DOI: 10.1002/ ((please add manuscript number))
Article type: Full Paper

Three-Dimensional Programmable Assembly by Untethered Magnetic Robotic Micro-Grippers

*Eric Diller and Metin Sitti**

5000 Forbes Ave. Pittsburgh, PA 15213. USA.
E-mail: sitti@cmu.edu

Keywords: programmable assembly, manipulation, micro-robotics, magnetic control, micro-grippers

Abstract: Mobile sub-millimeter micro-robots have demonstrated untethered motion and transport of cargo in remote, confined or enclosed environments. However, limited by simple design and actuation, they lack remotely-actuated on-board mechanisms required to perform complex tasks such as object assembly. A flexible patterned magnetic material is introduced here which allows for internal actuation, resulting in a mobile micro-gripper which is driven and actuated by magnetic fields. By remotely controlling the magnetization direction of each micro-gripper arm, we demonstrate a gripping motion which can be combined with locomotion for precise transport, orientation and programmable three-dimensional (3D) assembly of micro-parts in remote environments. This allows for the creation of out-of-plane 3D structures and mechanisms made from several building blocks. Using multiple magnetic materials in each micro-gripper, we also demonstrate the addressable actuation of gripper teams for parallel, distributed operation. These mobile micro-grippers can potentially be applied to 3D assembly of heterogeneous meta-materials, construction of medical devices inside the human body, the study of biological systems in micro-fluidic channels, 3D micro-device prototyping or desktop micro-factories.

1. Introduction

Remotely-actuated micro-devices powered by magnetic fields have recently gained significant attention for mobile micro-robotics and micro-fluidics applications, where a physical presence is required inside remote or enclosed micro-scale environments.[1,2] However, as these devices are typically made from a simple uniform distribution of magnetic moments in a rigid body, they lack the ability for complex internal actuation such as gripping, which could be required for three-dimensional (3D) object transport, assembly or micro-fluidic actuation.[3,4] It has been demonstrated that magnetic materials can be combined with flexible polymer materials to achieve internal actuation,[5,6] but these materials have not been applied to mobile micro-tools.

Micro-gripping using mechanical forces has been used in the literature for 3D pick-and-place manipulation and assembly of micro-scale objects. Typically this takes the form of a micro-scale end-effector tethered to a larger macro-scale robotic arm. Such micro-grippers are actuated by piezoelectric,[7,8] electrostatic,[9] electromagnetic,[10] laser,[11] and other means. However, this tethered approach has limitations when accessing remote environments such as inside the human body, and cannot be used to access confined or enclosed environments such lab-on-a-chip devices. Thus, untethered micro-grippers could operate in a wider range of applications. A few untethered micro-object manipulation schemes have been demonstrated previously, primarily relying on direct contact pushing on a two-dimensional (2D) plane[12,13,14,15,16] or fluid-based drag manipulation in 3D.[13,17,18] These methods result in limited manipulation capability and robustness, as control of part motion is often a secondary effect of the micro-robot motion. Thus, part assembly tasks are limited in precision, and capabilities for programmable 3D or complex assembly are limited.

Several examples of micro- or milli-scale untethered gripping-like manipulation have been shown in the literature. These have included a swimming helical micro-robot with an open cage on the front,[19] a magnetically-levitating centimeter-scale micro-robot with a thermally-actuated micro-gripper actuated by focused laser,[20] and chemically- or thermally-activated flexible grippers made from layered materials.[21,22] While these mobile manipulators have shown the untethered transport of cargo, they have not exhibited the ability to orient and assemble objects in 3D due to their lack of gripping precision and motion sophistication.

We present a flexible magnetic material with patterned and dynamic magnetization allowing for the creation of untethered mobile micro-grippers with remote magnetic actuation. These grippers can be moved and actuated using magnetic fields of varying strength using existing mobility methods such as magnetic gradient-based 3D pulling or field-based 2D rotational stick-slick locomotion developed previously for mobile magnetic micro-robots.[3,4,23] The ability to position and orient the gripper in 3D space allows the new micro-grippers to transport and assemble building blocks into out-of-plane or other 3D arrangements. Such assembly will allow for the creation of complex 3D micro-materials made from heterogeneous building blocks, which can be arranged in a programmable and dynamic manner in a remote or enclosed environment. These assemblies could form actuators inside microfluidic devices, complex meta-materials, or be used for patterned cell structures.

General programmable and dynamic assembly in remote or enclosed spaces is not possible by other methods. The novel advantage of this work over previous micro-grippers is that the gripper itself is mobile and untethered, yet capable of precise gripping. This can allow the gripper to noninvasively access small, enclosed spaces for out-of-plane 3D manipulation and assembly tasks. This work is distinct from our previous micro-robot assembly work[12] which used contact-based pushing, in that we now directly grab an object and manipulate it in 3D for precision transport and assembly. This allows for true 3D manipulation.

2. Micro-Gripper Concept

The micro-grippers are made designed a flexure-based mechanism to reduce complications with micro-scale friction and adhesion, which could be present with sliding or rotating mechanisms. The fabrication of micro-scale flexures is also relatively straightforward compared with traditional sliding or rotating mechanisms. The flexures allow for actuating torques or forces to result in gripper opening and closing, and were designed to be compact in size. The result is a simple single-piece, compliant, magnetic micro-gripper (Figure 1c and 1f).

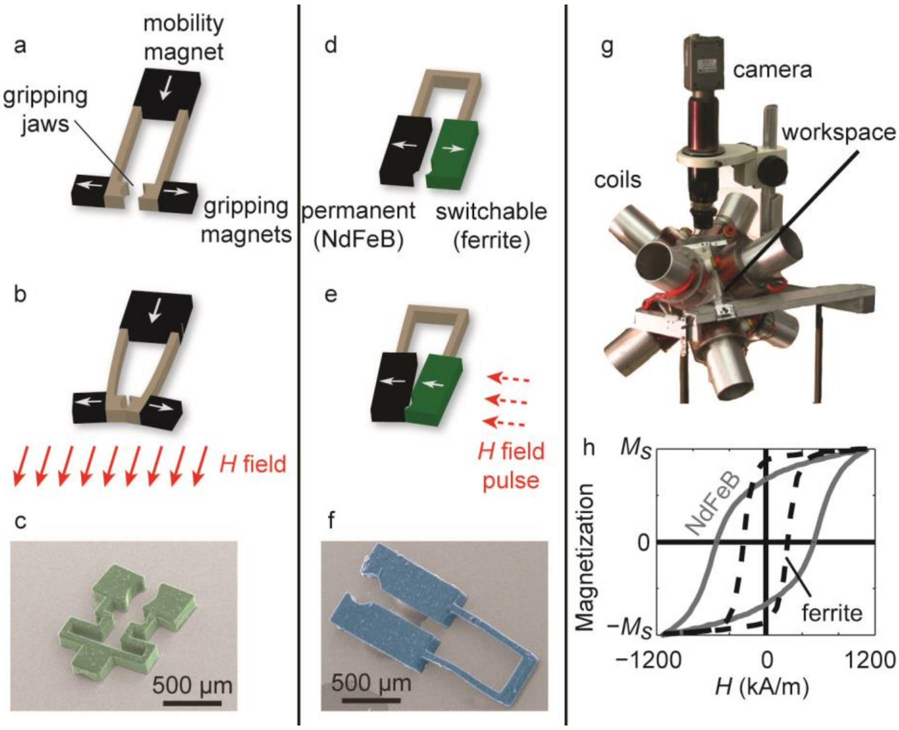

Figure 1. Remotely-actuated untethered micro-gripper designs. (a-c) *Torque-based addressable micro-gripper*. This micro-gripper is closed by application of a constant uniform magnetic field, which exerts a torque on each gripper arm. The 'mobility magnet' acts to move the gripper as a mobile micro-robot. (c) A scanning electron microscope (SEM) image of a fabricated torque-based gripper. (d-f) *Force-based addressable micro-gripper*. The gripping state is changed through the application of a large magnetic field pulse, which switches the ferrite magnet magnetization directions. This changes the arms from a repulsive to attractive state. The micro-gripper can be re-opened by applying a field pulse in the opposite direction. (f) An SEM image of a fabricated force-based gripper. (g) Magnetic coil system used to apply low and moderate fields of up to 22 kA/m. (h) Magnetization hysteresis loops of NdFeB and ferrite magnetic materials used, as measured in an alternating force gradient magnetometer. This shows the magnetization of the

permanent material NdFeB and the switchable material ferrite as a function of applied field *H*. Both curves are normalized to the saturization magnetization M_s of each material.

To increase speed and throughput of a manipulation operation using a mobile micro-gripper, it could be beneficial to operate multiple untethered micro-grippers simultaneously in parallel. This would require an individually-addressable magnetic control input to the gripping operation of each micro-gripper. Here, we also present such a scheme where each magnetic micro-gripper can be addressed through the use of multiple magnetic materials. We have demonstrated a similar addressing scheme in mobile micro-robotics agent groups before,[23] but here the open and closed states of the gripper team are addressed, rather than the motion of mobile micro-robots.

2.1. Torque-Based Micro-Gripper

The gripping concept is shown in Figure 1, and encompasses two different magnetic gripping schemes. The first scheme is referred to as a ‘torque-based’ gripper, as the gripper arms, which are magnetized in opposite directions, are actuated by applied magnetic torques. This gripper is made from a single type of permanent magnetic material throughout. The torque-based gripper, shown in Figure 1a and 1b, is opened and closed by application of constant uniform magnetic fields, and can be quickly and reversibly opened to a specified gap. The design includes a ‘mobility magnet’, which is used to propel the gripper as a mobile micro-robot. This magnet serves no purpose in the gripping action. The ‘gripping magnets’ are at the end of the flexible gripper arms, and experience magnetic torque due to a uniform applied field. The gripper can be designed to be ‘normally-open’, where an applied field is required to grip an object, or ‘normally-closed’, where the field is used to release the object. The difference in these two modes is in the magnetization directions of the ‘gripping magnets’ on the gripper arm tips. Thus, if both gripping magnets are magnetized inward, the gripper is ‘normally-closed’, while if the magnets are magnetized outward, the gripper is ‘normally-open’.

2.2. Force-Based Micro-Gripper

The second scheme, the 'force-based' gripper design, is shown in Figures 1d and 1e, and uses a different magnetic material for each gripping arm. One material is permanently magnetized while the other can be switched by application of a large field pulse. This scheme uses a latching-type mechanism, in that it does not require a static externally-applied field to maintain the closed or open state. Instead, a short magnetic field pulse is used to change the gripper state from open to closed. In this design, the gripper arms are designed to magnetically attract or repel depending on their relative magnetization direction. If the arms are magnetized in parallel, they will repel and the gripper will be open, as in Figure 1d. If one arm is remagnetized remotely such that the two magnets are magnetized anti-parallel, they will attract and the gripper would be closed, as in Figure 1e. Thus, the state can be remotely changed using a field pulse in the requisite direction. The micro-grippers have a preferred forward direction, allowing for multiple grippers to be addressed remotely depending on their orientation when the field pulse is applied. This will be used to achieve addressable open-closed behavior of a set of micro-grippers sharing the same workspace, although a different addressing method will be required to individually control the micro-gripper motion. For many gripping applications, parallel micro-gripper motion with addressable gripping could be useful to achieve parallel payload movement.

2.3. Smart Magnetic Materials for Actuation

Low-strength magnetic fields are applied to move and actuate mobile grippers using the coil system shown in Figure 1g, with details given in the methods section. Two different magnetic materials are used in this work, which can be remagnetized at different critical fields, known as the coercive fields. The magnetic hysteresis loop of the two materials, NdFeB and ferrite, are shown in Figure 1h for a range of magnetic fields H. The material NdFeB has a larger magnetic coercivity, and in this work we never apply fields large enough to switch its magnetization. The ferrite, however, can be switched at moderate fields of about 400 kA/m, allowing for dynamic remagnetization of this single material.

To fabricate micro-grippers from soft elastomer with included magnetic particles, a replica molding technique is used. The process, shown in the supplementary materials (Figure S1), includes shape definition by photolithography, replica molding to achieve flexible elastomer gripper shapes, and a magnetization process unique to the 'torque-based' and 'force-based' designs. This magnetization process is shown in Figure 2. Torque-based designs require that each gripper tip be magnetized in an opposite direction, which is accomplished at the magnetization step by deforming the micro-gripper arms 90° prior to magnetization. If it is desired to remove this deflection step, the gripper can be made in three pieces which are magnetized individually, and epoxied back together. Another alternative could use a tightly focused magnetic field during magnetization (e.g. through the use of magnetic pole pieces and pulsed field application) to selectively magnetize individual gripper sections, or the use of programmable magnetization anisotropy during the polymer molding step.[5] The force-based gripper is made from two different magnetic materials, which are molded in two separate batches and epoxied back together. To aid in precise assembly of these two pieces during this gluing step, they are placed into the rubber mold as a jig to hold them in place. The force-based gripper design is magnetized in one common direction, spanning the two gripper arms such that the magnetic moments of the arms are coaxially aligned and parallel.

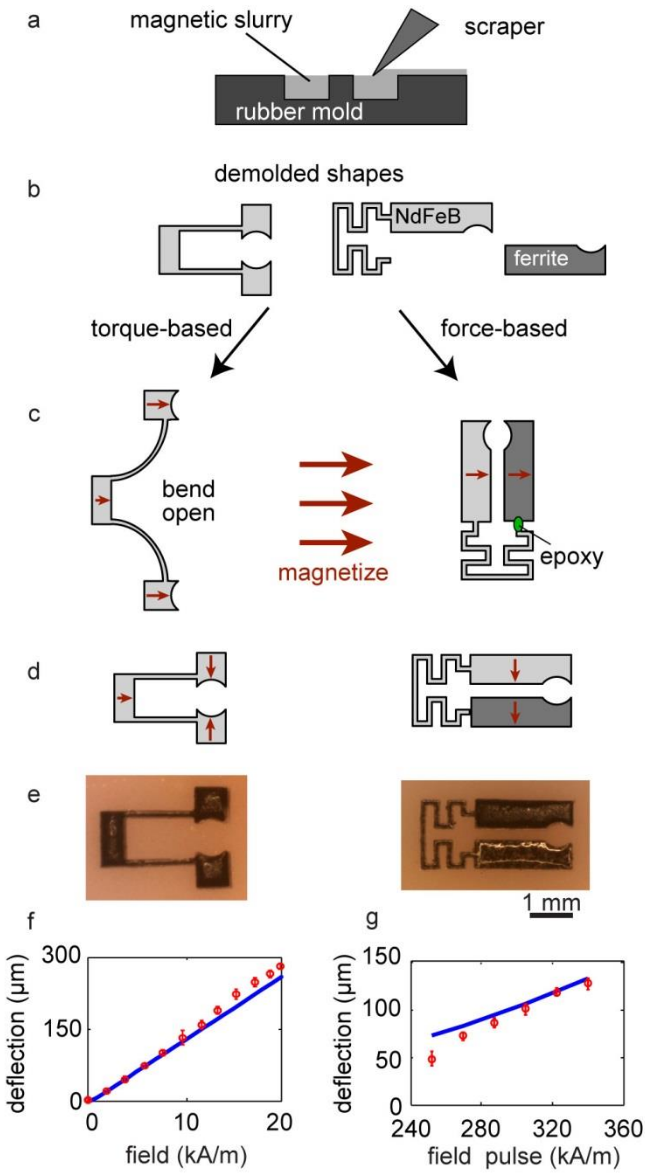

Figure 2. Micro-gripper fabrication and magnetization process. (a) A magnetic slurry consisting of magnetic micro-particles and polymer binding matrix is poured into the negative mold. Details of mold fabrication can be found in the supplementary files (Figure S1). (b) Micro-gripper shapes are pulled from the mold using tweezers. (c) Torque-based designs are spread open prior to magnetization, to allow each gripper tip to be magnetized in an opposite direction. The bend direction shown here will result in a normally-closed gripper. Force-based micro-grippers are molded from two magnetic materials, in two separate molding batches. The pieces are fixed together using UV-curable epoxy using a rubber mold as a jig to hold the parts precisely. These force-based gripper tips are

magnetized in one common direction. (d) After relaxation, the grippers are shown in their final magnetic configurations. (e) Fabricated designs are shown in the relaxed state after magnetization and assembly. (f-g) Deflection of micro-gripper tips under applied (f) fields for torque-based and (g) field pulses for force-based grippers. Circles represent mean of five experiments taken for various field or field pulse values. The lines indicate the theoretical model, with details given in the supplementary files.

A number of different torque- and force-based micro-gripper designs are fabricated, differing primarily in flexure design. The designs for a number of different flexures are shown in Figure 3. Each micro-gripper is designed to have approximately the same flexure stiffness, and it is seen that the use of a meandering spring in the design results in a more compact design. This could be critical in accessing small spaces with the mobile micro-gripper. Figure 3a and 3b show torque-based designs, while Figure 3c-e show force-based designs.

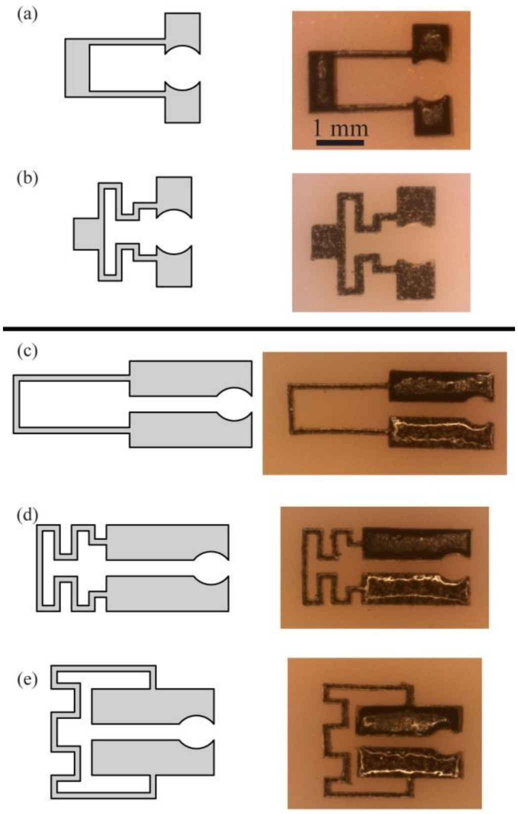

Figure 3. Fabricated micro-gripper shapes. Micro-gripper designs, with CAD model on the left and fabricated polymer-based flexible designs on the right. (a-b) Torque-based designs,

showing simple and meander flexure design. Each design has approximately the same flexure stiffness. The mobility magnet is seen on the left side of the design. (c-e) Force-based designs, showing simple and meander flexure design. Each design has approximately the same flexure stiffness.

2.4. Gripper deflection analysis

Torque-based micro-grippers. Assuming a straight flexure design, as shown in Figure 3a with arm thickness t, width w and length L, the deflection δ of the gripper tip under a magnetic torque of T is given as

$$\delta = \frac{TL^2}{2EI}, \tag{1}$$

where E is the elastic modulus and $I = \frac{tw^3}{12}$ is the area moment of inertia of the rectangular arm cross-section. The magnetic torque is proportional to the field strength B and the gripper tip magnetic moment m and the sine of the angle between the moment and the applied field. Assuming that the field is applied perpendicular to the gripper magnetization directions as shown in Figure 1b, the magnetic torque is $T = \mu_0 mH$, where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space. Thus, through substitution the gripper deflection can be found as

$$\delta = \frac{\mu_0 6mHL^2}{Etw^3}. \tag{2}$$

These equations have assumed small deflections and a simple flexure design, as well as no magnetic interaction between the magnetic elements in the micro-gripper. More complex designs, shown in Figure 3b, include meandering spring designs to achieve a more compact gripper design, and cannot be analyzed in such a simple manner. These designs can be analyzed by finite element analysis (FEA) or through meandering spring approximations.[25]

Force-based micro-grippers. Assuming a straight flexure design, as shown in Figure 3c with arm thickness t, width w and length L, the deflection δ of the gripper tip under a magnetic attractive force of F is given as

$$\delta = \frac{FL^3}{3EI}. \tag{3}$$

The magnetic attractive force depends strongly on the gripper tip center-to-center spacing z, and for magnetizations parallel or antiparallel and coaxially aligned, as shown in Figure 1c-d, is given as $F = \frac{\mu_0 m^2}{2\pi z^4}$. This model assumes that the magnetic mass is modelled as a magnetic dipole centered at the magnet center of mass, which may lose accuracy for very close spacing. For parallel/antiparallel magnetizations, which are 'next to' each other rather than coaxially aligned, the magnetic attraction/repulsion will be half this value. Thus, the coaxially aligned configuration is used.

The gripper deflection can be found as

$$\delta = \frac{\mu_0 m^2 L^3}{2\pi E t w^3 z^4}. \tag{4}$$

Gripper deflection is measured experimentally by observing the gripper tips in a microscope camera and manually measuring the distance.

2.6. Addressable micro-gripper actuation

Multiple force-based grippers can be independently opened and closed through magnetic pulses. Such parallel actuation and gripping could offer significant increases in the throughput of a mobile micro-robotic gripper system for moving cargo or assembling micro-objects in increasingly complex assemblies. Due to the biased nature of the force-based micro-gripper design, the open/closed state of each micro-gripper after a field pulse is dependent on its orientation during the pulse. Thus, to open or close just a single gripper in a set, it must be pointing in a different direction from the others prior to the pulse application. Selective orientation of grippers is conducted using magnetic fields and field spatial gradients, as shown in Figure 4. To achieve this selectively orientation without experiencing any translational motion before the switching pulse is applied, a four step method is employed as was demonstrated in our previous work:[25,26]

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 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 micro-grippers. This zero-field point can be shifted to select a different micro-gripper for opening.
3. A uniform -*y*-directed field is applied, rotating all micro-grippers 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 open all micro-grippers pointing in the +*y*-direction by remagnetizing the arm. Devices pointing in the –*y* direction remain closed because their orientation is parallel to H_{pulse}.

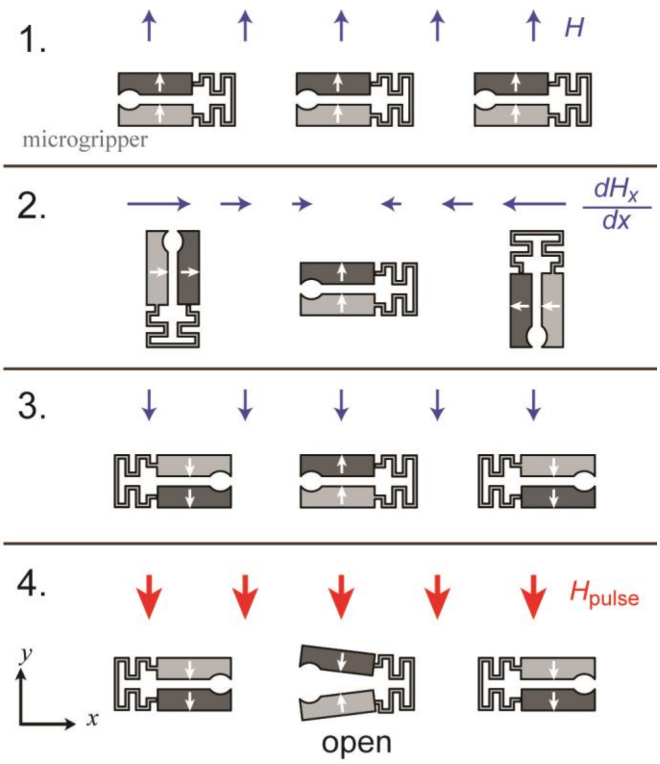

Figure 4. Selective orientation process to achieve addressable opening and closing of individual micro-grippers among a set. Gripper tip magnetization is shown as arrows. Dark sections indicate permanent NdFeB magnet materials, while light sections indicate switchable ferrite material.

Thus, a large number of micro-grippers can be independently addressed for opening or closing 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 micro-grippers in step 2 above. Using the applied magnetic torque of

$$T_{min} = \mu_0 m \times H, \tag{5}$$

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

$$s_{min} = \frac{T_{min}}{\mu_0 |m| \frac{dH_x}{dx}}. \tag{6}$$

When operating untethered magnetic micro-grippers in a shared workspace, a minimum micro-robot spacing must always be maintained to prevent the micro-robots from assembling together by magnetic attraction. This minimum distance is dependent on the surface friction and magnetic attraction force, and is typically several micro-gripper body-lengths.[1]

3. Results and Discussion

3.1. Micro-Gripper Characterization

The gripper tip deflection for torque-based and force-based designs is characterized under different field and field pulse values, as shown in Figure 2f. Circles represent the mean of five experiments taken for various field or field pulse values. The lines indicate the theoretical model, details of which are given in the supplementary materials. The material elastic modulus value used in the model is calibrated from two different grippers with different flexure designs. The same modulus value is used in the simulation for the force-based gripper, with results shown in Figure 2g for a range of applied field pulse values. In this experiment a reverse pulse of 450 kA/m was applied after each pulse to close the gripper. For opening field pulses less than 240 kA/m, the change in gripper deflection is negligible. The upper limit for applied field and field pulse represent the maximum capabilities of our coil system.

Mobile micro-grippers are moved and oriented using low-strength magnetic fields and spatial field gradients. Acting on the net magnetic moment of the gripper, magnetic fields exert torques, which act to align the net moment with the field, and field gradients exert forces, which tend to pull the gripper towards local field maxima. Thus, precise forces and torques can be applied to achieve five-degree-of-freedom control over the gripper (no magnetic torque can be exerted about the net moment direction). The grippers are moved in 2D by applying magnetic forces in conjunction with oscillating magnetic torques which serve to break the friction with the substrate, and in 3D by magnetic force which can levitate the grippers in liquid environments. Micro-grippers can thus be positioned with oriented in 3D space with a precision of tens of micrometers using visual feedback through a microscope. Control in this work is under teleoperation, but an autonomous controller can be developed for specific tasks.[13]

3.2. Micro-Assembly

Using controllable motion in 2D or 3D, mobile robotic micro-grippers are able to assemble structures in 3D with functional components. Figure 5a-g shows the assembly of a spinning ‘T’-shaped magnetic micro-part into a hole in the substrate. The part began lying prone on the substrate. Assembly required grasping the part, orienting it to the out-of-plane configuration and placing it in the hole. The part can be assembled into any hole location on the patterned substrate for programmable actuation. During assembly, the part is in a non-magnetized state. Once assembly is complete, as in Figure 5d, a short magnetic pulse magnetizes the part for actuation. Then the part can be rotated in-plane by an applied magnetic field, as shown in

Figure 5e. The rotation rate of the 'T' is in synchrony with the applied field, as shown in Figure 5f. The rotation induces a rotational fluid flow around the assembled part which manipulates 200 µm micro-spheres placed in the liquid, similar to our previous work on non-contact manipulation.[18]

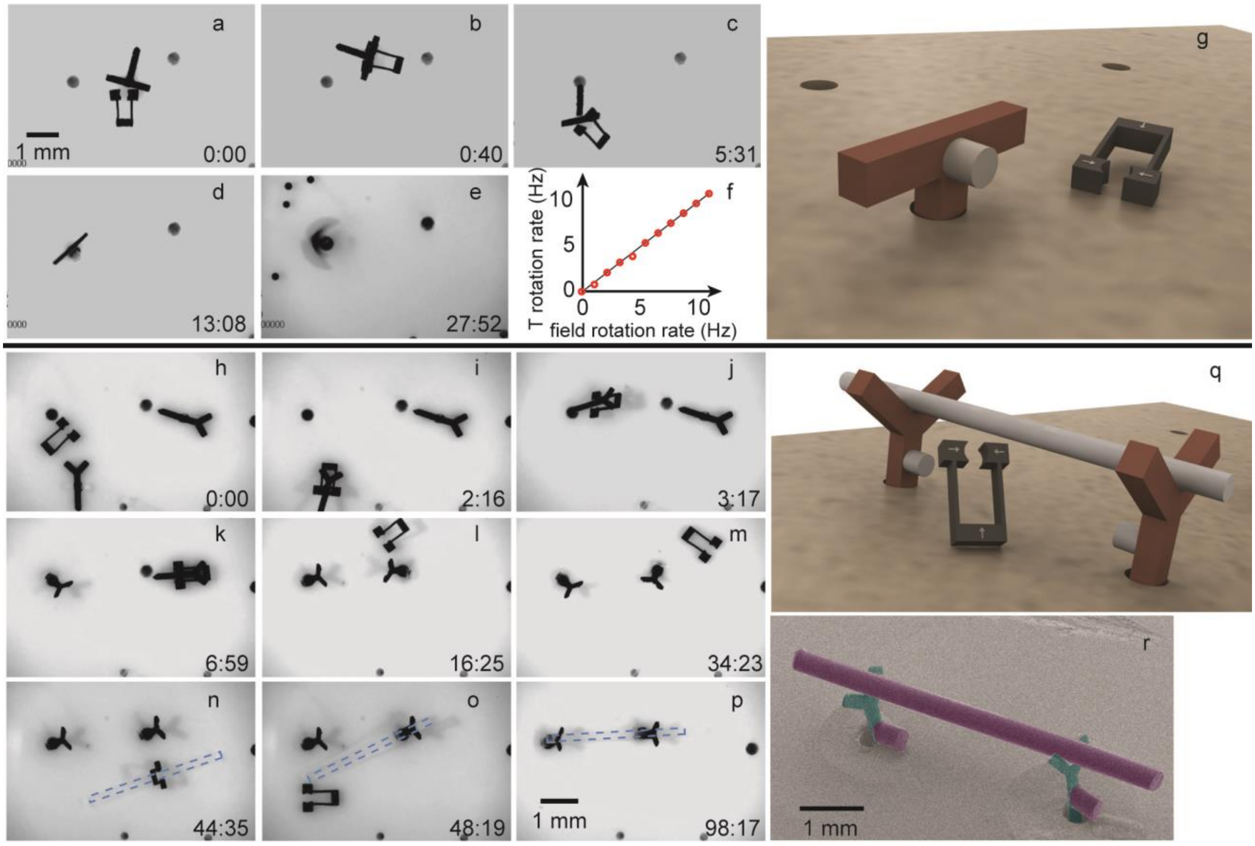

Figure 5. Demonstration of 3D micro-assembly using a mobile robotic micro-gripper. (a-g) A normally-closed torque-based gripper assembles a 'T'-shaped polyurethane and magnetic part in an out-of-plane configuration into a hole in the substrate. (a) The gripper approaches the object and the gripper tips are opened by application of a large field. (b) Once grabbed, the object is moved along with the gripper. (c) The object tip is placed at the opening of the hole, and the gripper raised up to insert the part. (d) After insertion, the gripper releases the part and moves away. At this point, the 'T'-shaped magnetic part is magnetized by a high-strength magnetic field pulse. (e) The 'T'-shape can now be rotated by low-strength magnetic fields for non-contact fluid manipulation. Tracer beads are added to the liquid to show the fluid flow. (f) The rotation of the 'T' matches closely with the

rotation of the applied field at a field magnitude of 13 kA/m. (g) A computer rendering of the assembled out-of-plane structure. A video of assembly and actuation are shown in Supplementary Video 1. (h-r) Assembly of an out-of-plane 3D four-bar linkage. (h-j) The gripper approaches the first vertical bar, grabs it and places it in the first hole. (k-l) The gripper assembles the second vertical bar. (m) The bars are rotated to the precise orientation for addition of the cross-beam. (n-o) The gripper assembles a nylon cylinder on top of one vertical bar. The cylinder is outlined with dotted lines for visibility. (p) The gripper lifts the cylinder onto the second vertical bar. Time indicated on each pane is minutes:seconds. (q-r) Schematic and SEM images of the assembled 3D structure. A video of assembly and actuation are shown in Supplementary Video 2.

Shown in Figure 5h-q is the assembly of a functional four-bar mechanism in an out-of-plane 3D configuration. This mechanism is made from assembling three links into mating holes in the substrate. These posts have a Y-shaped top to accommodate a connecting rod between them. The rod is assembled in the final step, as in Figure 5q. This assembly task required sequential grasping, orienting and assembly of three objects larger than the size of the gripper itself.

3.3. Addressable Micro-Gripper Team

Addressable grasping by a team of force-based micro-grippers can be achieved through control of the open or closed state of each gripper in the set, as shown in Figure 4. Frames from a video of two micro-grippers working in parallel to pick, move, and place two polyurethane blocks in 2D are shown in Figure 6. This demonstration shows the potential for increased throughput of the micro-gripper system. Addressable gripping cannot be achieved with the torque-style gripper design as it does not exhibit latching behavior. With the torque-style gripper, the magnetization direction of both gripper arms must be changed to adjust the gripping mode, which cannot be accomplished with a single field pulse. However, the force-based gripper only requires a single magnet arm to switch magnetization direction, and is thus suited for pulsed addressable actuation.

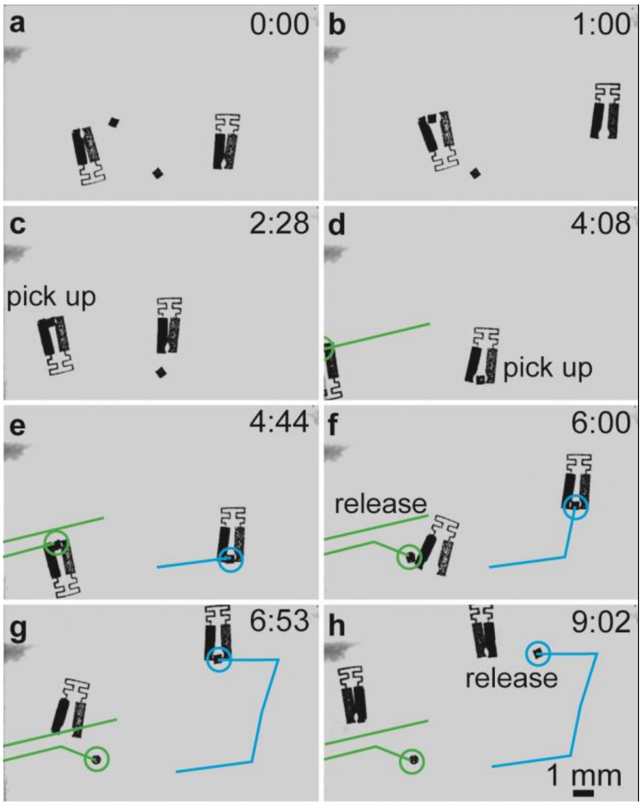

Figure 6. Parallel operation of two addressable mobile micro-grippers. (a) Two identical micro-grippers start in the closed configuration, with two polyurethane disks nearby. (b) The first micro-gripper approaches a disk. (c) The first gripper is closed over the disk, grasping it. (d) The second micro-gripper is positioned over the second disk, while the first gripper retains its cargo. (e) Both micro-grippers have grasped their cargo and carry it in parallel to the desired location. (f) The first gripper releases its cargo. (g) The second gripper moves to its goal position. (h) The second gripper releases its cargo. Time indicated on each pane is minutes:seconds. A video of assembly and actuation are shown in Supplementary Video 3.

4. Conclusion

Using a flexible material with programmed and dynamic component magnetization, we have shown the creation of mobile micro-grippers which can be actuated by remote magnetic fields.

The grippers were moved and oriented in 2D or 3D using low-strength magnetic fields, and opened or closed using large fields applied by a set of magnetic coils. This allowed for precise manipulation and assembly of micro-components in remote or enclosed spaces for the creation of multi-part functional assemblies. The actuation of these assemblies demonstrated that complex 3D materials and mechanisms could be created using single or groups of mobile micro-grippers. This capability could lead to new methods for cargo delivery or the fabrication of meta-materials, active components in microfluidic channels, or micro-factories for creation of advanced materials and structures from heterogeneous building blocks.

5. Experimental Section

Micro-gripper fabrication: Micro-grippers were fabricated using the micromolding process detailed in the supplementary materials (Figure S1). ST-1087 polyurethane (BJB Enterprises) is chosen for its moderate stiffness and ease of molding. This is mixed with magnetic powders with a polymer to magnet mass ratio of 1:1 for ferrite powder and 2:1 for NdFeB powder. Magnetic powders are ferrite ($BaFe_{12}O_{19}$, Hoosier Magnetics) and NdFeB (MQP-15-7, Magnequench), refined in a ball mill to a particle size of 5-10 µm.

Micro-part fabrication: Micro-cylinders are made from a nylon wire with a diameter of 300 µm. The wires are cut to length using a razor blade. Micro-objects with square cross-section are molded in a similar process to the micro-grippers, and are made from ST-1087 polyurethane. To make an object capable of magnetic activation, as shown in the demonstrations of Figure 5, ferrite particles are included with a mass ratio of 1:1 ferrite to polyurethane. To allow for ease of manipulation in the demonstrations, a 500-µm long nylon wire segment was fixed to the polyurethane object with UV-curable adhesive.

Magnetic field creation: Magnetic fields are supplied by a set of eight magnetic coils arranged pointing to a common center point. 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 is delivered by a 20-turn, low-inductance (8 μH) coil of inner diameter 23 mm, placed within the larger coil set. The pulsing coil is driven by a 0.8 mF electrolytic capacitor bank in a series LCR circuit, triggered by a silicon-controlled rectifier (SCR, Vishay, VS-70TPS12). The pulse strength is proportional to the capacitor charging voltage, and is applied manually using a switch to trigger the SCR.[24]

Modification of Scanning Electron Microscope (SEM) Images: For clarity, images acquired by SEM (Figures 1c, 1f and 3r) were modified using Adobe Photoshop using the Clone Stamp Tool to remove scale bars and text at the bottom of the image. New scale bars are overlayed in black. Artificial coloring was added in Photoshop by manually defining the part borders using the Lasso Tool. Image brightness levels were also increased.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
We thank J. Giltinan and X. Dong for assistance with magnetic micro-gripper fabrication and experimental setup. This work is supported by the National Science Foundation under NSF-NRI Award Number 1317477. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Received: ((will be filled in by the editorial staff))
Revised: ((will be filled in by the editorial staff))
Published online: ((will be filled in by the editorial staff))

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Supporting Information

Three-Dimensional Programmable Assembly by Untethered Magnetic Robotic Micro-Grippers

*Eric Diller and Metin Sitti**

Gripper fabrication

The full microfabrication process for mobile micro-gripper parts is shown in Figure S1a-d. This process allows for multiple permanent magnetic materials to be included in one micro-gripper design. The process steps include photoresist deposition and patterning, mold creation, and part molding.

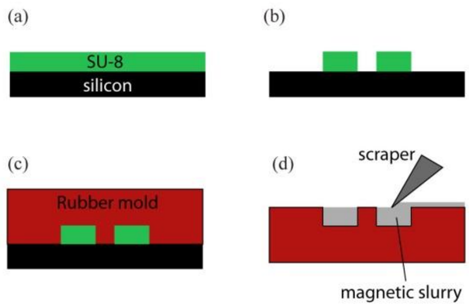

Figure S1. Micro-gripper fabrication process. (a) SU-8 photoresist is spun onto a silicon wafer. (b) By photolithography, the SU-8 is patterned into the extruded 2D shapes of the grippers. (c) A rubber mold is cast over the SU-8 positive features. (d) A magnetic slurry consisting of magnetic microparticles and polymer binding matrix is poured into the negative mold, degassed in vacuum and scraped level using a razor blade. (e-i) Micro-gripper shapes are pulled from the mold using tweezers. Micro-gripper designs, with CAD model on the left and fabricated polymer-based flexible designs on the right. (e-f) Torque-based designs, showing simple and meander flexure design. Each design has approximately the same flexure stiffness. The mobility magnet is seen on the left side of the design. (g-i) Force-based designs, showing simple and meander flexure design. Each design has approximately the same flexure stiffness.

Magnetic pulse generation for remote magnetic switching

The magnetic coils used to generate the short magnetic field pulses are a 20-turn, low-inductance (8 mH) coil of inner diameter 23 mm, placed inside the larger motion actuation coils as shown in Figure S2. This coil set is placed within the larger coils used to generate the low- and moderate-strength fields. Short pulses are required to remagnetize the ferrite magnetic elements of the force-based grippers before they reorient. A pulse which rises too slowly will fail due to the gripper reorienting to align with the pulse.

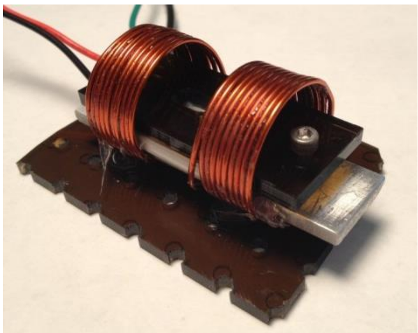

Figure S2. Magnetic coil pair used for magnetic pulse generation. The pair forms a 20-turn, low-inductance (8 mH) coil of inner diameter 23 mm. The gap between the coils allows for observation of the workspace, which is placed at the center of the coil pair.