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An Electromagnetic Soft Robot that Carries its Own Magnet

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***Abstract*— Existing magnetically actuated soft robots require an external magnetic field to generate motion, limiting them to carefully controlled laboratory settings. Here, we introduce an electromagnetically actuated soft robot that can locomote without an external magnetic field. The robot is designed to carry its own magnet, which it alternately retracts and repels. Friction-biased feet transform this back-and-forth linear motion into forward locomotion, mimicking an earthworm gait. We demonstrate a characteristic velocity of 1.5 body lengths per second (31.3 mm/s) and actuation speeds over 150 Hz. This work paves the way for fully autonomous, untethered magnetic soft robots.**

I. Introduction

Soft robotics is a burgeoning field motivated by the limitations of traditional, rigid robots and inspired by the elasticity of biological tissues. The natural compliance of soft robots makes them attractive for applications where they have close contact with humans and safety is a priority, including biomedical [1] and assembly line applications, while their robust ability to absorb unpredictable impacts makes them attractive for deployment to remote and unstructured terrains [2], [3]. These advantages motivate researchers to develop soft alternatives to components of traditional robots, including computation [4], sensing [5], and actuation. Soft actuators often rely on active material responses to stimuli such as heat [6]–[9], light [10], pressure [4], [7], [11], and magnetic fields [1], [10], [12], [13]. This work focuses on advancing the state of the art of electromagnetically actuated soft robots beyond current limitations.

A. Environment Dependence of Magnetic Soft Robots

Electromagnetically actuated soft robots typically rely on an external magnetic field for actuation and control. We refer to robots in this class as *environment dependent* since they cannot operate in the absence of this magnetic field. There is a large body of work on environment-dependent electromagnetic soft robots. Yang *et al.* presented a gluten-based ferromagnetic spray that can be coated or patterned onto soft bodies [1]. The spray acts as a magnetic "skin," allowing the substrate to become a soft robot actuated by an external magnetic field. The authors demonstrated the concept with origami robots that could walk in the presence of a pulsing magnetic field and a capsule robot that could be steered through a rabbit's stomach by a modulated magnetic field for targeted drug delivery. Mao *et al.* demonstrated a soft electromagnetic actuator made of liquid metal channels encapsulated in silicone [12]. These actuators could generate a magnetic field when current was sourced, so the robot body could align itself with an external field. The authors showcased a swimming fish as well as a ping-pong playing soft robot, both of which could actuate with applied current in the presence of a strong, external magnet. Novelino *et al.* introduced magnetic-responsive origami robots that exhibited distributed control of a robotic arm when placed in an apparatus that could modulate the magnetic field in two Cartesian directions [13]. Hu *et al.* designed a robot made from silicone elastomer and magnetic microparticles for multimodal locomotion [14]. By controlling the external magnetic field, they demonstrated the robot walking, rolling, crawling, jumping, swimming, and even transitioning from land to water and vice versa.

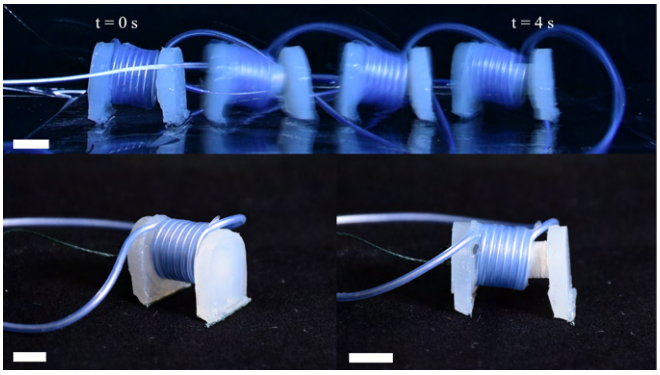

Fig. 1. An example locomotion trial. The robot achieves locomotion by repeatedly attracting and repelling an on-board permanent magnet. Scale bars: 1 cm.

B. Environment Independence

Outside of environments where magnetic fields can be carefully controlled, soft robots need to exhibit *environment independence* so that they can control themselves without relying on external magnetic fields. Few examples of environment-independent electromagnetic soft robots can be found in the literature. Kohls *et al.* created an electromagnetic actuator using compliant permanent magnets and silicone tubing filled with liquid metal [15]. When a current is applied, the magnets are attracted to the center of the coil, achieving actuation that mimics a *Xenia* coral. The authors further developed this actuation strategy to design a soft gripper that can grasp and hold pieces of paper [16]. Guo *et al.* designed a robot jellyfish, a robotic fishtail, and a gripper with soft, liquid metal coils and on-board permanent magnets [17]. Because these robots contain their

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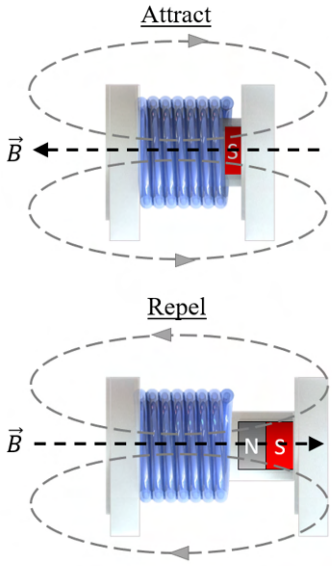

Fig. 2. Illustration of the actuation mechanism. The liquid metal coil alternately attracts and repels the magnetic foot. One cycle of these two motions is a step, and multiple steps with friction biased feet invoke forward locomotion.

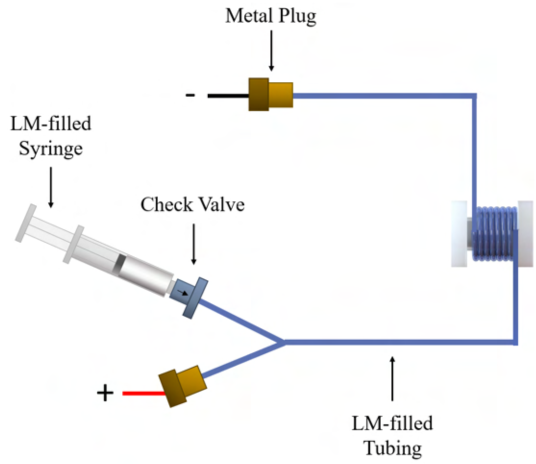

Fig. 3. Diagram of the fluidic circuit designed to mitigate the effects of electromigration. The tubes filled with liquid metal (LM) that make up the electromagnetic coil extend to two metal plugs to which wire leads were attached. LM was injected using a syringe until the tubes were filled, and then the tubes were capped with the metal plugs. A check valve was used to prevent back flow into the syringe.

own permanent magnets rather than rely on external magnetic fields, they are environment independent. Kohls's robotic gripper, however, is heavy and is demonstrated only as an end effector. Similarly, Guo's robots are not capable of locomotion. Nemitz *et al.* presented Wormbot, a locomoting robot actuated with on-board electromagnetic voice coils [18]. While Wormbot exhibits environment independence, it contains many rigid components, including 3D printed parts and rigid circuit boards, and the only soft component is the elastomeric body segment in between each voice coil. Wang *et al.* demonstrated a high-speed electromagnet robot with environment independence [19] where the only rigid components were the coil and the permanent magnet. Herein, we present a soft, electromagnetic robot that carries its own magnet (Figure 1). Our robot advances the state of the art by achieving environment-independent locomotion with a soft electromagnetic coil.

II. Design and Fabrication

To demonstrate environment-independent locomotion, we designed an earthworm robot inspired by work from Rothemund *et al.* [4] with electromagnetic actuators in place of pneumatic actuators. Back-and-forth linear motion is generated by repeatedly attracting and repelling a permanent magnet using a soft electromagnetic coil (Figure 2) made from eutectic gallium-indium (eGaIn), a room-temperature liquid metal. The 2 cm long robot has friction-biased silicone feet that transform this back-and-forth linear motion into forward locomotion (Figure 1). Designing this soft robot required us to solve two main challenges. First, we needed to generate a magnetic force strong enough to overcome internal friction in order for the robot to move. Second, we needed to mitigate the problem of electromigration failure. Electromigration is the transport of mass in metals subjected to high currents [20], and it has frequently caused open circuits especially when high currents are applied to liquid metals [21].

A. Magnetic Field Strength

The magnetic field B in the center of a solenoid is given by equation 1 where μ_0 is the magnetic permeability of free space, I is the current through the liquid metal coils, N is the number of turns, and l is the overall length of the device.

$$B = \frac{\mu_0 I N}{l} \tag{1}$$

The practical considerations for our design are current and weight. Since the magnetic field strength is directly proportional to current, higher currents yield stronger actuation forces. However, electronics cannot source infinite current, making current a limiting factor when designing the robot. Compensating for current limitations by increasing the number of turns comes with a weight trade-off since eGaIn is the heaviest component of the robot (see Table I for the mass bill of the robot). Coil density N/l is limited both by weight and the dimensions of the tubing. In practice, locomotion was best with a stronger magnetic field and a lighter robot. To accommodate these constraints, the thinnest available tubing (1/32” ID) was used to maximize the coil density and minimize the overall length of the robot—reducing its weight without affecting the magnetic field. The final length of the coil was chosen to be 1 cm.

B. Electromigration

Electromigration is a phenomenon that occurs when a high current is applied to a conductive material. If the current density is sufficiently high, atoms are broken off the structure and physically moved, creating areas of vacancies that can lead to open circuits [20]. Though this

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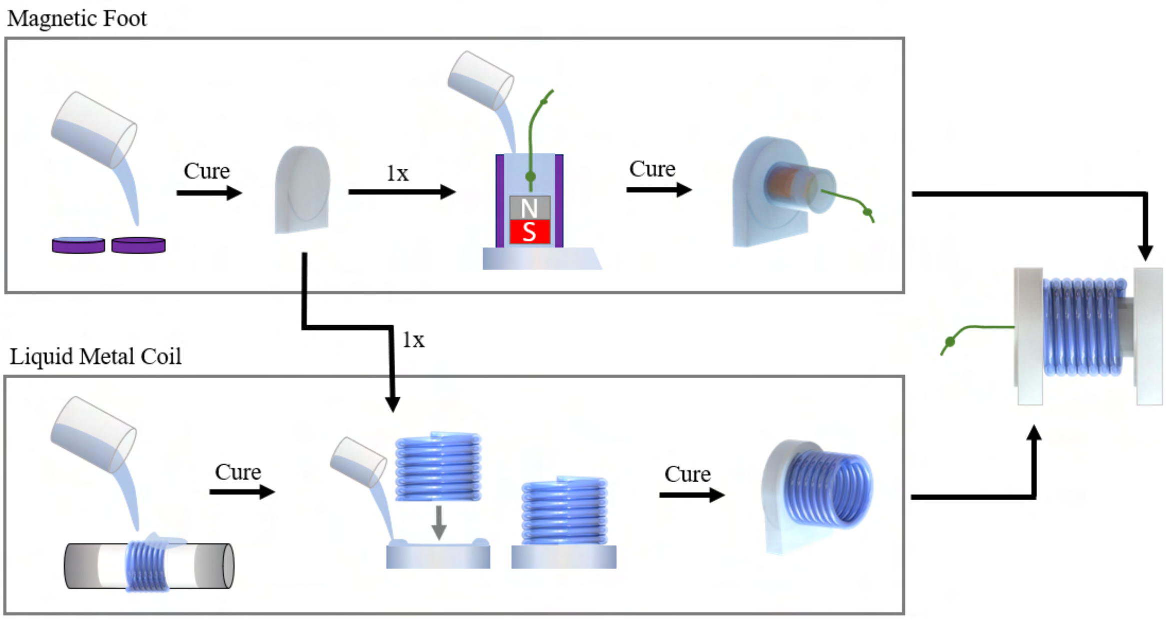

Fig. 4. The robot is manufactured in two halves, the *magnetic foot* and the *liquid metal coil*. In the first manufacturing step, two silicone feet are cast in 3D printed molds. To make the magnetic foot, a permanent magnet and a piece of string are overmolded with a cylinder of silicone on one of the silicone feet. To make the liquid metal coil, silicone tube is wrapped around a rod wrapped in Teflon and coated with silicone. This coil is then adhered to the second silicone foot, and a hole is cut in the end. The two halves are assembled by pulling the magnetic foot's string through the hole in the liquid metal coil's foot and tying a knot at the end.

occurs with all metals, the fluid state of liquid metals makes them especially susceptible [21]. When our robot was initially designed, it would only take a few steps before an electromigration failure caused an open circuit, stopping the robot where it stood. Existing strategies for mitigating electromigration failure did not suffice for our robot. Kent *et al.* addressed electromigration experimentally by measuring the mean time to failure for different currents through their circuits and avoiding high currents that they knew would cause failure [21]. Unfortunately, currents low enough to avoid electromigration failure do not generate enough force to overcome friction and make our robot move. Kohls *et al.* included liquid metal reservoirs at both ends of their circuit [16] perhaps to address failures they experienced due to electromigration, though they explain their strategy as one that accommodates thermal expansion and prevents oxide formation. Including reservoirs at either end of our coil did not work for us in practice (see Section III-A).

Our approach to mitigate electromigration is a fluidic circuit we designed to make our liquid metal coils a closed system (Figure 3). A syringe is used to inject eGaIn into the circuit via a one-way valve. Then, metal plugs (1/32" barbed to 1/8" NPT connectors filled with eGaIn and followed by 1/8" NPT plugs) are used to close the ends of the tubes as well as interface with the electrical leads that provide power. Closing the system mitigates electromigration because the eGaIn has no room to escape. This fluidic circuit allowed us to complete hours of locomotion trials without electromigration failure. After sustained use, electromigration still caused eGaIn to leak out of our metal plugs and create open circuits, but the robots were repaired instantly by injecting a small amount of additinal eGaIn into the circuit via the check valve.

C. Fabrication Process

The fabrication process for our robot is detailed in Figure 4. We refer to the half of the robot which holds the permanent magnet as the *magnetic foot*. The magnetic foot is made of silicone elastomers (DragonSkin 30 and DragonSkin 10; Smooth-On), a 1/4" $\times$ 1/4" cylindrical magnet, and a short length of string to enforce the step length. First, the foot is cast by pouring DragonSkin 30 into a 3D printed polylactic acid (PLA) mold and allowing the silicone to cure. The foot is 15 mm in diameter and has a slight bias at the bottom like the earthworm robot in [4]. A small length of string is attached to the bottom tip of the foot with a silicone adhesive (Sil-Poxy; Smooth-On) to reduce the friction between the foot and the substrate. Then, the magnet is placed in the center of the foot and overmolded with silicone (DragonSkin 10 Fast; Smooth-On) using another PLA mold. The end of the string is knotted and inserted into the elastomer after it is poured so that the magnetic foot is fabricated with a protruding string. The protruding boss where the magnet is embedded is wrapped in 1/2" Teflon tape and sprayed with ethanol to minimize friction as it slides along the inside of the coil during actuation.

The liquid metal coil makes up the larger half of the robot's body, consisting of coiled tubing adhered to a silicone foot similar to the one described above. To create the coiled tubing, Teflon film is wrapped around a 10 mm rod to create a low-friction interface, and a length of 10 mm is marked on the film. Then, 1/32" ID low-durometer, flexible silicone

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tubing (5236K203; McMaster-Carr) is wrapped seven times around the rod and encapsulated with silicone (DragonSkin 10 Very Fast; Smooth-On). After 20 minutes of curing, the coils are slid off the rod and glued to the foot using silicone (DragonSkin 10 Very Fast; Smooth-On). A hole is cut in the middle of the foot for the string to pass through. The magnetic foot is inserted into the coils to form the earthworm robot. The string embedded in the magnetic foot is pulled through the hole in the coil's foot and knotted such that the robot's maximum extension is limited by the knot at 6 mm. The tubing is then injected with eGaIn using a syringe via the fluidic circuit we discussed in Section II-B. Table I details the major components in terms of mass on each half of the robot, which has a total mass of 7.5 g.

TABLE I
MASS BILL

Magnetic Foot	**3.0 g**
magnet	1.5 g
silicone foot	1.1 g
Liquid Metal Coil	**4.5 g**
eGaIn	1.9 g
silicone coil	1.3 g
silicone foot	1.1 g

III. Experimental Methods

We characterize the system's robustness to electromigration, force output, and actuation frequency. Robustness to electromigration is compared to Kohls's solution of reservoirs [16] as well as simply inserting copper leads at either end of the coil. Magnetic force output is compared to a control robot that was the same size and shape but constructed with thin (32 AWG) copper wire inside the silicone tubing instead of eGaIn. We present locomotion trials conducted at different actuation frequencies where the robot achieves a speed of 1.5 body lengths per second. Finally, turning is demonstrated by attaching two robots together and actuating them at different frequencies.

A. Preventing Electromigration

We confirmed the efficacy of the fluidic circuit strategy described in Section II-B by comparing it experimentally to two other potential solutions to electromigration failure. For this experiment, 15 liquid metal coils were manufactured: five with the fluidic circuit, five with eGaIn reservoirs at either end like those mentioned in [16], and five with copper wire leads. Each sample was energized with 5 A of continuous current until an open circuit failure occurred. The time to failure for each sample is shown in Table II. Our fluidic circuit is the only solution that survived more than a few minutes of exposure to 5 A of current, lasting for more than 6 hours on average. As indicated in the table, several samples fabricated with the fluidic circuit had to be paused overnight—after handling many hours of high current—and then resumed the next day. One sample did not fail even after two days, at which point the test was stopped. The fluidic circuit is the only solution that made locomotion trials possible, and even when electromigration failures do occur, the fluidic circuit allows coils to be easily healed by injecting more eGaIn throught the one-way valve.

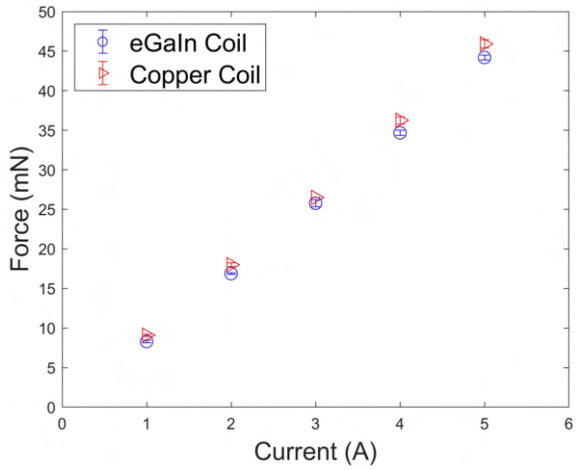

Fig. 5. Magnetic force output as a function of current for a LM coil with a copper coil as a control. Both coils exert the same force on the magnet for a given current. The magnetic force output varies linearly with the input current. Markers represent the mean and error bars represent the standard deviation of five trials.

TABLE II
COMPARISON OF ELECTROMIGRATION SOLUTIONS

Time to Failure	Electromigration Solutions		
	Fluidic Circuit	*Reservoirs*	*Wire Leads*
Sample 1	6 h 26 min[a]	1 min 24 s	2 min 2 s
Sample 2	1 min 34 s	2 min 42 s	1 min 0 s
Sample 3	53 min 44 s	7 s	1 min 17 s
Sample 4	7 h 45 min[b]	3 min 49 s	1 min 38 s
Sample 5	16 h 50 min[b,c]	7 s	1 min 39 s
Mean	**6 h 23 min**	1 min 38 s	1 min 31 s
Median	**6 h 26 min**	1 min 24 s	1 min 38 s

[a]Paused overnight at 5 h 5 min.
[b]Paused overnight at 7 h 43 min.
[c]Never failed.

B. Magnetic Blocking Force

The robot's coil was placed in a materials testing system (Instron 3345) to characterize the magnetic force it is capable of generating. A 1/4" neodymium magnet (the same magnet that we embed into the robot) was attached to the Instron's crosshead, which we lowered down until the whole magnet was just inside the coil, the same location where it would be for the forward stroke of its locomotion gait. The coil was energized with different currents, and the resulting force on the magnet was measured. The experiment was repeated with a control robot that was the same size but with copper wire inside the silicone tubing instead of eGaIn. The experiments show a linear dependence of magnetic force on applied current and no difference in force output between the liquid

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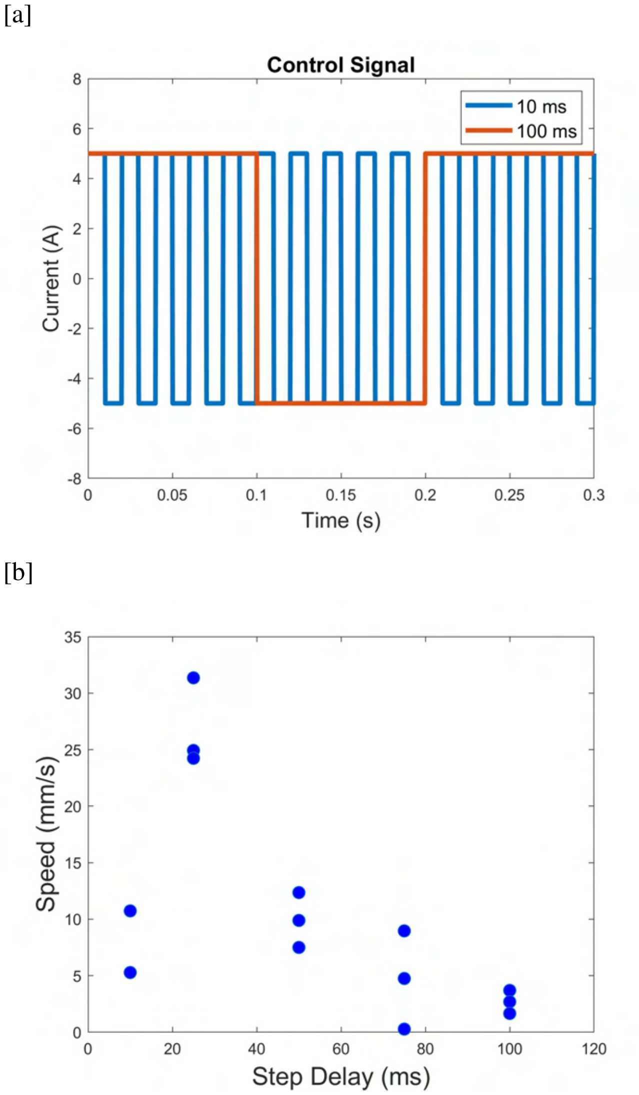

Fig. 6. [a] The robot is controlled by a square wave paramaterized by different step delays. Step delays of 10 ms and 100 ms are shown for reference. [b] The effect of step delay on speed when the robot was actuated at 5 A. A step delay of 25 ms generated the highest speeds, reaching 31.3 mm/s (1.5 body lengths per second). Longer step delays result in slower walking because the robot pauses between steps. Step delays smaller than 25 ms also result in slower speeds because the actuation is too fast for the robot to take full steps.

metal coil and the copper control (Figure 5), a result that is congruent with Equation 1. At 5 A of current, the robot exerts a 45 mN force on its magnetic foot.

C. Forward Locomotion

Friction-biased feet allow the robot to transform its back-and-forth linear motion into forward locomotion. The robot's gait comprises a forward stroke where the coil repels the magnet to push the robot's front foot forward and a back-stroke where the coil attracts the magnet and pulls the back foot forward. The robot is controlled with a high-power motor driver (Pololu G2 18v25), which switches the direction of current through the coil in order to proceed from the forward stroke to the backstroke and repeat. The eGaIn coil

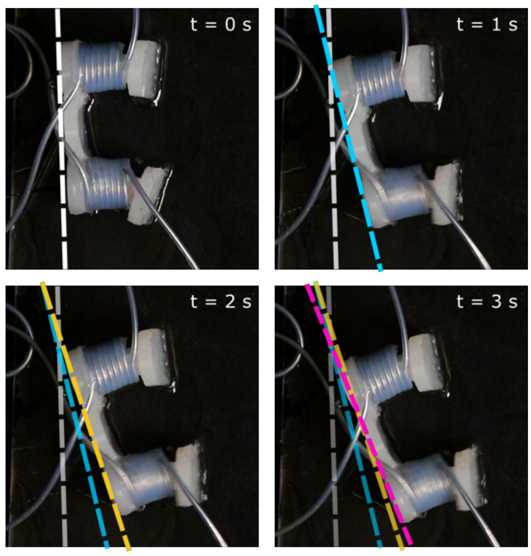

Fig. 7. A turning robot was created by adhering two robots together. Applying differential step delays to the actuators resulted in a turning gait. For the pictured trial, the top actuator had a step delay of 3 ms while the bottom actuator had a step delay of 25 ms.

and the metal plugs together have an electrical resistance of 0.6 Ω, so a potential difference of 3 V is required to energize the coil with 5 A of current. The control signal for the gait is a square wave parameterized by a step delay indicating how long the robot pauses before switching steps (Figure 6a). To find the optimal step delay for high-speed locomotion, we recorded the robot walking and varied the step delay between trials. The robot's speed was measured by tracking the recorded videos using a video analysis software (Tracker; physlets.org), and the results are plotted in Figure 6b. The highest speed of 31.3 mm/s was recorded for a step delay of 25 ms, corresponding to more than 1.5 body lengths per second for our 2 cm robot. The speed decreases with increasing step delay due to slower steps. Below 25 ms, the robot does not have enough time to take full steps before the direction of the current is switched, resulting in slower speeds.

The locomotion trials were conducted on an acrylic substrate lubricated with ethanol to reduce friction between the silicone feet and the substrate. In addition to friction, the robot's tether to the power supply plays a significant role in inhibiting locomotion. For this reason, the speed extracted from each video was the maximum constant velocity achieved throughout a trial.

D. Turning

To achieve turning gaits, two robots were attached together using a silicone adhesive (Sil-Poxy; Smooth-On). The turning strategy for this robot is to actuate one side with the optimal step delay of 25 ms and actuate the other side at a high frequency so that it vibrates and reduces static friction (Figure 7). To observe the turning gait and other locomotion trials, the reader is directed to the accompanying video.

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IV. Conclusion

This paper presents the first electromagnetic soft robot that carries its own magnet. We have demonstrated that electromagnetically actuated soft robots can operate with environment independence—without the need for controlling external magnetic fields—even for complex tasks like locomotion and even while avoiding rigid metal coils and other rigid components. This is a critical step toward making electromagnetism a viable actuation strategy for future soft robots that we envision operating in authentic environments and closely interacting with humans.

We also presented an innovative and straightforward solution to electromigration, representing a path forward for high-current applications with liquid metals where electromigration is a common failure mode. Future work will involve incorporating a soft permanent magnet to make the robot completely soft and untethering the system so that it can also carry its own controller and power supply.

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