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Inductively Triggered Capsule Robot for Needle-Based Drug Delivery

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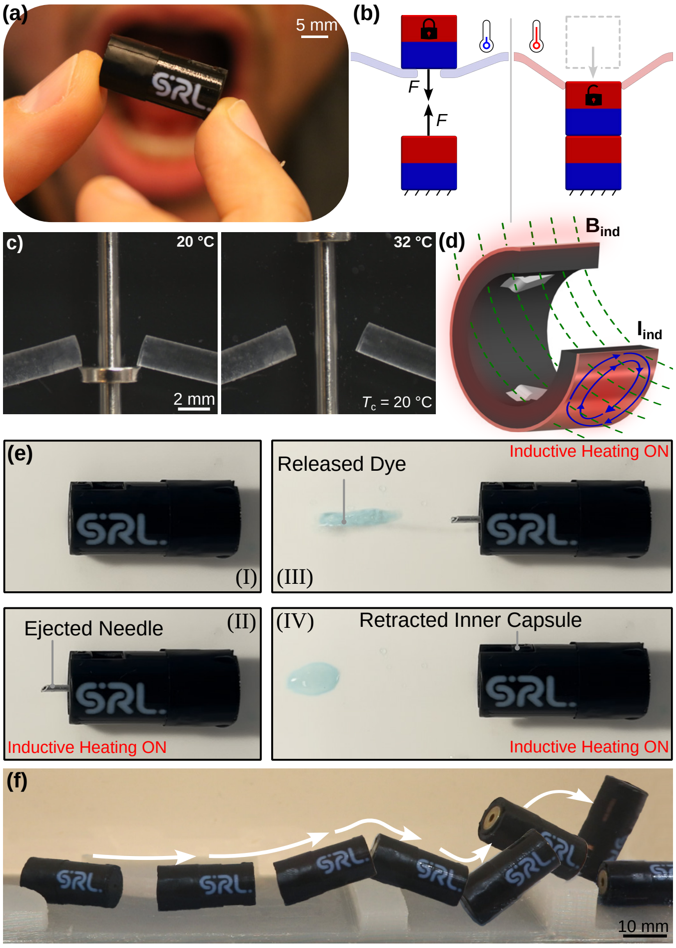

Figure 1. (a) Inductively triggered capsule robot for needle-based drug delivery. (b) Local actuation using thermally triggered magnetic springs (TTMS). (c) Thermal triggering of simplified TTMS structure. (d) Contactless inductive heating of conductive components via eddy currents (I_{ind}) induced by an oscillating magnetic field ($\mathbf{B}_{\text{ind}}$). (e) Representative actuation sequence: (I) initial state, (II) needle ejection, (III) dye release, and (IV) needle retraction. (f) The locomotion of the capsule robot can be adapted to different types of obstacles.

Ingestible capsule robots provide untethered access to the gastrointestinal (GI) tract with substantially reduced invasiveness compared to conventional endoscopic procedures. Among therapeutic applications, targeted drug delivery is of particular interest because it can increase therapeutic efficacy while reducing systemic exposure and off-target accumulation. However, most approaches rely on passive diffusion of the loaded drug across physiological barriers such as the mucus or epithelial layer, which limits delivery efficiency and restricts the classes of drugs that can be administered orally. Injection-based drug delivery can physically bypass these barriers and deliver therapeutics directly into underlying tissue, but integrating injection mechanisms in capsule robots requires actuation mechanisms capable of generating sufficient and controllable forces within a millimeter-scale untethered system compatible with magnetic navigation.

Magnetically actuated capsule robots have been proposed for controlled needle-based drug delivery, but existing approaches face fundamental trade-offs. Systems with integrated reed sensors can be triggered by weak magnetic fields (e.g., 0.5 mT), which enables remote control but restricts magnetic steering. Alternatively, magnetic fields can be used directly to generate continuous or pulsed forces within the capsule. However, whether using continuous or pulsed actuation, the maximum puncture force is limited by the performance of external actuation systems, especially when multi-newton actuation in clinical-scale workspaces is required. Consequently, there remains a need for an actuation strategy that can locally generate multi-newton forces while preserving magnetic steering and controllable triggering.

Here we present a programmable millimeter-scale capsule robot for needle-based drug delivery, enabled by thermally triggered magnetic springs (TTMS). TTMS are compact actuation mechanisms that combine preloaded magnetic springs with temperature-responsive locking structures fabricated from NOA63, a biocompatible shape memory polymer whose stiffness depends on both curing and ambient temperature. When a design-specific trigger temperature is reached, the locking mechanism transitions from a rigid to a soft state, releasing the magnetic spring, thereby converting stored potential energy into pushing or pulling forces independent of external magnetic fields. The trigger temperature can be programmed during fabrication by adjusting the curing conditions of the locking structure, allowing geometrically identical TTMS to activate at different temperatures and enabling programmable actuation sequences triggered by a single global thermal stimulus.

The capsule robot integrates multiple TTMS to perform a controlled multi-step actuation sequence: needle ejection, liquid payload release, and subsequent needle retraction. Contactless triggering is achieved through inductive heating of embedded copper elements at 16 kHz, while decoupled quasi-static magnetic fields enable navigation. The embedded permanent magnets serve both as local actuators and as magnetic dipoles for external steering, allowing the capsule to be translated, oriented, and rolled without integrating additional magnetic components. Experiments demonstrate programmable thermal response across different environmental conditions, including operation in aqueous media at physiological temperature. The capsule generates sufficient force to penetrate soft tissue mimics, with needle driving forces reaching up to 2 N. Controlled locomotion is demonstrated in a three-dimensional environment, where the capsule navigates across different obstacles using combined magnetic pulling and rolling. Together, these results establish TTMS as a viable actuation strategy for untethered capsule robots requiring multi-newton force generation, and demonstrate a programmable capsule robot that combines magnetic navigation with inductively controlled needle-based drug delivery within the gastrointestinal tract.