A grid-assisted 3D printing method for magnetically driven micro soft robot

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Abstract. The magnetically driven micro soft robot is one of the research hotspots in the field of micro robots. A 3D printing method for manufacturing micro soft robots with the help of auxiliary grids is proposed. The shape flexibility of the micro soft robots manufactured by the micro 3D printing method can be improved, and internal structures composed of different materials inside the micro robots can be printed using this method. The technical details of the grid-assisted 3D printing process are introduced in this article. Micro soft robots with specific patterns were 3D printed, and the deformation and movement capabilities of the robots were verified in magnetically driven motion experiments. The experimental results prove that the grid-assisted 3D printing technology can not only manufacture magnetically driven micro soft robots, but also adjust the internal structure and motion performance of the robots.

1. Introduction

Micro robots are one of the research hotspots in the field of robotics [1], and have broad application prospects in the fields of biology, medical treatment and micro-assembly. Micro soft robots imitate the movement mechanism of microbes in nature [2], interact with the surrounding environment through deformation, thereby pushing themselves to move on the surface of the liquid, inside the liquid or on the solid surface [3]. They received more and more attention from researchers in recent years [4]. Magnetically driving method is an important driving method for micro soft robots, which has many advantages such as high penetration and low side effects [5].

Since most of the soft materials are not magnetic, magnetically driven micro soft robots mostly use the method of adding magnetic powder into the soft materials to provide the robot with magnetism.
One manufacturing method is to magnetize the magnetic powder before manufacturing, and then adjust the magnetic moment direction of the magnetic powder through an external magnetic field during manufacturing the micro-robot [6]. Another manufacturing method is not to magnetize the magnetic powder before manufacturing, but to adjust the micro robot to a specific posture after the manufacturing is completed, and then uniformly magnetize the magnetic powder with an external magnetic field in this posture [7]. One way to control the shape of micro robots is additive manufacturing, that is, constantly adding new parts to the existing appearance [8]. Another way to control the shape of micro robots is conventional manufacturing, that is, the material is directly filled into the mold, or a large piece of material is manufactured and then cut into the desired shape by a knife or laser. The micro soft robots manufactured by the additive manufacturing method can be designed with shapes and internal structures more flexibly, so the additive manufacturing method is more advanced and convenient.

At present, much research on magnetically driven micro soft robots focuses on the overall shapes and movement mechanism of the robots [9] [10], and there is little research on the internal structures of the robots or their manufacturing methods. 3D printing is an advanced additive manufacturing method, which has the advantages of high flexibility and programmability, and has more and more applications in the manufacture of micro-robots [11]. Among the 3D printing methods, the material extrusion technology has the advantages of fast speed and low cost when manufacturing millimeter-level micro soft robots. In previous research, a material extrusion micro 3D printing technology that controls the shape of the print with the help of surface tension is published [12]. Based on the previous technology, the effect of grid-assisted 3D printing on the shape and structure of the micro soft robot is further studied in this article, and magnetically driven micro soft robots with specific internal structures are manufactured.

2. Materials and methods
The micro soft robot is composed of soft material with high flexibility and metal powder with high magnetism. The magnetic powder is mixed into the fluid soft material, then the soft material is converted into the solid micro robot with high flexibility through curing methods such as thermal curing and UV curing. This article uses silicone (Ecoflex 00-30 platinum cure silicone rubber compound, Smooth-On) as the main material of the micro soft robot, and uses neodymium iron boron magnetic powder (MQFP 15-7, Magnequench) to provide the micro soft robot with a magnetic field driving force. In the previous research, a method of using auxiliary wires to restrain the silicone, to programmatically 3D print the micro soft robots was published. In this paper, a piece of surfactant (hoda water and oil resistant) treated glass slide is used as the printing substrate, and the UV curing adhesive (loctite 352 light cure adhesive) is used to print auxiliary lines. The micro 3D printing equipment includes a material extrusion module, a three-dimensional motion platform and an image acquisition module. Its core functional structure is shown in figure 1(a). The micro 3D printing software is self-developed by our team, and multiple printing scripts can be written and loaded in the software, as shown in figure 1(b) [13].

In this article, based on the aforementioned research, the improvement brought by the auxiliary grids in the 3D printing process of the micro soft robots is further studied. With the help of the
auxiliary grids, the entire printing area is divided into multiple small areas adjacent to others, and each small area can be individually printed using different printing materials and printing parameters. A micro soft robot is composed of the printing materials in these small areas. By applying the printing materials and parameters for each area, the flexibility of the shapes and internal structures of the micro soft robots can be greatly improved.

Figure 1. The core structures (a) and script execution interface (b) of the micro 3D printing system.

3. Results and discussion

3.1 Printing the grid array

When using UV curing adhesive to print a grid array, choose different printing pressures and speeds to adjust the thickness and height of the grid lines. Lines of different thicknesses will affect the surface properties and overall rigidity of the printed micro soft robot to a certain extent, but the effect is not significant. When using a printing pressure of 80kPa and a printing speed of 500um/s, the printed auxiliary lines are shown in figure 2(a). When using a printing pressure of 150kPa and a printing speed of 200um/s, the auxiliary lines printed are shown in figure 2(b).

Different distances between lines determine the size of each area of the micro soft robot. Although in theory, the smaller distance between lines, the more precise the micro soft robot can be printed. However, the realization is limited by the caliber of the printing needle, so the line spacing cannot be set too small. The caliber of the printing needle is restricted by the printing material. According to previous research results, NdFeB magnetic powder with an average diameter of 5um requires a printing needle with a diameter of above 30um in order to print more stably. To avoid clogging of the print needle, a certain flow rate of silicone needs to be guaranteed, so the distance between the auxiliary lines is 200um.

Figure 2. The UV curing adhesive is used to print the grid array with thin (a) and thick (b) lines.
3.2 Printing designed patterns

The essence of the pattern is the difference information formed by different materials distributed in different areas with specific geometric relationships. There is not much research on the existing manufacturing methods of micro soft robots in this respect. With the help of auxiliary grids, the micro 3D printing method can print one material in an area with a specific geometric relationship and other material in other areas, thereby achieving differentiated printing. If these materials have different optical properties, the printed micro soft robot has a visible optical pattern structure. The internal structure printed in this way can not only change the deformation and motion performance of the robot, but also use patterns to convey other information.

With the help of the grid formed by auxiliary lines, silicone mixed with magnetic powder and silicone without magnetic powder were used for differential printing, thereby printing designed patterns. In the experiment, a micro soft robot with a length of 4mm, a width of 1mm, and an average thickness of about 70um was designed and printed. The robot consists of 5x20 areas, while each area is a square with a side length of 200um. The three letters "HIT" with silicone mixed with magnetic powder are printed first, as shown in figure 3(a). After printing the letters, the remaining areas are printed with silicone without magnetic powder, as shown in figure 3(b). In order to cope with the reduction of the magnetically driving force caused by the reduction of the magnetic powder area, a driving head entirely composed of silicone with magnetic powder is printed on one end of the robot.

![Figure 3. During printing patterns, the silicone with magnetic powder is printed first (a), then the silicone without magnetic powder is printed (b).](image)

3.3 Printing the two-layer structure

The printing height using the 3D printing method with the help of surface tension is directly affected by the printing area. If the entire area was printed directly, it is relatively difficult to reduce the overall print height. With the help of the grid-assisted printing method, the minimum height of the printing can be greatly reduced while the printing complexity is increased. Under the action of the surfactant, the actual flow of silicone is restricted by auxiliary lines. Before exceeding a certain limit, adding silicone to the restricted area will only increase the printing height of the area, and will not change the printing area. Therefore, after completing a print with a lower height, other materials can be added onto the printed material to achieve a two-layer structure composed of different materials.

In the experiments, the basic grids with a side length of 200um were printed first. Then the cross-shaped silicone mixed with magnetic powder in a 3x3 grid was printed, as shown in figure 4(a).
In the four adjacent areas around the cross, silicone without magnetic powder was printed, as shown in figure 4(b), so the flat structure of 3x3 grids is formed. Silicone without magnetic powder was added directly above the area to increase the overall printing thickness, as shown in figure 4(c)(d). It can be seen from figure 4(c) that the silicone mixed with magnetic powder and the silicone without magnetic powder have an obvious interface, although the interface is not flat due to surface tension.

Figure 4. The two-layer structure silicone block with a cross-shaped pattern is printed. (a) The lower layer with magnetic powder. (b) The lower layer without magnetic power. (c) The horizontal viewing of the higher layer. (d) The oblique view of the higher layer.

3.4 The Magnetically Driven Motion Experiments

After being magnetized, the micro soft robot is placed in glycerin, then deformed and moved under the action of a magnetic field. Experiments proved that the printed micro soft robot can deform under the action of a magnetic field, thereby pushing itself forward. Based on the scallop theorem, when a micro robot moves in a fluid with a low Reynolds number, it must have time-reversal asymmetry, which is the natural advantage of soft materials. The use of glycerin with a low Reynolds number is to mimic the fluid environment at a smaller scale.

In order to carry out the magnetically driven experiments, two different micro soft robots with the "HIT" pattern were printed. The thickness of the first robot is 70um, and the grid lines are thin, so it is difficult to see the grid in the image, as shown in figure 5(a). The second robot has a two-layer structure with a total thickness of 130um and thicker grid lines, so the grids were clear in the monitor image, as shown in figure 5(b). In the experiments, the first robot was driven by the swinging magnetic field, pushing itself downstream through the deformation of the tail, as shown in figure 5(c)(d). The second robot is thicker than the first robot and contains less magnetic particles, resulting in smaller deformations driven by the magnetic field. The greater thickness brings greater buoyancy, so the driving force brought by its deformation cannot overcome the buoyancy to push itself to move.
Figure 5. Patterned micro soft robots with thinner (a) and thicker (b) sizes are placed in glycerin, and the thinner one swims downwards driven by a swinging magnetic field (c-d).

4. Conclusion

Many existing additive manufacturing methods for micro soft robots can only manufacture micro soft robots with common structures, and lack flexibility in shapes. The grid-assisted 3D printing method introduced in this article can be used in printing micro soft robots with internal structures composed of different materials, and improve the shape control ability of the original 3D printing method. This method has high flexibility, low cost, and great expansion potential.

Through the grid-assisted 3D printing method, magnetically driven micro soft robots with specific patterns, better shapes and two-layer structures were successfully printed. In the experiment, it was found that because the total amount of magnetic powder forming a specific pattern is less than the total amount of magnetic powder filling the entire area, the micro-soft robot with a specific pattern has a lower driving force. Adding other areas with magnetic particles besides the pattern can be effective to improve the movement performance of the robot. The two-layer structure increases the thickness of the micro soft robot while reducing the total amount of magnetic powder, so further reducing the deformability of the micro soft robot. However, the auxiliary grids reduce the minimum printing height of the micro 3D printing method based on surface tension, and can print thinner and softer micro soft robots, thereby improving the robots' deformability.

Using the grid-assisted 3D printing method, the specific printing parameters and structure can be arbitrarily selected according to the needs, so the flexibility of the micro 3D printing method based on surface tension is greatly improved. In the following research, we will continue to improve this 3D printing method, and study the influence of other materials, other parameter grids and other patterns on printing accuracy, stability and application scenarios. The grid-assisted 3D printing technology can enrich the structure types and motion forms of magnetically driven micro soft robots, and further promote the development of the field of micro robots.

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References

[1] Abbott, J. J., Peyer, K. E., Lagomarsino, M. C., Zhang, L., Dong, L., Kaliakatsos, I. K., Nelson, B. J. (2009) How Should Microrobots Swim? The International Journal of Robotics Research, 28(11–12): 1434–1447.

[2] Palagi, S., Fischer, P. (2018) Bioinspired microrobots. Nature Reviews Materials, 3(6):113-124.

[3] Ng, C.S.X., Tan, M.W.M., Xu, C., Yang, Z., Lee, P.S., Lum, G.Z. (2021) Locomotion of miniature soft robots. Advanced Materials, 33:2003558.

[4] Mariana Medina - Sánchez, Magdanz, V., Guix, M., Fomin, V. M., Schmidt, O. G. (2018). Swimming microrobots: soft, reconfigurable, and smart. Advanced Functional Materials, 28(25):1707228.1-1707228.27.

[5] Eshaghi, M., Ghasemi, M., Khorshidii, K.. (2021). Design, manufacturing and applications of small-scale magnetic soft robots. Extreme Mechanics Letters, 1:101268.

[6] Kim, Yoonho, Yuk, Hyunwoo, Zhao, Ruike, et al. (2018). Printing ferromagnetic domains for untethered fast-transforming soft materials. Nature, 558:274-279

[7] Hu, W., Lum, G. Z., Mastrangeli, M., Sitti, M. . (2018). Small-scale soft-bodied robot with multimodal locomotion. Nature, 554:81-85.

[8] Huang, H. W., Sakar, M. S., Petruska, A. J., S Pané, Nelson, B. J. . (2016). Soft micromachines with programmable motility and morphology. Nature Communications, 7:12263.

[9] Rus, Daniela, Tolley, Michael, T. (2015). Design, fabrication and control of soft robots. Nature, 521:467-475.

[10] Tian, Tung-Chun, Mark, Andrew, G., Morozov, Konstantin, I., et al. (2014) Swimming by reciprocal motion at low Reynolds number. 5:5119

[11] Li, J., Pumera, M. (2021) 3D printing of functional microrobots. Chemical Society Reviews, 50(4): 2794-2838.

[12] Gao, J., Rong, W., Gao, P., Wang, L., Sun, L. (2021). A programmable 3D printing method for magnetically driven micro soft robots based on surface tension. Journal of Micromechanics and Microengineering, 31(8):085006.

[13] Gao, J., Rong, W., Zhang, Y., Wang, L., Sun, L. (2020) Semi-automated 3D Printing System for Magnetic-driven Microrobots. In: 2nd IEEE Eurasia Conference on IOT, Communication and Engineering 2020, Yunlin, p 407-409.