Herein, a new method for steering liquid metals (LMs) using only a magnetic field in open 3D space is proposed. The magnetic LM is composed of the alloy GaIn and iron particles. The 3D horizontal and vertical manipulation of a magnetic LM can be realized via an external magnetic field. The magnetically actuated LM is not only manipulated on various complex pathways in the horizontal plane, but also vertically in 3D space without the use of electrolytes and electrodes. As a proof-of-principle, an intelligent delivery vehicle that can avoid obstacles and traps horizontally and overcome gravity vertically to offload a cargo is designed and implemented successfully. Furthermore, a biomimetic soft robotics that can realize both in-plane and out-of-plane locomotion is demonstrated using only magnetic field. The novel 3D motion of the demonstrated system facilitates the development of practical LM-based smart structures and devices.

1. Introduction

Recently, room temperature liquid metals (LMs) have attracted significant scientific attention. In particular, interest in nontoxic gallium-based alloys, such as eutectic gallium–indium alloys EGaIn and Galinstan, has grown owing to their intriguing and unexpected properties, including high flexibility, low viscosity, and excellent fluidity. Consequently, EGaIn and Galinstan have been used for various applications, such as pumps, electrical devices, actuators, wearable electronics, and soft robotics. Manipulating LMs as flexibly and freely as in the movie Terminator has long been a dream for many scientists across a range of scientific and technological disciplines, ranging from mechanics to biology. Tremendous progress in controlling the locomotion and deformation of LMs has been demonstrated experimentally. Among them, the actuating method of LMs via the application of an external electric field is the most investigated approach and one that has led to remarkable progress. Nevertheless, the use of an electric field has some limitations. First, this actuating method requires certain conditions, such as the use of an electrolyte and electrodes, which make the actuating process complicated. In addition, a channel is necessary for the LM to move. The need for a channel limits the directionality and flexibility of the LM’s locomotion. The production of hydrogen gas owing to electrochemical reactions also has safety issues.

Magnetic manipulation of LM is an alternate approach that avoids some of the aforementioned limitations, and opens a new path to achieve practical LM-based smart structures and devices. Several magnetic-field-based control approaches have been experimentally demonstrated by mixing different magnetic particles (e.g., gadolinium, nickel, iron, copper–iron magnetic nanoparticles) into LMs, resulting in excellent magnetic steering capacity. For example, LM droplets simultaneously actuated by both magnetic and electric fields showed good analogous properties as those of pure LM. The climbing motion of LM droplets against gravity could be realized by both magnetic and electric effects for the first time. A recent experimental investigation explored the manipulation of LMs magnetically in the 3D space. The magnetic LM droplet was composed of Galinstan and iron particles. It exhibited good stretching capacity, and an intelligent scalable conductor was achieved in 3D space; however, deformation and locomotion in 3D space also required the presence of both magnetic and electric fields (i.e., the electrolyte was still essential), which hindered the development of LMs for practical application. To date, the locomotion and actuation of LMs via only a magnetic field in 3D space remain underexplored.

In this study, a new method for manipulating LMs in open 3D space using only a magnetic field is introduced. The magnetic LM device was moved not only along various complex pathways in the horizontal plane, but motion was also realized for the first time in open 3D space without the use of electrolytes and electrodes. As a proof-of-principle, we designed and implemented an intelligent delivery vehicle, which could avoid obstacles and traps horizontally and overcome gravity to move vertically in an open 3D space. A cargo could be unloaded under the actuating force of only the magnetic LM. In parallel, a biomimetic soft robotics that can realize both in-plane and out-of-plane locomotion is demonstrated using only magnetic field. The novel and desirable properties demonstrated by this system could greatly facilitate the practical development of LM-based smart structures and devices.
2. Results and Discussion

2.1. The Preparation of Magnetic LM Droplet

Figure 1 shows the main fabrication process for the magnetic LM. First, 2.85 g of Galinstan was put into a dish without any solution, as shown in Figure 1a. Next, we added 0.3 g of iron particles onto the surface of Galinstan, as shown in Figure 1b. An oxide layer formed easily on the surface of both the Galinstan and the iron particles when exposed to air and prevented other materials from entering into the Galinstan droplet. The oxide layer was viscous enough that the iron particles could stick to the surface of the Galinstan. After that, 4 mL of hydrochloric acid was added into the dish to remove the oxide skin of both the iron particles and Galinstan (Figure 1c), which contributed to the mixing of the iron particles with LM.\(^{35,36}\) Then, the mixture was stirred with a magnetic stirrer for 2 min to accelerate the mixing of the iron particles with the LM. The ratio of the iron particles in the mixture was calculated by weighing the LM droplet (3.02 g). Finally, a 3.02 g magnetic LM droplet with an iron mass fraction of 5.6% was realized (see the maximum amount of the iron particles deposited on the LM droplet in Figure S1, Supporting Information). The mixture of the iron particles and the LM was uniform and maintained its metallic luster, liquidity, and the electrical actuating performance (see Figure S2–S4, Supporting Information). When stirred with a glass rod, the magnetic LM droplet still showed excellent flexibility and mobility. As expected, the magnetic LM droplet could move flexibly when attracted with several permanent magnets.

2.2. The Critical Separation Force between the Magnetic LM and the Iron Particles

When the magnetic LM droplet was manipulated via the external magnetic field, a critical separation force existed between the magnetic LM droplet and the iron particles. The iron particles would separate from the magnetic LM droplet if the attraction between the magnets and the iron particles was greater than the adhesion force between the iron particles and the LM droplet. We defined this applied force as the critical separation force. To guarantee controllable manipulation of the magnetic LM droplet, bevel experiments on the magnetic LM droplets were designed and conducted to investigate the critical separation force under different mass fractions of iron particles and different magnetic induction intensities. We fabricated eight magnetic LM droplets (≈3 g for each droplet) with the abovementioned method, and the weight ratios of the iron particles in the magnetic LM droplets were ≈0.5%, 1%, 2%, 3%, 4%, 6%, 6.5%, and 9%. The experimental setup is shown in Figure 2a. The experimental results were recorded, such as the critical angle and the lifting height of the bevel. The critical separation force can be expressed as

\[
F = mg \sin \theta = \frac{mgH}{L}
\]

where \(F\) is the critical separation force, \(m\) is the mass of the magnetic LM droplet, \(g\) is the gravitational acceleration, and \(\theta\) is the angle between the bevel and the horizontal plane. \(L\) and \(H\) are the side length of the bevel and the lifting height of the other end of the bevel, respectively.

Figure 2b shows the relationship between the critical separation force and the magnetic induction intensity with different mass fractions of iron particles. For a certain mass of the magnetic LM droplet, the critical separation force increases alongside the increasing magnetic induction intensity. We also observed that the critical separation force increases with increasing iron particle content in the LM droplet. Moreover, the critical
separation force goes up to a saturation position when the magnetic induction intensity was ≈1300 Gs. It is probably owing to the magnetic field force is larger than the critical force between the iron particles and LM material, resulting in a clumping of the iron particles in the magnetic LM droplet. As shown in Figure S5a,b, Supporting Information, under the condition without magnetic field or in a weak magnetic field, the iron particles were well distributed in the LM droplet, because the attraction between the magnetic field and the iron particle was too little to change the location of the iron particle. However, as shown in Figure S5c–f, Supporting Information, as the magnetic field gets stronger than the critical force, the iron particles in LM droplets gathered obviously near the magnetic field.

2.3. Complex Motions of the Magnetic LM Droplet in a Plane

To show the flexibility of the magnetic LM droplet manipulated by the external magnetic field, we manipulated the magnetic LM droplets along various designed paths on a horizontal plane, as shown in Figure 3. Magnetic LM droplets were placed on a plane (≈3 g for each LM droplet, 6 wt% iron particles). The magnetic LM droplets were controlled simultaneously by several magnets, which provided a magnetic induction intensity of 1300 Gs each.

As shown in Figure 3, the designed motion pathways were round, rectangular, S-shaped, as well as one imitating the Earth’s rotation around the Sun. The flexibility of the magnetic LM can be observed more intuitively from Movie S1, Supporting Information. The magnetic LM droplet could clearly move not only in a straight line but also in a complex curved path. Moreover, linear acceleration experiments of the magnetic LM droplet were carried out with a magnet in the plane over 15 cm of acceleration distance. The velocity of the magnetic LM reached 0.8 m s⁻¹, and the velocity could be further increased if a longer acceleration distance is used. Flexibility of locomotion would allow for magnetic LMs with greater potential for both scientific research and applications. For example, the magnetic manipulation of complex motion can benefit the liquid cooling system [6,37] and can be used for the accurate deposition of LM droplet onto the hot spots to enhance the heat transfer via conduction and convection mechanisms.

2.4. Bouncing Motion of the Magnetic LM Droplet in 3D Free Space

A series of experiments were conducted to explore the locomotion of the magnetic LM droplet in 3D free space. As shown in Figure 4a, by increasing the mass fraction of the iron particles and adjusting the magnetic induction intensity and the distance between the two parallel sheets, we obtained a suitable set of parameters to make the LM droplet bounce in free 3D space (see Movie S2, Supporting Information, for more details). The distance between the two parallel acrylic sheets was 20 mm, and the magnetic induction intensity was 250 Gs. The mass of the magnetic LM droplet was 2 g, and the mass fraction of the iron particles was 15%. Through a series of experiments, the critical mass fraction of the iron particles was obtained, which could make the magnetic LM droplets to bounce in 3D space. The relationship between the critical mass fractions of the iron particles and the mass of the magnetic LM droplets is shown in Figure 4b. However, the magnetic field strength of the magnets was limited. If the distance between the two sheets was too large, the magnetic field could not lift the magnetic LM droplet. To obtain the desired magnetic induction intensity practically, we investigated the relationship between the magnetic induction intensity and the distance between the magnetic LM droplet and the magnets. We divided a number of magnets into three different combinations, which had the surface magnetic induction intensities of 3100, 2400, and 1560 Gs. Then, the different magnetic combinations were placed on a plane with a scale, and then, the magnetic induction intensity was measured at different positions. The results are shown in Figure 4c. The magnetic induction intensity decreased rapidly when the distance varied from 0 to 20 mm. According to the red curve of the experimental results, the distance between the two plates (equal to the distance between the magnet and the magnetic LM droplet) was selected as 20 mm, and the magnetic field intensity at this distance was 250 Gs. We could also increase the distance between the two plates if a stronger magnetic field was generated.

Apart from making the LM ferromagnetic, the iron particles could also provide a cohesive force for the magnetic LMs, which makes the LM mechanically robust under impact and maintains the LM structure as a whole sphere (see Figure S6, Supporting Information). To demonstrate that the abovementioned property of the magnetic LM droplet was induced by the iron particles, we prepared a Galinstan droplet and a magnetic LM droplet with 20% iron particles (≈5 g of each droplet), respectively. Then, released the two droplets from different heights of 15 and 5 cm. As experimentally shown in Figure 4d, when they collided in the dish, the pure LM droplet deformed to a thin

Figure 3. Different movement paths of the magnetic LM droplet in a plane. a) The circle path. b) The rectangular path. c) The eight-shaped path. d) The path of imitating the Earth’s rotation around the Sun.
droplet or dispersed and was unable to be restored to its spherical shape. The pure LM droplet could maintain its shape because of the high surface tension. According to the Young–Laplace equation:

\[ \Delta p = \gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \]  

(2)

where \( \gamma \) is the surface tension of LM droplet, \( 1/R_1 \) and \( 1/R_2 \) are the principal curvatures for the curved surface at the periphery of the droplet, and \( \Delta p \) is the pressure difference between the LM droplet and the air. However, oxide formed on the surface of the LM droplet during the fall, which severely decreased the surface tension of the LM droplet. The pressure difference (\( \Delta p \)) decreased alongside the decrease of the surface tension (\( \gamma \)). Therefore, the LM droplet could easily deform when an external pressure (provided by the impact) was applied to it, which was consistent with the experimental results. When the drop height was small (the external pressure was small), the LM droplet could maintain its shape owing to the surface tension but deformed to a thin droplet. During this process, new surfaces were exposed to air and quickly oxidized. The new oxide layer formed on the LM droplet further reduced the surface tension of the droplets. Therefore, the LM droplet did not revert to its original spherical shape. However, the surface tension lost its effectiveness if the collision had sufficient force (the external pressure was large, e.g., \( H = 15 \) cm). Consequently, the LM droplet dispersed into many independent droplets, which could not be gathered without an additional external force. The abovementioned phenomenon limits the locomotion performance of the LM droplet in 3D space. Fortunately, as the experiments showed, the iron particles in the magnetic LM droplet could prevent the LM droplet from dispersing when subjected to an impact. The magnetic LM droplet maintained an approximately spherical shape when the height of the drop was small. Even for a strong impact (\( H = 15 \) cm), the magnetic LM still could maintain its shape, as shown in Figure 4d. A series of experiments were also conducted to measure the contact angles of LM droplets with...
different mass fractions of iron particles to rule out the influence of wettability (see Figure S8, Supporting Information, for more details). We used two diagrams to analyze the forces imposed on the pure LM droplet and the magnetic LM droplet during the crash process. As shown in Figure 4e, when the pure LM droplet was subjected to impact, the dish applied a pressure ($P_1$) to the droplet and compressed it. The horizontal pressure ($P$) was produced by the compression process. Therefore, the deformation took place at the periphery of the pure LM droplet. However, the iron particles could reduce the deformation of the magnetic LM droplet in two ways, as shown in Figure 4f. The iron particles reduced the degree of compression, which resulted in a smaller horizontal pressure ($P_2$). In addition, the adhesive force between the iron particles and the LM would further reduce the horizontal pressure ($P_2$), which resulted in the pressure on the magnetic LM droplet ($P_2$) being much smaller than that of the pure LM droplet. Therefore, the magnetic LM droplet could more easily maintain its shape. In addition, we released the magnetic LM droplet for the height of 20 cm and repeated the impacting experiment for 100 times. After exposed it to air and oxidized for 24 h, we put it in HCl solution and stirred with a glass rod for 2 min, and then repeated the impacting experiments for 100 times again. As shown in Figure S7, Supporting Information, the magnetic LM droplet still maintain its integrity shape and metallic luster. The measured results further prove that the magnetic LM droplet has good mechanical robustness.

### 2.5. Intelligent Vehicle

As a practical proof-of-principle application, we designed an intelligent vehicle driven only by the magnetic LM. It was expected to avoid obstacles and traps according to the various path conditions and unload a cargo via a jump of the magnetic LM droplet. For miniaturization of the vehicle, we used 1 g of magnetic LM as the actuating power system. The mass fraction of the iron particles was set at 15% to increase the power of the vehicle. The route of the LM vehicle is shown in Figure 5a, and we set obstacles and traps on the designed path. The magnetic LM vehicle moved straight initially, and then turned left to avoid the obstacle when approaching it. After avoiding obstacles, it continued forward to deliver the cargo until it encountered a trap. By turning right, it bypassed the trap and continued its delivery mission. After the vehicle reaching the destination, the magnetic LM droplet inside the vehicle was moved to the rear of the vehicle. Then, the magnetic LM droplet jumped up via the external magnetic field, leading to a certain angle of rotation of the vehicle, and ultimately, the cargo was offloaded.

To further explore the automatic unloading capability of the vehicle, we investigated the vertical actuating force of the magnetic LM under different magnetic induction intensities and iron mass fractions. We prepared three magnetic LM droplets (1 g of each droplet) with the mass fractions of 10%, 15%, and 20%. Then, we tested the attraction of the magnetic field to the magnetic LM droplet at different magnetic induction intensities.

As shown in Figure 5b, both the magnetic induction intensity and the mass fraction of the iron particles had large effects on the actuating force of the magnets to the magnetic LM droplet. In our intelligent vehicle experiment, the distance between the magnets and the magnetic LM was 22 mm, higher than the distance in the jumping experiment (20 mm). Therefore, the magnetic induction intensity would decrease (down to 220 Gs), which influenced the vertical acting force between the magnetic LM and the magnets. Thus, the mass fraction of iron was increased to 15% to enhance the vertical tension. More details on the locomotion of the vehicle are provided in the Supporting Information (Movie S3, Supporting Information). The results show that the magnetic LM vehicle possessed excellent cargo transport capability. The proportion of the overall weight of the vehicle and the weight of magnetic LM was up to 3.7/1. The proportion could be further improved by decreasing the friction and enhancing the magnetic induction intensity. Moreover, increasing the mass of the magnetic LM and the mass fraction of the iron particles could also improve the delivery capacity. In short, not only did the vehicle have excellent cargo delivery capacity, but it also had the ability to choose the appropriate path.
when encountering obstacles. In addition, it could unload a cargo automatically against gravity via only the magnetic field.

2.6. Biomimetic Soft Robotics

The excellent deformability and mobility of LM objects exhibit significant potential as soft robots or machines. We designed and demonstrated a biomimetic soft robotics to explore the freely manipulating ability in the open 3D space. We prepared the magnetic LM of 20 g with the mass fractions of 20% Fe; then, we put it on a horizontal acrylic sheet, which daubed a uniform layer of HCl solution. The magnetic LM was manipulated into a cylindrical shape with a glass rod, and the length of the magnetic LM was about 5 cm. Placed a vertical acrylic sheet on one side of the magnetic LM, and used magnets to steer magnetic LM across the vertical acrylic panels. The magnetic induction intensity applied to the magnetic LM by magnets was about 800 Gs. Finally, we realized the movement of magnetic LM such as a worm, as shown in Figure 6 and Movie S4, Supporting Information. We repeated the bionic movement of magnetic LM for 50 times successfully. Owing to the HCl solution daubed on the acrylic sheet evaporated over time, then the oxide was formed on the surface of magnetic LM. The magnetic LM could not realize the bionic movement on the acrylic sheet for more times. To confirm our analysis, we daubed a layer of HCl solution on the acrylic sheet, and the magnetic LM could realize the bionic movement again. The proof-of-principle experiment shows the strong deformability and mobility of our treated magnetic LM.

3. Conclusions

In summary, a novel, non-contact, and electrolyte-free container manipulation method was developed using only a magnetic field and a magnetic LM to achieve 3D motion and actuation. We fabricated the magnetic LM by mixing iron particles with pure Galinstan, and it exhibited an excellent appearance, flexibility, and mobility. The critical separation force between the magnetic LM and the iron particles was analyzed to ensure controllable steering to the magnetic LM. The magnetic LM was actuated to not only move along various complex paths in the horizontal plane, but to also realize 3D locomotion of the LM without electrolyte and electrodes, which had not been previously accomplished. As a conceptual product, we created an intelligent delivery vehicle that could realize complex locomotion both horizontally and vertically in 3D free space to offload a cargo using only the magnetic LM. We also demonstrated a biomimetic soft robotics that can realize both in-plane and out-of-plane locomotion using only magnetic field. The novel and meaningful manipulation capability has the potential to promote current work on anti-gravity locomotion and actuation of magnetic LMs in open 3D space.

4. Experimental Section

Materials: All the magnetic LM droplets used in these experiments were synthesized from iron particles and Galinstan (composed of 68.5% Ga, 21.5% In, and 10.0% Sn by weight) with a purity of 99.99%. The iron particles (≈45 μm in diameter) were purchased from XiangTian Nano Materials Technology. All the HCl solutions (HCl, 10 wt%) used in experiments were prepared with deionized water and standard hydrochloric acid solution (37 wt%). The weight of the Galinstan and the iron particles was measured using an electronic balance (an accuracy of 0.001 g). The model of the magnetic stirrer used for materials mixing process was JJ-1A-300W. The magnetic field was provided by several permanent magnets (NdFeB). Then, the figures and videos of the magnetic LM droplet were recorded using a digital video equipment, Canon EOS M6.

The Setup of the Bevel Experiment: The bevel experimental setup consisted of two similar acrylic sheets. The length, width, and thickness of the acrylic sheets were 200, 200, and 1 mm, respectively. One acrylic sheet was placed horizontally, and the other was tilted. A magnet was fixed on the back of the bevel (the tilted sheet), and the magnetic LM droplet was placed on the front of the bevel. Raised the angle of the bevel slowly until the magnetic LM droplet slid. Then, recorded the critical angle and the lifting height of the bevel.

The Experimental Setup of Complex Motions in a Plane: First, we prepared a smooth plastic plate with a surface that was covered with a uniform layer of HCl solution to prevent the magnetic LM from sticking.

![Figure 6](https://www.advancedsciencenews.com/)

**Figure 6.** The biomimetic soft robotics of the magnetic LM in the 3D space.
Galium is oxidized to Ga$_2$O$_3$ when exposed to air.[38] The oxide is prone to stick to the surface of most materials, which prevents locomotion of the magnetic LM droplet. However, the layer of HCl solution allows the magnetic LM droplet to move smoothly on the surface of the plate. The HCl solution could not only remove the oxide where the magnetic LM contacts with the plate, but could also volatilize a small amount of gaseous HCl to reduce the formation of the oxide when the magnetic LM was exposed to air.[39]

The Setup of the Bounce Experiment: Two parallel acrylic sheets were used to form a space in which the LM droplet could bounce. A magnet was then placed above the acrylic sheet, and a magnetic LM droplet was used to form a space in which the LM droplet could bounce. A magnet to reduce the formation of the oxide when the magnetic LM was exposed with the plate, but could also volatilize a small amount of gaseous HCl and height of the vehicle was a chamber (l, w, and h were 20, 10, and 8 mm, respectively). The top of the vehicle was a bucket, and the total weight of the LM vehicle was ≈3.7 g. The magnetic LM droplet was allowed to move inside the chamber, to control the vehicle steering and unloading of the cargo. Furthermore, to clearly observe the actuating process of the magnetic LM, a transparent acrylic board was used to build the vehicle body. The bucket was made by polyactic acid (PLA) polymer material with a 3D printer.

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

Acknowledgements
The authors thank the support of National Natural Science Foundation of China (Grant No. 51575431), China Scholarship Council (Grant No. 201806285008), China Postdoctoral Science Foundation funded project (Grant No: 2014M550485 and 2015T81019), and Shaanxi Province Postdoctoral Science Foundation funded project. They also thank Mr. Zijun Ren at Instrument Analysis Center of Xi’an Jiaotong University for their assistance with the scanning electron microscope analysis.

Conflict of Interest
The authors declare no conflict of interest.

Keywords
3D manipulation, biomimetic soft robotics, free locomotion, intelligent vehicle, magnetic liquid metals

Received: December 10, 2019
Revised: June 1, 2020
Published online: July 12, 2020

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