Flexible magnetic small-scale robots (overall dimensions smaller than 1 cm) can use a patterned magnetization profile to noninvasively access a confined, enclosed liquid environment and therefore achieve applications in object manipulation or in minimally invasive procedures. Existing magnetic-controlled small-scale robots have shown wide usage for their high mobility and higher degrees of freedom than their rigid counterparts. Herein, an octopus-like soft robot is proposed for potential use in biomedical and engineering fields. First, a magnetic control system is established, which uses the minimum number of coils arranged by a regular tetrahedron structure. This system responds quickly and with high precision to propel a robot in 3D space utilizing the coupled field from multiple electromagnets in concert. An octopus-like robot with three legs is designed, which moves freely in the workspace without constraints. A time-asymmetric gradient magnetic field is applied, to ensure that the movement of the robot is more stable and controlled. At the same time, the movement of the tail improves the precision of the robot and makes control easier.

1. Introduction

The noncontact operation of microminiature robots has attracted considerable attention in recent years and demonstrated great application prospects.\[1–3\] These include light field propulsion,\[4,5\] chemical energy, acoustic radiation force driving,\[6\] and bioenergy propulsion. These methods have been used to direct a variety of small robots, for example, the microassembly or object transportation,\[7–9\] and they have demonstrated high precision in their applications. Among these methods, the magnetic actuating technique is particularly promising, because the magnetic force can be controlled in 3D space and provides sufficient force.\[8,10–16\] Magnetic field can be transmitted without any medium; therefore, the ability to use remote control in certain environments is promising.\[17–19\] Through magnetic control, noncontact manipulation can be realized and considerably extend the operational scope of these instruments, compared with traditional methods.\[20–22\]

As magnetic devices can be miniaturized, the potential in medical applications is considerably high.\[23–25\] In recent years, there has been considerable attention in this area, particularly, in vivo microsurgery, biological monitoring, and drug delivery.\[26–28\]

Because the magnetic field $B$ generated by different coils can be vector superimposed, fields of any desirable directions can be acquired. The 3D distribution of a magnetic field can therefore be achieved.\[29\] Many magnetic systems have been built and used in various applications.\[30–32\] For example, the Helmholtz coil can generate fields with high uniformity and different field directions. However, the magnetic flux density is generally small. Maxwell coils can produce a uniform gradient magnetic field and can control a robot using a gradient force; however, this gradient magnetic field is usually weaker in strength. In addition, permanent magnets are also promising, for example, the precise control of robots on the chip,\[33,34\] and another example is the individual manipulation of multiple soft robots regulated by a single axial magnetic rotation beneath the center of the substrate inspired by the celestial bodies in our solar system.\[35\] Several magnetic control systems have been developed for 3D microrobots. Examples include the Octomag system that uses eight coils for retinal procedures\[17\] and the enhanced electromagnetic system with six coils for microparticle manipulation.\[36\] These systems use several coils that are distributed in 3D space and can produce magnetic fields in different directions. It was observed that in many systems the position of the coils coincides with the platonic polyhedral. For example, the cube structure with six coils and a regular octahedron with eight coils,\[8,36\] as shown in Figure 1a, epitomize a high degree of symmetry and order. To control an unconstrained magnetic object, four magnetic sources are required for three degrees of freedom force control.\[37\]
Because the magnetic field will interact with any magnetic object, a magnetic device can convert magnetic energy into kinetic movement to overcome viscous resistance. Various robots have been developed that can change posture, speed, and direction by changing the frequency, size, and direction of the magnetic field.\cite{34,38-40} Because robots of different structures will respond entirely differently to the magnetic field,\cite{41,42} it is possible to realize the multidegree of freedom of a robot. For example, a mobile microgripper used to carry microgels,\cite{8} an untethered magnetic microrobot that moves freely on a surface,\cite{43} a highly efficient magnetic nanoswimmer,\cite{44} a bioinspired multilegged soft millirobot that functions in both dry and wet conditions,\cite{45} and a small-scale soft robot with multimodal locomotion\cite{46} can all have practical applications.

Inspired by the regular tetrahedron of the high degree of symmetry and order, we establish in this study a magnetic control system using minimum number of coils, as shown in Figure 1b. The angles of the four electromagnets are equal to each other, as shown in Figure 1c: the angle $\beta_0$ between the upper three electromagnets and the angle $\beta_1$ between the upper electromagnets and the lower electromagnets are both $\arccos(-1/3)$, which reflects the high symmetry of the system, making it feasible to control the robot. The system is controlled by a computer using a proportional integral (PI) controller, to ensure that the field response is timely. Because the iron core is a soft magnetic material, the hysteresis is negligible, and the direction and intensity of the magnetic field in the working area can therefore be controlled with precision. We developed an octopus-like robot that can travel stably in 3D space. Previous jellyfish-like robot focusing on the multifunction demonstrates multiple applications by producing diverse controlled fluidic flows around its body; however, 3D movement at different directions requires improvement.\cite{47} To offset the gravity, the structure was further improved with a bubble in the middle part of the robot, as shown in Figure 1c. By adopting the established system, the robot will emerge at the desired time-varying postures at actuating magnetic fields and can travel in enclosed liquid environment. Because the gradient is the main driving force, the swing of the tail increases the stability of the robot when swimming in the working area.

2. Results and Discussion

2.1. Parameter Analysis for System Design

Inspired by the regular tetrahedron, the magnetic system utilizes lesser number of coils for three degrees of freedom control of the robot.\cite{37} The distribution of the magnetic field is influenced by parameters such as position, radius of the electromagnets, turn number of coils, and core material. Herein, we analyzed two relatively important parameters including the position and radius of
the electromagnets, as shown in Figure 2a. As all four electromagnets have the same parameters, the analysis was based on coil G, which was energized with a current of 10 A. Though the remaining three coils are not energized, their cores will be magnetized and in turn affect the magnetic field.

The influence of the core position (the distance from the core to the central point shown in Figure 2a) was analyzed first. The core position should be sufficiently large to ensure a reasonable working space. Table S1, Supporting Information, shows the parameters for analyzing the core position. As shown in Figure 2b, the magnetic field decreases as the distance increases. When the distance is shorter, the magnetic field increases; however, the working area reduces. To balance the working space and the magnetic flux intensity, the distance is 45 mm; this means that the spherical working area has a diameter of 90 mm.

The diameter of the core does affect the uniformity of the magnetic field, and the parameters used to analyze the core diameter are shown in Table S2, Supporting Information. Figure 2c shows the magnitude of the magnetic field on the Z-axis at different core diameters. The gradient of the field on the Z-axis decreases as the diameter increases. Figure 2d also shows the magnetic field distribution on the Z = 0 plane. It shows that as the diameter increases, the uniform range of the magnetic field at the center increases. A much larger core diameter may also cause interference between different coils. Therefore, 55 mm is considered for the analysis. Based on these analyses, the parameters of the system and the system setup are shown in Table 1 and Figure S1, Supporting Information, respectively.

Table 1. Electromagnet parameters.

| Description          | Value | Units |
|----------------------|-------|-------|
| Number of turns      | 914   | –     |
| Distance from center | 45    | mm    |
| Diameter of wire     | 2.24  | mm    |
| Coil resistance      | 1.0   | Ω     |
| Coil inner diameter  | 55    | mm    |
| Coil outer diameter  | 90    | mm    |
| Core length          | 220   | mm    |
| Core diameter        | 55    | mm    |
| Maximum current      | 15    | A     |

Within a given static arrangement of electromagnets, the magnetic field throughout the workspace can be computed. For a single coil, the magnetic field on its axis can be obtained by

\[
B = \left( \frac{\mu_0 R^2}{2(R^2 + x^2)^{3/2}} \right) I
\]

where \( R \) is the radius of the coil, \( x \) is the distance from a point on the axis to the center of the coil, and \( \mu_0 = 4\pi \times 10^{-7} \text{ N/A}^2 \), representing the magnetic permeability in classical vacuum. Therefore, the magnetic field generated is only related to the current in the coil. PI controller was used to ensure that the output current reaches the expected current in a timely fashion. PI controller can be achieved by adjusting the value of \( K_p \) and \( K_i \), where

![Figure 2. a) Parameter analysis for the electromagnet. The coil G is energized with 10 A current, whereas the others are not. b) Simulation results of the magnetic field along the Z-axis at different positions of the core. c) Simulation results along the Z-axis with cores of different radii. d) Simulation results at Z = 0 in a 50 mm-diameter circle with cores of different radii, areas within the red line are considered uniform areas.](image-url)
guarantees the correspondence between the output signal and the input signal and $K_I$ eliminates any deviation. In Figure S2, Supporting Information, triangular wave and square wave signals are separately introduced (15 Hz, with an amplitude of 4 A), and as observed in Figure S2(a) and S2(c), Supporting Information, there is a large error between input and output prior to making adjustments. After adjusting $K_P$ and $K_I$, the output signal responds well to the input signal, as shown in Figure S2(b) and (d), Supporting Information.

The presence of the core greatly enhances the strength of the magnetic field, causing the magnetic field to be much stronger. Because the core always experiences a hysteresis effect, the relationship between the magnetic field and magnetic current is not always linear and therefore complicates modeling and control. For soft magnetic materials, however, the situation is different. For example, for the core material like pure iron, the hysteresis is negligible within the linear magnetization region and imposes only a very minor constraint on modeling and control.

Figure 3a shows the distribution of magnetic induction line when only electromagnet G is energized. The other three cores are magnetized, which increases the field in the working area. Figure 3b–d shows both the experimental and the simulation results of the magnetic flux density at three positions along the Z-axis. As observed, the magnetic field is proportional to the magnitude of the current, and there is negligible hysteresis effect. Deviations between the experimental and the simulation results may be due to model uncertainty and the environment. Thus in a system, the magnetic flux density $B_p = [B_x, B_y, B_z]^T$ at point P in the working area can be expressed as the vector sum of magnetic fields generated by all the coils:

$$B_p = \sum_{e} B_e i_e$$  \hspace{1cm} (2)

where $e$ is the code number of an electromagnet in the system, which can be taken as D, E, F, and G, $i_e$ is the current flowing through coil $e$, and $B_e$ is the magnetic flux density generated by the unit current of an electromagnet in the system.

### 2.2. Distribution of Magnetic Field

The symmetry of the spatial positioning of the electromagnets allows us to consider only a subset of all possible conditions in assessing the magnetization effect or the coupling magnetic field produced by different electromagnets. Figure 4a shows the magnetic induction lines of four electromagnets working simultaneously, it can be seen that the cores can influence the magnetic field distribution. To analyze the coupling field generated by the electromagnets, and the impact of iron cores on the distribution of the field, the magnetic field at the working area was simulated, as shown in Figure 4b–e. The distribution of the field when only coil G is energized is shown in Figure 4b. Energizing

---

Figure 3. a) Distribution of magnetic induction line when only coil G is energized ($i_G = 10$ A). b–d) Experimental and simulation results of the magnitude of $B$ at $Z = -10, 0, 10$ mm, respectively, when only electromagnet G is energized.
the other three electromagnets simultaneously produces a coupled gradient field $\nabla B$, with the same direction as when only an electromagnet coil G is energized, as shown in Figure 4c. In this case, the magnetic field generated by electromagnets D, E, and F magnetizes electromagnet G, which therefore generates an enhanced magnetic field without energizing G. Accordingly, the gradient magnetic field can be enhanced by making the electromagnets work together, as shown in Figure 4d,e, and it can be found that the magnitude of $\nabla B$ is nearly the same in the central area. This explains why the magnetic agents are ideally manipulated in the central region, with a nearly uniform gradient. Figure 4f shows the magnetic flux intensity along the Z-axis at various conditions (as shown in Figure 4b–e). It is shown that when these electromagnets work together, a uniform gradient magnetic field $\nabla B$ with a larger value is generated. Magnetic field measurement along the Z-axis in the central working area ($I_G = 10 \text{ A}$, $I_D = I_E = I_F = -10 \text{ A}$) is shown in Figure 4g, and it reveals a good correlation between the simulation and experimental results, whereas $\nabla B$ reaches approximately 2.76 T m$^{-1}$. As the maximum current capacity is 15 A, the gradient can reach approximately 4.14 T m$^{-1}$.

### 2.3. Robot Design and Analysis

Any magnetic substance in a magnetic field experiences the magnetic force $F$ and the magnetic moment $T$, where the magnetic force leads to the movement of the magnetic substance, and the magnetic moment causes rotation. The magnetic force is proportional to the magnetic field gradient, whereas the magnetic moment is proportional to the magnetic flux density $B$. For a magnetic element, the magnetic moment $\tau$ and magnetic force $f$ can be obtained from the following equation

\[ f = \mu_0 \nabla \times \mathbf{B} \]

where $\mu_0$ is the permeability of free space and $\nabla \times \mathbf{B}$ is the magnetic field gradient.
\[ \tau = m \times B \] (3)

\[ f = (m \cdot \nabla)B \] (4)

where \( m \) represents the magnetization of the element, \( V = \left[ \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z} \right] \), \( B = [B_x, B_y, B_z]^T \). As there is no current in the working space, the force of the microelement in the magnetic field is obtained from Maxwell’s equation

\[ f = (m \cdot \nabla)B = \begin{bmatrix} \frac{\partial B_x}{\partial x} & \frac{\partial B_x}{\partial y} & \frac{\partial B_x}{\partial z} \\ \frac{\partial B_y}{\partial x} & \frac{\partial B_y}{\partial y} & \frac{\partial B_y}{\partial z} \\ \frac{\partial B_z}{\partial x} & \frac{\partial B_z}{\partial y} & \frac{\partial B_z}{\partial z} \end{bmatrix} m \] (5)

\[ \tau = m \times B = \begin{bmatrix} 0 & B_z & -B_y \\ -B_z & 0 & B_x \\ B_y & -B_x & 0 \end{bmatrix} m \] (6)

The force of the magnetic elements in the magnetic field can be obtained by the aforementioned formula. The magnetization \( m \) of the element can be expressed as

\[ m = \frac{dM}{dV} \] (7)

where \( M \) represents the magnetization magnitude of the robot, the total magnetic moment \( T \) and magnetic force \( F \) can therefore be expressed as

\[ T = \int \tau \, dV \] (8)

\[ F = \int f \, dV \] (9)

Based on the magnetic system, a magnetic octopus-like robot was designed. This can achieve 3D motion, and there is a cavity structure at the head of the robot and several smaller cavities on the legs to increase the buoyant force when in the liquid environment. A mixture of NdFeB, as shown in Figure S3(a), Supporting Information, and ecoflex polymers was used to manufacture the robot. Figure S3(b), Supporting Information, shows the scanning electron microscope (SEM) images of the composites. Figure 5a shows the \( B-M \) cure (i.e., field flux intensity \( B \) and magnetization \( M \)) of the magnetic material and reveals a huge residual magnetization in the absence of applied field.

To prepare the robot, a mold, as shown in Figure 5b, is obtained using 3D printing technology (photosensitive resin material). The liquid magnetic material is then poured into the model, as shown in Figure 5c, which will solidify after 4 h at 30 °C. After solidification, take the robot out of the mold and an octopus-like robot is obtained, as shown in Figure 5d. To obtain the required magnetization curve, the robot is placed in a transparent tube with a diameter of 1.6 mm, and the tail of the robot deforms. The tube is then placed in a strong magnetic field (where the magnetic flux density reaches 1.6 T), as shown in Figure 5e,f. Because the material has a high residual magnetization, when the strong magnetic field disappears, the robot will remain magnetized and will not be remagnetized in the weak magnetic field. After the robot is removed from the tube, the tail returns to its original shape because of its elasticity, as shown in Figure 5g, and the magnetization direction is along the direction of the tail. Thereby, a robot with the required magnetization profile is obtained, as shown in Figure 5h.

For clear observation, the robot is placed in a transparent resin environment. This ensures that the robot’s motion is easily observed.

**Figure 5.** a) \( B-M \) curve of the material (mixture of ecoflex and NdFeB) to make the robot. b–d) Schematic diagram of the manufacturing process of the octopus-like robot. e,f) The magnetization process. g) The magnetization profile of the octopus-like robot, along the direction of the tail. h) Photo of the octopus-like robot. (thickness of the tail: 120 \( \mu \)m.)
tracked without the need for a fast camera. Because the head of the robot is designed with a cavity structure, a bubble will appear when in the liquid, and the gravity is offset by the buoyant force, as shown in Figure S4, Supporting Information, where gravity $G = F_{\text{float}}$. When placed in the working area, the robot moves forward due to the uniform gradient magnetic field. Because the resistance is related to the speed of the robot, the robot will accelerate until the magnetic force $F$ is balanced by the resistance, which can create complexity in controlling the robot. To increase the moving accuracy and the stability of the robot, a triangular wave form is chosen to drive the robot.

Figure 6. a) Different postures of the tail when the magnetic field is on and off. b) The relationship between the angle $\alpha$ and the magnetic field when the robot is magnetized and demagnetized, respectively. c) The image of the robot at different magnetic fields. d) The angle that the tail of the robot bends as the frequency of the triangular magnetic field varies. (magnetic amplitude: 21 mT.)
As the octopus-like robot is magnetized in a strong magnetic field, the magnetization curve will remain when the strong magnetic field disappears. Thus, in the absence of a magnetic field, the robot will remain in its initial state. When an external magnetic field is applied, the tail of the robot will deform to align with the applied magnetic field. Figure 6a shows the initial state and the deformed state of the robot tail, where $\alpha$ is the bending angle of the robot’s tail. Figure 6b shows the relationship between the angle $\alpha$ and the magnetic field. When the robot is magnetized, the angle will become larger as the magnetic field increases, but when the external field is above 15 mT, it will only increase slightly or remains unchanged. However, the angle changes slightly if the robot is demagnetized. Figure 6c shows the state of the robot when in the magnetic field of different flux intensities. If the external magnetic field is periodic, for example, a triangle wave, the tail

Figure 7. The movement of the robot in the closed transparent resin environment. By adjusting the magnetic field, the robot can reach any position in the space. a) The top view and side view of the robot and at different time periods, frequency: 1 Hz, scale bar: 1.5 mm. b) Experimental results of tracking the octopus-like robot along a 3D route. c) Trajectory of the robot from the top view. d) Trajectory of the robot from the side view. e) The distance to the desired position. f) Experimental robot velocity at a varying gradient field, with a constant pulse frequency of 1 Hz (triangular wave).
of the robot will periodically bend accordingly as if it is swimming. However, when the robot is placed in the periodic field, instead of bending from angle $0^\circ$ to $\alpha'$, it rather bends from $\alpha_0$ to $\alpha_1'$, as shown in Figure 6d (see Video 1, Supporting Information). As the frequency increases, the range of the bending angle decreases, implying the angle $\alpha_0$ increases, whereas the angle $\alpha_1'$ decreases. This is because the response speed of the robot’s tail cannot keep up with the periodic field at increased frequency. Therefore, a frequency below 4 Hz is considered for the triangular wave to propel the robot.

2.4. Swimming Octopus-Like Robot in 3D Space

When placed in the working area of the magnetic system, the robot moves forward under the gradient magnetic field. However, if a time-asymmetric oscillating magnetic field is applied, the tail of the octopus-like robot will bend periodically, which causes a reverse flow of the liquid that propels the robot forward. In contrast, when the field is on, the gradient force will propel the robot to move and the tail of the robot will bend which reduces the resistance of the liquid environment. Meanwhile, when the magnetic field decreases, the tail of the robot will stretch, which increases the resistance and helps overcome the inertial force, making the robot’s motion control more sensitive. By this means, the inertial force of the robot can be overcome and a higher precision control of the robot can be achieved. A time-asymmetric actuation triangle wave, as shown in Figure S5, Supporting Information, is used to propel the robot.

Therefore, the octopus-like robot was propelled using the triangle wave form gradient field. Figure 7a shows the movement of the robot in the liquid environment, viewed from both the top and the side of the workspace at different $t$ periods. As observed, the robot moves steadily in the field using the triangular wave magnetic field (see Video 2, Supporting Information), whereas the maximum field at the central area is 15 mT, with a gradient of 0.49 T m$^{-1}$. By controlling the magnetic field generated by these electromagnets, the robot can move in different directions. Figure 7b shows the 3D path in the trajectory tracking, and Figure 7c,d shows the motion trajectory of the controlled robot from top and side views, respectively. It is shown that the robot can move with a relatively high positional precision, and errors are likely due to gravity of the robot and adhesive force of the liquid. Figure 7e shows the distance to the desired positions $a$, $b$, $c$, $d$, and $e$ shown in Figure 7b, where distance $= \sqrt{d_x^2 + d_y^2 + d_z^2}$, and $d_x$, $d_y$, $d_z$ represent the distance to the desired position in the $x$, $y$, and $z$ directions, respectively. It is shown that the distance decreases step by step, not linearly. Therefore, errors due to inertia force can be decreased and the maximum error can be limited within the one “step.” To analyze the relation between the moving speed and the gradient field, we propel the robot using the same field but with different amplitudes (triangle wave, 1 Hz). Figure 7f shows that the translational velocity (step size) of the octopus-like robot increased in proportion to the applied magnetic field gradient.

3. Conclusions

Our studies have shown a magnetic control system for noncontact control of the octopus-like robot. This system uses the minimum number of coils which takes the structure of a regular tetrahedron and produces a uniform gradient field in the working area. We characterized the influence of the position and radius of cores on the generated electromagnetic field, then we designed the magnetic system that can reach a spherical volume with 90 mm diameter and a magnetic field gradient of 4.14 T m$^{-1}$. The system can respond quickly for real-time control with high accuracy and high precision when propelling magnetic objects in 3D space. However, the complicated motion of the robot with high accuracy is still challenging which has to be solved in the future.

The octopus-like robot is designed to ensure that its gravity could be compensated for by its buoyancy. The 3D movement of the robot can be obtained by the uniform gradient field and the movement of its tail. By applying a triangular wave magnetic field, the robot can travel more stably, guaranteeing a higher positional precision. As the robot propels forward in the magnetic field, the bending of its tail reduces resistance, whereas the swing provides additional propulsion. In the absence of a magnetic field, the tail of the robot unfolds; this increases the resistance of the liquid, helps reduce the inertial force, and improves precision. The octopus-like design provides a new strategy in propelling robots in a 3D environment.

4. Experimental Section

Materials Used to Fabricate the Octopus-Like Robot: The primary material used to construct the octopus-like robot was Ecoflex 00-10 polymer matrix (Smooth-On Inc., USA; density: 1.04 g cm$^{-3}$), loaded with neodymium–iron–boron (NdFeB). The NdFeB powders (Toda Magnequench Magnetic Material (China) Co., Ltd.) with diameters of 4.5–6.5 μm and a density of 7.61 g cm$^{-3}$ were used, as shown in Figure S3(a), Supporting Information. These powders had very good magnetic properties, with a remanence Br of 838–878 mT, and would not be demagnetized if the field was less than 600 mT. The NdFeB powder was mixed into the ecoflex with a mass fraction of 15% to produce a liquid magnetic material that would be solidified after $\approx$4 h at 30 °C. The magnetic particles would randomly disperse in the matrix without aggregation, as shown in Figure S3(b), Supporting Information. The obtained magnetic elastomer had a density of 1.10 g cm$^{-3}$ and an excellent elasticity, for example, it will deform once there is torque on it and will return to its original shape when the external torque is removed.

Control Components: The magnetic control system was driven by a computer control, an AD/DA module (using the USB-6211 data acquisition system: National Instruments Inc., USA), four digital drivers (DZRALTE-040L080 motor driver: AMD, USA), four direct current (DC) power supplies, and a magnetic generating device, as shown in Figure S1, Supporting Information. The computer control uses Visual Studio 2010 (C# language) to generate digital signals, which were then converted to analog signals by the AD/DA conversion modules. The driver’s maximum output voltage and continuous working current were 80 V and 20 A, respectively. The drivers can output the desired current to the electromagnets; therefore, the required magnetic field in the working area was generated.

Image Acquired System: The image processing module consisted of two charge-coupled device (CCD) cameras which were used to observe the top view and side view of the working area individually, as shown in Figure S1, Supporting Information. These cameras provided real-time images of the
robot from different perspectives to the computer. The position of the robot was obtained in real time, and close-loop control was realized.

Bending of the Tail: In Figure 6, to calibrate the deformation of the robot’s tail, a pair of Helmholtz coils with iron cores was required to generate a uniform magnetic field. The robot’s head was fixed, whereas the tail moved freely. The bending angle of the tail was determined through the image acquisition and analysis system.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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