A low-cost, 3D-printed magnetorheological fluid clutch utilizing electropermanent magnet arrays

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***Abstract*— In this work, we develop a small, partially 3D-printed magnetorheological fluid (MRF) clutch that operates by variably and reversibly altering the shear stress of the fluid through the local activation of an array of electropermanent magnets (EPMs). By toggling the magnetization of each EPM independently, we allow for rapid response times and variable torque transmission. This approach could enable joint stiffness control of robotic linkages, where each joint is comprised of such a clutch. Driving an underactuated linkage with a single motor while simultaneously controlling the joint stiffness could potentially enable repeatable and variable kinematic trajectories of the end effector from a single actuator in the base of the robot.**

I. INTRODUCTION

There are multiple approaches for the design of robotic grippers. Fully actuated designs such as the anthropomorphic Shadow Hand [1] can be very precise. However, the Shadow Hand is expensive, has a large, bulky base, and integrates multiple actuators for each finger, which requires a large amount of computational control and synchronization. On the other end of the spectrum of control and complexity, fully soft grippers are relatively simple, inflatable, and shape agnostic [2]. Another popular approach towards robotic grasping is underactuated grippers; benefits of such devices include shape adaptation, fewer actuators, and relatively simple control commands. However, prior to contact, the closing trajectory of the coupled fingers/linkages of an underactuated device is predetermined and is a function of mechanical features such as joint stiffness and transmission ratios – this constraint limits the range of achievable grasp primitives. In the field of robotic grasping, there is a need for variable joint stiffness to control finger kinematic trajectories during an underactuated grasp as well as overall hand stiffness (e.g. increase stiffness of a completed grasp).

Researchers are exploring ways to alter the stiffness of joints in an underactuated design by incorporating programmable material systems with properties that can be tuned by selectively changing inputs such as electric currents, magnetic fields, temperatures, pressures, and internal friction. For example, researchers recently developed laminar jamming joints for a robotic gripper [3]. The variable stiffness was achieved by embedding sandpaper within a collapsible elastic joint under vacuum. This work demonstrated the efficacy of variable stiffness and underactuated linkages.

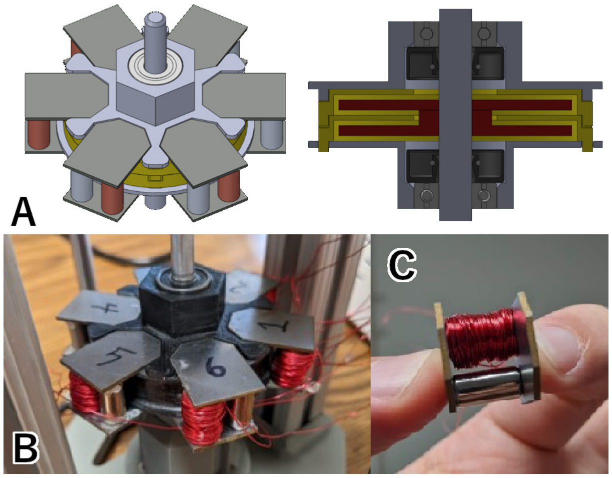

Fig. 1. An assembled MRF Clutch with six EPMs. A) 3D Model of the clutch with an isometric and cross-sectional view. B) The physical, assembled MRF Clutch in the torque-testing apparatus. C) A single EPM, viewed head-on to see the two magnets and coil.

One type of smart material that has received considerable attention is magnetorheological fluid (MRF), which changes viscosity in response to the strength of the applied magnetic field. A recent publication developed and characterized a 5-DOF robotic arm with MRF clutches in each joint; electromagnet torque modulation was used to achieve variable joint stiffness at each joint [4]. Another recent publication developed a hybrid MRF and shape-memory alloy (SMA) linkage [5]. The SMAs are deployed along the length of the linkage, while each joint of the linkage consisted of a MRF-filled bearing which responds to an electromagnet coil adjacent to it to increase local joint stiffness.

Other recent research has demonstrated that electropermanent magnets (EPMs) are viable control tools for MRF-related actuation strategies, such as McDonald et al. [6]. This work demonstrated control over the flow of MRF through a series of soft robotic actuators using EPMs, generating bending in the actuators by building pressure behind an EPM-based valve. This highlights the importance of EPMs as latching, low-power devices, and their capacity to be used with MRF for controlling actuators. With all of these developments in mind, we propose MRF-filled joints coupled with EPM arrays as a *low-power density* method for changing joint stiffness in a programmable manner within an underactuated joint linkage. Our prototype clutch design is visible in Figure 1.

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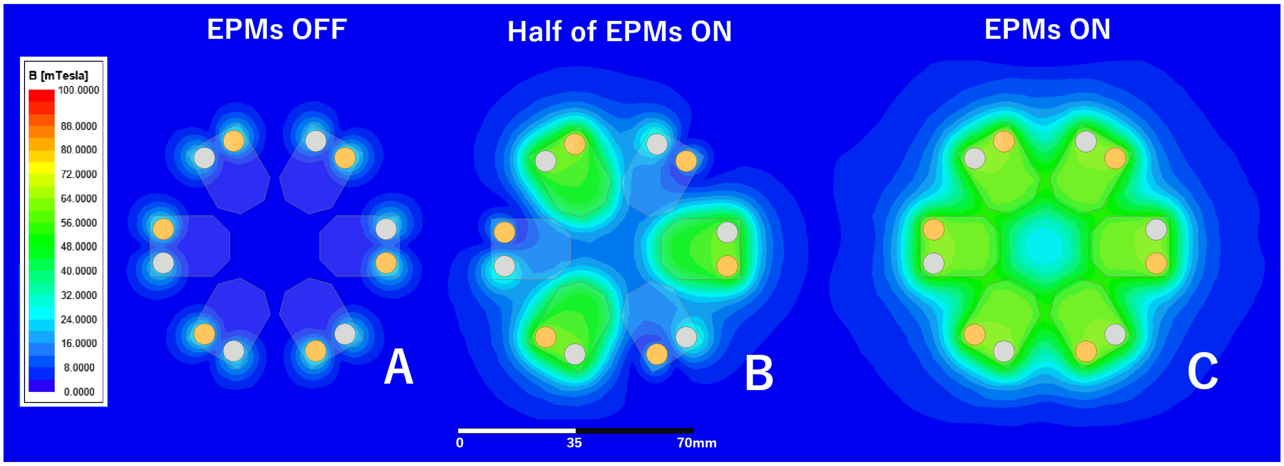

Fig. 2. Depicted are three simulations completed in Ansys Maxwell of the EPM array from the top-down perspective. A) All EPMs are in the OFF configuration. B) Three of the EPMs are ON, while the other three remain OFF. C) All six EPMs are active, demonstrating fields of approximately 55 to 65 mT in the regions of interest.

II. METHODOLOGY

First, we wanted to validate that the scale and design of an EPM array would perform within the boundaries of what is required to generate the MR effect in a fluid-based clutch. Physical parameters for a modular EPM were selected based on available materials, size, and power considerations. Each EPM consists of a NdFeB grade 42 hard permanent magnet (12.7mm length, and 6.35mm diameter), an AlNiCo grade 5 magnet of the same size, two thin steel rectangular plates, and a magnet wire coil of copper wire around the AlNiCo 5 magnet (120 windings). Each element was positioned and glued in place with cyanoacrylate glue (see Figure 1C). After making all six EPMs, each was tested for its polarizing and depolarizing ability, with an analog Hall effect sensor, as well as a gaussmeter to validate with more precision. The values for each EPM were between 45 to 55 mT in magnetic flux when on, and around 0 to 5 mT when off. Each EPM was polarized by applying a current of approximately 2.5 amps first in one direction to polarize the EPM, and later in the opposite direction to depolarize. This was handled with a manual switching panel, but will be digitally controlled in future revisions.

This EPM array was also modeled and simulated in Ansys Maxwell Magnetostatic to predict the magnetic field formation characteristics. The cylinder representing the AlNiCo 5 magnet was given properties corresponding to a magnetization in the positive or negative z-direction for a given simulation and at values appropriate for that grade of magnet. The N42 magnet was given a constant magnetization of a set value using the built-in magnetic properties library for Maxwell. The results of this simulation are shown in Figure 2, and demonstrate that each EPM can be expected to generate up to 65 mT in ideal conditions. This validation enabled us to proceed with further modeling and construction of the MRF clutch.

To predict the torque transmission behavior of the clutch design, the MR effect was modeled in MATLAB (Mathworks, Natick, MA, USA) for various physical parameters of the MRF Clutch. We approximated the field within the MRF Clutch as a scalar value for simplicity, since the majority of the volume of the MRF will be between the fins of the EPM, where the field is primarily linear. We utilized the Bingham model [7] for a viscoplastic fluid with a finite yield stress to represent the MRF's yield behavior, also leveraging characterization data from the manufacturer of the fluid (LORDE Corp, Cary, NC, USA). We varied the gap-spacing between the fins of the MRF Clutch, the thickness of the fins, the number of fins, and the fin diameter. As expected, the conclusions from this modeling demonstrated generally that for larger surface areas, greater torque will be transmitted. Based on the physical parameters of the fabricated MRF-EPM clutch, we expect the design to be capable of transmitting up to 1 N*m of torque in ideal conditions (see Figure 3).

III. RESULTS

After several design iterations of the MRF clutch, we achieved measurable output torque. The testbed consisted of a stepper motor driving the clutch's input shaft at a constant 40 rpm, a 6-axis force/torque sensor (ATI, Apex, NC, USA) rigidly fixed between the base of the testbed and the clutch, and a rigid 3D-printed scaffold to align the motor with the centerline of the torque sensor and the MRF clutch. The results from preliminary testing are shown in Figure 3 where each successive EPM activation demonstrates a significant jump in the transmitted torque. For this test, only five were activated; one of the EPMs had a physical disconnect between the power source and the winding. The magnitude of the transmitted torque went from 0.06 N·m at baseline to 0.18 N·m, a 3x increase with all five active.

This maximum value is only ∼15% of the projected maximum transmitted torque. This discrepancy is partially explainable by non-ideal conditions from manufacturing imperfections and modeling assumptions, but not entirely. Most likely, the MRF used in this test may be operating at less than

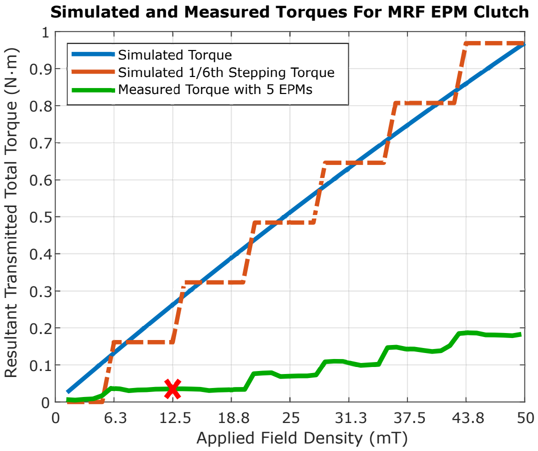

Fig. 3. Simulated and measured torques of the MRF Clutch by activating six of the EPMs in increasing order (0.5 second pulse duration to polarize). The blue line is the predicted transmitted torque as a function of the applied magnetic flux. The orange dotted line is a step-wise approximation of the predicted output, where each increase is the result of an additional EPM being activated. The green line is measured data collected from the prototype clutch, and demonstrates a step-wise behavior, but at about 20% of the predicted values. The second EPM for this trial failed to polarize.

its characterized behavior, as it is several years old and has been stored in sub-optimal conditions. It is also possible that the internal fin geometry is subject to flexing when the fluid is active, leading to irregular torque transmission. Further tests are needed, and validation of the MRF efficacy will be performed. In spite of this, the torque's increase with each activation demonstrates the functional concept and constitutes a successful attempt. Future work will involve fine-tuning the MRF clutch, EPMs and modeling to all agree with each other with an acceptable degree of accuracy. After that, a robotic linkage will be created and driven by a single actuator to demonstrate variable trajectories with underactuated control, involving few moving elements beyond the necessary axles and driving motor. The resulting linkage should require lower power than an equivalent design using electromagnets, but still demonstrate fast response times and scalability.

REFERENCES

[1] F. Rothling, R. Haschke, J. J. Steil, and H. Ritter, "Platform portable anthropomorphic grasping with the bielefeld 20-dof shadow and 9-dof tum hand," in *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2007, pp. 2951–2956.

[2] J. Zhou, S. Chen, and Z. Wang, "A soft-robotic gripper with enhanced object adaptation and grasping reliability," *IEEE Robotics and automation letters*, vol. 2, no. 4, pp. 2287–2293, 2017.

[3] L. Gerez, G. Gao, and M. Liarokapis, "Laminar jamming flexure joints for the development of variable stiffness robot grippers and hands," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, 2020, pp. 8709–8715.

[4] S. Pisetskiy and M. Kermani, "High-performance magneto-rheological clutches for direct-drive actuation: Design and development," *Journal of Intelligent Material Systems and Structures*, p. 1045389X211006902, 2021.

[5] J. Yang, S. Sun, X. Yang, Y. Ma, G. Yun, R. Chang, S.-Y. Tang, M. Nakano, Z. Li, H. Du, S. Zhang, and W. Li, "Equipping new sma artificial muscles with controllable mrf exoskeletons for robotic manipulators and grippers," *IEEE/ASME Transactions on Mechatronics*, pp. 1–12, 2022.

[6] K. J. McDonald, L. Kinnicutt, A. M. Moran, and T. Ranzani, "Modulation of magnetorheological fluid flow in soft robots using electropermanent magnets," *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 3914–3921, 2022.

[7] E. C. Bingham, *Fluidity and plasticity*. McGraw-Hill, 1922, vol. 2.