Pros and Cons: Magnetic versus Optical Microrobots

Metin Sitti* and Diederik S. Wiersma*

Mobile microrobotics has emerged as a new robotics field within the last decade to create untethered tiny robots that can access and operate in unprecedented, dangerous, or hard-to-reach small spaces noninvasively toward disruptive medical, biotechnology, desktop manufacturing, environmental remediation, and other potential applications. Magnetic and optical actuation methods are the most widely used actuation methods in mobile microrobotics currently, in addition to acoustic and biological (cell-driven) actuation approaches. The pros and cons of these actuation methods are reported here, depending on the given context. They can both enable long-range, fast, and precise actuation of single or a large number of microrobots in diverse environments. Magnetic actuation has unique potential for medical applications of microrobots inside nontransparent tissues at high penetration depths, while optical actuation is suitable for more biotechnology, lab-/organ-on-a-chip, and desktop manufacturing types of applications with much less surface penetration depth requirements or with transparent environments. Combining both methods in new robot designs can have a strong potential of combining the pros of both methods. There is still much progress needed in both actuation methods to realize the potential disruptive applications of mobile microrobots in real-world conditions.

1. Introduction

Mobile microrobotics has emerged as a new robotics field within the last decade to create untethered tiny robots that can access and operate in unprecedented, dangerous or hard-to-reach small spaces noninvasively toward disruptive medical, biotechnology, desktop manufacturing, environmental remediation, and other potential applications.[1–7] Such field has many scientific challenges related to miniaturization limitations on on-board actuation, powering, sensing, communication, computing, and application-specific functions. For resolving such challenges, two main approaches have been proposed in the literature so far: external-physical-force-driven and self-propelled (using self-generated gradients or moving parts and deformation) microrobots. Both strategies typically require an external source of energy since it is very challenging to create tiny robots with internal energy storage at the micrometer scale. Typical approaches involve external magnetic, optical, acoustic, and electrical fields, or a combination of these, but in principle also the local chemical environment (e.g., a sugar solution) could be utilized in the future as an energy source. Among these current approaches, energy delivery via magnetic and optical fields are currently the most widely used in microrobotics. Although acoustic fields and biological (cell-driven biohybrid robot designs) actuation methods are also very promising and widely used microrobot actuation approaches, this pros and cons article will focus on the magnetic and optical field-based actuation methods only.

Magnetic and optical fields typically enable long-range, dexterous, precise, fast, and robust actuation and control of microrobots. An important point to consider is how (and if) tiny robots can take autonomous decisions for their actions. In the more traditional approach, the robots are controlled externally by humans or computers, typically via one of the external fields listed above. An interesting possibility is that of developing untethered tiny robots that can make decisions autonomously[8] based on their local environment or on the behavior of their neighboring robots.[9,10]

In magnetically driven microrobotic systems as illustrated in Figure 1, an external permanent magnet or electromagnetic coil system exerts pulling magnetic forces or rotating magnetic torques on a magnetic microrobot body. Externally applied magnetic fields \( \mathbf{B} \) induce a magnetic steering/rotation torque \( \tau_m \) and spatial magnetic field gradients \( \mathbf{V} \mathbf{B} \) induce a pulling magnetic force \( \mathbf{F}_m \) as described below:

\[
\tau_m = V (\mathbf{M} \times \mathbf{B}) \quad (1a)
\]
\[
\mathbf{F}_m = V (\mathbf{M} \cdot \mathbf{V}) \mathbf{B} \quad (1b)
\]

where \( \mathbf{M} \) is the magnetization vector and \( V \) is the volume of the magnetic part of the robot body. Moreover, multiple electromagnetic coils or multiple permanent magnets can be used to

 DOI: 10.1002/adma.201906766
create nonuniform magnetic fields to induce magnetic pulling forces.

In optically driven microrobotic systems, the propulsion mechanism is different and typically based on the movement or deformation of body parts. For instance, a typical design can involve moving legs that make the robot walk autonomously\(^{[11]}\) or body deformations\(^{[12]}\) used for swimming\(^{[12]}\) or providing inchworm-type locomotion.\(^{[13]}\) This is made possible by using shape-changing materials (typically polymers) that are sensitive to light. The most used is liquid-crystalline elastomers—crosslinked polymer networks that can deform upon illumination by light. Two main mechanisms exist for creating deformation for such polymer networks. The first one is based on a configurational shape change of part of the molecule (e.g., an azobenzene group) upon light absorption, which disturbs the order of the liquid-crystal network.\(^{[14]}\) The second one makes use of an intermediate heating step where light is absorbed and a shape change occurs through local heating.\(^{[15]}\)

Both optical and magnetic microrobots can achieve various solid surface, underwater, and air-water interface locomotion modes, such as crawling, rolling, swimming, and jumping, to navigate in diverse environments to achieve their desired tasks. Here we will confront these two approaches.

2. Pros and Cons Discussion

Below, we discuss the pros and cons of these two most widely used external actuation and control methods in microrobotics.

2.1. Materials

2.1.1. Typical Materials

In magnetic microrobotics, the microrobot body can be made of hard or soft magnetic materials. The most common magnetic materials are hard NdFeB microparticles\(^{[16-24]}\) superparamagnetic iron oxide nanoparticles (SPIONs)\(^{[25-29]}\), CrO\(_2\) powder\(^{[30]}\), FePt nanoparticles, and other hard or soft magnetic micro/nanoscale particles, molecules, discs, or wires embedded inside or absorbed onto the surface of the robot body. Moreover, nickel, cobalt, and other magnetic materials can also sputtered on the robot outer surface as a nanofilm coating. From the magnetic actuation perspective, magnetization property \(\mathbf{M}\) and volume \(V\) of these magnetic materials are the most important design parameters, where the materials with the highest magnetization value and largest volume would exert the highest magnetic forces and torques on the robot body.

The shape-change materials used for optical microrobots are based on light-responsive polymers, biological materials, or a combination of these two.\(^{[10,12]}\) Liquid-crystalline elastomers are smart materials that combine the entropic elasticity of elastomers with the ability of self-organization into liquid-crystal phases.\(^{[11]}\) Their deformation is anisotropic and can be very large (up to a factor of 2–3) upon illumination with light. Also, the forces involved are huge compared to those, for instance, of optical tweezers. An alternative to liquid-crystal elastomers is the use of hydrogels. Hydrogels are hydrophilic polymers capable of holding large amounts of water in the interspatial spaces of their 3D network. Upon illumination their volume shrinks by expelling water, which is useful for isotropic actuation, but limited to liquid environments.\(^{[34]}\) The mechanism is similar to that of plants where the amount of water in cells and tissue is varied to invoke bending or twisting. The recent development of biohybrid materials involves the integration of synthetic polymers and other materials with alive phototactic bacteria, algae, or muscle cells.\(^{[35-37]}\) Chemical engineering is essential for optical robotics, and important design parameters include spectral response, sensitivity and response time. A wealth of different types of polymers are either available and can be custom made, to reflect requirements in elasticity, strength, and spectral response of individual parts of the robot.

At the moment, most of the activity on optical microrobots focuses on shape changing liquid-crystalline polymers, which can be divided in two main categories, namely liquid-crystalline elastomers (LCEs), which have a glass transition temperature, \(T_g\), lower than room temperature and a Young’s modulus on the order of MPa or lower) or liquid-crystal networks (LCNs), which exhibit a higher \(T_g\) and elastic modulus.\(^{[38]}\) LCEs typically exhibit a larger deformation but their backbone is quite soft, which means they produce small forces under actuation.
LCNs, on the other hand, produce stronger forces that can be of the order of hundreds of mN mm\(^{-2}\).[39] The liquid-crystalline order at room temperature (typically resulting in a highly anisotropic medium) is lost upon heating resulting in a controlled and fully reversible shape change. In addition to this photothermal form of actuation, there exists the possibility of creating materials that have a photochemical response by adding covalently bonded mesogens or crosslinkers that change their physical configuration upon absorption of a photon at a specific wavelength and reverse back by absorbing a photon of a slightly different wavelength.[40] Most photochemical materials also respond thermally but not vice versa.[41]

**Pros and Cons Comparison:** Optical materials can be typically much softer (elastic modulus on the order of 10\(^4\)–10\(^9\) Pa) and are more similar to biological tissues so that they can be used to mimic the natural environment for cell growth and muscle functionality.[42] Next, it is much easier to make optical materials biocompatible, where they do not typically need any additional micro/nanomaterials embedded inside or coated outside that are not easy to make biocompatible while having high performance actuation. Moreover, such micro/nanomaterial additives or coatings also make magnetic materials denser than optical materials, which makes it more challenging to create and control neutrally buoyant magnetic microswimmers in 3D immersed fluids.

### 2.1.2. Ease and Scalability of Fabrication

Magnetic microrobots are typically fabricated by molding[22,43–46] magnetic micro/nanoparticle–polymer composites into 2D or 3D templates that are fabricated by optical lithography and two-photon polymerization techniques, laser micromachining-based cutting of magnetic sheets,[47–50] and two-photon polymerization-based direct 3D printing (additive micromanufacturing) in the case of SPION-based photocurable polymer composite materials.[26,27,29,51] In the direct 3D-printing method, there is a maximum nanoparticle density limit to not interfere with the two-photon polymerization process,[29] which limits the maximum volume of the magnetic material of such magnetic robots. Similar volume limit exists for thin-film magnetic materials due to limited thickness sputtering. Such volume limit constrains the maximum exerted magnetic actuation forces and torques. On the other hand, if the magnetic material volume is too high, the robot would be much heavier and sediment quickly, which would make the vertical gravity compensation of the robot more challenging in 3D fluidic environments. Moreover, after or while fabricating the magnetic robot body, strong hard magnetic materials need to be magnetized under high magnetic fields (e.g., 1–1.5 T) in most cases using a vibrating-sample magnetometer (VSM) or a custom permanent magnet system. Finally, assembling pre-magnetized tiny cubic or other-shaped micro-modules[21,52] in 2D or 3D could give the most advanced, heterogeneous, and complex magnetic micro-robots, which needs an automated or teleoperated specialized robotic assembly system.

3D printing with very high resolution (down to 100 nm) exists for polymers in general,[53,54] and has been developed recently also for liquid-crystal elastomers.[55,56] A pulsed laser is scanned through a mixture containing monomers, crosslinkers, catalysts, dyes, and other building blocks, which polymerize point by point into the desired 3D structure. This allows for a
large freedom of design, both regarding the structure and the combination of materials. In the case of liquid-crystalline polymers, special attention has to be dedicated to the alignment of the molecules, since this determines the direction in which actuation takes place. By local control over the alignment during fabrication, one can use this effect to program the type of actuation (e.g., bending, contraction, expansion, torsion). While 3D printing offers high-resolution arbitrary designs at the microscale, the production is relatively slow and limited to individual prototypes. Serial manufacturing can be implemented, for instance, using photolithography and soft lithography, but in that case the design has to be relatively simple. A continuous roll-to-roll printing technology could also be envisioned for simple designs fabricated in large numbers, using a mask to stamp out the polymer structures in the future.

Pros and Cons Comparison: Optical microrobot fabrication processes could be more facile and scalable than the magnetic ones, where an extra postfabrication magnetization, film coating or assembly step could be needed in most cases for magnetic robot fabrication. Micromolding is the most facile and scalable fabrication method for the composite magnetic materials-based robot fabrication, while magnetization step is still needed after molding typically, and molding is not a continuous and fast production method. However, optical robots can be fabricated in more diverse ways in a facile and scalable manner. Programming the shape-changing behavior of LCN microrobots is obtained by choosing the liquid-crystal alignment inside the structures without the need of any postfabrication treatments.

2.1.3. Compatibility with Biological Environments (Biocompatibility)

Compatibility of microrobots to their operation environment is essential for a given specific application. As one of the main challenges in this requirement for medical applications, microrobot materials must be biocompatible to use them inside the human body for short or long durations. Moreover, biodegradability would be an important another material requirement of the microrobot body in such application scenarios, if the microrobots cannot be removed from the body naturally or by catheter type of medical devices.

For magnetic microrobots, biocompatibility and biodegradability are easy to achieve for the polymer or nonmagnetic part of the robot body by using existing wide range of materials approved by the U.S. Food and Drug Administration (FDA). However, for the magnetic part, many widely used magnetic materials, such as NdFeB microparticles and Ni and Co thin-film coatings, are not typically biocompatible. Such materials can be coated by a gold nanofilm or Paralyne C and PEGDA type of biocompatible coatings. However, the safety regulations would still require to have the entire medical device, not only the surface coating, to be biocompatible in most implanted medical device applications; therefore, magnetic materials for untethered medical microrobots to operate inside the body for some duration should be also biocompatible. In this regard, SPIONs are the current best biocompatible magnetic materials. Moreover, SPIONs are also biodegradable, which make them also attractive for fully degradable robots inside the body. However, SPIONs have very weak magnetization properties, which make magnetic actuation weaker for robots with a size of a few micrometers or tens of micrometers. Therefore, biocompatible magnetic nanoparticles with stronger magnetization properties are needed for such robots.

For optical microrobots, the wide range of available polymers allows to select and optimize those which are most compatible with the human body, or biological environments in general. An example of such excellent biocompatibility is that of the growth of heart muscle cells on liquid-crystalline elastomer networks, where the heart muscle cells can survive and are able to reproduce on the polymer substrate. Many combinations of materials are possible and biocompatibility is more easily obtained, for instance by the use of crosslinker proteins. It is interesting to note that a combination of photosensitive polymers with heart muscle cells grown into a patterned tissue could, in principle, lead to future microrobots where part of the motion is invoked by the muscle tissue (and hence make use of a chemical form of energy in addition to light). Preliminary studies in this direction demonstrated the possibility to guide the unidirectional growth of muscular cells following the liquid-crystalline order of the polymer, which is a first step toward biohybrid light-fueled actuators.

Pros and Cons Comparison: Optical materials are easier to make biocompatible and biodegradable than magnetic materials, although the examples reported in the literature are still few. There are even fewer biocompatible and biodegradable material options for magnetic microrobots.

2.2. Actuation Performance and Limitations

For efficient, fast and precise actuation of microrobots for their locomotion and other functions/tasks, the performance of the actuation method needs to be optimized at the micrometer scale in the sense of the robot motion speed, motion range, applied force and torque on the robot, the smallest possible robot size, motion precision, motion degrees of freedom (DoF), and energy efficiency.

Using magnetic actuation for microrobots, fast motion and high force/torque on the robot body are possible depending on the speed and magnitude of the magnetic field generator and the robot's shape and size. Scaling down a magnetic microrobot size (with the scaling factor L) down to a few micrometers is very challenging since the magnetic forces scale with L^2–L^4 depending on the constant parameters of the magnetic actuation system. Therefore, only very small forces and torques can be exerted to drive robots with a size of a few micrometers. However, magnetic actuation works well for robots with a scale of tens or hundreds of micrometers. Precise and high DoF control (typically 5-DoF control possible, which can be extended to 6-DoF control) depending on the robot magnetization uniformity and precision and DoF capability of the magnetic field generator. Energy efficiency of magnetic actuation is very low for the electromagnetic coils-based field generation cases since the coils dissipate significant energy due to the wire resistance and the permanent magnets need to be typically moved mechanically to modulate the magnetic field.
Optical actuation can take place over even larger distance, with laser beams capable of travelling in a straight line if not disturbed (depending on atmospheric conditions one can easily reach a satellite in geostationary orbit around the earth). This immediately points also at a limitation for optical actuation, namely, that the light has to reach to the robot and should not be scattered or absorbed excessively beforehand. Optical actuation is therefore ideal if the robot remains “in sight” of the light source. While lasers have the advantage of directionality, optical actuation is relatively simple and can be done with any type of light source, including lamps and laser diodes, which are cheap and readily available. Note also that the microrobot not necessarily has to be illuminated by a direct beam of light. Also, diffuse illumination (e.g., through opaque/scattering material) is enough to deliver energy to the microrobot. Few recent examples introduce the possibility to actuate photonic polymers by sunlight. In this case, light can be concentrated with simple optics to obtain enough power and photoswitches can be realized that continuously interconvert under visible light to generate self-sustained oscillations.

Current polymer technology allows for an optical sensitivity that is relatively high and robots can be operated with intensities as low as 1 W cm\(^{-2}\) or better. One can expect that material optimization in the future will allow for microrobots to run at intensities comparable to that of sunlight, acquiring this way a high degree of independence. The speed of motion depends on the response time of the polymer and is currently on the order of a few body lengths per second. The time of actuation of a single component (like an arm or a leg) is in the millisecond range or better. The maximum energy efficiency of optical microrobots is currently not known and an important topic of future investigation.

In many cases, by tailoring a proper chemical design, the deformation behavior is ruled by well-defined dose–response curves. The shape change of the polymer can be designed to be bistable or continuous over a broad range of light intensities. In addition to light, polymers can be actuated by various other stimuli, such as electric and magnetic fields, pH variation or other changes to the environment. These actuation mechanisms are not the topic of this paper but their sensitivity can be useful to create robots that respond to their local environment. It also potentially allows for a combination of optically and magnetically actuated robots.

**Pros and Cons Comparison:** Magnetic actuation methods can create higher speed motion and force output, depending on different design and actuation parameters, than the optical ones. However, motion range of both methods is limited to the applied magnetic field workspace or the light focus size or motion range, as a drawback in both methods. It is easier to create high DoF with magnetic actuation than the optical one since magnetic fields and gradients are easy to be generated in 3D space. It is also possible to generate such high DoF actuation with optical methods if the robot operates in free space by using complex 3D interference patterns with light. Motion precision of both methods could be very high with the proper feedback control, depending on the input stimulation and locomotion precision. Energy efficiency of optical actuation can be higher than the magnetic one, if the light source is always shined on the robot with minimum scattering and loss until it reaches the robot surface.

### 2.3. Auxiliary Hardware and Imaging System Requirements

Both magnetic and optical actuation methods require auxiliary actuation/control and imaging equipment to drive and control mobile microrobots remotely. In the magnetic case, an external magnetic actuation system, robot localization and tracking system, control hardware and computer, user interface, and imaging system are needed to actuate and control the motion of microrobots in closed loop for a given application. A magnetic actuation system can consist of custom-designed or Helmholtz/Maxwell electromagnetic coils, magnetic resonance imaging (MRI) gradient coils inside an MRI scanner, a coil array, or a permanent magnet (e.g., single or two dipole permanent magnets, a Halbach array) system. Such hardware can be very bulky since it could require active cooling of the coils (in the case of coil-based and MRI scanner-based actuation systems) if very high magnetic fields or gradients are required to be generated for a given magnetic microrobot system and application. Permanent-magnet-based designs do not need cooling, but they need to be large and bulky for human-scale medical applications that require high magnetic gradient or field generation in long distances. Therefore, most magnetic microrobot designs try to minimize the required magnetic gradients or fields for their operation as an important design challenge.

In the optical actuation case, a light source is required that can have modest dimensions. Diode laser sources are sufficient for actuation and control, and can be of the order of centimeters in size including the power supply. Simple light sources like lamps have similar dimensions. If the future goal of operation in sunlight is achieved, optical robots will also be able to become autonomous without external equipment in open, well-illuminated, environments.

In addition to the actuation/control hardware, an imaging system is required to track any magnetically or optically actuated microrobots and visualize their operation environment for precise feedback control. Single or double optical camera system with a zooming optics is a typical 2D or 3D imaging system for microrobots. However, for medical applications inside the human body, such visual-wavelength optical imaging is not possible. Therefore, photoacoustic, ultrasound, near infrared (NIR), MRI, positron emission tomography (PET), X-ray fluoroscopy, and other possible medical imaging hardware needs to be integrated to the actuation system, which could make the overall system more complicated and bulkier.

**Pros and Cons Comparison:** Magnetic actuation systems require bulkier and more complicated auxiliary actuation/control equipment compared to the optical case. However, both methods require similar integrated imaging systems, independent from the actuation method, to monitor the robot(s) and the operation environment for a given specific application.
2.4. Control

2.4.1. Ways to Address Multiple Robots with Control Signals

In many applications, a team or swarm of microrobots need to operate in parallel to increase the operation speed (e.g., in desktop manufacturing applications) or deliver large amounts of cargo (e.g., in targeted drug delivery applications). Therefore, many microrobots need to be actuated and controlled individually or in ensembles for these application scenarios.

In magnetic actuation, multirobot operation on a 2D planar surface is achieved in three ways typically: localized selective trapping,[8] through the use of heterogeneous microrobot designs,[49,66] and through selective magnetic disabling methods.[46,67] The localized selective trapping method is potentially scalable to a large number of microrobot control in 2D, but requires micropatterned specialized surfaces and localized electrical or magnetic fields, which are not feasible for most applications, as the main drawback. The second method is possible if each robot differently responds to the applied magnetic fields or gradients. While such heterogeneous microrobot design approach is easy to implement, it cannot be used in the control of a large number of microrobots since it is very challenging to make each robot’s unique response fully independent from the others. The third method uses multiple magnetic materials with varying magnetic hysteresis characteristics in tandem to achieve addressable magnetic control, where different composite magnetic materials-based microrobots can be remotely turned into a nonmagnetic or a reversed magnetization robot body.[46] This method is scalable to a large number of robots if the robot orientations can be controlled precisely. Such remote magnetic switching control needs an additional pulsing electromagnetic coil that can apply fast (a few microseconds) high fields in any 3D direction for the robots moving in 3D space. Finally, multirobot operation in 3D has been demonstrated through heterogeneous microrobot designs,[48] which is limited to a small number of microrobot teams and not possible to scale up to a large number of robots easily. Swarm control of magnetic microrobots has also become possible recently, where the mean and variance of the swarm shape and dynamics can be controlled on solid surfaces,[60] at the water–air interface,[70] and in fluids,[71,72] using dynamic self-assembly methods and ensemble locomotion behavior controlled by the external magnetic fields/gradients.

Optical control works differently and makes use of different properties of the light field. Robots can be made to respond differently to different parts of the optical spectrum,[73] with, in principle, a large degree of freedom in “spectral fingerprint.” The polarization of light is the second control mechanism,[74,75] and the third is spatial patterning of the light.[12] Control light can be either scanned (e.g., with micromirrors) or projected with the desired pattern. An advantage of this option is a high degree of freedom in complex motion generation. A disadvantage is that the robot has to be targeted and followed by a (patterned) beam all the time in a given motion range.

Optical robots can also be made such that they perform tasks autonomously and take simple decisions (e.g., grabbing particles only of the right color)[8,76]. In that case, the light only serves as source of energy (using simple lamps, or, in the future, possibly sunlight) while the action of the robot is determined by its local environment (temperature, light scattering, chemical parameters like pH and presence of certain molecules, etc.). Light could also be used, in future studies, for some form of interaction between robots, since their body shape and structure influences (by scattering and absorption) the light distribution of the environment. Due to their typically low refractive index, however, this effect is quite small and difficult to use in practice over large distances—although it can be very useful for self-assembly. A collection of robots, made sensitive by proper chemical design, could assemble into a metastructure upon optical stimulation. Temperature sensitivity is an important issue for optical robots since most materials will respond to changes in the environment temperature.

Pros and Cons Comparison: Both magnetic and optical actuation methods can address multiple microrobots with control signals for independent or ensemble-based motion control. Depending on the addressing method, the number of robots that can be addressed could be limited to a team of robots only in both cases. However, they both have methods that can address a large number of microrobots in parallel, which are limited to only specific environments and conditions currently. Swarm control using both methods can be achieved by controlling the mean position and variance of the shape of the swarm ensemble. Although there have been many swarm control demonstrations of magnetic method, swarm control with optical methods is still in its infancy.

2.4.2. Sensitivity to the Operation Medium and Possible Workspace

Optical actuation has the challenge of not being able to penetrate nontransparent media deeply for a given utilized wavelength of light, which is a limiting factor for actuating microrobots in deep locations of such media, e.g., inside the human body. Larger wavelength light sources like NIR light has more penetration depth under skin up to 1–2 cm. However, magnetic actuation can penetrate any nonmagnetic media deeply; a clinical MRI scanner can cover a whole human body cross-section with a 3 T uniform magnetic field and uniform magnetic field gradients in 3D with no tissue penetration problem. Here, the only limiting penetration depth constraint could be the magnetic field generator’s range, where magnetic fields decay exponentially with distance from the source location.

The operation workspace of the microrobot is determined with the uniform magnetic fields/gradients or a focused light area that can be generated in a given distance/depth. In the magnetic actuation case, the workspace is determined by the magnetic field or gradient generator’s range, which is typically a given limited volume. Such limited workspace is no problem for medical or biotechnology applications in a confined operation spaces (e.g., inside the human body or inside a microfluidic lab-on-a-chip device), but is a problem for environmental remediation type of applications in large workspaces or outdoors.

Pros and Cons Comparison: Magnetic actuation can penetrate the deep regions of the human body while the optical one has a very limited penetration depth, which is the main drawback of optical actuation methods for medical applications. However,
if a light source is brought inside the body using a catheter or if a swarm of microrobots that includes some robots that can emit light using remote powering or environmental interaction methods, optical actuation might be also used in deep regions of the human body.

2.4.3. Independent Autonomous Action without Human Intervention

In both magnetic and optical actuation methods, the robot would fully stop moving if the external magnetic or optical source is turned off with a human or computer intervention. In that sense, they are always dependent on the external energy source and cannot be self-propelled independently as in the case of self-propelled biohybrid or catalytic microswimmers. Such a property is very advantageous for safe medical applications, where the robot can be fully stopped in case of any emergency if the external energy source is turned off. However, if the light is used to propel a microparticle using photocatalytic effects, the optical actuation can create independent self-propelled autonomous microswimmers. The advantage of such photocatalytic microswimmers is enabling autonomous swimming behavior, while still being able to be stopped from outside in case of emergency.

A different line of thought is that of creating microrobots that perform tasks autonomously without external control. Creating robotic elements, like a microscopic hand, that would fully stop moving if the external magnetic or optical source is turned off with a human or computer intervention.

| Table 1. Summary of properties and comparison of magnetic and optical actuation methods for microrobots in a given context. |
| Magnetically driven microrobots | Optically driven microrobots | Magnetic vs optical comparison |
| Typical materials | Hard (NdFeB, FePt, Alnico, SmCo, Cr, and Co2, Ni, Co, Gd, NiFe, and FePt) magnetic materials as micro/nanoscale films, particles, discs, wires | Light-responsive polymers (liquid-crystalline elastomers, liquid-crystal networks, and hydrogels), biological materials (algae and bacteria), or a combination of these two | A wide range of different materials possible in both cases |
| Material composition, hardness, and density | Composites (stiff magnetic micro/nanomaterials embedded inside soft or hard polymers; magnetic nanofilms coated on polymers or metals) with high density | Soft or flexible polymeric materials with low density | Optical materials are much softer and lower density similar to biological tissues |
| Fabrication methods | Two-photon polymerization (3D microprinting); optical lithography and/or micromolding (2D); laser micromachining (2D); robotic microassembly (3D) | Two-photon polymerization (3D); photolithography and micromolding (2D) | Diverse 2D and 3D microfabrication methods available for given material and size scale of a microrobot design |
| Ease and scalability of fabrication | Micromolding as the main facile and scalable method for composite magnetic microrobots | Most optical microrobot fabrication processes typically facile and potentially scalable | Optical microrobot fabrication processes typically more facile and scalable; magnetic microrobot ones needing postfabrication treatments |
| Biocompatibility | Limited amount of biocompatible and biodegradable magnetic materials (SPIONs) | Possible to have many diverse biocompatible photosensitive polymers | Optical materials easier to make biocompatible and biodegradable than magnetic materials |
| Actuation performance | Long distance; possible to have fast, precise, and 5/6-DoF motion and high force/torque on the robot body; low energy efficiency for the electromagnetic actuation cases | Long distance; possible to have fast, precise, and 5/6-DoF motion and high force/torque on the robot body; low energy efficiency for the electromagnetic actuation cases | Higher speed and DoF motion and force output by the magnetic actuation methods; higher energy efficiency by the optical actuation methods |
| Actuation limitations | Requirement for the robot to remain in line of sight of the light source during actuation; sun light-based optical actuation still not advanced enough; needing high light powers for actuation under liquids | Limited motion range for both methods due to limited applied magnetic field workspace and limited light focus size or motion range |
| Auxiliary hardware requirement | Typically requiring bulky magnetic actuation systems with active cooling or large permanent magnets | Light source and optical setup needed externally unless sunlight can be used in the future | Magnetic systems typically bulkier than optical ones |
| Multirobot control | Diverse methods to address multiple microrobots in 2D and 3D | Diverse methods to address multiple microrobots in 2D and 3D | Both methods capable to address multiple microrobots for independent or ensemble-based motion control |
| Sensitivity to the operation medium and workspace | No penetration issue for the human body; penetration issue only for magnetic operation media; fixed/limited workspace determined by the magnetic actuation system | Challenge of not being able to penetrate nontransparent media deeply (NIR penetration depth: around 1–2 cm) | Specific sensitivity to the magnetic or nontransparent operation media |
| Autonomous (self-propelled and self-sensing) action capability | Not possible to do with magnetic methods due to the necessity of an external magnetic field generator | Possible to design autonomous optically driven microrobots (e.g., if sun light used as the light source) with self-sensing | Potentially possible to achieve with optical methods |
| Medical application capability | Promising for a wide range of medical applications inside the human body | Limited to a few centimeters-deep regions under the skin or biological tissues | Magnetic actuation superior to the optical one in a much wider range of medical applications |
respond automatically to objects of certain spectral properties (color) is an example of such behavior. The sensitivity of polymers to their environment can also be used to create robots that move based on chemical gradients, thermal gradients, differences in pH, or the presence of other robots. One can envision the future realization of microscopic robots that perform simple tasks without human intervention or self-assemble into more complex objects.

Pros and Cons Comparison: While magnetic microrobots cannot have self-autonomy since they always need an external magnetic field control, optical microrobots can have self-regulatory autonomous behavior depending on the environmental stimuli that can actuate a specific polymer robot material.

3. Conclusion and Outlook

Magnetic and optical actuation methods, as the most widely used actuation methods in microrobotics currently, have different pros and cons as reported above and summarized in Table 1, depending on the given context. They can both enable long-range, fast, and precise actuation of single or a large number of microrobots in diverse environments. Magnetic actuation has unique potential for medical applications of microrobots inside nontransparent tissues at high penetration depths, similar to acoustic actuation methods for microrobots, while the optical one is suitable for more biotechnology, lab/organ-on-a-chip, and desktop manufacturing types of applications with much less surface penetration depth requirements or with transparent environments. Combining both methods in magneto-optic material actuation applications for magnetically programmable optical surfaces could have a strong potential of combining the pros of both methods.

There is still much progress needed in both actuation methods to realize their potential unique applications in real-world conditions. In magnetic microrobotics, first, new magnetic micro/nanomaterials that have strong magnetization and are biocompatible and possibly biodegradable are needed to create high performance microrobots with an overall size on the order of a few micrometers or tens of micrometers scale. Second, magnetic actuation is used for mainly locomotion, navigation and shape change of microrobots; we need more multifunctional magnetic materials (e.g., magnetopiezoelectric materials) and mechanisms combined with stimuli-responsive more functional (e.g., stimuli-responsive) polymer material matrices for more advanced and diverse functionalities. Next, the miniaturization limit of magnetic microrobots needs to be pushed down to a few micrometers size scale in high body penetration depths for cardiovascular and other medical applications, which require access to microcapillaries with no invasiveness. Moreover, due to magnetic propulsion scaling laws not favoring actuation of robots on a scale of a few micrometers well, combining magnetic steering with biological cell-powered or acoustic propulsion techniques could be promising in such cases. Finally, achieving reconfigurable swarms of magnetic microrobots with adaptive morphology to different tasks and environments is an important future challenge.

Research on optical materials, on the other hand, should involve the optimization of their sensitivity, which as such is already very high but the prospect of using sunlight as energy source is of course extremely interesting. This would require an additional increase in sensitivity of about 1–2 orders of magnitude, without sacrificing the optical response time. A useful focus point is also that of expanding the scale of available materials toward more complex spectral response functions and structural properties like elasticity and rigidity. The realization of hybrid structures, including living muscle cells embedded in complex microscopic networks would open up a range of interesting possibilities, including the use of chemical forms of energy.

Operation of optical microrobots deep inside the human body remains a challenge, and light might not be the best strategy to achieve this. However, one can envision some improvement in that respect, for instance by using optical fibers. Wavefront shaping could also be an interesting optical technique to explore for partially overcoming scattering and focusing light inside the human body, although the penetration depth will always remain much smaller than that of magnetic fields. Much research effort should be dedicated to the development of combined technologies using optical robots and elements in combination with photonic circuits and in nanofluidic/photicon devices.

Conflict of Interest

The authors declare no conflict of interest.

Keywords

magnetic actuation, microfabrication, microrobotics, nanofabrication, optical actuation

Received: October 15, 2019
Revised: November 21, 2019
Published online:

[1] M. Sitti, Mobile Microrobotics, The MIT Press, Cambridge, MA, USA 2017.
[2] M. Sitti, Nature 2009, 458, 1121.
[3] M. Sitti, H. Ceylan, W. Hu, J. Giltinan, M. Turan, S. Yirm, E. Diller, Proc. IEEE 2015, 103, 205.
[4] M. Sitti, Nat. Rev. Mater. 2018, 3, 74.
[5] H. Ceylan, J. Giltinan, K. Kozielski, M. Sitti, Lab Chip 2017, 17, 1705.
[6] H. Ceylan, I. C. Yasa, U. Kılıç, W. Hu, M. Sitti, Prog. Biomed. Eng. 2019, 1, 012002.
[7] H. Zeng, P. Wasylczyk, D. S. Wiersma, A. Priimagi, Adv. Mater. 2018, 30, 1703554.
[8] D. Martella, S. Nocentini, C. Parmeggiani, D. S. Wiersma, Adv. Mater. Technol. 2019, 4, 1800571.
[9] B. Vigit, Y. Alapan, M. Sitti, Adv. Sci. 2019, 6, 1801837.
[10] S. Li, R. Batra, D. Brown, H. D. Chang, N. Ranganathan, C. Hoberman, D. Rus, H. Lipson, Nature 2019, 567, 361.
[11] H. Zeng, P. Wasylycz, C. Parmeggiani, D. Martella, M. Burresi, D. S. Wiersma, Adv. Mater. 2015, 27, 3833.
[12] S. Palagi, A. G. Mark, S. Y. Reigh, K. Melde, T. Qi, H. Zeng, C. Parmeggiani, D. Martella, A. Sanchez-Castillo, N. Kapernaum, F. Giesselmann, D. S. Wiersma, E. Lauga, P. Fischer, Nat. Mater. 2016, 15, 647.
