Magnetically Actuated Sub-Millimeter Squeezing Soft Robot Toward Targeted Therapy

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***Abstract*— This work presents the design and development of an untethered sub-millimeter magnetic soft robot designed for active targeted drug release. The robot features a ravioli-inspired geometry with an overall dimension under 2 mm, and fabricated from a polydimethylsiloxane (PDMS) elastomer infused with Neodymium-Iron-Boron (NdFeB) microparticles. Its unique design incorporates a hollow internal reservoir for liquid cargo encapsulation. Locomotion and functional control are achieved via an Electromagnetic Actuation System, utilizing a rotating magnetic field at 20 mT for planar spinning navigation and high-gradient magnetic field at 80 mT for the squeeze-to-release mechanism. Experimental results in a 50-cst. silicone oil environment demonstrates stable navigation and successful on-demand expulsion of the encapsulated liquid through micro-orifices on its surface. While currently limited to laboratory settings, this active squeezing mechanism offers a superior alternative to passive diffusion for precision medicine, and this work paves early stage of the way for minimally invasive therapeutic interventions using soft microrobotic platforms.**

I. Introduction

The paradigm of modern medicine is shifting rapidly from systemic drug administration toward highly localized and minimally invasive therapeutic interventions. Targeted drug delivery systems offer the potential to maximize therapeutic efficacy while significantly reducing adverse side effects on healthy tissues [1, 2]. Among various delivery platforms, untethered Micro/Nanorobots have emerged as a promising solution for navigating complex anatomical environments. These miniature agents can bypass the limitations of traditional catheters, which are often restricted by their rigidity and limited reach in distal branches of the vasculature [3]. In particular, magnetic actuation provides a safe and effective means of wireless control through deep biological systems. The robot employs the external magnetic fields for precise locomotion and orientation without the need for onboard power sources [4]. Consequently, the development of sub-millimeter scale robots represents a critical frontier in enhancing the precision of localized medical treatments.

Soft property creates a new chance to the design of medical microrobots by utilizing compliant materials that mimic biological properties. Traditional rigid robots often pose risks of mechanical trauma to delicate vessel walls or soft tissues during navigation. In contrast, soft robots fabricated from flexible materials can deform and adapt to confined spaces, ensuring safer interactions within the human body [5]. The integration of magnetic active particles (e.g., Neodymium-Iron-Boron (NdFeB) into elastomer allows capabilities of shape-morphing under the magnetic manipulation based on various form of electromagnetic actuation systems [6, 7]. These soft magnetic composites can be programmed to exhibit specific mechanical responses when exposed to tailored magnetic field and gradient. This synergy between material compliance and magnetic responsiveness enables the soft magnetic robot to perform intricate tasks that might previously be impossible. Thus, magnetic soft robots are becoming the preferred candidates for biomedical applications promisingly.

A significant challenge in Micro/Nanorobotics is the integration of an active drug release mechanism within a miniature frame. Most existing small-scaled robots rely on passive or environmental triggers for drug release, which often lack of a precise control [8]. To address this, this work proposes a soft robot with an overall dimension of less than 2 mm (approximately 1.8 mm x 1.8 mm x 130 µm) featuring an internal reservoir for liquid cargo. This design allows for the encapsulation of specific therapeutic agents (e.g., liquid drugs, water) within a protected hollow chamber. Two functions of the robot can be controlled by type of magnetic actuations, magnetic torque to spin the robot for locomotion and magnetic force to squeeze the robot to release the stored liquid. The use of a squeezing mechanism driven by magnetic force provides a novel way to actively expel the contents at a target site. By modulating the intensity and direction of the external magnetic field, the robot can be move to a targeted position and compressed to release a controlled volume of the payload. Such a mechanism ensures that the drug is delivered only when the robot has reached its desired destination.

The fabrication of these sub-millimeter robots requires advanced manufacturing techniques to ensure structural integrity and functional accuracy. In this work, the robot body is composed of a PDMS elastomer embedded with NdFeB microparticles to achieve magnetic sensitivity. The internal cavity is carefully engineered to maintain a balance between structural stability during locomotion and flexibility during the squeezing phase. At a scale of less than 2 mm, the surface effects and fluidic resistance become dominant factors influencing the release kinetics.

The operational capability of the proposed magnetic soft robot is demonstrated through controlled navigation and targeted release experiments in a laboratory environment. During the navigation phase, the robot exhibits spinning mode for locomotion, facilitated by precise magnetic torque. Once the robot reaches the target zone, magnetic force is active to

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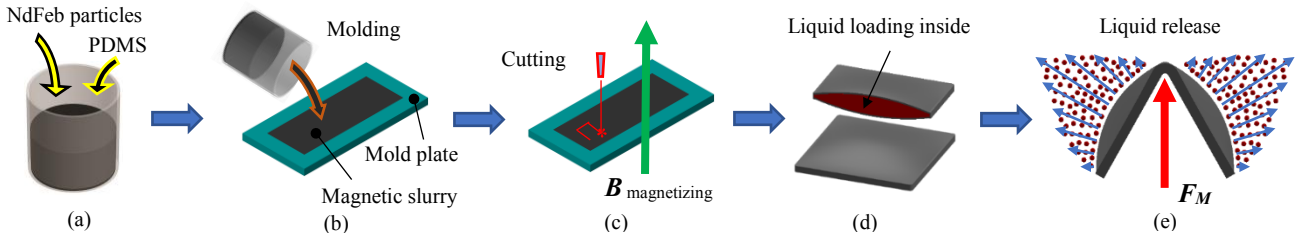


Fig. 1 To fabricate and actuate a magnetic soft sub-milli squeezing robot. (a) PDMS substances and NdFeb micrparticles with 2:1 of mixing ratio. (b) Molding the slurry and heat treatment. (c) Cutting into a rectangular flat shape and magnetizing process. (d) Liquid loading inside the film cavity. (e) Liquid release function is activated by Magnetic force.

trigger the squeezing action of the elastomeric body. This process results in the successful discharge of the encapsulated liquid through a micro-orifice, validating the targeted release concept. Although the current success is limited to laboratory-scale testing, the implications for precision medicine and minimally invasive surgery are profound. This work contributes to the growing body of knowledge in soft robotics and paves the way for the next generation of smart medical robots, which can offer a robust alternative to existing drug delivery methods.

II. Materials and Methods

A. Robot Design and Fabricaion

The magnetic soft robot was carefully designed as a flat bag, resembling a ravioli, with overall dimensions not exceeding 2 mm (approximately 1.8 mm x 1.8 mm with a thickness of 130 µm). This specific geometry was chosen to optimize both its maneuverability within confined spaces and its deformation capability for liquid expulsion. The robot comprised a hollow space, serving as an internal reservoir capable of encapsulating liquid payloads (e.g., deionized water or drug solutions).

As shown in Fig. 1, the fabrication process involved the preparation of a magnetic elastomeric composite. Polydimethylsiloxane: PDMS (Sylgard 184, Dow Corning) was selected as the base elastomer due to its biocompatibility, mechanical tunability, and ease of processing [9]. Neodymium-Iron-Boron microparticles (MQA-NdFeB, Magnequench, 5-10 µm particle size) were uniformly dispersed within the PDMS pre-polymer mixture. The concentration of NdFeB microparticles was optimized (PDMS:NdFeB 2:1) to achieve sufficient magnetic responsiveness without compromising the mechanical flexibility of the elastomer [10].

A two-part molding technique was employed to create the desired a rectangular shape with an internal cavity. First, a sacrificial mold (polylactic acid) was created to define the internal hollow core. This core was then embedded within the magnetic PDMS composite during the molding process. The PDMS mixture was poured into a master mold containing the sacrificial core, followed by curing at 80°C for 2 hours. After curing, the outer mold was carefully removed, then the sacrificial core was dissolved using water, and then the finishing was magnetized in 850 mT, leaving behind the hollow magnetic soft robot. Finally, a small orifice with 100-200 µm in diameter was created at two large surfaces on the robot's surface using a punch to serve as the outlet for the liquid payload.

B. Modeling for navigation and squeezing

The locomotion of the soft robot is governed by the interaction between its embedded magnetic microparticles and an externally applied magnetic field. The magnetic force, $\boldsymbol{F_M}$ and torque, $\boldsymbol{T_M}$ experienced by the robot can be described as

$$\boldsymbol{F_M} = (\boldsymbol{M}.\boldsymbol{\nabla})\boldsymbol{B} \quad (1)$$

$$\boldsymbol{T_M} = \boldsymbol{M} \times \boldsymbol{B} \quad (2)$$

where $\boldsymbol{M}$ is the magnetic dipole moment of the robot and $\boldsymbol{B}$ is the external magnetic field. For the flat plate (ravioli) shape, the magnetic moment $\boldsymbol{M}$ is primarily determined by the specific magnetization during fabrication and the concentration of NdFeB microparticles. To generate the desired magnetic field

In our setup, the external magnetic field is generated by a system of iron-cored solenoid coils for localized squeezing [11]. By precisely controlling the current supplied to these coils, the magnitude and gradient of $\boldsymbol{B}$ can be modulated to achieve desired motion of the robot within a fluidic environment. The navigation strategy involves creating the rotating magnetic field to induce rotational motions along a specified path.

In case of the squeezing mechanism for liquid release, the action is primarily driven by the magnetic force acting on the soft elastomeric body. When the robot reaches the target site, a strong localized magnetic field is applied. Since the magnetic field is generated in the reciprocal manner, and interacts with the embedded NdFeB microparticles within the soft robot, inducing continuous deformation like squeezing and loosening. The magnetic pressure $\boldsymbol{P_M}$ exerted on the robot's deformable surface can be related to the magnetic field strength and the magnetic properties of the material.

When the robot containing embedded NdFeB microparticles is subjected to a localized magnetic field, each magnetic domain experiences a magnetic torque $\boldsymbol{T_M}$ and a magnetic force $\boldsymbol{F_M}$. Since these microparticles are rigidly constrained within the PDMS matrix, these microscale interactions translate into a macroscopic magnetic body force density $\boldsymbol{f_b} = \boldsymbol{\nabla}.\boldsymbol{\sigma_m}$ and an equivalent magnetic Maxwell stress $\boldsymbol{\sigma_m}$. The total Cauchy stress $\boldsymbol{\sigma_{total}}$ within the robot wall is defined as

$$\boldsymbol{\sigma_{total}} = \boldsymbol{\sigma_{elastic}} + \boldsymbol{\sigma_m} \quad (3)$$

where $\boldsymbol{\sigma_{elastic}}$ represents the mechanical restorative stress of the elastomer.

For hyperelastic deformation and volume reduction, given the compliant nature of the PDMS-NdFeB composite, the robot exhibits significant geometric changes under a high-intensity magnetic field gradient. This deformation results in a reduction of the internal hollow core volume, denoted as

$$\Delta \boldsymbol{V} = \boldsymbol{V_0} - \boldsymbol{V_B} \tag{4}$$

where $\boldsymbol{V_0}$ is the initial reservoir volume and $\boldsymbol{V_B}$ is the instantaneous volume under magnetic influence.

Assuming the encapsulated liquid (e.g., drug solution) is incompressible, the reduction in reservoir volume leads to a rapid increase in the internal hydrostatic pressure $\boldsymbol{P_{int}}$. This pressure generation is governed by the equilibrium between the magnetic compressive force and the combined fluidic and elastic resistance. The internal pressure can be approximated by

$$\boldsymbol{P_{int}} \sim \frac{\boldsymbol{F_M}}{A_{eff}} - \boldsymbol{P_{res}} \tag{5}$$

where $\boldsymbol{F_M}$ is the net magnetic force pushing the reservoir walls inward, A_{eff} is the effective contact area of the hollow core, and $\boldsymbol{P_{res}}$ is the structural resistance of the elastomer, which can be ignored when the mixture ratio of PDMS is much higher. The pressure gradient, $\Delta \boldsymbol{P} = \boldsymbol{P_{int}} - \boldsymbol{P_{ext}}$, where $\boldsymbol{P_{ext}}$ is the ambient pressure, serves as the driving force for drug release.

For a soft elastomeric structure, the deformation under external pressure can be modeled using hyperelastic material constitutive equations [12]. The internal pressure $\boldsymbol{P_{int}}$ within the hollow core increases as the robot is compressed, forcing the encapsulated liquid out through the orifice. The expulsion of the liquid through the micro-orifice as the volumetric flow rate $\boldsymbol{Q}$ of the liquid is released, modeled by using the Hagen-Poiseuille equation for laminar flow, considering the small diameter of the orifice and the properties of the liquid

$$\boldsymbol{Q} = \frac{\pi \boldsymbol{R}^4 \Delta \boldsymbol{P}}{8 \boldsymbol{\mu} \boldsymbol{L}} \tag{6}$$

where $\boldsymbol{R}$ is the orifice radius, $\boldsymbol{\mu}$ is the liquid viscosity, and $\boldsymbol{L}$ is the orifice length. The magnetic field parameters (e.g., current in the solenoid, coil geometry) directly control the deformation of the robot, which in turn dictates $\boldsymbol{F_M}$, then $\boldsymbol{P_{int}}$ and thus the release rate $\boldsymbol{Q}$.

C. Magnetic Actuation Method

To actuate the robot, the magnetic actuation system comprises an array of eight iron-cored solenoids arranged in a hemispherical configuration, providing a 12-cm diameter central workspace, as shown in Fig. 2. Magnetic field modulation is achieved via four custom-built dual-channel current drivers (25 kHz, 100V/100A per channel), powered by a high-capacity 30kW power supply. These drivers are interfaced through a multifunctional I/O card (Sensoray) and managed by a custom GUI. For real-time feedback, a dual-camera stereo vision system is implemented, consisting of two CMOS cameras equipped with zoom lenses (working distance: 6–120 mm, depth-of-field: 1.6 mm).

The 3D localization of the sub-millimeter robot is achieved through a stereo-vision feedback system. Two orthogonal cameras, top and side views, capture the robot's coordinates,

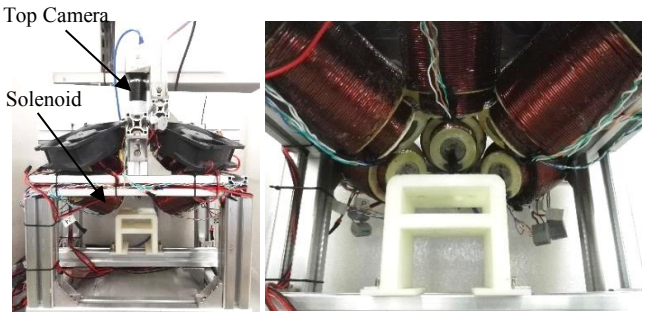


Fig. 2. Electromagnetic actuation system of eight iron-cored solenoids arranged as a nest. At the top and back, two cameras are mounted to capture a soft robot as well as obtain location used to feed back to the control algorithm based on visual servoing.

which are processed via a triangulation algorithm to provide the actual position. The error signal is then processed by a PID-based controller to modulate the flow of electric current for the 8 iron-cored solenoids. To compensate for the non-uniformity of the magnetic field, a dynamic actuation matrix is calculated based on the robot's instantaneous position within the workspace. This ensures that the generated rotating magnetic field for navigation and the gradient magnetic force for squeezing remain consistent and precise throughout the operation.

To achieve precise untethered control over the soft robot, the relationship between the input electric currents and the generated magnetic field is established. Since the magnetic field is generated by the arrangement of eight iron-cored solenoids, the total magnetic field $\boldsymbol{B}$ at any given position $\boldsymbol{p}(x, y, z)$ within the workspace is the result of the superposition of the magnetic fields produced by each individual coil. This relationship is mathematically represented by

$$\boldsymbol{B}\,(\boldsymbol{p}) = \boldsymbol{A}\,(\boldsymbol{p})\boldsymbol{I} \tag{7}$$

where $\boldsymbol{I} = [\boldsymbol{I_1} \quad \boldsymbol{I_2} \quad \ldots \quad \boldsymbol{I_8}]^{\boldsymbol{T}}$ is the vector of electric currents supplied to the solenoids. Due to the non-uniform nature of the magnetic field produced by the solenoids, the components of $\boldsymbol{A}\,(\boldsymbol{p})$ vary as the robot moves through the workspace.

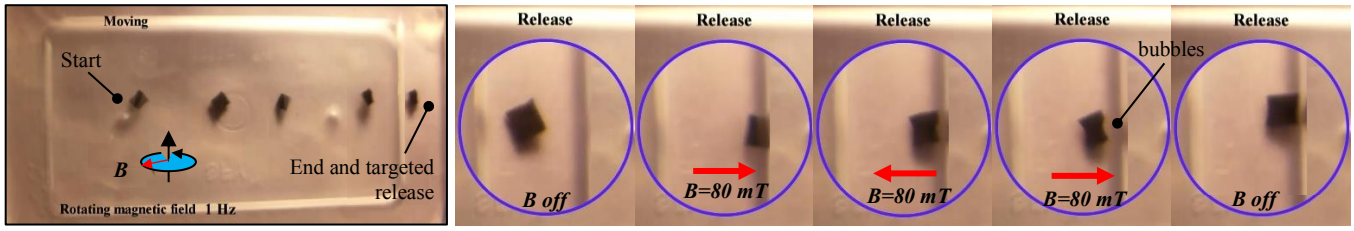
To ensure consistent navigation and squeezing forces, a dynamic control law is implemented. The required currents to generate a desired magnetic field $\boldsymbol{B_{des}}$ are computed by solving the inverse problem

$$\boldsymbol{I} = \boldsymbol{A}^{\dagger}(\boldsymbol{p})\boldsymbol{B_{des}} \tag{8}$$

where $\boldsymbol{A}^{\dagger}(\boldsymbol{p})$ is the Moore-Penrose pseudo-inverse of the dynamic actuation matrix. In our closed-loop system, the computer-controlled GUI updates $\boldsymbol{A}^{\dagger}(\boldsymbol{p})$ in real-time based on the 3D coordinates provided by the stereo-vision feedback. This dynamic updating mechanism compensates for the non-uniformity, ensuring that the rotating magnetic field for locomotion and the magnetic force for squeezing remain precise and stable regardless of the robot's displacement from the center of the workspace.

III. RESULTS

The experimental validation of the Magnetic Sub-millimeter Squeezing Soft Robot was conducted within a controlled workspace surrounded by the system of eight iron-



(a) navigation (b) squeeze to release

Fig. 3 Time-lapse motion sequence of the soft robot under magnetic field. (a) the 20-mT rotating magnetic field exerts torque on the soft robot to navigate in the workspace. (b) the stronger magnetic field about 80 mT exerts force to squeeze the soft robot to release the encapsulated liquid at the desired target.

cored solenoids, as shown in Fig. 3 and Supplementary Video. To simulate a low-Reynolds-number environment similar to biological fluids, the workspace was filled with silicone oil with a kinematic viscosity of 50 cst. The primary phase of the experiment focused on the planar navigation of the soft robot using a rotating magnetic field generated by the superposition of magnetic field produced by those eight coils. By precisely adjusting the intensity and rotational frequency of the magnetic field (20 mT, 1 and 2.5 Hz), the robot exhibited a stable spinning motion, allowing it to translate across the fluidic medium with high directional accuracy. The translation speed was linearly proportional to the rotation frequency of the magnetic field until a step-out frequency at 6 Hz was reached. These results confirm that the elastomeric body embedded with NdFeB microparticles provides sufficient magnetic torque for reliable untethered locomotion.

Upon reaching the targeted position, the magnetic control strategy transitioned from a rotating field to a localized strong magnetic force via a high-gradient magnetic field (80 mT) to trigger the liquid release mechanism. This concentrated magnetic force induced a compressive strain on the robot's flat structure, reducing the internal volume of the hollow core as predicted by our hyperelastic mathematical model. Real-time optical monitoring captured the instantaneous deformation of the robot, which reached a maximum compression of approximately 50% of its original thickness. This rapid deformation generated the necessary internal pressure $\boldsymbol{P_{int}}$ to overcome the capillary forces at the micro-orifice. Consequently, the successful expulsion of the encapsulated liquid was observed, manifesting as tiny bubbles into the surrounding silicone oil.

Multiple release cycles were performed on a single robot to test the fatigue limits of the PDMS-NdFeB composite, and demonstrated that the soft robot could undergo repeated squeezing without permanent structural failure. While these results were obtained in a laboratory setting, the high repeatability of the "spin-to-navigate" and "squeeze-to-release" sequence highlights the potential of this platform for future medical applications.

IV. Conclusion and Discussion

This research successfully demonstrated the design, fabrication, and functional validation of a magnetic sub-millimeter squeezing soft Robot tailored for active targeted drug release. The soft robot is a flat-plate geometry with an internal hollow core, and provides a high payload-to-volume ratio within a compact 2-mm body. The fabrication process which involves NdFeB micro-particles embedded in a PDMS matrix proved robustness for creating a responsive magneto-elastic body capable of both locomotion and reversible deformation. Our experimental results confirmed that the electromagnetic actuation system provides a precise control over the robot's navigation via rotating magnetic fields and its subsequent squeezing via high-gradient magnetic fields. The transition from planar spinning to localized compression allowed for the successful expulsion of encapsulated liquids in a viscous medium environment. These findings validate the use of hyperelastic deformation and fluid dynamics proposed in this microrobotic study to mark a significant step toward active drug delivery. Ultimately, this work provides a foundational framework for the next generation of untethered, soft-bodied medical micro-robots capable of performing complex mechanical tasks inside the human body.

The proposed system offers several advantages. One of them would be the ability to perform on-demand active release rather than relying on passive diffusion, which enhances temporal control over therapeutic delivery. The use of soft and compliant materials minimizes the risk of mechanical damage to delicate vascular environments or tissues during navigation. However, certain limitations remain such as the leaching of NdFeB microparticles are possible due to biocompatible issues for applications in lives. Another would be that the current success is still in the early stage of laboratory-scale testing, but the implications is worth to work further in various more details. Future work might focus on the relationship between magnetic field strength and the volume of released liquid is essential to optimize to ensure repeatable and predictable performance under simulated and real physiological conditions, and enhancing the biocompatibility of the elastomeric composite and integrating real-time medical imaging (e.g., ultrasound, X-ray) to track the soft robot in opaque regions. Despite these challenges, the squeeze-to-release mechanism presents a highly promising platform for precision medicine, particularly for treating localized pathologies (e.g., arterial thrombosis, tumors).

Appendix

The supplementary Video is available on the link (https://drive.google.com/file/d/1ssobV7e_yZW-sf_fu6pE_NIj2GdENe62/view?usp=sharing)

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