Magnetic Hysteresis for Multi-State Addressable Magnetic Microrobotic Control

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Abstract— **We present a new scheme of remote addressable magnetic actuation for sub-mm microrobotics which uses the hysteresis characteristics of multiple magnetic materials to achieve advanced state control of many magnetic actuators sharing the same magnetic control inputs. Using this standard approach, remote magnetic actuation of a single magnet has been achieved for untethered motion control with a single magnetic control input. We propose the simultaneous use of multiple magnetic materials with varying hysteresis characteristics to effectively gain multiple control inputs as different applied magnetic field strengths. As a first experimental implementation of this idea, we present a set of three heterogeneous magnetic modules floating on a liquid surface which can be remotely reconfigured by application of a field of varying magnitude. As a second implementation, we present a team of up to six independently actuated walking microrobots made from a composite material whose net magnetic moment can be selectively turned on or off by application of a large magnetic field pulse. We also demonstrate a team of two addressable microrobots performing a task requiring cooperative teamwork. The presented concept providing multiple magnetic control inputs could be applicable in various areas of milli- or microrobotics to address multiple magnetic elements for motion or actuation control.**

I. INTRODUCTION

Research in magnetic actuation at the micro-scale has resulted in the creation of micron-scale permanent magnets for the application of forces and torques via externally-applied magnetic fields for mobile microrobots [1]–[4], microfluidic pumps and mixers [5], [6], and other microactuators [7], [8]. The independent control of many of these devices sharing the same workspace for distributed operation has evolved as a desired capability [4].

Independent control of microrobotic devices has been attempted [9]–[12], but all presented methods have major limitations in performance or number of addressable devices. In addition, the presented methods are all robot design-specific i.e. they typically take advantage of a microrobot-specific dynamic response which is not applicable to other microrobotic platforms. Thus, the ability to independently address multiple generic magnetic devices which share the same workspace in enclosed environments such as in microfluidic channels or even the human body is an unsolved challenge. This study presents a method to remotely change the state, in effect reversing or even turning off, of micromagnetic actuators in an addressable manner. In addition, the presented method is general in nature and can be applied to nearly any microrobotic system which is actuated by remotely-applied magnetic fields, at the microscale or larger. In one form, the presented method also has the capability to scale for the independent addressing of a large number of microrobotic elements.

We propose the use of multiple magnetic materials with varying magnetic hysteresis characteristics in tandem to achieve addressable control. The magnetization of so-called "permanent" magnet materials in fact can be reversed by applying a large field against the magnetization direction, with the field required to perform this switch (i.e. the magnetic coercivity, H_c) being different for each magnetic material. For permanent magnetic materials, H_c is much larger than the fields at which the microrobots are actuated for motion, allowing for motion actuation and magnetic switching to be performed independently. By using multiple materials with different magnetic coercivities, the magnetic reversal of each can also be performed independently by applying magnetic fields of the correct strength.

This independent magnetic switching can be used in microrobotic actuators to achieve addressable control of microrobotic elements. Our first addressable actuation scheme consists of several heterogeneous (each made from a different magnetic material) micromagnet modules interacting locally via magnetic forces. Selectively reversing the magnetization of one module can change the system from an attractive to a repulsive state. We present an experiment of this form, containing a set of heterogeneous magnetic modules floating on a liquid surface which can be remotely reconfigured by application of a field of varying magnitude. In such a way, the pattern of the assembly can be altered into a number of states using a single applied field of varying strength. This implementation could be used for shape-changing microrobots which adapt to the task at hand.

As a second actuation scheme, a pair of magnetic materials can work together in one actuator, forming a magnetic composite whose magnetic moment sum interacts with externally-applied or locally-induced fields. Experimentally, we introduce a microscale permanent magnet composite material that can be remotely and reversibly turned off and on by the application of a magnetic field pulsed along the magnetic axis which reverses the magnetization of one of the materials. For completely remote operation, this pulsed field is supplied by electromagnetic coils outside the device workspace. This scheme is similar to electropermanent magnets [13], [14], in which electromagnetic coils are wrapped directly around some of an array of switchable permanent magnets. When a

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strong current is pulsed through the coils, the magnetization of some of the permanent magnets is flipped, allowing for an off-on net magnetization of the set. Electropermanent magnets were originally used as centimeter-scale or larger magnetic work holders as an alternative to a mechanical vice [13]. While millimeter-scale electropermanent magnets have been fabricated [14], they contain integrated switching coils, preventing their scaling down to the micrometer scale for untethered operation.

The magnetic composite material proposed in this paper can be scaled down to the micron-scale and enables remote wireless control. The anisotropic composite is made from two materials of equal magnetic moment: one permanent magnet material of high coercivity and one material which switches magnetization direction by remotely applied fields. By switching the second material's magnetization direction, the two magnets either work together or cancel each other, resulting in distinct on and off behavior of the device. The device can be switched on or off remotely using a field pulse of short duration. Because the switching field pulse covers the entire workspace, this method could be used to selectively disable and enable many microdevices concurrently based on their orientations. Orientation control is achieved by a multi-step process using a field gradient to select a device for disabling by controlling each device's orientation. This selective disabling method was first presented in [15], where it was demonstrated for an array of micropumps. In this paper, we use the method to create addressable mobile microrobots which are free to move on a 2D surface and perform a task as a team.

The proposed multi-state control method could be used to addressably control microfluidic pumps, valves and mixers, allowing for simple fluidic channels to be used while retaining advanced control. For medical applications, multi-state microrobotic control could be used inside the human body for distributed drug delivery, sensing or surgical tasks.

II. Hysteresis for Magnetic State Control

A. Addressable magnetization direction

To achieve many-state magnetic control of a number of microrobotic actuators, we require a number of magnetic materials with different hysteresis characteristics. The magnetic coercivity and remanence (retained magnetization value when the applied field H is reduced to zero) for a few commonly-used materials are compared in Table I, with coercivity values for ground powders measured in an alternating gradient force magnetometer (AGFM). In addition, the experimentally measured hysteresis loops for ground NdFeB, ferrite, alnico and iron are shown in Fig. 1. These materials cover a wide range of hysteresis values, from NdFeB and SmCo, which are permanent under all but the largest applied fields, to iron, which exhibits almost no hysteresis. For comparison, the magnetic fields applied to actuate magnetic microactuators are typically smaller than 12 kA/m, which is only strong enough to remagnetize iron. Thus, the magnetic states of SmCo, NdFeB, ferrite and alnico can be preserved when driving an actuator. This can be used to independently

TABLE I
MAGNETIC MATERIAL HYSTERESIS CHARACTERISTICS FROM [16]
(* DENOTES MEASURED IN AGFM AFTER GRINDING)

Material	Coercivity (kA/m)	Remanence (kA/m)
SmCo	3100	∼700
NdFeB	620*	∼1000
ferrite	320*	110–400
alnico V	40*	950–1700
iron	0.6*	<1

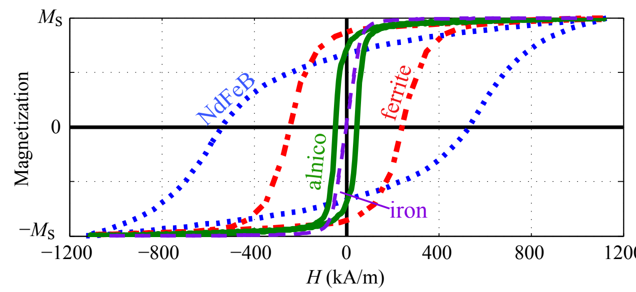

Fig. 1. H-m hysteresis loops of microrobot magnetic materials, taken in an AGFM for applied field up to 1110 kA/m shows distinct material coercivity values. The magnetization is normalized by the saturation magnetization M_s of each sample.

control the magnetization of each material, even when they share the same workspace. By applying a pulse in the desired direction greater than the coercivity field (H_c) of a particular material, an independent magnetization state of each magnet material can be achieved instantly, as shown schematically in Fig. 2(a) for a set of three independent micromagnetic elements. Here, a set of three magnetic actuators made from iron, NdFeB and alnico are shown, and the magnetization direction of each actuator can be selectively switched by applying small or large magnetic fields.

B. Powder composite magnetization disabling

As a second scheme, we are interested in demagnetizing a number of microrobotic actuators in an addressable manner to achieve independent control. In general it is difficult to demagnetize a single magnet by applying a single demagnetizing field because the slope of the hysteresis loop (i.e. the magnetic permeability) near the demagnetized state is very steep, as seen in Fig. 1. Thus, such a demagnetization process must be very precise to accurately demagnetize a magnet. While steadily decreasing AC fields can be used to demagnetize a magnetic material, this method does not allow for addressable demagnetization because it will disable all magnets in the workspace. This motivates the use of a magnetic composite to enable novel untethered addressable magnetic disabling.

We employ a different demagnetization procedure to achieve a more precise demagnetization by employing two materials, both operating near saturation where the permeability is relatively low. In this method, shown schematically in Fig. 2(b), an applied switching field H_{pulse} can be applied to switch only one material's (ferrite in this example) magnetization without affecting the second material (NdFeB). This

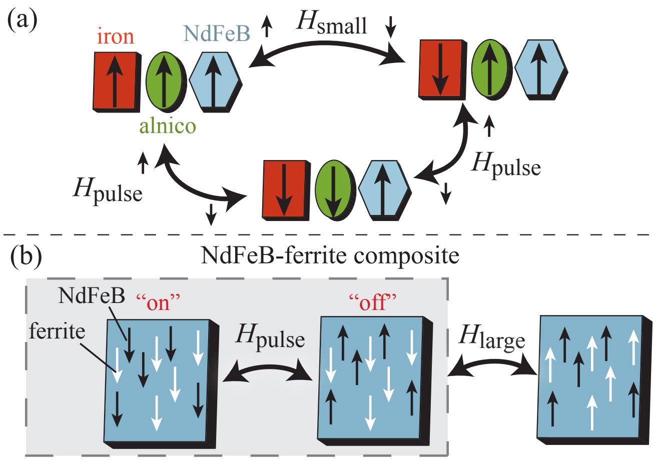

Fig. 2. Schematic showing the multiple magnetic states which can be achieved through the use of a variety of magnetic materials. (a) Three separate magnetic actuators, each made from a different magnetic material, the magnetization of which can be independently addressed by applying magnetic field pulses of various strengths. Here, H_{pulse} is a large field pulse and H_{small} is a small static field. (b) A single magnetic composite actuator can be switched between the "up", "off" or "down" states by applying pulses of different strength. Here H_{large} is a very large field pulse which switches the actuator to the "down" state.

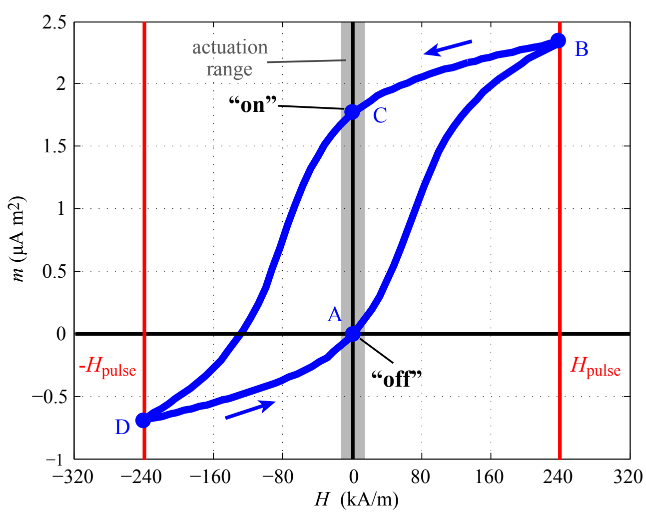

Fig. 3. The H-m hysteresis loop of a composite microrobot made from ferrite and NdFeB. A 240 kA/m field switches the ferrite magnetization while leaving the NdFeB unaffected, resulting in a vertically-biased loop intersecting the origin, showing clear "on" and "off" states.

switching allows the device to be switched between "on" and "off" states as the magnetic moments add in the "on" state or cancel in the "off" state. While the internal field of the magnet will not be zero, the net field outside the magnet will be nearly zero, resulting in negligible net magnetic actuation forces and torques. By applying a very large field pulse H_{large}, the NdFeB magnetization could also be switched, reversing the "forward" direction of the actuator, shown as the third state in Fig. 2(b).

When fields are applied below the NdFeB coercivity, the NdFeB acts as a permanent magnet, biasing the device magnetization, as shown in the H-m loop of Fig. 3 for H_{pulse} up to ± 240 kA/m. Traversing the hysteresis loop, the device begins in the off state at point "A", where motion actuation fields, indicated by the ± 12 kA/m range, only magnetize the device to about 0.08 μA m^2, resulting in minimal motion actuation. To turn the device on, a 240 kA/m pulse is applied in the forward direction, bringing the device to point "B". After the pulse, the device returns to point "C", in the "on" state. Here, motion actuation fields vary the device moment between about 1.7 and 1.8 μA m^2. To turn the device off, a pulse in the backward direction is applied, traversing point "D", and returning to the "off" state at point "A" at the conclusion of the pulse. For small motion actuation fields in the lateral direction, the device is expected to show even lower permeability in the on or off state due to the shape anisotropy induced during the molding process.

When disabling a device by applying a pulse in the backward direction, the alignment of the device with respect to the pulse is critical. Even a minor misalignment will result in in-plane torques which would rotate the device into alignment with the pulsed field before the device is disabled. Further theoretical and experimental investigation of these requirements is given in [15].

C. Magnetic actuation

Microrobotic magnetic motion actuation can be achieved through inter-magnet interactions or remotely by magnetic coils which apply magnetic torques and forces to the microrobotic elements. These fields, typically smaller than ± 12 kA/m in strength, are here provided by three air-core electromagnetic coil pairs, which can create a uniform field in any direction in the workspace, similar to that in Diller et al. [17]. The coils and workspace setup used in this work are shown in Fig. 4(a). The electromagnetic coil currents are controlled using a PC with data acquisition system using linear electronic amplifiers (Dimension Engineering Inc., SyRen 25) with feedback from Hall-effect current sensors (Allegro Microsystems Inc., ACS714). The workspace is observed by a CCD camera (Foculus). The high strength field pulse H_{pulse} is delivered by a 20-turn, low-inductance (8 μH) coil of inner diameter 23 mm, placed within the larger coil sets as shown in Fig. 4(a). The pulsing coil is driven by a 0.8 mF electrolytic capacitor bank in a series LCR circuit, triggered by a silicon-controlled rectifier (Vishay, VS-70TPS12). The applied flux density is governed by the second order series LCR circuit equation [18]

$$\frac{1}{D}\frac{d^2H(t)}{dt^2} + \frac{R}{LD}\frac{dH(t)}{dt} + \frac{1}{LCD}H(t) = 0, \quad (1)$$

where D is a constant relating coil current $i(t)$ to the flux density as $H(t) = Di(t)$ ($D \approx 8.83\,\text{m}^{-1}$ for the pulsing coil used), R is the coil resistance, L is the coil inductance and C is the system capacitance. The initial condition is specified by the initial voltage on the capacitor bank V_0 as

$$\left.\frac{dH(t)}{dt}\right|_{t=0} = \frac{V_0}{LD}. \quad (2)$$

The H_{pulse} strength is measured in the workspace using a Hall effect sensor (Allegro 1321), and is shown in Fig. 4(b) for a capacitor charge of 130 V, reaching a peak current of about 450 A. In additional experiments, it is verified that the pulse peak amplitude is linearly proportional to the capacitor charge voltage, and has a duration of several milliseconds. Such a short pulse acts to magnetize the microrobotic elements before they rotate into alignment with the pulse. Fluid drag, substrate friction and inertia act to slow this rotation, so the microrobots are operated in a viscous silicon oil (Dow Corning, 5-20 cSt) to lessen the requirements on the coils. Thus, the approximately 100 μs H_{pulse} rise-time switches the microrobot magnetization before it orients with the field.

1) Micromodules: The workspace is located within both the actuation and pulsing coils, and consists of a fluid container several cm wide. The microrobotic elements used in experiments are shown in Fig. 4(c,d). In Fig. 4(c) is shown a number of free-moving magnetic modules, each containing a different magnetic material for addressable magnetic switching. These modules float at a liquid interface, and assume positions relative to each other dependent on the magnetic interaction forces between them. In Fig. 4(d) is shown a mobile microrobot which moves by untethered crawling motion, using the method introduced in Pawashe et al. [3]. In short, this actuation method involves oscillating magnetic fields, resulting in stick-slip motion of the microrobot across a 2-D surface. This torque-based stick-slip method is advantageous over force-based magnetic field gradient pulling methods due to the superior scaling of magnetic torques to the micro-scale [19]. Microrobots moved with this method are shown to exhibit high speed and precision motion with step sizes of down to several μm, in a variety of liquid or gas environments [3]. These microrobots are made from a magnetic composite, and can be individually addressed for motion by selectively turning off the magnetization of each microrobot.

2) Magnetic materials: The disabling microrobot consists of a composite of two magnetic powders, bound in a non-ferromagnetic polyurethane binder (BJB Enterprise, TC-892). Neodymium iron boron (NdFeB, Magnequench MQP-15-7), refined in a ball mill to particles under 10 μm in size, is chosen as the high-coercivity material, with measured coercivity of around 620 kA/m. Once magnetized, the NdFeB retains its magnetization direction and magnitude during the experiments. Ferrite ($BaFe_{12}O_{19}$), ground using an endmill to grains approximately 10-50 μm in size, is chosen as the switchable material due to its large remanence and coercivity of around 320 kA/m. This coercivity is larger than the device motion actuation range of ± 12 kA/m, but much smaller than the coercivity of NdFeB, which allows for the ferrite to be switched while retaining the NdFeB magnetization. Both NdFeB and ferrite can be ground to micrometer size without significant change in magnetic properties, allowing for a versatile molding fabrication method to be used. To switch the magnetization of the ferrite, a field H_{pulse} greater than the coercivity of ferrite, but less than the coercivity of NdFeB, is applied. This allows the device to be switched between “on” and “off”

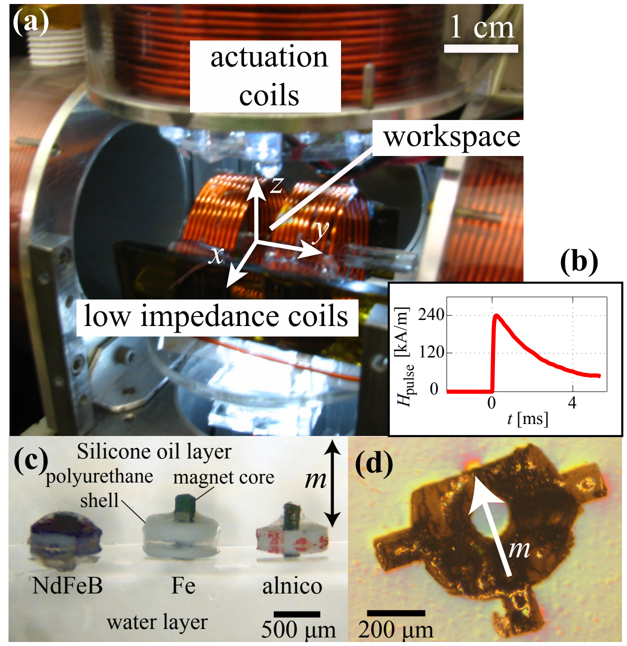

Fig. 4. Photographs of the electromagnetic coil system and magnetic microrobotic elements. (a) Actuation and pulsing coils surrounding the workspace. (b) Measured H_{pulse} as a function of time for a 130 V capacitor charge, showing a peak of 240 kA/m and duration of several milliseconds. (c) The reconfigurable micromodules used in this study, showing the two liquid layers and the module components. (d) The molded mobile microrobot design used in this study.

states as the magnetic moments add or cancel each other.

3) Composite magnet fabrication: The magnetic slurry is poured into a rubber mold fabricated using soft-lithography techniques. After pouring, the entire mold is placed in a strong uniform magnetic field (800 kA/m) to induce a preferential “forward” direction and magnetize both magnetic materials. This field orients the individual grains and causes the magnetic particles to form long chain aggregates [20]. This orienting process results in an anisotropic increase in remanent magnetization and coercivity of about 10% in this preferential direction, when compared with a non-oriented sample.

Due to their proximity in the microrobot body, the magnet particles can potentially interact with each other via exchange coupling, an effect seen in exchange spring magnets [21]. In such a case, the ferrite magnetization would be biased by the NdFeB, preventing it from switching magnetically. However, as the coercivity of ferrite is much higher than the remanence of NdFeB, exchange coupling is considered negligible. This is verified experimentally by noting that the effective observed coercivity of the ferrite is not changed when in composite form with NdFeB.

As the magnetic particles are encased within the polyurethane matrix, the materials are protected from oxidation, and microrobots have been shown to retain their properties for months, when stored in oil, water or air. In addition, microrobots are relatively tolerant to small temperature changes, and the magnetic properties of the materials used are not expected to change for temperatures normally encountered in microfluidics or medical applications.

D. Selective microrobot actuation

The presented disabling method for mobile microrobots can be used to selectively disable multiple microrobots. Based on its orientation when the pulse is applied (and independent of its position), each microrobot will be enabled or disabled. To achieve this selectively orientation without experiencing any translational motion before the switching pulse is applied, a four step method is employed, as shown in Fig. 5:

1) Using a uniform field, all devices are pointed in the $+y$-direction.
2) Using two horizontal coils operated in opposition, a horizontal field gradient $\frac{dH_x}{dx}$ is applied. At the center of the coil system, a point of zero field exists, which is positioned over one of the microrobots. This zero-field point can be shifted to select a different microrobot for disabling.
3) A uniform $-y$-directed field is applied, rotating all microrobots except the selected one, which experiences no torque due to being antiparallel to the field.
4) The downward field pulse H_{pulse} is applied to disable all microrobots pointing in the $+y$-direction. Devices pointing in the $-y$-direction remain "on" because their orientation is parallel to H_{pulse}.

Thus, a large number of microrobots can be independently addressed for magnetic disabling if they are adequately spaced in a single direction. The minimum horizontal spacing s_{min} will depend on the magnitude of the magnetic gradient field created and the minimum torque T_{min} required to orient the microrobots in step 2 above. Using the applied magnetic torque of

$$\vec{T}_m = \mu_0 \vec{m} \times \vec{H} \tag{3}$$

where $\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$ is the permeability of free space, $\vec{m}$ is the device magnetic moment, and $\vec{H}$ is the applied field, this minimum spacing can be derived as

$$s_{\text{min}} = \frac{T_{\text{min}}}{\mu_0 |\vec{m}| \frac{dH_x}{dx}}. \tag{4}$$

In addition, when operating untethered magnetic microrobots in a shared workspace, a minimum microrobot spacing must always be maintained to prevent the microrobots from assembling together by magnetic attraction. This minimum distance is dependent on the surface friction and magnetic attraction force, and is typically several microrobot body-lengths [17].

Multiple microrobots can be disabled by repeating the process for each to be disabled. Previously disabled microrobots will remain oriented in the $+y$-direction while subsequent microrobots are disabled. Selective actuation could be achieved for two-dimensional arrays of microrobots through the concurrent use of x- and y-directed field gradients, but is not shown in this work.

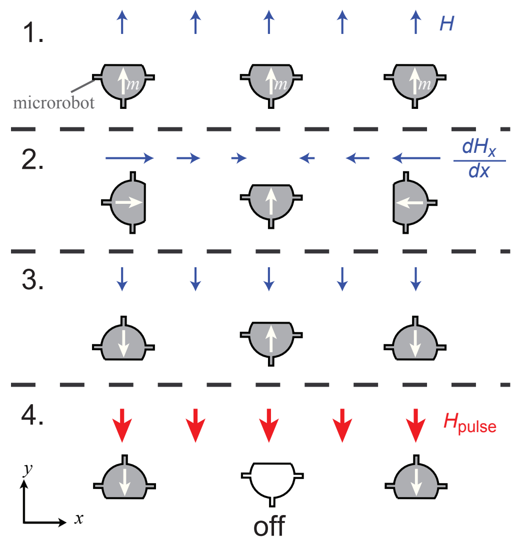

Fig. 5. Selective microrobot orientation control method. Using a four step application of magnetic fields and field gradients, a single device is chosen to be disabled. Blue arrows indicate low-strength actuation magnetic fields, while red arrows indicate a large H_{pulse}.

III. Experiments

A. Reconfigurable module demonstration

The first experimental demonstration involves a set of circular magnetic modules which arrange themselves into different configurations based on the inter-magnetic attractive and repulsive forces. We perform the transition paths between some of the possible morphologies with a set of three modules in a plane, as shown in Figure 6, which represents one continuous experiment. Between each image, the strength and direction of the applied magnetic field is altered to induce a magnetization change in one or more modules, depending on their magnetic properties. In this experiment, one each of round NdFeB (N), alnico (A), and iron (F) modules are used, with widely varying magnetic coercivities as shown in Fig. 1. It is seen that any reorganization of modules is possible, with modules settling into a location of minimum energy based on their relative magnetic moment directions. Here, antiparallel magnetizations attract while parallel magnetizations repel, with the force acting on one module given by

$$\vec{F}_m = \frac{\mu_0}{V} \int_V (\vec{m} \bullet \vec{\nabla}) \vec{H}(x,y,z)\,\mathrm{d}V, \tag{5}$$

where $\vec{H}(x,y,z)$ is the field produced by nearby modules, and V is the magnetic volume of the module.

The experiment is conducted on a concave liquid interface between water and silicon oil (Dow 200® 5 cSt), such that the weight of the modules pulls them towards the center. It is possible with three modules for the system to become trapped in a local minimum configuration which disrupts the transition process.

Since all the transitions are reversible, the initial configuration can be set to any configuration. Here in Fig. 6(a), it is set to N(↑)-F(↓)-A(↑), where N and A each attract to F. By applying a small magnetic field in the upward direction

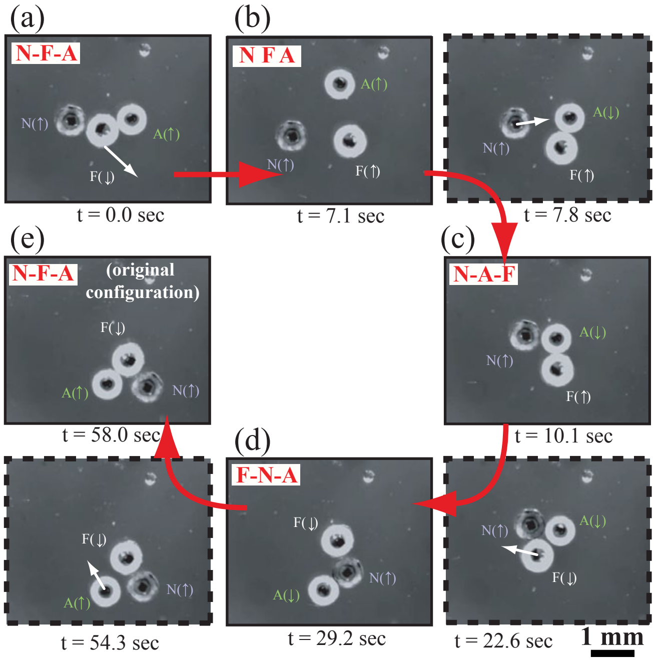

Fig. 6. Reversible and repeatable self-reconfiguration process, achieved by selectively switching the magnetization of each module. Included is one each of round NdFeB (N), alnico (A), and iron (F) modules, resting on a fluid interface. The magnetization direction of each module is given by an upward or downward arrow in parenthesis. Upcoming module motions are shown with white arrows. All the transition paths between different morphologies are performed, as indicated by the red arrows, with intermediate motion positions shown as insets in dotted boxes.

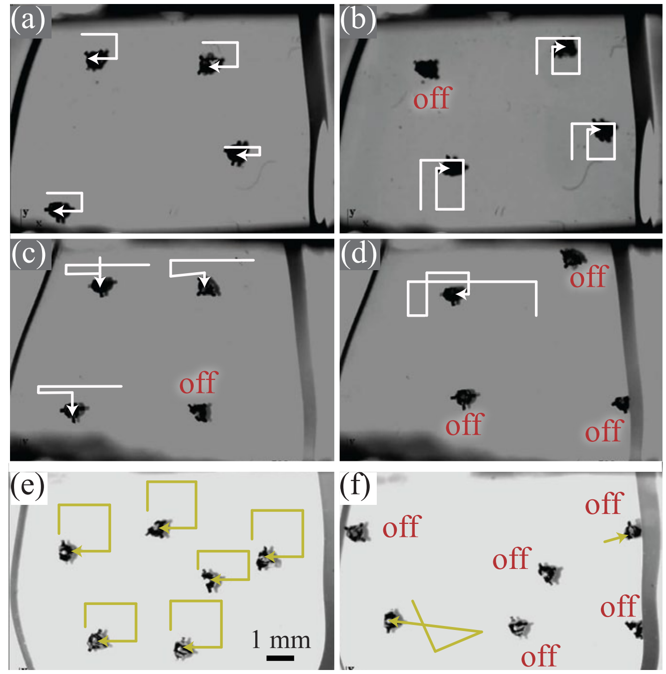

Fig. 7. Frames from a video of addressable microrobot motion on a 2D glass surface. Frames show microrobot paths traced. (a) Four microrobots are enabled, and move in parallel. (b-c) One microrobot is disabled and others move in parallel. (d) All but one microrobot is disabled, leaving the single microrobot to move. (e) Six microrobots move in parallel. (f) All but one microrobot is disabled, leaving the single microrobot to move. Video is available in supplementary files.

$H_{act}(\uparrow)$, the magnetic polarity of only F is inverted so that all three modules are repelling (N(↑) A(↑) F(↑)), shown in Fig. 6(b). In this state, the spacing of the modules can be modulated by changing the applied field strength, which directly affects the F magnetization value. The equilibrium state is where the magnetic repulsion matches the restoring force caused by the sloped liquid surface which pushes the modules towards the center of the workspace. Next, the polarity of the alnico module is switched down using a large H_{pulse} field. This results in both N and F attracting A (N(↑)-A(↓)-F(↑)), shown in Fig. 6(c). Next, the F is switched down using a weak downward field $H_{act}(\downarrow)$, causing it to move from A to N, shown in Fig. 6(d). Next, the A is switched up using a upward $H_{pulse}(\uparrow)$, causing it to move from N to F, shown in Fig. 6(e). The system has thus returned to the original configuration (N(↑)-F(↓)-A(↑)).

B. Addressable mobile microrobot demonstration

The next experimental demonstration uses mobile magnetic microrobots which are constructed from the magnetic composite material, allowing for on-off control of each microrobot. Four and six microrobots are moved using stick-slip motion on a glass slide surface in a viscous oil environment. The viscous fluid environment is provided here to increase the fluid drag to retain microrobot orientation during the pulse. The experimental workspace is placed inside the coil system, allowing for both stick-slip motion on the 2D surface using small magnetic fields up to 2.4 kA/m and magnetic state changes by a larger field pulse. Independent addressing of the "on" and "off" states of each microrobot is accomplished by H_{pulse}, applied in-plane.

Fig. 7 shows the microrobots being disabled using the methods presented to show addressing of multiple devices, and to show that any combination of microrobot on/off states are achievable. Microrobots in the "off" state are not completely disabled, and vibrate slightly without translating. This incomplete demagnetization is done on purpose to retain a small degree of control, and can be elimated through a slightly larger pulse. Microrobots in the "on" state translate in parallel. Here, four microrobots are addressed in Fig. 7(a-d) and six in Fig. 7(e,f) in a 20 cSt silicone oil environment. This demonstrates the scalability of the presented disabling method, towards the goal of massively parallel microrobotic actuation.

To demonstrate the usefulness of a team of microrobots, a simple cooperative teamwork task is conducted and shown in Fig. 8, where two microrobots of different sizes attempt to reach a goal location. Here, the two microrobots begin trapped in an enclosed area. The door to the goal is covered by a plastic blockage. As the large microrobot is too big to fit through the door and the small microrobot is too small to move the blockage, both must work together as a team to reach the goal.

IV. Conclusions

We demonstrated a new remote microscale magnetic addressable actuation concept which uses the hysteresis characteristics of several magnetic materials to achieve independent

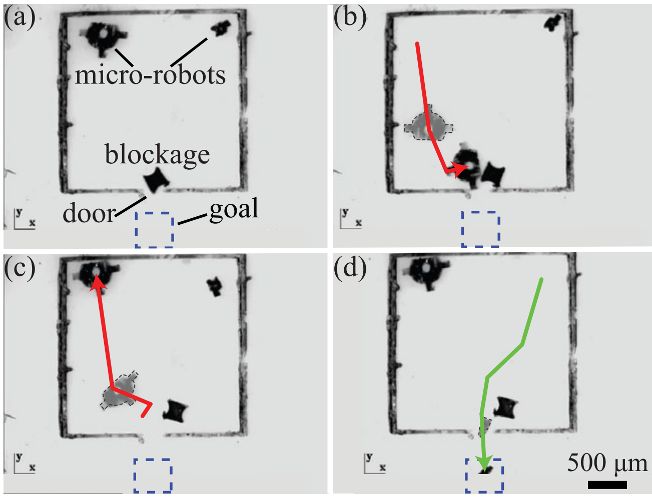

Fig. 8. Addressable microrobot teamwork task, requiring the cooperative contribution of two mobile microrobots of different sizes working together to reach a goal. Frames each show two superimposed images, with the microrobot paths traced. (a) Both microrobots lie inside an enclosed area with the door to the goal blocked by a plastic blockage. Only the larger microrobot can move the blockage, while only the smaller microrobot is small enough to fit through the door. (b) The larger microrobot removes the blockage while the smaller disabled microrobot remains in place. (c) The larger microrobot returns to its staring point and is disabled. (d) The smaller microrobot is enabled and is free to move through the door to the goal. Video is available in supplementary files.

control of the magnetic state of a number of actuators. We demonstrated two schemes, the first of which uses one magnetic material for each microrobotic element, allowing for independently addressable magnetic switching of each module into forward or reverse magnetization states. This allowed us to create a 3-module reconfigurable assembly on a 2D surface which could reconfigure into any connected state by inter-module magnetic attraction forces.

As a second case, we paired two magnetic materials into a composite which can be remotely and repeatedly switched between "on" and "off" states by an externally-generated magnetic field pulse. The switching behavior was found to clearly reduce the motion actuation of magnetic microrobots in the "off" state to nearly zero. Through the use of spatial magnetic field gradients, single or multiple microrobots were selected for disabling, leading to addressable motion behavior for multiple microrobots moving on a 2D surface. The scalability of the concept was demonstrated by independently controlling up to six microrobots, and the usefulness of such an addressable concept demonstrated through a maze task which required the coordinated contributions from two microrobots.

Although the microrobots shown are 300-800 μm in size, the presented addressability concepts are expected to scale smaller or larger without change in performance as long as the magnetic properties are maintained. High viscosity liquid was used in this study to allow for easier disabling, but the scheme could work in liquid such as water if the charge voltage of the pulsing circuit is increased several times and the capacitance reduced, allowing a faster pulse rise time with the same H_{pulse} peak value. The addressable magnetic composite microdevice concept can be extended to other microscale systems using magnetic actuation, and the composite material can be simply molded into any desired shape. Future works will include the use of this switching device as an addressable actuation method for microfluidic valves, and other magnetic actuators at the micron, mm and cm-scales.

References

[1] T. Honda, K. Arai, and K. Ishiyama, "Micro swimming mechanisms propelled by external magnetic fields," *IEEE Transactions on Magnetics*, vol. 32, no. 5, pp. 5085–5087, 1996.

[2] D. R. Frutiger, K. Vollmers, B. E. Kratochvil, and B. J. Nelson, "Small, fast, and under control: Wireless resonant magnetic micro-agents," *The International Journal of Robotics Research*, vol. 29, no. 5, pp. 613–636, 2009.

[3] C. Pawashe, S. Floyd, and M. Sitti, "Modeling and experimental characterization of an untethered magnetic micro-robot," *The International Journal of Robotics Research*, vol. 28, no. 8, pp. 1077–1094, 2009.

[4] M. Sitti, "Voyage of the microrobots," *Nature*, vol. 458, pp. 1121–1122, 2009.

[5] K. S. Ryu, K. Shaikh, E. Goluch, Z. Fan, and C. Liu, "Micro magnetic stir-bar mixer integrated with parylene microfluidic channels." *Lab on a Chip*, no. 6, pp. 608–13.

[6] K. Ishiyama, M. Sendoh, A. Yamazaki, and K. Arai, "Swimming micro-machine driven by magnetic torque," *Sensors and Actuators A: Physical*, vol. 91, no. 1-2, pp. 141–144, 2001.

[7] J. Judy, "Magnetic microactuation of torsional polysilicon structures," *Sensors and Actuators A: Physical*, vol. 53, no. 1-3, pp. 392–397, 1996.

[8] T. Sawetzki, S. Rahmouni, C. Bechinger, and D. W. M. Marr, "In situ assembly of linked geometrically coupled microdevices." *Proceedings of the National Academy of Sciences*, vol. 105, no. 51, pp. 20 141–5, 2008.

[9] A. Agarwal, S. Sridharamurthy, and D. Beebe, "Programmable autonomous micromixers and micropumps," *Journal of Microelectromechanical Systems*, vol. 14, no. 6, pp. 1409–1421, 2005.

[10] E. Diller, S. Floyd, C. Pawashe, and M. Sitti, "Control of multiple heterogeneous magnetic microrobots in two dimensions on nonspecialized surfaces," *IEEE Transactions on Robotics*, vol. 28, no. 1, pp. 172–182, 2012.

[11] B. Donald, C. Levey, and I. Paprotny, "Planar microassembly by parallel actuation of MEMS microrobots," *Journal of Microelectromechanical Systems*, vol. 17, no. 4, pp. 789–808, 2008.

[12] C. Pawashe, S. Floyd, and M. Sitti, "Multiple magnetic microrobot control using electrostatic anchoring," *Applied Physics Letters*, vol. 94, no. 16, p. 164108, 2009.

[13] P. Braillon, "Magnetic plate comprising permanent magnets and electropermanent magnets," patent 4075589, 1978.

[14] K. Gilpin, A. Knaian, and D. Rus, "Robot pebbles: One centimeter modules for programmable matter through self-disassembly," in *IEEE International Conference on Robotics and Automation*, 2010, pp. 2485–2492.

[15] E. Diller, S. Miyashita, and M. Sitti, "Remotely addressable magnetic composite micropumps," *RSC Advances*, vol. 2, no. 9, pp. 3850–3856, 2012.

[16] B. Cullity and C. Graham, *Introduction to Magnetic Materials*. IEEE Press, 2009.

[17] E. Diller, C. Pawashe, S. Floyd, and M. Sitti, "Assembly and disassembly of magnetic mobile micro-robots towards deterministic 2-D reconfigurable micro-systems," *The International Journal of Robotics Research*, vol. 30, no. 14, pp. 1667–1680, 2011.

[18] J. Nilsson and S. Riedel, *Electric Circuits*, 8th ed. Prentice Hall, 2010.

[19] J. J. Abbott, Z. Nagy, F. Beyeler, and B. J. Nelson, "Robotics in the small, part I: Microrobotics," *IEEE Robotics and Automation Magazine*, vol. 14, no. 2, pp. 92–103, 2007.

[20] J. Kim, S. E. Chung, S. Choi, H. Lee, J. Kim, and S. Kwon, "Programming magnetic anisotropy in polymeric microactuators," *Nature Materials*, vol. 10, pp. 747–752, 2011.

[21] E. Fullerton, "Hard/soft magnetic heterostructures: Model exchange-spring magnets," *Journal of Magnetism and Magnetic Materials*, vol. 200, no. 1-3, pp. 392–404, 1999.