Based on nanoparticles
Orientable ferromagnetic
Liquid

Adilzhan Ayazbek

Abstract

Soft robots controlled by an external magnetic field are capable of performing movement and manipulation tasks effectively thanks to their ability to undergo programmed deformations, which in turn opens up access to hard-to-reach areas of the human body and expands the possibilities for minimally invasive medical interventions. Despite the potential of such systems, most existing solutions are based on the use of elastomeric materials, whose mechanical properties limit the degree of their deformation, reducing their effectiveness in confined spaces and fixing their functionality at the design stage without the possibility of adaptation during operation.

This project has developed a control system for ferrofluid droplets that function as programmable magnetic soft robots. Using programmable electromagnets, the system allows temporary adjustment of external magnetic fields. This enables the movement of droplets through narrow channels, their separation and merging for targeted delivery of liquid cargo, as well as dynamic reconfiguration for precise manipulation of delicate objects. The behavior of ferrofluid droplets was also studied under magnetic attraction, which allowed their behavior in response to changes in magnetic fields to be recorded. This approach demonstrates significant potential for application in confined spaces, including biomedical devices and spacecraft, where autonomy is critical to the success of long-duration space missions.

1. Introduction

Soft robotics is a rapidly developing field focused on creating flexible mechanisms based on soft, pliable materials, and in recent years it has attracted particular attention from the scientific community [1-3]. Unlike traditional rigid structures, soft robots have the ability to bend, stretch, and deform, which opens up fundamentally new approaches to performing standard robotics tasks, such as precise manipulation of objects and adaptive locomotion. The use of soft robots is particularly relevant in biomedicine, where high safety, minimal risk of damage, and wireless control are required [11,12].

This study considers a new class of soft systems—ferrofluid droplets controlled by external magnetic fields. The liquid nature of ferrofluid provides maximum flexibility and biocompatibility, allowing the droplets to penetrate narrow channels and bypass complex obstacles [18–20]. However, many existing control methods do not provide the necessary force and accuracy for complex manipulation and targeted delivery tasks [24,25]. Our goal is to create a control system for our own ferrofluid and find out how its droplets behave under different magnetic fields. To do this, we are improving the stability of the nanoparticles so that the droplets do not oxidize and retain their shape, and then use electromagnets to program their movement and deformation.

2. Literature Review

Among the various areas of soft robotics, the development of soft magnetically controlled systems with a high degree of controllability and functional flexibility occupies a special place. [4] It is important to note that, compared to other activation methods, such as light [5,6], heat [7], electricity [8,9], and chemicals [10], soft robots with magnetic control have a number of obvious advantages. They provide wireless control, are highly safe, and can respond quickly to control inputs, making them particularly suitable for use in hard-to-reach and sensitive environments, as well as attractive for biomedical applications [11,12]. Modern developments in soft robotics actively use composites that include magnetic elements, such as micro- and nanoparticles, embedded in malleable materials: elastomers [13,14] and hydrogels [15]. These flexible designs allow the creation of micro-robots capable of performing a variety of tasks under the influence of an external magnetic field. Their distinctive feature is not only their ability to deform, but also their ability to change their mode of movement, for example, to switch from translational to rotational depending on the environment [16].

However, the potential advantages of such systems are limited by engineering solutions that are laid down at the design stage. In particular, the predetermined shape and trajectory of the robot's deformation reduce its ability to adapt to rapidly changing conditions or pass through particularly narrow and complex areas. This can not only affect the effectiveness of control, but also lead to mechanical damage to both the device itself and the surrounding tissues or structures [17].

Unlike soft robots based on elastomers, magnetic field-controlled droplets, such as ferrofluids, which are stable colloidal solutions of magnetic nanoparticles and combine excellent magnetic and fluid properties [18], are much softer and gentler [19].

Due to their liquid nature, they are able to move in narrow and confined spaces more effectively than soft robots made of elastomers, while maintaining biocompatibility and minimizing the risk of damage to surrounding biological tissues during biomedical procedures [20]. Many research groups around the world are actively studying the potential of miniature robots based on ferrofluids. Their experiments have not only demonstrated impressive results, but also helped to reveal the key mechanisms that control the behavior of such systems [20-23]. For example, in one of their significant works, Natsov and colleagues proposed an innovative method of controlling magnetic fluids for the precise delivery of therapeutic particles. Using synchronous control of multiple electromagnets, they were able to direct a ferrofluid spot from the periphery to a deep-seated target with minimal loss of shape and volume, opening up new possibilities for high-precision navigation in biological tissues [22].

Recent impressive research in the field of ferrofluid robotics has demonstrated the potential for creating liquid-based robots. By precisely tuning external magnetic influences in time and space, it has been possible to implement a number of complex functions: shape transformation, separation followed by regeneration, movement through difficult environments, and the capture and manipulation of objects [26,27]. However, all these breakthroughs were achieved using commercial ferrofluids, which have a number of serious limitations—low stability and a tendency to oxidize quickly. These properties make it difficult to control robots. In addition, current control strategies are limited to single-stage manipulation of small droplets of ferrofluid using either electric and permanent magnets or three-dimensional Helmholtz coils, which significantly limits their potential capabilities [24,25]. Joint motion control remains a serious scientific and technical challenge.

3. Methodology

3.1 Manufacturing ferrofluids

The main problem in creating durable ferrofluids is that their nanoparticles constantly tend to stick together. This occurs for two main reasons: Van der Waals forces and magnetic attraction. Over time, these forces overcome Brownian motion (the chaotic vibration of particles), and the process of clumping begins. First, chains and lumps form, then larger clusters, which eventually settle to the bottom [28]. To avoid agglomeration, magnetic particles must be coated with a suitable material. The classification of ferrofluids by type of stabilizing coating includes two key categories [29]:

1. Ionic ferrofluids (IFF).

2. Surface-active ferrofluids (SAF).

In ionic ferrofluids [30], colloidal stability is achieved by forming an electric charge on the surface of magnetic nanoparticles, such as maghemite and transition metal ferrites, synthesized by chemical co-precipitation. The key stabilization mechanism is acid-base interaction at the particle-solution interface, in which dynamic proton exchange between the surface and the bulk of the liquid generates a double electric layer [31]. However, some IFMs, especially those with hydrophobic anions, can accumulate in the body and cause cytotoxicity. For example, lidocaine docusate requires careful dosage selection [32]. The main methods for producing ferrofluids include the following approaches [33,34]:

• **Chemical precipitation (co-precipitation)**: formation of iron oxides from Fe^{2+}/Fe^{3+} salt solutions upon addition of a base.

• **Mechanical grinding**: ball or planetary grinding of large magnetite particles in the presence of surfactants to prevent agglomeration.

• **Thermal decomposition:** decomposition of organic precursors (e.g., iron acetylacetonates) in high-boiling solvents followed by stabilization of the particles with surface-active molecules.

However, traditional approaches to ferrofluid synthesis are often characterized by low efficiency and product yield. In this regard, an improved strategy for obtaining ferrofluid has been developed.

In the first stage, acetic acid is added to deionized water heated to 70 °C, which prevents premature oxidation of iron ions at high temperatures [33]. Next, a mixture of iron sulfate ($FeSO_4 \cdot 7H_2O$) and iron (III) chloride hexahydrate ($FeCl_3 \cdot 6H_2O$) is added to the solution in turn to create the required ratio of Fe^{2+} and Fe^{3+} ions necessary for the formation of magnetite nanoparticles.

In the next stage of synthesis, an ammonia solution is rapidly added to the reaction mixture, which leads to an increase in pH and triggers the process of iron oxide precipitation. As a result, Fe_3O_4 nanoparticles begin to form, the structure and properties of which depend on the exact parameters of the reaction, such as the rate of ammonia addition and the temperature regime [34]. Oleic acid was pre-dissolved in excess ammonia, after which the previously precipitated Fe_3O_4 nanoparticles were gradually added to the resulting alkaline solution. This allowed the oleic acid molecules to adsorb onto the surface of the particles, forming an organic shell that effectively prevents their aggregation and ensures a stable dispersed state of the ferrofluid [35].

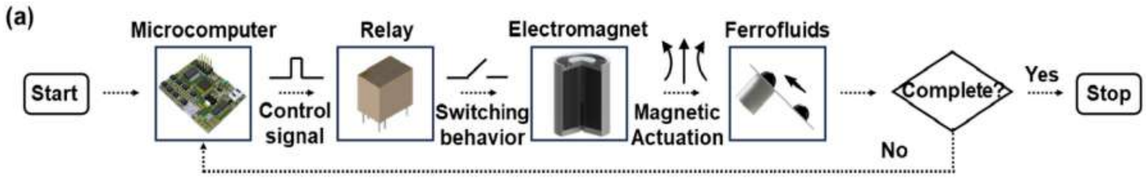
To convert ammonium oleate into oleic acid, acetic acid is added to the solution. Under the action of the acidic environment, the ammonium ion is displaced and free oleic acid is formed. In this form, the molecules bind better to the surface of the nanoparticles, forming a stable shell that prevents their aggregation and improves the stability of the ferrofluid. This step is important for obtaining a high-quality and long-lasting dispersion [36].

Then, isopropyl alcohol was added to the system to remove residual water and facilitate the precipitation of nanoparticles. Isopropanol effectively displaces water from the colloidal solution, reduces the polarity of the medium, and promotes the aggregation of particles into a precipitate. In addition, its high volatility simplifies subsequent drying, accelerating moisture removal and stabilizing the resulting nanoparticles [37].

Finally, the purified nanoparticles were redispersed in kerosene, which was chosen as the carrier liquid due to its low volatility, high chemical stability, and non-toxicity. Kerosene also minimizes contamination and provides good ferrofluid stability by preventing nanoparticle aggregation. This allows for stable and effective ferrofluids that can be used in various applications, including magnetic technologies [38].

3.2. Control

A programmable platform was created that allows controlling the movement of ferrofluid, as shown schematically in Figure 3.



(б)

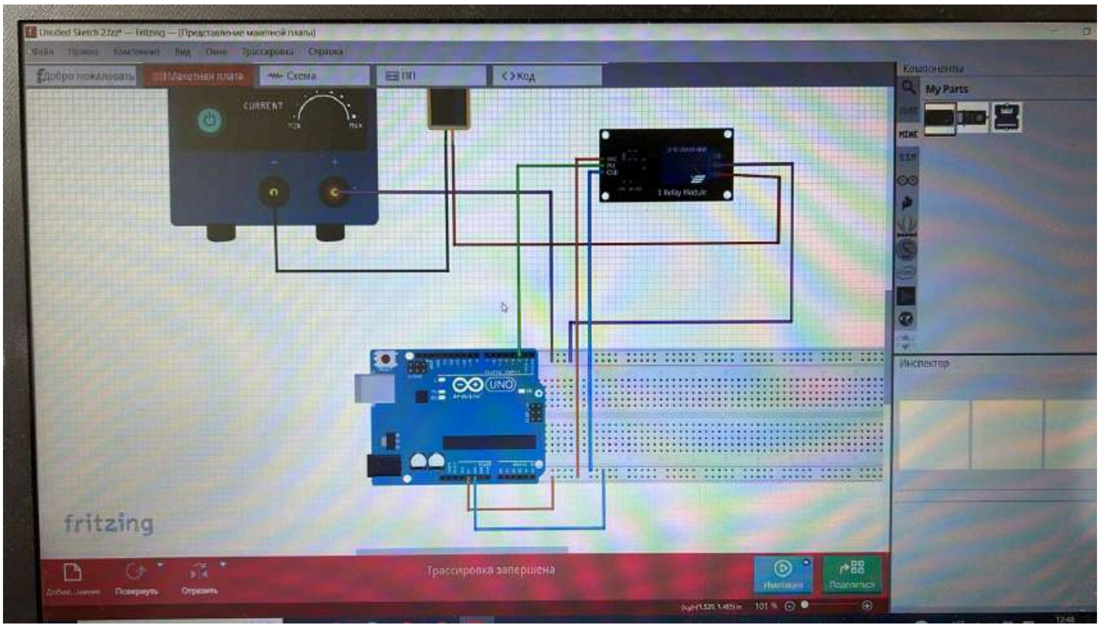


Figure 3. Controlling ferrofluid motion using a programmable platform. (a) Platform control logic architecture. (b) Control platform model.

The platform's operation was based on the use of a microcontroller that received commands from the user interface and converted them into control pulses. These pulses were sent to relays that controlled the supply of electric current to the electromagnets [39]. A schematic representation of this system is shown in Figure 3(a). The ferromagnetic nanoparticles we prepared were used in a demonstration experiment on ferrofluid control. They were placed in a glass container and served as a working medium for simulating behavior under the influence of an external magnetic field. The electromagnets, located behind the display module, were connected to a relay-based control system and an external power source, forming a drive module. They were arranged in a 3 by 3 configuration, which allowed the creation of specified magnetic fields to display the movement of the ferrofluid. Control was performed by a microcomputer connected to the relay unit [40]. A schematic representation of this system is shown in Figure 3(b). Glass bottles containing ferrofluid were additionally filled with water due to the immiscibility of the liquids.4.Основная часть

4.1. Production of ferrofluids

$FeCl_3 \cdot 6H_2O$ – iron chloride hexahydrate or iron chloride 6-hydrate
Molecular weight = 270.3 g/mol

$FeSO_4 \cdot 7H_2O$ – iron sulfate heptahydrate or iron vitriol
Molecular weight = 278.06 g/mol

NH_4OH – ammonia or ammonia spirit

Molecular weight = 35.04 g/mol

$2FeCl_3 \cdot 6H_2O + FeSO_4 \cdot 7H_2O + 8NH_4OH \rightarrow Fe_3O_4 + 6NH_4Cl + (NH_4)_2SO_4 + 23H_2O$ (Figure 4(b))

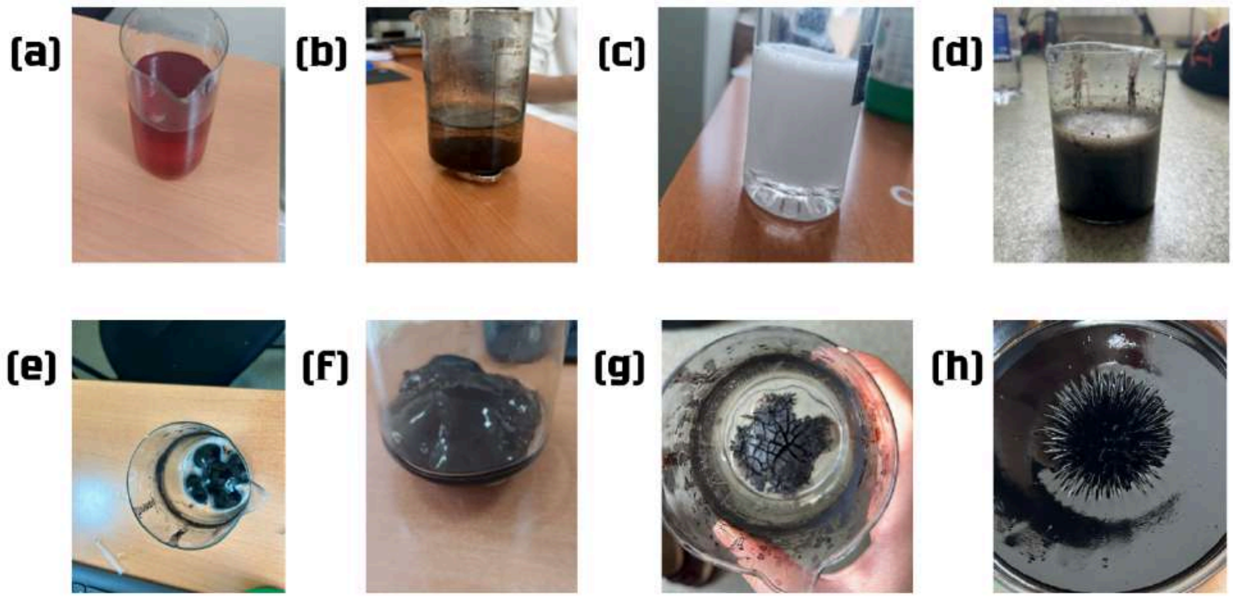


Figure 4. Ferromagnetic liquid production. (a) Adding iron salts to an aqueous solution, (b) Precipitation of Fe_3O_4 nanoparticles under the action of ammonia, (c) NH_4OH in a separate flask before adding oleate, (d) Formation of an oleate coating on the magnetite, (e) Acid hydrolysis of ammonium oleate, (f) Purification of nanoparticles with isopropanol, (h) Dispersion of magnetite in kerosene

Let's calculate how much iron sulfate ($FeSO_4 \cdot 7H_2O$) will be needed for the reaction if 10 g of iron chloride ($FeCl_3 \cdot 6H_2O$) is added to 300 ml of water (temperature 70°C).

From 10 g of $FeCl_3 \cdot 6H_2O$, we can calculate the number of moles: 10/270.3 = 0.0370 mol.

For 2 moles of $FeCl_3 \cdot 6H_2O$, 1 mole of $FeSO_4 \cdot 7H_2O$ is required. Now let's calculate the mass of $FeSO_4 \cdot 7H_2O$ that will be required for the reaction:

0.0185×278.06 g/mol = 5.1 g of iron vitriol

Now, taking into account the volume of water, add 5.1 g of iron sulfate ($FeSO_4 \cdot 7H_2O$) and 10 g of iron chloride ($FeCl_3 \cdot 6H_2O$) to the solution. (Figure 4(a))

Now, after adding iron sulfate ($FeSO_4 \cdot 7H_2O$) and iron chloride ($FeCl_3 \cdot 6H_2O$) to the solution, add 100 ml of ammonia (NH_4OH). At this stage, magnetite nanocrystals form and grow. We place the jar on a magnet and wait for it to solidify (Figure 4(b)). Next, we wash off the water and begin cleaning to remove excess impurities and undissolved substances remaining after synthesis. Only magnetite nanoparticles remain.

Add 20 ml of ammonia to another flask (Figure 4(c)). Now, stirring gently, add oleic acid (1.3 ml). This will help coat the magnetite nanoparticles and improve their stability in solution. If oleic acid is added too quickly, it may not dissolve properly, leading to agglomerates or uneven coating of the nanoparticles. Therefore, it is important to add oleic acid slowly and carefully so that it is evenly distributed over the surface of the nanoparticles and a stable dispersion is formed.

Next, leaving a small amount of water in the magnetite sediment, add a mixture of oleic acid and ammonia to the solution and stir gently again. Leave for 5 minutes so that the molecular chains of ammonium oleate are attracted to the magnetite particles by their polar head and stick to them (Figure 4(d)). Now, to convert ammonium oleate back into oleic acid, acid hydrolysis must be performed. To do this, add acid (for example, 20 ml of acetic acid) to the solution. The acid will displace the ammonium ion, converting ammonium oleate into oleic acid.

We can observe how magnetite particles become hydrophobic thanks to their surface being coated with oleic acid. We begin rinsing with water again to remove residual reaction products and excess impurities, leaving only stable hydrophobic magnetite nanoparticles (Figure 4(e)). Next, we clean with isopropyl alcohol to remove any remaining water and ensure that the magnetite nanoparticles are dry (Figure 4(f)). After cleaning with isopropyl alcohol, we dry the nanoparticles with a cold hair dryer (Figure 4(g)) to carefully remove residual moisture without overheating them or changing their structure. All that remains is to add 5 ml of kerosene, and the stable ferrofluid is ready (Figure 4(h)).

4.2. The behavior of ferrofluid under magnetic attraction

With precise control of external magnetic fields (using electromagnets or permanent magnets), the system demonstrates unique transformational capabilities: dynamic separation and merging of modular elements, adaptive modification for access to confined spaces, formation of complex configurations, and synchronized group movement. Here, we create external magnetic fields using an array of electromagnets or permanent magnets in various shapes. (a)

(b) (c) (d)

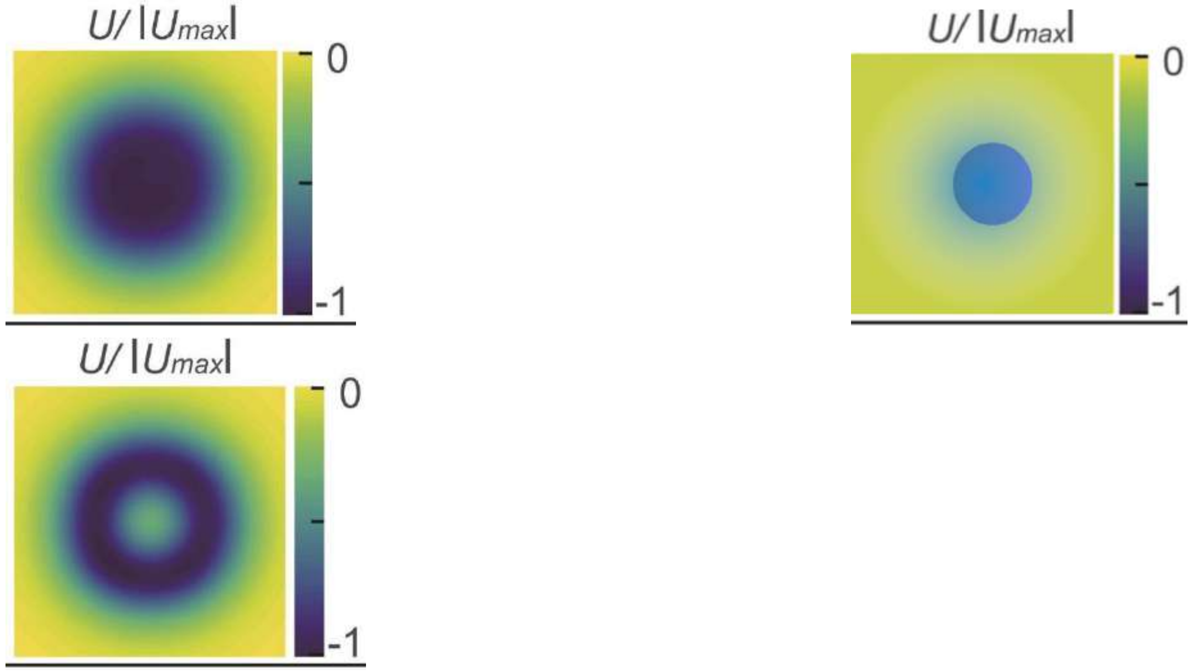


Figure 5.

Control mechanism and characteristics of extreme and complex deformations of ferrofluid (a) Ring magnet, parallelepiped magnet, standard cylindrical magnet. (b) Change in the shape of ferrofluid on a standard cylindrical magnet, (c) Change in the shape of ferrofluid on a parallelepiped magnet, (d) Change in the shape of ferrofluid on a ring magnet.

Figure 5 shows that ferrofluids have a morphology similar to the shape of a magnetic energy potential well. Magnetic fields inside nanoparticles tend to move toward areas of minimum energy due to a fundamental physical principle: any system in nature tends to move toward a state of minimum potential energy in order to achieve maximum stability. This is similar to how a ball rolls into a depression (potential well) to occupy the position with the minimum energy.

A comparison of the effects of three different magnets on ferrofluids is shown below.

Magnet	Magnetic field	Distance at which the reaction begins (cm)	Reaction speed
round neodymium magnet	0.45 Тл	5.3	The liquid moves quickly toward the magnet.
ring magnet	0.5 Тл	6.4	The liquid moves quickly toward the magnet.
parallelepiped magnet	0,12 Тл	2.6	The liquid moves relatively slowly toward the magnet.

4.3. Control of ferrofluid by a programmable platform.

(A) (B)

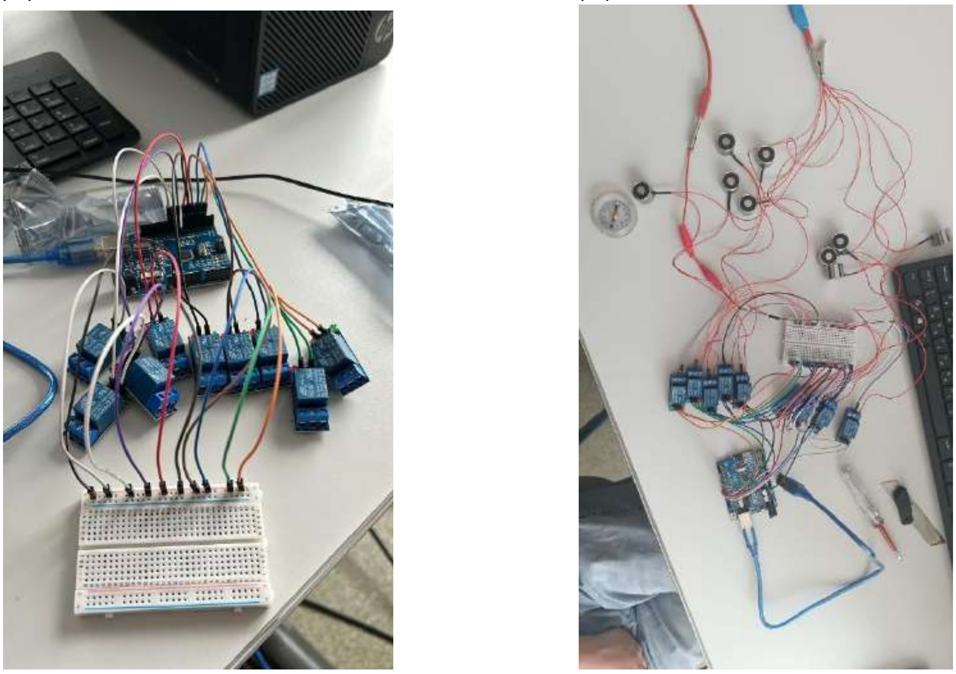


Figure 6. Programmable circuit. (a) Connection of the microcontroller to the relay modules, (b) connection of the electromagnets to the relay modules.

In the first stage of implementing the ferrofluid control system, an Arduino Uno platform was used in combination with nine single-channel relay modules (Figure 6(a)). This configuration made it possible to alternately turn on and off nine electromagnets located under the working surface with ferrofluid.

Each relay was connected to a separate digital output of the Arduino Uno and was used to control the current supply to the corresponding electromagnet. This solution provided simple and reliable switching, but had limitations in terms of switching speed and scalability due to current consumption.

Connecting electromagnets

In the next stage, the electromagnets were connected to relay modules and an external power supply (12V 2A) (Figure 6(b)). Each electromagnet was powered through a corresponding relay, which allowed it to be turned on and off by a command from the Arduino. Control signals from the Arduino activated the relay, closing the power circuit and turning on the corresponding electromagnet. As a result, we obtained a controllable ferrofluid (Figure 7).

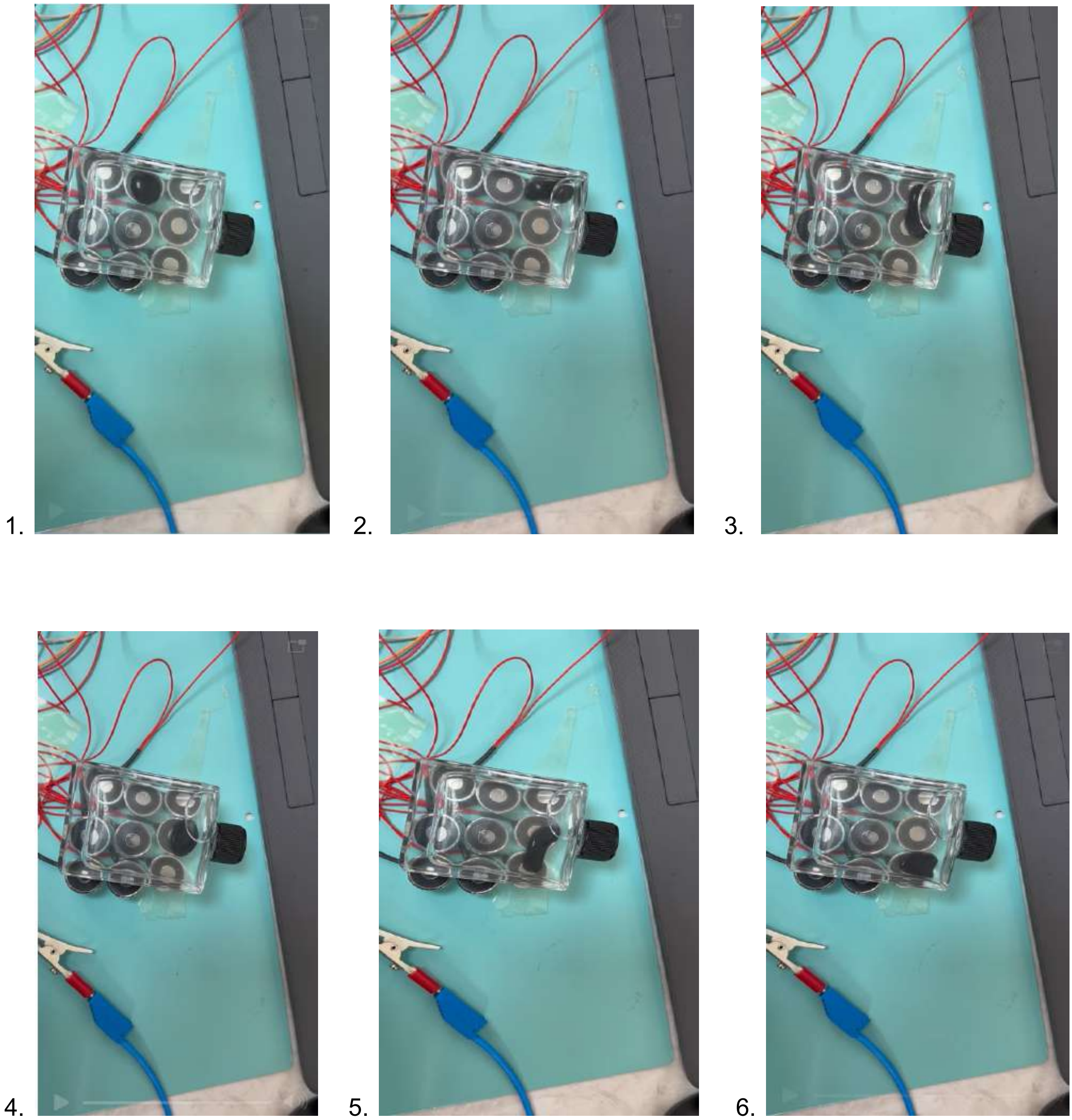


Figure 7. Step-by-step process of ferrofluid movement

5. Results and discussion.

5.1. Stability of ferrofluid

The synthesized ferrofluid based on magnetite nanoparticles demonstrated high stability for more than 7 days without aggregation or sedimentation. The use of oleic acid as a surface stabilizer ensured uniform coating of the particles, as evidenced by the absence of visible clusters and stable dispersion color. Visual inspection and observation under a magnetic field showed that the ferrofluid retained its fluidity and was deformable even after repeated activation of magnetic fields.

5.2. Controllability using a programmable platform

The platform developed based on Arduino Uno, relays, and an external power supply allowed for precise control of nine electromagnets. This made it possible to move a ferrofluid drop step by step across the surface. The software allowed specific magnetic cells to be activated, thereby “attracting” the drop to the desired area.

Observed effects:

• Movement of the drop in eight directions across the matrix;

• Formation of elongated shapes when two or more adjacent electromagnets are activated;

• Return of the drop to its original shape when the field is turned off;

• Ability to hold the drop in a fixed position.

Figure 7 shows step-by-step photographs of the drop's movement, demonstrating the precision of the control.5.3. Влияние формы магнита на поведение капли

Three types of permanent magnets were used to evaluate the response of ferrofluid to a magnetic field: cylindrical, ring, and parallelepiped. The field strength, the distance at which interaction began, and the speed of fluid movement were measured. The ferrofluid took on a shape corresponding to the profile of the potential well created by the magnetic field, striving for a state of minimum energy. This confirms the possibility of precisely controlling the geometry of the drop through the configuration of the field.5.4. Обсуждение

The study showed that ferrofluids can serve as effective components in a new generation of soft robotics systems capable of adaptive behavior and high compliance in confined spaces. The successful synthesis of stable ferrofluid and the demonstration of its controllability using a programmable platform based on electromagnets confirm the possibility of creating elementary liquid microrobots capable of targeted delivery.

The results of the work prove that programmable magnetic fields controlled by accessible microelectronics (e.g., Arduino) are capable of forming various scenarios for the behavior of ferrofluid droplets. Such a system can be easily adapted to various tasks, including in biomedicine, for example, for the targeted delivery of drugs in minimally invasive procedures. Its compactness and autonomy also make the technology promising for use in space missions, where space and energy consumption are limited.

However, in its current implementation, the system had a number of limitations. The use of a relay control circuit reduced the response speed of the electromagnets and limited the scalability of the platform. In addition, the accuracy of controlling the shape and position of the ferrofluid drop could be improved with the introduction of a feedback system and more precise magnetic field gradation. Furthermore, no quantitative analysis of the force of attraction and deformation was performed, which is necessary for accurate modeling of behavior in biological environments.Будущие исследования могут быть направлены на:

• transition to transistor control to increase speed and reliability;

• integration of sensors and computer vision to implement adaptive control;

• expansion of the number of active magnetic elements to work with several drops simultaneously;

• investigation of the biocompatibility of synthesized ferrofluid under in vitro and in vivo conditions.

Thus, the technologies presented have significant potential for creating personalized, autonomous medical solutions of a new generation that can improve the safety and survivability of crews during long-duration space flights.

References

[1] D. Rus and M. T. Tolley, “Design, fabrication and control of soft robots,” Nature, vol. 521, pp. 467–475, 2015. doi: 10.1038/nature14543.

[2] C. S. X. Ng, M. W. M. Tan, C. Xu, Z. Yang, P. S. Lee, and G. Z. Lum, “Locomotion of miniature soft robots,” Adv. Mater., vol. 33, no. 19, p. 2003558, 2021. doi: 10.1002/adma.202003558.

[3] G. M. Whitesides, “Soft robotics,” Angew. Chem. Int. Ed., vol. 57, no. 16, pp. 4258–4273, 2018. doi: 10.1002/anie.201800907.

[4] C. Huang, Z. Lai, X. Wu, and T. Xu, “Multimodal locomotion and cargo transportation of magnetically actuated quadruped soft microrobots,” Cyborg Bionic Syst., vol. 2022, no. 39, 2022. doi: 10.34133/cbsystems.0004.

[5] H. Shahsavan, A. Aghakhani, H. Zeng, M. Sitti, and J. A. Rogers, “Bioinspired underwater locomotion of light-driven liquid crystal gels,” Proc. Natl. Acad. Sci. U.S.A., vol. 117, no. 10, pp. 5125–5133, 2020. doi: 10.1073/pnas.1917952117.

[6] Y. Chen et al., “Light-driven bimorph soft actuators: Design, fabrication, and properties,” Mater. Horiz., vol. 8, pp. 728–757, 2021. doi: 10.1039/D0MH01406K.

[7] Y. Song, M. Zadan, K. Misra, Z. Li, J. Wang, C. Majidi, and S. Kumar, “Navigating soft robots through wireless heating,” in Proc. IEEE Int. Conf. Robot. Autom. (ICRA), London, UK, May–Jun. 2023, doi: 10.1109/ICRA48891.2023.10161540.

[8] Z. Ma and D. Sameoto, “A review of electrically driven soft actuators for soft robotics,” Micromachines, vol. 13, no. 11, p. 1881, 2022. doi: 10.3390/mi13111881.

[9] J. Ahn et al., “A review of recent advances in electrically driven polymer-based flexible actuators: Smart materials, structures, and their applications,” Adv. Mater. Technol., vol. 7, no. 11, p. 2200041, 2022. doi: 10.1002/admt.202200041.

[10] S. Tang et al., “Enzyme-powered Janus platelet cell robots for active and targeted drug delivery,” Sci. Robot., vol. 5, no. 43, p. eaba6137, 2020. doi: 10.1126/scirobotics.aba6137.

[11] B. J. Nelson, I. K. Kaliakatsos, and J. J. Abbott, “Microrobots for minimally invasive medicine,” Annu. Rev. Biomed. Eng., vol. 12, pp. 55–85, 2010. doi: 10.1146/annurev-bioeng-010510-103409.

[12] M. Sitti, “Miniature soft robots—Road to the clinic,” Nat. Rev. Mater., vol. 3, pp. 74–75, 2018. doi: 10.1038/s41578-018-0001-3.

[13] Y. Kim, H. Yuk, R. Zhao, S. A. Chester, and X. Zhao, “Printing ferromagnetic domains for untethered fast-transforming soft materials,” Nature, vol. 558, no. 7709, pp. 274–279, 2018. doi: 10.1038/s41586-018-0185-0.

[14] T. Wang, Z. Ren, W. Hu, M. Li, and M. Sitti, “A light-driven artificial flytrap with directional leaf closure and ultrafast motion,” Sci. Adv., vol. 7, no. 19, p. eabf7364, 2021. doi: 10.1126/sciadv.abf7364.

[15] H. Zhou et al., “Hydrogel-based stimuli-responsive micromotors for biomedicine,” Cyborg Bionic Syst., vol. 2022, art. 9852853, 2022. doi: 10.34133/2022/9852853.

[16] J. Zhang et al., “Voxelated three-dimensional miniature magnetic soft machines via multimaterial heterogeneous assembly,” Sci. Robot., vol. 6, no. 53, p. eabf0112, 2021. doi: 10.1126/scirobotics.abf0112.

[17] H. Song et al., “Reprogrammable ferromagnetic domains for reconfigurable soft magnetic actuators,” Nano Lett., vol. 20, no. 7, pp. 5185–5192, 2020. doi: 10.1021/acs.nanolett.0c01418.

[18] O. Oehlsen, S. I. Cervantes-Ramírez, P. Cervantes-Avilés, and I. A. Medina-Velo, “Approaches on ferrofluid synthesis and applications: Current status and future perspectives,” ACS Omega, vol. 7, no. 4, pp. 3134–3150, 2022. doi: 10.1021/acsomega.1c05631.

[19] P. Dunne et al., “Liquid flow and control without solid walls,” Nature, vol. 581, no. 7807, pp. 58–62, 2020. doi: 10.1038/s41586-020-2254-4.

[20] F. Serwane et al., “In vivo quantification of spatially varying mechanical properties in developing tissues,” Nat. Methods, vol. 14, no. 2, pp. 181–186, 2017. doi: 10.1038/nmeth.4101.

[21] A. Komaee and B. Shapiro, “Magnetic steering of a distributed ferrofluid spot towards a deep target with minimal spreading,” in Proc. IEEE Conf. Decis. Control, 2011, pp. 7950–7955. doi: 10.1109/CDC.2011.6160737.

[22] A. Nacev et al., “Towards control of magnetic fluids in patients: Directing therapeutic nanoparticles to disease locations,” IEEE Control Syst. Mag., vol. 32, no. 3, pp. 32–74, 2012. doi: 10.1109/MCS.2012.2189052.

[23] X. Fan, M. Sun, L. Sun, and H. Xie, “Ferrofluid droplets as liquid microrobots with multiple deformabilities,” Adv. Funct. Mater., vol. 30, no. 24, p. 2000138, 2020. doi: 10.1002/adfm.202000138.

[24] A. Li et al., “Programmable droplet manipulation by a magnetic-actuated robot,” Sci. Adv., vol. 6, no. 7, p. eay5808, 2020. doi: 10.1126/sciadv.aay5808.

[25] M. H. Sarkhosh, M. Yousefi, M. A. Bijarchi, H. N. Pishkenari, and K. Forghani, “Manipulation of ferrofluid marbles and droplets using repulsive force in magnetic digital microfluidics,” Sens. Actuators A: Phys., vol. 363, p. 114733, 2023. doi: 10.1016/j.sna.2023.114733.

[26] M. Sun, X. Fan, C. Tian, M. Yang, L. Sun, and H. Xie, “Swarming microdroplets to a dexterous micromanipulator,” *Adv. Funct. Mater.*, vol. 31, p. 2011193, 2021. doi: 10.1002/adfm.202011193.

[27] M. Sun, S. Yang, J. Jiang, and L. Zhang, “Horizontal and vertical coalescent microrobotic collectives using ferrofluid droplets,” *Adv. Mater.*, vol. 35, p. 2300521, 2023. doi: 10.1002/adma.202300521.

[28] Y. Lalatonne, J. Richardi, and M. P. Pileni, "Van der Waals versus dipolar forces controlling mesoscopic organizations of magnetic nanocrystals," *Nature Materials*, vol. 3, pp. 121–125, 2004. doi:10.1038/nmat1054

[29] C. Scherer and A. M. Figueiredo Neto, "Ferrofluids: Properties and Applications," *Brazilian Journal of Physics*, vol. 35, no. 4, pp. 718–727, Sep. 2005. doi:10.1590/S0103-97332005000400018

[30] F. Batalioto, A. M. Figueiredo Neto, and G. Barbero, "Ions, adsorption and electric response of a ferrofluid cell," *Phys. Chem. Chem. Phys.*, vol. 24, no. 5, pp. 3400–3409, 2022. doi:10.1039/D1CP04724H

[31] R. Massart, E. Dubois, V. Cabuil, and E. Hasmonay, "Preparation and properties of monodisperse magnetic fluids," *Journal of Magnetism and Magnetic Materials*, vol. 149, nos. 1–2, pp. 1–5, Aug. 1995. https://doi.org/10.1016/0304-8853(95)00316-9

[32] K. S. Egorova, E. G. Gordeev, and V. P. Ananikov, "Biological activity of ionic liquids and their application in pharmaceuticals and medicine," *Russian Chemical Reviews*, vol. 117, no.10, pp. 7132–7189, Jan. 2017. doi:10.1021/acs.chemrev.6b00562

[33] M. Bhatnagar and M. Vishnoi, “Different methods of ferro-fluids production with their stability and its applications especially in internal combustion engines–a review,” *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 2021. doi:10.1080/15567036.2021.1998251

[32] S. Genc and B. Derin, “Synthesis and rheology of ferrofluids: a review,” *Current Opinion in Chemical Engineering*, vol. 3, pp. 118–124, 2014. doi:10.1016/j.coche.2013.12.006

[33] M. Thirumalai, B. Bharathy Jesuraja, and P. Paulraj, "Effects of salt, vinegar and bleach in accelerating rusting of iron," *International Journal of Innovative Research and Advanced Studies (IJIRAS)*, vol. 7, no. 6, pp. 1-5, Jun. 2020. Available: https://www.ijiras.com

[34] A. Lesbayev, D. Akalim and D. Yerezhep, " Investigation of nanostructured composite fibers based on Fe3O4," *Журнал проблем эволюции открытых систем*, *26*(2), 25–36. https://doi.org/10.26577/JPEOS.2024.v26-i2-a4

[35] S. Sun, H. Zeng, D. B. Robinson, S. Raoux, P. M. Rice, S. X. Wang, and G. Li, "Monodisperse MFe_2O_4 (M = Fe, Co, Mn) nanoparticles," *J. Am. Chem. Soc.*, vol. 126, no. 1, pp. 273–279, 2004. doi:10.1021/ja0380852

[36] S. Xie, C. Zhao, B. Fan, Z. Yu, M. Xia, L. Tu, J. Song, X. Zhao, and M. Wang, "Metabolic network of ammonium in cereal vinegar solid-state fermentation and its response to acid stress," *Food Microbiol.*, vol. 95, p. 103684, May 2021. https://doi.org/10.1016/j.fm.2020.103684

[37] C. B. Murray, S. Sun, W. Gaschler, H. Doyle, T. A. Betley, and C. R. Kagan, "Colloidal synthesis of nanocrystals and nanocrystal superlattices," *IBM J. Res. Dev.*, vol. 45, pp. 47–56, 2001. https://doi.org/10.1147/rd.451.0047

[38] D. Susan-Resiga, I. Malaescu, O. Marinica, and C. N. Marin, "Magnetorheological properties of a kerosene-based ferrofluid with magnetite particles hydrophobized in the absence of the dispersion medium," *Phys. B: Condens. Matter*, vol. 587, p. 412150, 2020. https://doi.org/10.1016/j.physb.2020.412150

[39] X. Fan, X. Dong, A. Karacakol, H. Xie, and M. Sitti, "Reconfigurable multifunctional ferrofluid droplet robots," *Proc. Natl. Acad. Sci. USA*, vol. 117, pp. 27916–27926, 2020, doi: 10.1073/pnas.2016388117.

[40] F. Kong, Y. Zhu, C. Yang, H. Jin, J. Zhao, and H. Cai, "Integrated locomotion and deformation of a magnetic soft robot: modeling, control, and experiments," *IEEE Trans. Ind. Electron.*, vol. 68, pp. 5078–5087, 2021, doi: 10.1109/TIE.2020.2992000.