Magnetorheological fluid based flow control for soft robots

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Pressure and Time Response Testing

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Caption for Movie S1

Caption for Movie S2

Caption for Movie S3

Other Supplementary Materials for this manuscript include the following:

Movie S1

Movie S2

Movie S3

Pressure and Time Response Testing

To validate the behavior of the fluid in relation to the model derived above, a test was developed to explore the relationship between the current applied to a flow of MR fluid and the resulting change in pressure. Using a Harvard Apparatus Pico Plus Elite syringe pump, MR fluid was driven through a 2 mm inner diameter PVC tube at flow rates of 5, 15, and 25 mL/min. An electromagnet coil with a radius of 10 mm and thickness of 5 mm was placed in contact with the tube at a distance of 5 cm from the tube's outlet into an open reservoir. A pressure transducer (Nidec Copal Electronics P-7100-102GM5) was used to monitor the pressure 5 cm upstream from the magnet. The coil itself was wrapped using 36 gauge copper wire and was connected to a variable DC power supply (B&K Precision 1671A) through a MOSFET switching circuit used to turn on and off the current. To ensure the delivery of a steady current, the DC power supply was manually adjusted to deliver a precise current in increments of 100 mA from 0 to 600 mA. Figure S1 shows a schematic of the testing setup.

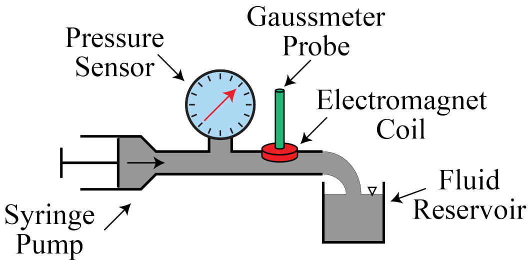

Figure S1: Schematic of the testing setup

For each current value, three trials were conducted as follows: pressure data was collected for 10 s with the MOSFET switch open, at which point the circuit was closed and current was fed through the electromagnet for 10 s. The switch was then opened once more, and pressure data was collected for an additional 10 s. All data was collected using a National Instruments USB-6353 X-Daq and an automated Virtual Instrument in Labview. Figure 2c shows a representative graph for one combination of current and motor speed. The line and shaded region denote the pressure mean and standard deviation respectively across the three trials.

The data from the test outlined above was then analyzed to determine the time response of the MR fluid actuation system, as well as the change in pressure associated with each current and motor speed combination. For each trial, the pressure was averaged in the magnet-on and magnet-off periods and the difference computed to find the change in pressure. The rise time was calculated as the time from the moment the magnet was turned on to the time the system first reached the average magnet-on pressure. The fall time was calculated as the time from the moment the magnet was turned off to the time the system first returned to the average magnet-off pressure. The values for each of the three trials were then used to compute means and standard deviations, reported in Figure 2d.

Crosstalk Testing

To determine the influence of an electromagnet on an adjacent tube carrying MR fluid, a crosstalk test was conducted. For this test, a 10 mm long electromagnet consisting of 400 turns of 36 gauge copper wire was wrapped around an equivalent length of 2 mm ID silicone tube and connected to a variable DC power supply (B&K Precision 1671A) via a MOSFET switching circuit used to turn on and off the current. The tube at the center of the coil was filled with a static volume of MR fluid. An adjacent tube was filled with MR fluid flowing at 10 ml/min into an open reservoir, pumped using a syringe pump (Harvard Apparatus Pico Plus Elite). The electromagnet was placed parallel to the flow tube, and the distance between the two was controlled with millimeter precision using a custom built, motor driven linear stage. The electromagnet was placed adjacent to the flow tube 5 cm upstream from the open reservoir into which the MR fluid flowed. The flow pressure was monitored 5 cm upstream from the electromagnet using a Balluff BSP B010-EV002-A00A0B-S4 pressure transducer. The magnetic field was monitored at the surface of the electromagnet using a gaussmeter (Lake Shore Cryotronics Model 425).

For each test, the electromagnet's distance to the flow tube was adjusted. Flow was then turned on for 10 s, at which point the electromagnet would be engaged for 20 s while the MR fluid continued to flow, and flow then continued for an additional 10 s with the magnet turned off. This was conducted at each combination of current (0.1 A, 0.3 A, 0.5 A) and distance (1 cm, 2 cm, 3 cm). All data was collected using a National Instruments USB-6353 X-Daq and a script written in Python.

The data was then analyzed in MATLAB to determine if any noticeable crosstalk was present. For each combination of parameters, the pressure was averaged in the magnet-on and magnet-off periods and the difference computed to find the change in pressure. This was then plotted against the distance between the electromagnet and flow tube for each current (Figure S2). No pattern was evident in the results, suggesting negligible influence of crosstalk on centimeter scale devices with electromagnets using the currents within the range tested.

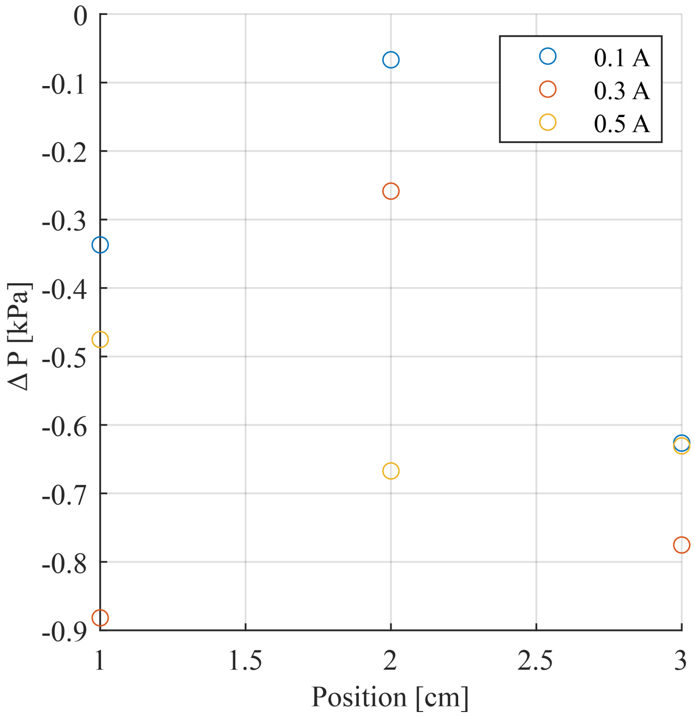

Figure S2: Crosstalk as quantified as the change in pressure vs. distance between flow tube and electromagnet

Temperature Testing

A test was conducted to determine if the heat generated by the operation of an electromagnet with parameters similar to those discussed in the previous supplement sections would cause the water in the MR fluid to evaporate. A thermocouple probe (McMaster part number 9251T94) was placed inside a 2 mm ID silicone tube around which a 1 cm long electromagnet consisting of 400 turns of 36 gauge copper wire was coiled. Currents ranging from 0.35 A to 0.5 A were provided to the coil using a variable DC power supply (B&K Precision 1671A) and a MOSFET switching circuit to turn on and off the current. The temperature was recorded until 100 °C was reached, at which point the current was disconnected from the coil and the coil was allowed to return to room temperature. Three trials were completed at each current tested. Data was logged using a National Instruments USB-6353 X-Daq and a script written in Python. Figure S3 compiles the average and standard deviation of the times to reach 100 °C.

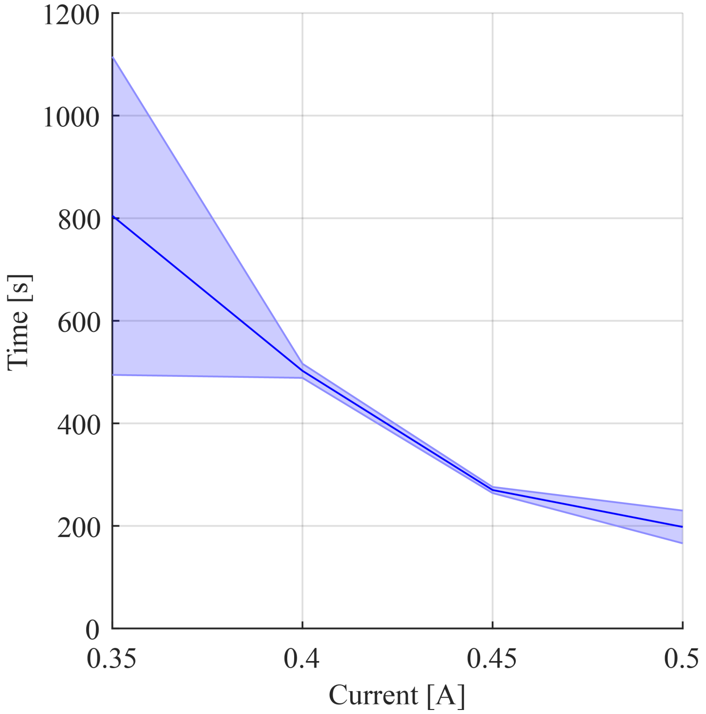

Figure S3: Time to reach 100 °C vs. current

Magnetic Field Estimation

The magnetic field produced by the disk magnets used in this paper can be predicted by the following equation.

$$B_x = \frac{B_r}{2}\left(\frac{x+T}{\sqrt{R^2+(x+T)^2}} - \frac{x}{\sqrt{R^2+x^2}}\right) \tag{4}$$

Where B_x is the magnetic flux density at a given distance from the surface along the axis of a permanent disk magnet, B_r is the residual flux density of the magnet, x is the distance along the axis to the point of interest, T is the magnet's thickness, and R is the magnet's radius.

The magnetic field produced by the electromagnets used in this paper can be predicted using the following form of Ampere's Law. However, since the coils used were multiple layers, this provides only an estimate.

$$B = \mu_0 \mu_r \frac{N}{L} I \tag{5}$$

Where B is the magnetic flux density, μ_0 is the permeability of free space, μ_r is the relative permeability of the magnet's core, N is the number of turns in the magnet, L is the magnet's length, and I is the current supplied to the magnet.

Movie S1

This movie shows the three class of devices tested. For each, a continuous flow of MR fluid was provided using a peristaltic pump. First, the 1 DoF loop actuator is shown. With the application of a magnetic field downstream of the actuator, the pressure increases, and the actuator bends. Second, the gripper consisting of three coupled actuators is shown. With the application of a magnetic field downstream of the device, all three actuators bend simultaneously. Finally, the device consisting of two independent actuators is shown. Using two magnets, every combination of the device's bending states can be achieved. The inset shows the location of the magnetic fields and the resulting bending states. Upon removal of the magnets, some undesired movement is observed in the actuators as the pressure in the device comes to equilibrium. Asynchronous deactivation of the fields such that the pressurized actuator could drain directly to the outlet before allowing flow into the unpressurized actuator could be used to compensate for this phenomenon.

Movie S2

This movie shows the gripper actuator consisting of three coupled PneuNet actuators being used to grip a plastic cup. With the application of a magnetic field downstream of the actuator, the three coupled actuators simultaneously inflate, allowing the gripper to grasp a 4 g cup. When the magnetic field is removed, the actuators deflate and the gripper drops the cup.

Movie S3

This movie shows selective actuation of a robot with five magnetically controlled DoFs: four independent legs and one gripper consisting of six coupled actuators. Each DoF has its own logic node which in combination can be used to achieve all the logical states of actuation. Since the actuators are connected in series, actuating one DoF also actuates the other DoFs upstream. This may be avoided by using the magnets to block the actuation of the upstream actuators. It may also be exploited to inflate sets of actuators as desired. The inset diagram shows the locations of the magnets in red and the inflated actuators in blue. The video includes several actuator combinations from both a top-down and front view. Other actuator combinations are possible, but are not shown.