# Innovative magnetic field design and modulation for 3D printing biomimetic microrobots with programmable material distribution


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## How to build a device to create a programmable magnetic field to aid in the development of helical microrobots?

**Background:**

Helical microrobots are microscale mechanisms capable of infiltrating very small areas with no connection to an external mechanism, meaning they can be operated inside a large range of settings, including the human body. To achieve a strong enough motion, the microrobots are loosely modeled after the flagella of eukaryotic bacteria, which use helical swimming to produce a fluid displacement and move forward. Helical microrobots have many uses in the medicine field, as they make it possible to perform minimally invasive procedures, drug delivery, and in-vitro fertilization. To react to an external magnetic field, the helical microrobots are impregnated with ferromagnetic particles. Several techniques exist to manufacture the microrobots, 3D lithography is a recent advancement that has the benefit of being able to manufacture a wide variety of shapes and sizes of microrobots, making it ideal for testing multiple microrobot designs.

**Microbots and Manufacturing:**

The microrobots are 3d printed resin coils embedded with ferrous particles. This manufacturing process creates the possibility of a high degree of optimization and design exploration. The design of the robot can be changed, as well as the percent composition of the ferrous material and its alignment in the matrix of the polymer material. The device designed for testing microrobots can be easily configured to work with the 3-D printer to ensure a proper alignment of the ferrous particles in the microrobot, as seen in figure XX. Figure (XX) shows the dimensions of the microrobots used on the testing. These are printed in batches, as shown in figure (XX). This means the magnetic field applied during printing must be as homogenous as possible, to keep consistency on each batch.

*Figure 1: Microrobot 3D printed batch*

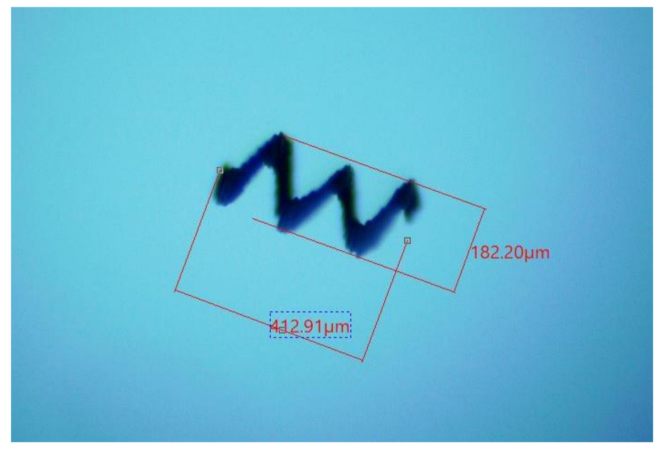



*Figure 2: Microrobot dimensions*

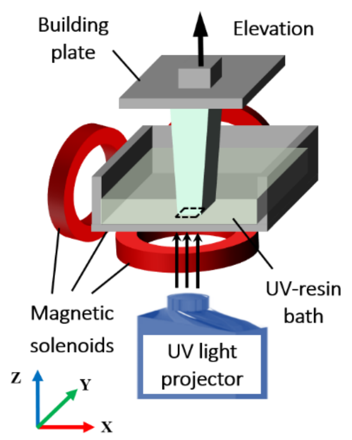



*Figure 3: Microrobot ferrous particle alignment on 3D printer.*

**Previous Prototypes:**

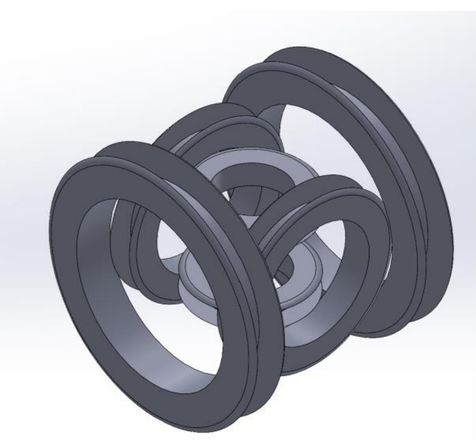


*Figure 4: Prototype 1 design*

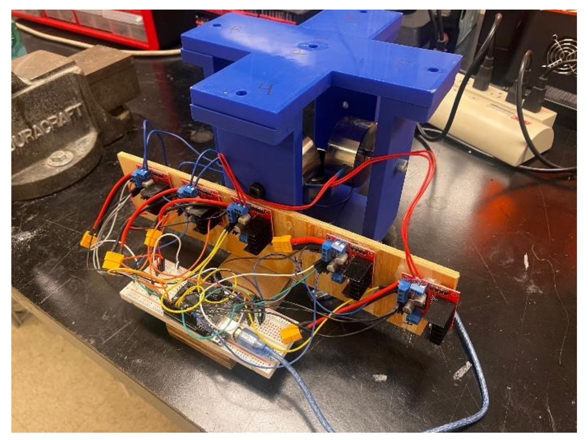


*Figure 5: Prototype 2 design*

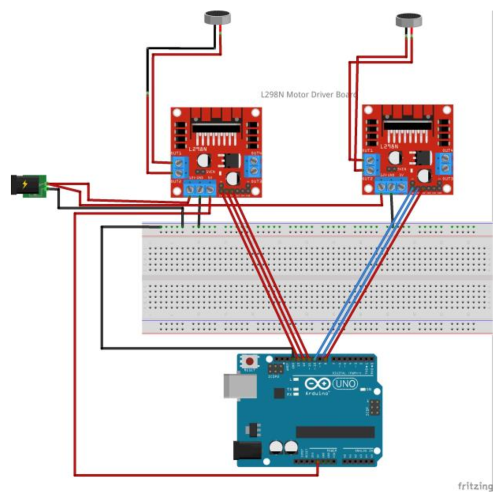


*Figure 6: Prototype 2 and 3 H-Bridge connection*

**Design:**

The device consists of a 3d printed frame with a 30mm x 30mm work space. Using a 300W power source, the magnetic field at the center of the work space had a strength of about 30mT, much more than the 10mT required to actuate the robot. For the magnet at the +Z axis, there must be a way to leave space for the lab camera to record the microrobot, so an electromagnet with a large core is used and a 1 1/8" hole drilled to leave space for the camera. To control the device an Arduino MEGA is used, with enough pins to control each coil individually with different power and polarity. This power adjustability is key to perform testing when a singular voltage is used, as well as to easily program changes in power to the device operation pattern. To distribute the power, h-bridge circuits are used, with a maximum capacity of 50V and 32A, higher than the supply of the power source. Since the electromagnet used at the top is still a 12V electromagnet, a separate power source must be used to ensure this voltage is not surpassed.

**Design and Experimental Setup:**

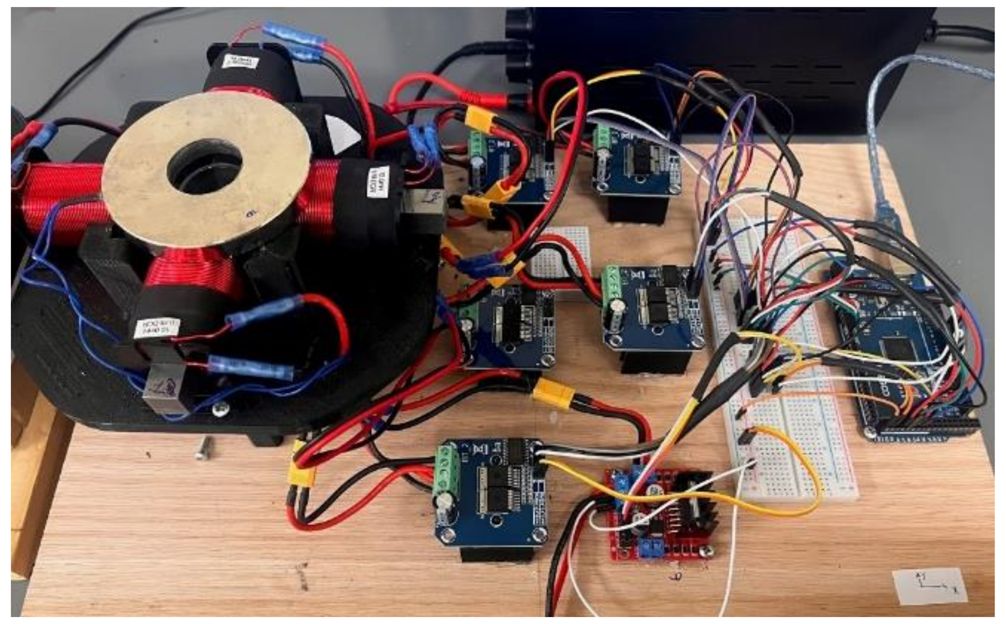


*Figure 7: Device design*

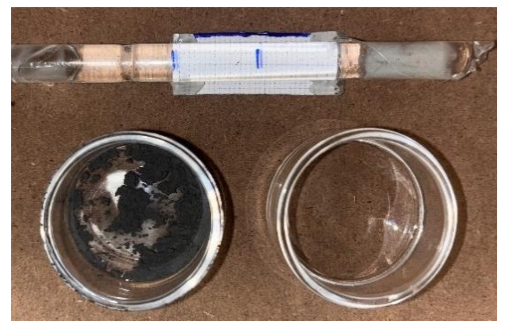


*Figure 8: Testing Specimens*

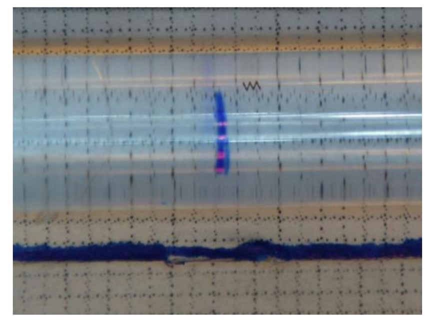


*Figure 9: Tube Testing Specimen*

**Robot Actuation:**

To actuate the robot, a magnetic field is used, as the robots have ferrous material embedded in their matrix. For the robot to spin and move through the water, the magnetic field must rotate at the desired frequency. The Arduino is used to program the following patterns into the device. Pattern 1 shows how to cause the rotation of the microrobot on an X-Z cross section, while Pattern 2 shows how to create an equivalent magnetic field to cause to robot to change direction. By controlling the power that goes to each coil, the angle the robot runs to is controlled. The figures below show the robot pointing in different directions, as well as a visualization of the magnetic field lines with the two patters described above.

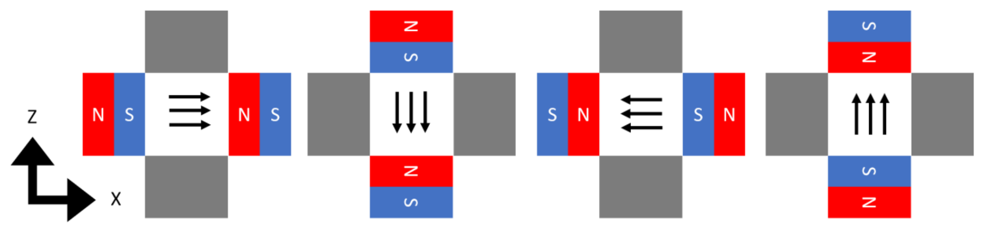


*Figure 10: Pattern 1 for rotating magnetic field*

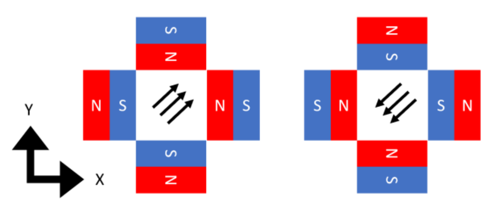


*Figure 11: Pattern 2 for equivalent magnetic field*

*Figure 13: Field Lines*

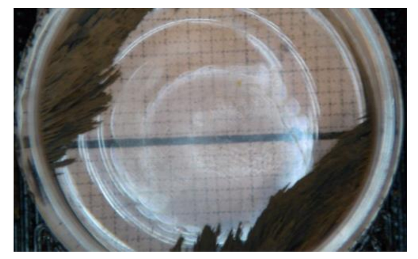


*Figure 14: Field Lines*

**Robot centering techniques:**

*Technique 1:* Change the power between each electromagnet in the same axis, keep this dissymmetry for a certain number of cycles, then reverse the dissymmetry. Rather than keeping the robot in a straight line, this method purposely attracts it to each side but keeps it in a certain range.

*Technique 2*: To solve the rotational friction problem, the test tube is placed closer to one electromagnet until a balance is reached. This balanced was found to be then the center point of the test tube was 7.5 to 10mm from the center point of the work area, depending on the power and frequency being used.

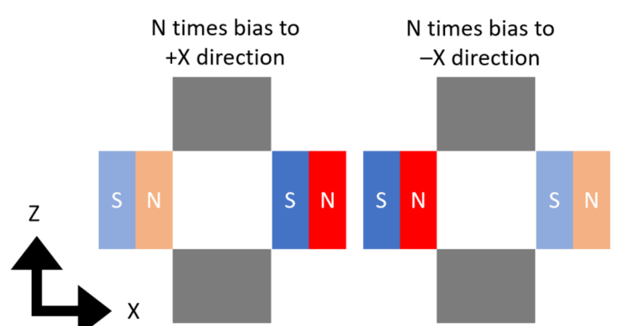



*Figure 15: Centering technique 1*

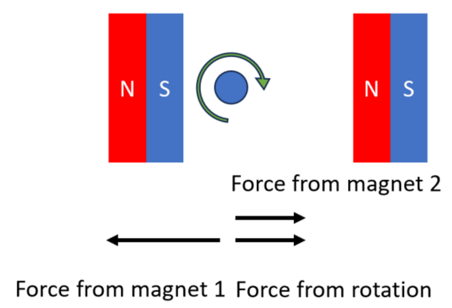



*Figure 16: Centering technique 2*

**Constant Voltage Configuration:**

The power delivered to each coil can be controlled with the Arduino PWM (Power Modulation) and can be set from 0 to 255, 255 being 100% power delivery of the input power available from the power source. The first plot shows that the maximum frequency that the robot is able to follow follows a near linear relationship to the power delivery programmed, with 30V creating greater frequencies. Note that if a high frequency is not being tested, it is advisable to stay with a 20V power source. The next plot shows that at a constrained voltage and a PWM of 255, the device will only be able to convert a certain amount of power into a magnetic field. Note that if the frequency is low, the device will create a very string magnetic field and a high heat, so this must be controlled with the PWM programming to keep the power used under 80W.

*Figure 17: Required Voltage for Rotation Frequency*

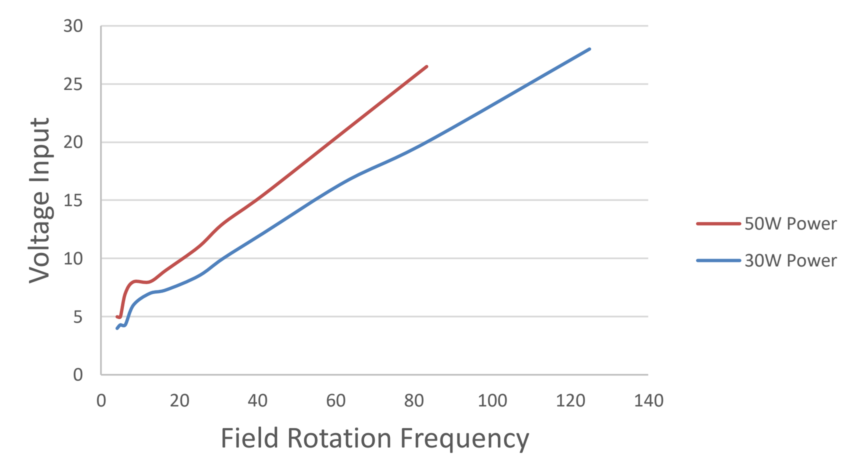
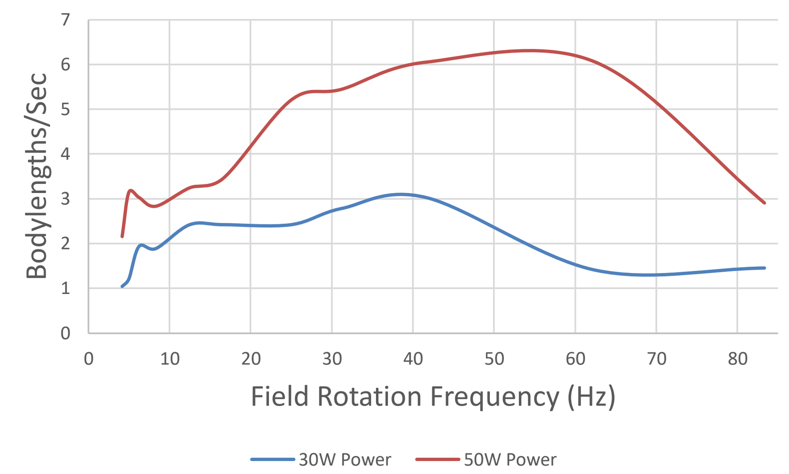



*Figure 18: Linear Speed at Frequency*




**Constant Power Configuration:**

If the power source used has an adjustable voltage, this can be used to always keep the same power usage in the device, thus being able to test different rotation frequencies with the same magnetic field strength. As explained on the previous section, the voltage needed to create the same power at differ rotation frequencies varies. The plot below was created to show users what voltage they should input when trying to keep a constant power at different rotational frequencies. The next plot shows the linear speed achieved by the robot at a specific power. Note that the speed is nearly constant, but when reaching high frequencies, it decreases because the robot cannot fully keep up with the rotation of the magnetic field and some steps are skipped. This effect can be mitigated by using a higher power when high frequencies will be tested, as shown in the difference between 30W and 50W.

*Figure 19: Maximum Frequency for Constant Voltage Power Source*

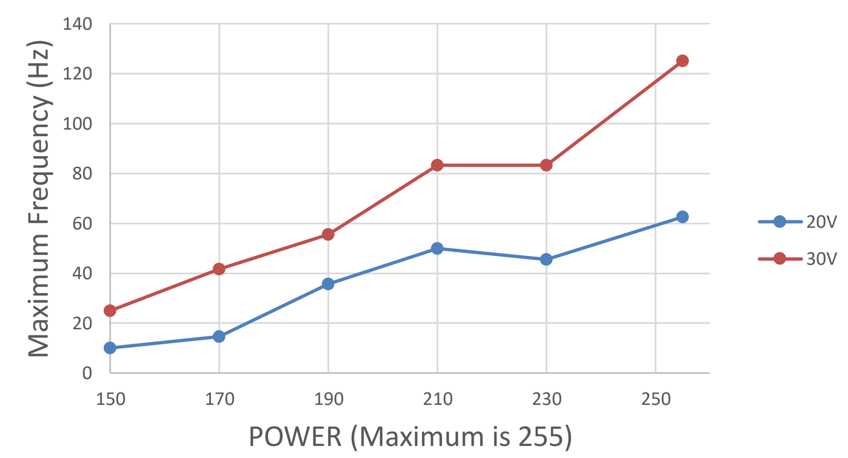
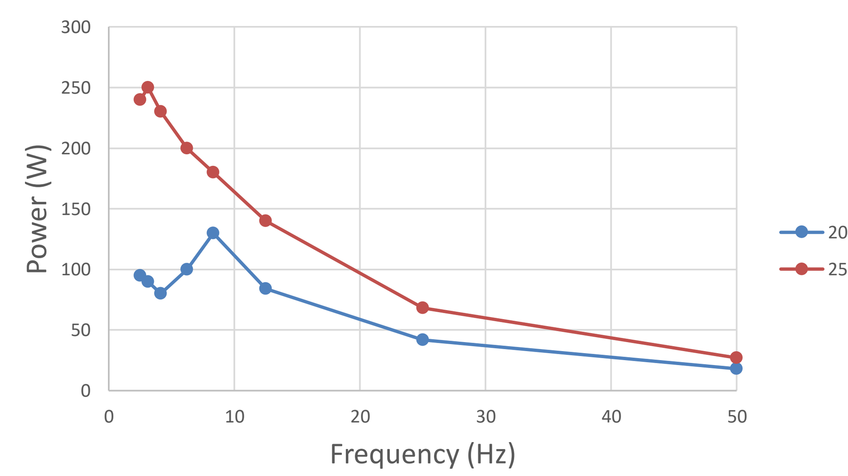



*Figure 20: Power at Frequency for Voltage Level*




**Conclusion and Improvements:**

The device has successfully created a strong magnetic field, to be used for testing and aid in the 3D printing of helical microrobots. It is recommended to test the robots with a power of 50W and a frequency under 50Hz to see the best results possible. Some improvements that would be beneficial is a higher quality power source that can more easily keep up with fast changes in voltage, which could help with rotating the filed at faster frequencies. Another improvement would be an active cooling system to keep the temperature of the coils down when creating stronger magnetic fields. Lastly, although not cost efficient for this purpose, it would be greatly beneficial to manufacture a system able to create a more homogenous magnetic field, such as a Helmholtz coil system. It was also concluded that in order to maximize safety, the device must be used with a maximum power of 80W, aiming to stay at 50W. When using the device for extended periods of time, the temperature stabilized at 40 and 60 deg C for 30W and 50W power usage.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