not allow navigation of the microrobots to the arbitrary locations independently due to the global effect of the magnetic fields, it allows independent control of the microrobots in some specific regions in the workspace.

Lee et al. [54] fabricated a microelectromagnetic matrix by arranging two layers of equally spaced current carrying conductors. Each layer is separated from each other by an insulator layer and the conductors in each layer are arranged orthogonal to that of other layer. When current is applied to two conductors in two layers, there is spike in magnetic field at the point where they cross each other. The point of intersection is utilized as a sink for controlling the magnetic microrobot. The authors have demonstrated independent control of two groups of microparticles by actively controlling the spike locations in the microelectromagnetic matrix.

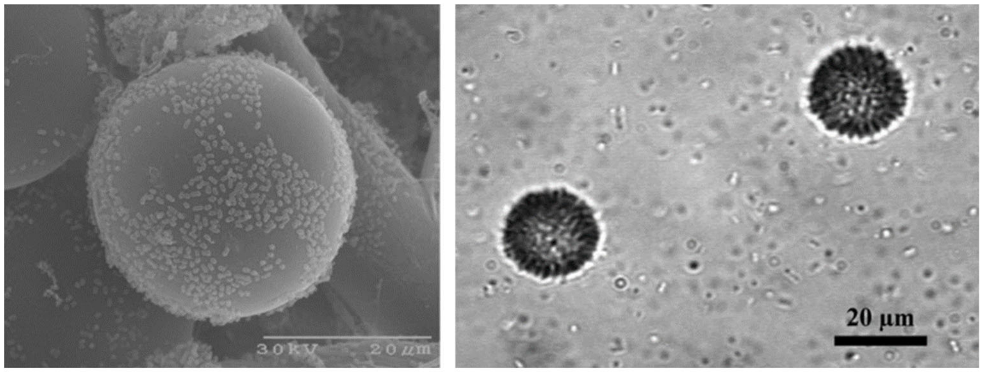
Cappelleri et al. [3] have developed a special substrate with an array of planar microcoils to generate local magnetic fields for independent actuation of multiple microrobots. The microrobots are placed on the substrate and actuated by controlling the local magnetic field generated by respective microcoils. Chowdhury et al. [40] has developed a planning and control approach for independent navigation of multiple microrobots by utilizing the local magnetic fields generated by planar microcoils. Lee et al. [55] developed a hybrid system by integrating a microfluidic device with planar microcoils for independent control of magnetically tagged cells. Rida et al. [56] have developed a hybrid system with permanent magnets for providing a static magnetic field and a planar coil array to provide a magnetic gradient to manipulate magnetic microparticles over a long distance. Lehman et al. [57] utilized a similar system for two dimensional magnetic manipulation of aqueous droplets.

4 Multi-microrobot control using physiological energy

The physiological energy of the living organisms can be utilized to actuate a system by controlling their movement. The overall systems consists of living organisms that can be naturally produced or artificially modified, a guiding system that can be either magnetotactic, phototactic, or chemotactic to control their motion, and a microscope equipped with a CCD camera to obtain the visual feedback (Fig. 4). The main difference between the physiological systems and the yeast microrobots mentioned in Section 2 is that the yeast microrobots are immobilized and dragged by the laser beam in the later while the motion of the living organism is utilized in the former.

The motility of a swarm of flagellated bacteria named *Serratia marcescens* have been utilized by Kim et al. [58] to turn them into a propulsion system to manipulate microspheres. A swarm of bacteria is attached to each microsphere. The authors have designed a microfluidic device that can provide a selective chemical gradient to the swarm of bacteria. The natural behavior of the swarm of bacteria to follow a chemical gradient is utilized to control the propulsion of the bead.

Steager et al. [59] also utilized the motility of a *S.marcescens* swarm to develop a micro-bio-robot. An engineered structure is coated with bacteria cells. The movement of the structure can be controlled by the motility of the bacteria cells in a fluidic medium. The rotational movement



(a) (b)

Fig. 4 Multi-microrobot control using physiological energy. A microobject is typically coated with flagellated bacteria. The movement of the bacteria can be controlled by external signals. The signals can be created either by artificial magnetic, chemical, or optical gradients. The microobject can be actuated towards the desired direction by utilizing the motility of the microorganism: **a** Scanning electron microscope (SEM) image of 30 μm diameter beads with attached bacteria (appearing as dots on the smooth surface of the bead) **b** Microscopic image (40X magnification) of 20 μm diameter beads suspended in motility medium (black spots on the bead surface are motile bacteria). (adapted from [58])

of the structure is controlled by the ultraviolet light while the translational motion is controlled by electric field. Similarly, Behkam and Sitti [60] have actuated a silica microsphere with the attached $S. marcescens$ swarms. They have developed a chemical induced on/off control for the movement of the microsphere. The motility of the bacteria population can be stopped by introducing copper ions into the solution and can be resumed back by introducing ethylenediaminetetraacetic acid. Martel et al. [61] have steered a micro-scale sized swarm of magnetotactic bacteria (MRB) towards a remote location inside blood vessels to demonstrate targeted drug delivery operation utilizing the magnetic forces generated by the gradient coils of MRI.

The guiding system mentioned above cannot address individual cell separately. Hence, the swarm of bacteria moves in a certain direction based on the artificial signals. Kim et al. [62] utilized the motility of a eukaryotic cell $Tetrahymena\ pyri\text{-}formis$ to turn it into a microrobotic system. $T. pyriformis$ cells are artificially treated with ferromagnetic nanoparticles to impart magnetism. Cells align themselves towards the direction of an applied magnetic field. In the absence of a magnetic field the cells move randomly. Therefore, the movement of the cells can be controlled by simply switching on and off the magnetic coils.

De et al. [63] utilized a magnetic field generated by three orthogonal pairs of electromagnetic coils to control the movement of a swarm of magnetotactic bacteria (MTB). By controlling the global magnetic field, the aggregation of magnetotactic bacteria can be controlled. While the swarm of MTB were controlled by aggregating them at a desired location, the individual control of each MTB could not be achieved.

Becker et al. [64, 65] have investigated the independent control of multiple $T. pyriformis$ cells using a global magnetic field by utilizing the non-uniformity of magnetic materials consumed by each cells. The time taken for a cell to align itself towards the direction of a magnetic field depends on the amount of magnetic materials consumed in the body. By utilizing the heterogeneity among the cells in terms of magnetic materials, the authors developed a feedback controller [64, 65] that can enable individual control of multiple $T. pyriformis$. However, the cells cannot exhibit complex motion, e.g. obstacle avoidance, shortest path, etc., since they rely on a single global input.

5 Other types of control schemes for microrobots

Donald et al. [66] developed a microrobot that is driven by capacitance generated by an array of electrodes and the microrobot itself. The microrobot consists of a scratch drive actuator for linear motion and an arm for steering. By changing the amount of voltage in the electrodes the scratch drive actuator can be stressed and relaxed to provide a forward thrust. On the other hand, by controlling the voltage, the steering arm can be moved up and down relative to the electrodes which can provide the desired rotating torque. By combining these two motions the microrobot can be navigated to a goal location on the substrate. By varying the lengths of the steering arm multiple microrobots can be designed such that each of them responds differently to the same global voltage input. The authors have exploited their differences to develop a controller that can enable simultaneous control of multiple microrobots. The

Table 1 Comparison of different independent microrobot control approaches

Approach	Max. number of robots	Size (μm)	Pros	Cons	Typical force	References
Optical force	6	2–10	Independent, Highly precise	Small workspace, small force	pN[a]	[27–33, 38, 39]
Global magnetic	3	150–500	Large force, simple design	Coupled, Not suitable for large numbers of robots	nN to μN[b]	[48–51, 53]
Specialized substrate	64	150–250[c]	Independent, large force	Complex fabrication, limited workspace	nN to μN	[3, 40, 54–57]
Physiological energy + global field	6	few nm to several μm	Suitable for biological applications	Coupled, slow	pN[d]	[58, 59, 62–65]

[a]In specialized condition optical force in the range of nN can be generated [36]

[b]It depends on the volume of the robot, magnetic filed generated by the electromagnetic coils, and the distance of the robot from the coil

[c]This can be the size of an aggregate of nanoparticles

[d]Here we only report force due to physiological energy

authors developed a global control input that makes all the other microrobots move in a limit cycle while a target microrobot moves to a goal location to avoid their interaction. The authors have demonstrated simultaneous control of three such microrobots to enable a microassembly operation [66].

Helical swimmers [67] under the influence of weak rotating magnetic field demonstrate effective locomotion fluid environment at low Reynolds number. Ghosh and Fischer [68] developed a process to fabricate micron size helical structures in large number that can be controlled by rotating magnetic field. Zhang et al. [69] also designed a helical swimmer that mimic the motion characteristics of bacterial flagella. Sakar et al. [70] developed helical microswimming microrobots that can be actuated to a forward direction by rotating magnetic field. The rotating magnetic field induces a rotation on the helical structures resulting in a forward thrust to the microrobot. By changing the thickness of ferromagnetic material the swimming characteristics can be changed in multiple microrobots. By varying the rotational frequency of the magnetic field multiple microrobots can be independently addressed. The authors independently control two microrobots to manipulate a microbar to the desired position and orientation.

Li et al. [71] developed a nanorobot that can be actuated by either magnetic or acoustic fields. The nanorobot has a helical structure with a Nickel coating with a concave nanorod feature. The Nickel coating provides propulsion with a rotating magnetic field and the nanorod feature responds to the acoustic field. The authors have demonstrated a number of biomimetic collective behaviors with a swarm of nanorobots by applying a combination of magnetic and acoustic fields. While the actuation system enables collective behavior of multiple nanorobots, individual control of nanorobots cannot be achieved with the global actuation fields.

6 Discussion and challenges

6.1 Trends

In the above sections we have summarized different approaches that are aimed to control multiple microrobots independently. We have focused on four different aspects: (1) source of actuation and power; (2) maximum number of the microrobots that can be handled independently; (3) minimum size of the microrobot; and (4) the potential of the approach to handle large number of microrobots. We have discussed the different approaches in details in previous sections and they are summarized in Table 1.

We have seen four major approaches in terms of power actuation. While microrobots can be independently controlled with optical forces, the actuation force is really small. Even the very high intensity laser can only generate a force as weak as 10 pN. Thus, it can only actuate very small microrobots (2–10 μm). Another big disadvantage of optical actuation is the workspace. The workspace is not more than 100 μm $\times$ 100 μm. Hence, it cannot be utilized for independent control of large number of microrobots and its application is limited to only biological cell manipulation.

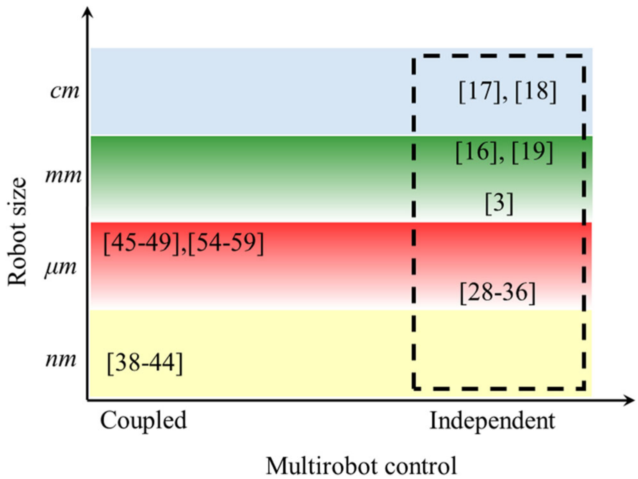


Fig. 5 Summary of multi-microrobot control approaches

Global magnetic fields have been a popular actuation approach for microrobots of size 150 to 250 μm. Due to the global field, independent actuation of multiple identical microrobots is very difficult. Various groups have achieved independent control by introducing heterogeneity in the microrobots so that they can respond differently to the same control input. Because of the coupled nature of the actuation, it is not suitable for truely independent control of large numbers of microrobots.

A specialized substrate is a very promising approach. A small number of research groups have developed magnetic coils on specialized substrates that can create localized fields to address individual microrobots. Using specialized substrates large number of microrobots can be actuated independently. However, their applications are limited to workspaces that the substrate can reside.

Actuating microrobots with the motility of a living organism is a new approach but the independent control of microorganisms is very difficult. There have been several approaches ranging from optical to magnetic fields to control the motility of the organisms which can be utilized to control the microrobots. These hybrid approaches also suffer from coupling where the heterogeneity among multiple organisms are utilized to control them independently with a single global input.

6.2 Future directions

To summarize the future directions we have looked into difficulties of the current approaches. We have divided all the approaches into two categories: Independent control and coupled control (Fig. 5). Coupled control utilizes the heterogeneity among the microrobots for simultaneous actuation with a global input. Because of the coupling they are not suitable for individually controlling large number of microrobots. We have further classified the independent control approaches (dotted box in Fig. 5) in terms of the number of robots the individual system can handle in Fig. 6. In both the cases, we have used the biggest dimension to define the size of the robot. We can clearly see the absence of independent control at the nano and micro scales. The optical force based independent control approaches in [27–33, 38, 39] can handle at most six robots. The workspace is too small to move more robots than this effectively. The figure suggests that there is a large research gaps, particularly at two size scales for independent control of large number of robots: the 150–500 μm size range and the 10–800 nm size range (dotted rectangle in Fig. 6). The applications of robots of nm size scales are currently limited to targeted drug deliveries where the goal is to navigate thousands of microrobots to a particular location inside human body [24]. Hence, independent control of each robot is not very important for this application. However, the ability to control each robot independently will allow us to focus on multiple locations inside human body simultaneously.

Unfortunately, there has not been a single approach that can address the problem of independent control of a large team or swarm of microrobots which is essential to realize future microsystems that can be useful in widespread areas ranging from manufacturing to in-vivo drug delivery (Fig. 6). A more systematic approach to design, fabricate, and control is necessary to realize such a team of microrobots that are capable of performing the assigned tasks independently and/or in parallel. Hence, we believe that there are many promising areas of future research. We list them and briefly discuss how they may help in addressing the current challenges.

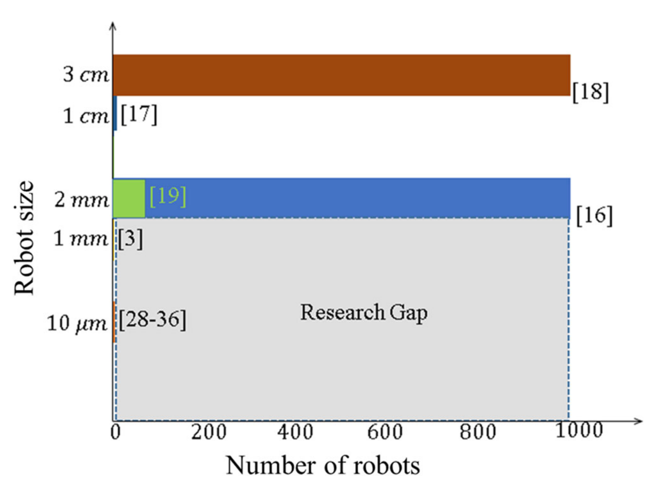


Fig. 6 Maximum number of robots that can be controlled independently

6.2.1 New fabrication approaches for specialized substrates

Specialized substrates have been demonstrated as a promising technology to address each microrobot independently. It has been done so by Pelrine et al. [18] and Cappelleri et al. [3] on mm scale robots. The fabricated magnetic tracings on specialized substrates generate the localized magnetic field that is used to drive the robot independently from the others in the workspace. The region of independent control depends on the resolution of the tracings. Fabricating these tracings with fine resolution at microscale is challenging. Vitoroulis and Cappelleri [72] have proposed a fabrication process to develop such a specialized substrate. However, more research is needed to develop and realize an optimized fabrication process that will increase the success rate.

6.2.2 Hybrid actuation with global and local fields

Instead of actuating the microrobots with a single global field, they can be actuated by a hybrid of global and local fields. This is very common in small scale biological cell manipulation stations [73]. A hybrid system can be comprised of a global strong force field (i.e. magnetic field) to navigate microrobots to a target zone and a local field (specialized substrate, optical force, etc.) for precise navigation and positioning of the microrobots inside the target zone. We believe that a hybrid system will increase the speed of microscale operations in large workspaces.

6.2.3 Development of specialized microrobots

To perform a cooperative assembly task, each microrobot will be assigned an individual task or role. Hence, each microrobot can be designed with specialized tools (e.g., grippers, pushers, etc.) depending on their role. In some cases, the microrobot has to be able to actively measure some data. For example, in a microassembly task, in case of handling delicate objects, the microrobot has to be careful about applying the amount of force. Going beyond the recommended force limit that the object can handle will result in unsuccessful assembly and/or damage to the object being manipulated. Microrobots with in-situ sensing technology will be well-equipped to perform this task [74–76].

6.2.4 Developing control algorithms for large number of microrobots

Developing control algorithms for a large number of microrobots where each microrobot is assigned to complete a certain tasks is a necessary step to realize an automated microfactory. There has been a number of control algorithms that can deal with multi-agent microrobot systems [77]. However, a good model of the microrobot motion is necessary to develop a good control algorithm. The motion of a microrobot depends on a number of microscale forces, e.g., surface tension, surface friction, viscous forces, etc. Accurate estimation of the forces is very challenging. Developing a systematic approach to estimate those forces will enable precise modeling for motion characteristics of the microrobots. This, in turn, will lead to reliable simulations of microrobot behavior and allow for accurate motion planning and control algorithms to be developed.

7 Conclusions

In this survey article, we have provided a comprehensive summary of microrobotic systems where multiple microrobots are actuated simultaneously. In this paper, we have focused on microrobots that are too small to carry dedicated power, sensors, communication, and control units. Hence, all the microrobots in a team or swarm have to share these units which make them difficult to control independently. We have observed two common approaches to solve the problem of independent control of a team of robots: (1) introducing heterogeneity in the microrobot design: each robot in the team is made different from each other, hence, they respond differently when exposed to the same global input signal, and (2) developing local actuation to the robot: local fields are generated with the help of a specialized substrate. Each robot in the team can be controlled independently in the vicinity of the local field.

We have provided an in-depth summary of both of these technologies. We have also identified the future challenges in both the technologies in the light of controlling a team or swarm of robots. Apart from the challenges regarding the robot fabrication and actuation, there is a challenge from the control perspective as well. The control of a team of robots is slightly different from swarm intelligence or the aggregate behavior of a swarm. In a swarm, each robot does not need to be intelligent, rather the intelligent behavior emerges from the group. On the other hand, in the smaller teams each robot has to perform a specialized task. Hence, each robot has to be intelligent and needs to be controlled independently. In some cases, we can break the swarm up into a team of smaller swarms, with each swarm having it's specialized role. This will pose an interesting challenge on both computation and synchronization. In the light of these challenges, we have provided a list of future research directions that might help the researchers in solving the problem of independent control of multiple microrobots.

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