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A Multifunctional Capsule and Magnetic Navigation Platform for Controlled Actuation and Task Execution in GI Environments

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***Abstract*— Wireless capsule endoscopy provides a minimally invasive method for examining the gastrointestinal (GI) tract; however, most existing systems are limited to passive operation and single functions, restricting control and functionality. This work presents the design, fabrication, and experimental evaluation of a multifunctional magnetically actuated capsule for drug delivery, sampling, and cargo transport. The capsule incorporates a novel spring–magnet mechanism that enables controlled, repeatable opening and closing under external magnetic fields using a single actuation input. In parallel, a large-workspace magnetic actuation platform is developed to support autonomous navigation and task execution. Iterative capsule designs improved fabrication and sealing performance, guided by analytical modeling. Experimental results demonstrate a substantial reduction in the required magnetic field for actuation (from 38.3 ± 7.7 mT to 12.7 ± 2.5 mT), alongside an approximately 4-fold reduction in leakage (6.19% vs. 23.59%). The actuation platform achieved accurate path tracking with a mean deviation of 2.63 mm across multiple trajectories and enabled navigation in a stomach phantom. These results demonstrate the feasibility of a multifunctional capsule platform with integrated actuation for minimally invasive GI interventions.**

I. INTRODUCTION

The gastrointestinal (GI) tract hosts a complex microbial community, making it vulnerable to infectious diseases and cancers. Conventional endoscopes used to diagnose these conditions, are invasive, expensive, and unable to access deep GI regions [1]. In contrast, wireless capsule endoscopes are untethered, patient-friendly and offer greater maneuverability and reach [2]. Beyond imaging, wireless capsules can perform drug delivery and sampling, but most are limited to a single function, or rely on passive actuation. Incorporating active actuation enables controlled movement, thereby improving clinical utility. Magnetic actuation, allows tetherless operation without onboard power. Permanent magnet-based systems use large external magnets to generate strong fields and high force-to-volume ratios without cooling requirements. However, challenges remain in scaling these systems to be cost and power efficient [3]. Combining multiple actuation elements within a single capsule can enhance functionality and simplify control strategies. We address these limitations by integrating a spring–magnet mechanism with one control input, enabling diverse functionality.

II. RESEARCH OBJECTIVES

The objective of this research is to develop a multifunctional capsule capable of drug delivery, cargo transport, and sample collection using a novel magnetic actuation system. Enabling remote control of these functions will advance the treatment and monitoring of GI conditions. This work aims to improve fabrication from previous capsule iterations, optimize opening behavior, and design a sealing mechanism to prevent leakage. These advancements will enable repeatable fabrication, supporting rapid iteration and consistent experimental validation. Additionally, developing a model to characterize opening behavior and minimize the required magnetic flux density will support reliable remote control in clinical environments. Demonstrating controlled navigation and successful task execution of the capsule will validate its operation in constrained, anatomically relevant conditions.

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III. METHODS

A. Working principle of the capsule mechanism

Magnetic fields can penetrate biological tissue and apply forces and torques to drive capsule motion. We leverage this principle to develop a spring-magnet mechanism that facilitates both controlled navigation and capsule opening and closing. The capsule contains internal magnets that enable navigation through gradient-based magnetic pulling, while also responding to externally applied fields for actuation. During actuation, these magnets attempt to align with the field, generating torque that drives the capsule open while simultaneously compressing an internal spring. When the external magnetic field is removed, the capsule actively closes due to the release of stored potential energy in the spring. This repeatable opening and closing mechanism enables the capsule to perform multiple functions including drug delivery, cargo transport and sample collection.

B. Capsule Iterations and Fabrication

The capsule prototype was iterated to improve fabrication and functionality. The baseline design (Capsule-A) established the core mechanism described previously. It consists of multiple assembled components, including separate shell pieces, a central rod, and stoppers to house the spring. A soft tape hinge connects the upper and lower shell halves. However, fabrication complexity and hinge instability led to misalignment of these components. This motivated Capsule-B, which incorporated a living hinge. This improved the stability of the hinge and reduced assembly steps as the capsule shell could be fabricated as a single component. Building on this, Capsule-C introduced a sealing mechanism to prevent leakage of liquid and contamination. Additionally,

the magnets were reoriented and repositioned to eliminate sharp protrusions that could damage surrounding tissue.

C. Magnetic Actuation Platform

Wireless actuation of the capsule was achieved using gradient-based magnetic pulling. A 5 degrees-of-freedom magnetic actuation system was validated while maneuvering the robotic capsule and demonstrating its multifunctional capabilities. The system translates a 1.5-inch permanent magnet using a motorized belt-driven mechanism along the X and Y axes, and a non-captive lead screw for Z-axis motion. This configuration enables vertical translation without a fixed stroke limit. The mechanism also enables yaw and roll motion, allowing control of magnetic field strength and direction through magnet orientation. Moreover, the design has low power consumption, enabling extended operation (>1 hour), and offers a large workspace suitable for benchtop validation and whole-body navigation experiments.

IV. RESULTS AND DISCUSSION

A. Capsule Opening Behavior

Mathematical models were developed to characterize capsule opening angle using force- and energy-based approaches. Model accuracy was evaluated using root mean squared error (RMSE) against experimental results. The force model better predicted the behavior of Capsule-A (RMSE = 3.5°), whereas the energy model better predicted Capsule-B (RMSE = 4.0°). The model was also used to guide design decisions, including spring stiffness, string tension, and magnet size, to minimize the required magnetic flux density required for opening the capsule. Moreover, the sealed design (Capsule-C) required significantly lower fields (12.7 ± 2.5 mT) than the unsealed design (Capsule-A, 38.3 ± 7.7 mT), improving actuation distance and enabling more feasible operation in clinical settings.

B. Sealing Performance and Liquid Sampling Capacity

To evaluate the sealing mechanism of Capsule-C, a strong acid–strong base neutralization reaction was used. Leakage volume was determined from pH changes in the surrounding solution. Under vigorous agitation simulating GI peristalsis, the sealed capsule exhibited 6.19% (5.98–6.40%) leakage, compared to 23.59% (22.81–24.39%) for the unsealed design, corresponding to an approximately 4-fold reduction. While the seal significantly reduced leakage, it did not meet the 2% target threshold, highlighting the need for further refinement. Additionally, the theoretical sampling capacity of Capsules A and B was 0.5698 mL, closely matching the experimental value of 0.5572 ± 0.1528 mL, indicating full volume utilization during sampling.

C. Controlled Actuation and Navigation

The magnetic actuation system was experimentally validated through autonomous path tracking of Capsule-A across four shapes and over a large workspace. The system is designed with an accessible workspace of approximately 100 × 50 × 17 cm, representing an average 50× increase in volume compared to existing systems [4], [5], [6]. Capsule translation was achieved via gradient pulling with a field gradient of 0.75 T/m at an actuation distance of 5 cm. The system achieved a mean path deviation error of 2.63 mm across all shapes. It also enabled successful navigation within a phantom and maze. To achieve capsule opening, a maximum separation distance of 4 cm was required. However, the system can support payloads up to 10 kg, enabling the use of a larger 4-inch magnet in future work. Combined with the nearly 3-fold reduction in required field for Capsule-C, this would substantially increase the actuation distance.

D. Experiments for Multifunctional Capability

The active spring–magnet mechanism enables repeated, controlled opening and closing of the capsule, allowing functions such as targeted drug delivery, microbiome collection, and tissue sampling. During navigation of Capsule-A through a 3D-printed maze, the capsule successfully sampled and transported cargo and performed targeted drug delivery in a stomach phantom. This mechanism enables multifunctionality without redesign or additional actuation systems. Using a single mechanism, the capsule supports targeted therapy while minimizing patient discomfort. It may also improve clinical adoption, requiring training on a single device.

V. CONCLUSION

This work presents a multifunctional capsule that integrates a spring–magnet mechanism to enable controlled navigation and repeatable opening using a single actuation input. In parallel, a large-workspace magnetic actuation platform is developed to support autonomous navigation and task execution. Experimental results demonstrate accurate path tracking, reduced actuation requirements, and improved sealing performance. These results establish a unified framework for capsule design and control in minimally invasive GI interventions. Future work will focus on improving sealing to meet clinical thresholds and extending actuation range.

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