Magnetically Programmed Diffractive Robotics

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Principal Investigator(s): Itai Cohen, Paul L. McEuen
User(s): Conrad Smart, Zexi Liang, Melody Xuan Lim, Weiyi Li

Affiliation(s): Kavli Institute at Cornell for Nanoscale Science, School of Applied and Engineering Physics, Laboratory of Atomic and Solid-State Physics, Department of Physics; Cornell University

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Contact: itai.cohen@cornell.edu, plm23@cornell.edu, cs2239@cornell.edu, zl467@cornell.edu, mxl3@cornell.edu, wl689@cornell.edu

Primary CNF Tools Used: Oxford 81/82 etcher, YES EcoClean Asher, ASML DUV Stepper, Gamma Automatic Coat-Develop Tool, JEOL 9500 EBL, JEOL 6300 EBL, SC 4500 Odd-Hour Evaporator, AJA Sputter Deposition, Heidelberg DWL2000, PT770 Etcher (left side), Unaxis 770 Deep Silicon Etcher, Oxford FlexAL, Oxford PECVD, Plasma-Therm Takachi HDP-CVD, Zeiss SEM, Veeco AFM

Abstract:

We introduce a new class of magnetically controlled microscopic robots (microbots) that operate at the visible-light diffraction limit, which we term diffractive robots. We combine nanometer-thick mechanical membranes, programmable nanomagnets, and diffractive optical elements to create untethered microbots small enough to diffract visible light and flexible enough to undergo complex reconfigurations in millitesla-scale magnetic fields. We demonstrate applications including sub-diffractive imaging using a novel variant of Structured Illumination Microscopy (Robot-SIM, or R-SIM), tunable diffractive optical elements for beam steering and focusing, and force sensing with piconewton sensitivity. This platform offers a powerful new tool for high-resolution imaging, tunable optics, and ultra-small force sensing, merging robotics and optical technologies at the microscale.

Summary of Research:

Microscopic robots with features comparable to the wavelength of light introduce diffractive optical effects, creating exciting new opportunities at the intersection of robotics and optics for probing the microscopic world and controlling light. Although the intersection of diffraction and tunable mechanics have been pioneered in the fields of micro-optical MEMS [1-3], these systems have never been miniaturized into a microscopic robotics package.

The two key elements that enable diffractive robots are programmable nanomagnets and ALD hinges. The nanomagnet arrays consist of single-domain cobalt nanomagnets ~ 100 nm wide with varying aspect ratios. The coercive fields and magnetic dipole directions of these nanomagnet arrays are controlled by shape anisotropy [4,5]. The moments align along each magnet's long axis, and higher shape anisotropy (aspect ratio) magnets have higher coercive fields.

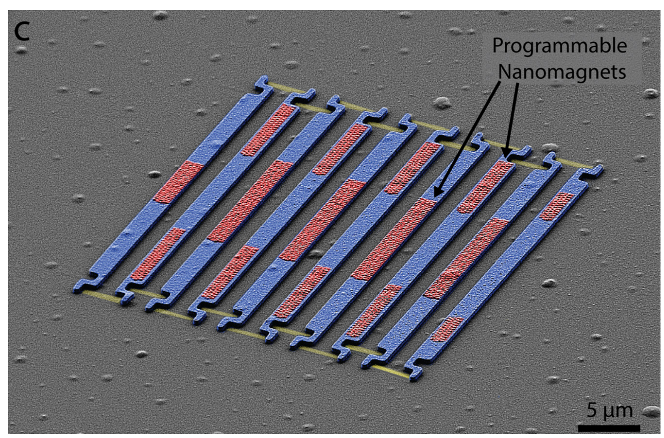

Figure 1: False-color scanning electron microscope image of a diffractive robot, consisting of (yellow) ALD silicon oxide hinges, (red) programmable cobalt nanomagnets, and (blue) rigid silicon oxide panels.

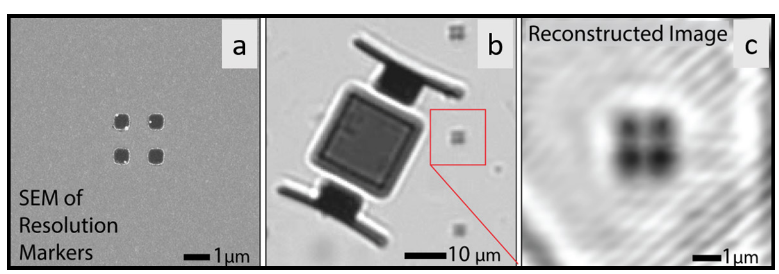

Figure 2: (a) SEM of the 2D resolution markers, (b) micrograph of diffractive robot near markers, (c) R-SIM reconstruction of the markers using the diffractive robot.

Using the disparate coercive fields, we sequentially magnetize the nanomagnet arrays in opposite directions to program the microbot magnetic control. The nanomagnets are embedded in 300 nm thick silicon dioxide panels and capped with chromium. Finally, 5 nm-thick ALD SiO2 membranes connect the panels (Figure 1) to form a durable flexible joint [6].

As an illustration of the possible applications of diffractive robotics, we use a diffractive robot as a mobile optical element to image beyond the standard diffraction limit of a microscope. We do this using a variant of Structured Illumination Microscopy (SIM), where we use the body of a diffractive robot to create a structured light field, as well as to sample the rotated images for reconstruction. We call this technique Robotic SIM, or R-SIM. Our robot consists of a diffraction grating (1000 lines/mm) body connected to two magnetized panels. We implement R-SIM by walking the robot across the features to be imaged and collecting a series of images at a variety of angles and phases. We demonstrate the power of R-SIM by imaging a pattern of four metal dots spaced 600 nm apart (shown in the SEM in Figure 2a) that cannot be resolved using standard optical microscopy.

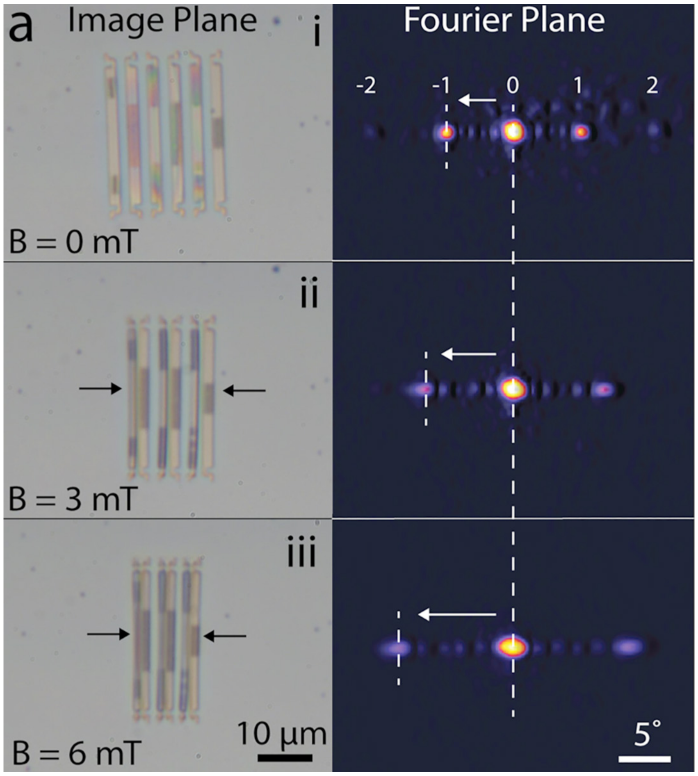

Figure 3: Image plane (left) and Fourier plane (right) of the diffraction grating in a uniform magnetic field of 0 mT, 3 mT, and 6 mT.

The robot is scanned across the feature to collect three angles and five phases per angle, with an overall acquisition time of ~ 30 seconds. The diffraction-limited object in Figure 2b is reconstructed in Figure 2c, demonstrating that R-SIM can resolve the four isolated dots.

To demonstrate beam steering, we fabricate microscopic diffraction gratings with magnetically tunable periodicities as shown in Figure 3. At zero magnetic field, the grating has a periodicity of 500 lines/mm. As the field increases (i-iii) the panels compress. In the corresponding diffraction images, three bright spots are seen: a central bright peak and lesser bright peaks to the left and right which move away from the central peak with increasing magnetic field (i-iii). These peaks are the zeroth, -1, +1 diffractive orders of the grating, corresponding to beams deflected by angles $\theta = \arcsin(n\lambda / a)$, where a is the grating spacing. The mechanical structure of the robot thus allows us to magnetically beam steer the diffractive orders. These gratings can also locomote across the surface to enable mobile, local control of light fields.

Inversely, this coupling between the internal configuration and the optical properties can be used to measure small forces acting on the microbot, by measuring the location of the +1 diffractive order. We measure a noise floor of 5 μT at a 30 Hz bandwidth, with a force sensitivity of 1 pN.

MECHANICAL DEVICES

References:

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