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ABSTRACTS

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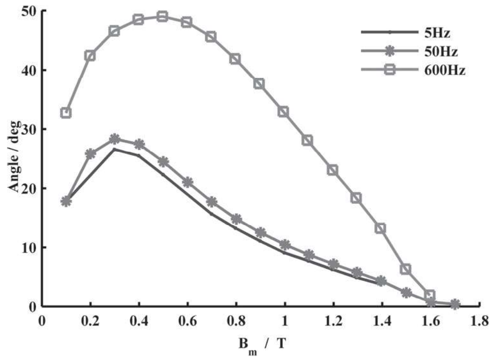

Fig.1 Relationship between amplitude and space angle of the rotation magnetization

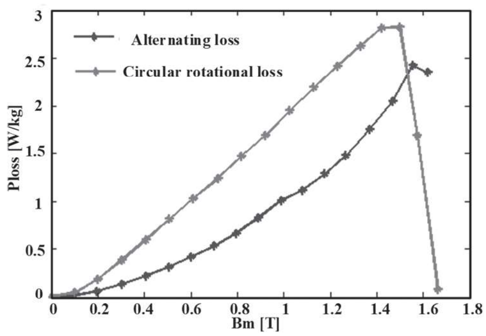

Fig.2 *B-P* curve of B35A210 specimen at 50Hz

Session FP
MAGNETICS FOR KINETIC MANIPULATION AND TRANSPORTATION
(Poster Session)

Hellen Jiang, Chair
PNNL, Richland, WA, United States

FP-01. Optical Control of Diamagnetically Levitated Pyrolytic Graphite.

J. Young[1], S. Yee[1] and H. ElBidweihy[1] *1. Electrical and Computer Engineering, United States Naval Academy, Annapolis, MD, United States*

Pyrolytic graphite (PyG), when levitated above an array of alternating-pole permanent magnets, can be displaced by a localized increase in temperature due to the temperature dependence of its magnetic susceptibility. The increase in local temperature decreases the local diamagnetic forces, inducing a tilt and displacing the PyG sample in the plane of the permanent magnet array. Previous work has verified and demonstrated the optomechanical actuation of PyG using experiments and simulations [1]. Small-scale assembly methods can be extraordinarily complex processes because of the mediums in which they operate [2, 3]. This work proposes a milli-scale assembly system based on optical control of levitating diamagnetic milli-robots in air that minimizes undesirable effects such as stiction prevalent in systems with denser mediums [4]. Additionally, optical control allows accurate addressable control of multiple milli-robots able to move in close proximity to each other throughout the working surface with no work surface segmentation, a limitation of other diamagnetic control schemes [5]. A laser diode mounted on a 2-axis motorized translational stage and coupled to a controller accurately irradiates and actuates the PyG sample, which acts as a milli-robot with variable speed and acceleration. An infrared camera provides vision feedback to a MATLAB-based controller and user interface, permitting open loop or closed loop control. Figure 1 shows overlaid images providing an overview of an example trajectory of a PyG milli-robot levitating and actuated on top of an array of 6.35mm-diameter cylindrical NdFeB permanent magnets. The *x* and *y* pixel coordinates and yellow outline shown are MATLAB-generated computations of the milli-robot centroid and boundary, respectively. Figure 2 tracks the displacement of the PyG sample according to the same open loop input trajectory over a 23-second period.

[1] Miriam Ewall-Wice et al., IEEE Trans. Magn., 2019. [2] P Chen et al., Adv. Mater. 26, 2014. [3] F Xu et al., Adv. Mater. 37, 2011. [4] Z Zhakypov et al., IEEE T. Robot. 34, 2018. [5] A Hsu et al., J. Micro-Bio Robots, 2018.

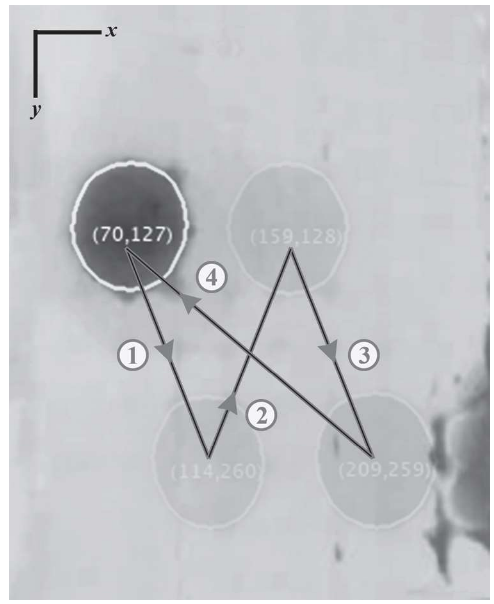

Fig. 1. Overlaid MATLAB-processed IR camera images depict an example overall trajectory of a 14mm diameter 25um thick PyG milli-robot actuated by laser irradiation.

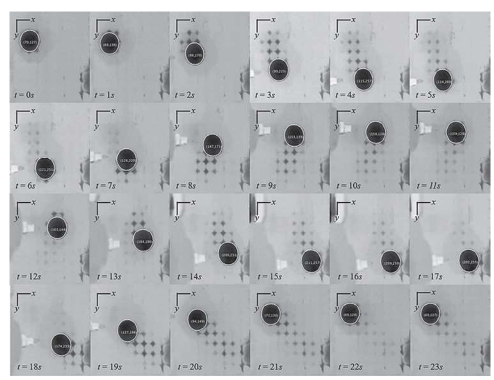

Fig. 2. IR camera images taken at one second intervals indicate the path of travel for the motion summarized by Figure 1.

FP-02. Magnetic Levitation of a Ferrofluid Droplet in Mid-Air.

T. Ohji[1], *S. Yamaguchi*[1], K. Amei[1] and K. Kiyota[1] *1. University of Toyama, Toyama, Japan*

This paper reports that the levitation of a ferrofluid droplet in the air at room temperature was realized using our magnetic levitation (maglev) device fabricated for non-contacting gripping and transport of ferrofluid droplets. The ferrofluid in a DC magnetic field theoretically deforms into an elongated spheroid in the direction of the magnetic field, as long as the surface tension of the droplet is higher than the tensile stress due to the magnetic field [1, 2]. Magnetic levitation system is suitable for experimentally verifying the droplet deformation. Rhee et al. have reported on active magnetic levitation experiments of encapsulated ferrofluid in silicone oil [3]. The ferrofluid in the capsule floated at the steady position, but the viscous drag and buoyancy from the immiscible silicone oil slowed the capsule movement. Besides, the capsule filled with ferrofluid itself did not allow the deformation of the ferrofluid. We fabricated a new maglev system to observe the deformation and behavior of ferrofluid in an external DC magnetic field in mid-air. The maglev setup consists of an I-shaped electromagnet with a tapered magnetic pole tip, a laser displacement sensor, AD/DA, DSP, and power amplifier. The apex of a ferrofluid droplet (Base liquid: poly-alpha-olefin, viscosity: 5,000 mPa.sec, mass: 15 mg) placed on an oil-repellent film (Toyo Aluminium Inc., Toyal Ultra Lotus) was detected using the displacement sensor and actively stabilized by a PID controller. Figure 1 is a photograph of a magnetically levitated ferrofluid droplet. Figure 2 shows continuous shooting immediately before and after the levitation start with a high-speed camera (Photron Ltd., FASTCAM mini AX-50). The droplet extended upward just before leaving the oil-repellent film. After levitation, the droplet's apex fluctuated up and down for 2.5 seconds with deformation of the droplet. Finally, after 2.5 seconds, the droplet was stably levitated while keeping an oval shape of 3.4 mm height and 2.1 mm symmetrical axis length. Details of this research will appear at the conference.

[1] J. C. Bacri, et al., "Instability of ferrofluid magnetic drops under magnetic field," *J. Physique Lettres*, 43, (1982) 649-654. [2] L. D. Sherwood, "Breakup of fluid droplets in electric and magnetic fields," *J. Fluid Mech.* 188, (1988) 133-146. [3] E.J. Rhee, et al., "The position control of a capsule filled with magnetic fluid," *J. MMM*, 252, (2002) 350–352.

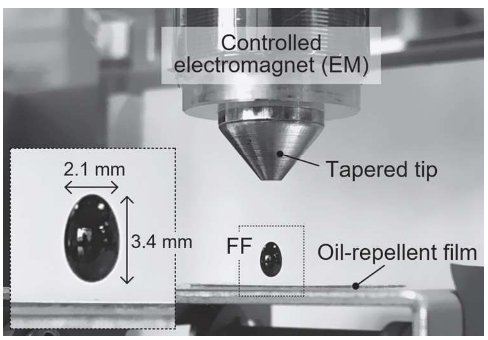

Fig. 1 Magnetically levitated ferrofluid droplet in mid-air.

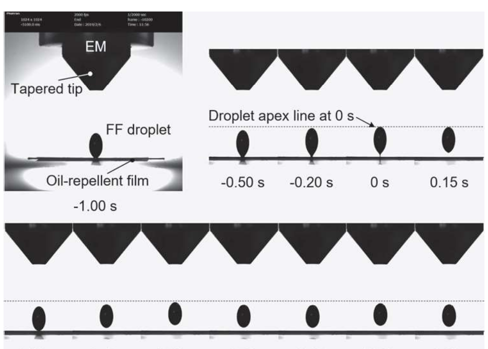

Fig. 2 Continuous shooting before and after levitation start.

FP-03. The Interaction between Two Permanent Magnets with Significantly Different Permeance Coefficients. *H. Meng*[1], Q. Wei[1], G. Tang[2], L. Cheng[3], G. Mizzell[4] and C.H. Chen[5] *1. Hangzhou Foresee Group Holding Co., LTD., Hangzhou, China; 2. Hangzhou Quadrant Technology Co. LTD, Hangzhou, China; 3. Hangzhou Magmax Technology Co., LTD., Hangzhou, China; 4. SuperMagnetMan, Pelham, AL, United States; 5. Quadrant Solutions, Louisville, KY, United States*

Even though Gauss' law for magnetic flux density (B-field) indicates there is no free magnetic charge, we can still define the effective bound magnetic charges from the magnetization of magnetic material [1]. The positive magnetic charge is what we usually called the "north pole", and correspondingly, the negative magnetic charge is what we usually called the "south pole". The interaction between the magnetic charges is governed by Coulomb's law so that like poles repel and unlike poles attract [2]. However, experiment shows that when two permanent magnets with significantly different permeance coefficients Pc (say, a small one with dimension of D4mm*4mm and Pc of 3.46, and a big one with dimension of D24mm*2mm and Pc of 0.18) were put together, with their directions of magnetization (DOM) pointing against each other, instead of repelling, they will attract to each other, especially when the coercivity of the big magnet is relatively low. This phenomenon may lead people to think that Coulomb's law for magnetic charges is not always right, and in some cases, like poles attract. In this work, we show that the above bizarre phenomenon is caused by the partial demagnetization in the low Pc magnet, rather than violation of Coulomb's law. When the experiment is carried out using sintered NdFeB magnet of N50 grade, the working point for the stand-alone low Pc magnet is very near to the knee of its demagnetizing curve, so it's very vulnerable to the external and its self-demagnetizing field. Finite Element Analysis (FEA) shows that demagnetization happens obviously in the central region of the magnet with low Pc, but the magnetization remains in the same direction all over the magnet. FEA also gives an attractive force when the above low Pc and high Pc magnets are close to each other and with opposite DOMs. Based on the magnetic charge model and Coulomb's law, the numerical integration of Coulomb's force is carried out, which gives almost the same attractive force as FEA.

[1] J. M. D. Coey, Magnetism and Magnetic Materials, 2010, Cambridge University Press, p.45. [2] Soshin Chikazumi, Physics of Ferromagnetism, second edition, 1997, Oxford University Press, p.3.

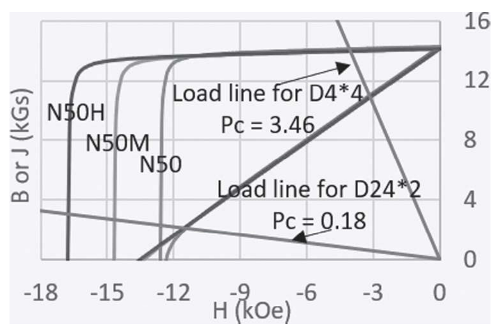

Fig.1 working point for the small and big magnets of different NdFeB grades.