Magnetic Tweezers

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Background

- Magnetic tweezers were developed for microrheology experiments and research purposes
  - Measures the rheological properties of cells and tissues via the measurement of the trajectory of a tracer
  - Generate electromagnetic force to manipulate paramagnetic beads, creating a small force on biological samples, such as cells or tissues
- Related Technology:
  - Optical Tweezers
  - Atomic force microscopy
- Benefits of magnetic tweezers:
  - Small-scale precision
  - Non-invasive, doesn't damage specimens
  - Controllability through feedback loop

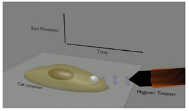


Figure 1: Animation of working Magnetic Tweezer [1]

Purpose

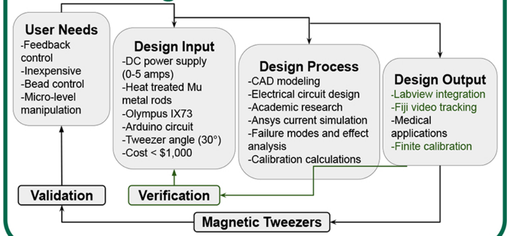
Design and create a device to carry out active microrheology force production in or on cells and tissues with control of bead movement in three dimensions.

Goals and Constraints

Goals
1. Have 3D Control of Magnetic Beads
2. Measuring the Magnetic Force Output
3. Low Overall Cost

Constraints
1. Budget
2. Microscope geometry
3. Electromagnet capability
4. COVID-19

Design Control Process



User Needs
-Feedback control
-Inexpensive
-Bead control
-Micro-level manipulation

Design Input
-DC power supply (0-5 amps)
-Heat treated Mu metal rods
-Olympus IX73
-Arduino circuit
-Tweezer angle (30°)
-Cost < $1,000

Design Process
-CAD modeling
-Electrical circuit design
-Academic research
-Ansys current simulation
-Failure modes and effect analysis
-Calibration calculations

Design Output
-Labview integration
-Fiji video tracking
-Medical applications
-Finite calibration

Validation

Verification

Magnetic Tweezers

References and Acknowledgments

Acknowledgements: Dr. Dave Bark, Dr. Ashok Prasad, Iain Briongos, and Steve Johnson

References:
[1] Magnetic Tweezers. http://biomechanicalregulation-lab.org/magnetic-tweezers-1 (accessed Dec 4, 2019).
[2] Matsuura D, Aoki H, Takeda Y. Development of a 3D-magnetic tweezer system having magnetic pole positioning mechanism. 2016 IEEE International Conference on Robotics and Automation (ICRA), Stockholm, Sweden. 1745-1750. Doi: 10.1109/ICRA.2016.7487318.
[3] Zhang Z. Magnetic tweezers: actuation, measurement, and control at nanometer scale. 2009 Ohio State University, Columbus.
[4] Menq C, Huang Y, Zhang Z. Actively controlled manipulation of a magnetic microbead using quadrupole magnetic tweezers. 2010 IEEE Transactions on Robotics, Vol 3, No 3, 531-541. Doi: 10.1109/TRO.2010.2047526.

Final Design

- Final design of mounting optimizes system customization
  - 110° rotation of electromagnets
  - Adjustable height of yolks
  - Independent sample mount for ease of sample change
  - Adjustable sample height
  - XY µm control of sample positioning
  - Mounting holes for pairing with Olympus IX73
- Final prototype machined in Aluminum using CNC machining capabilities

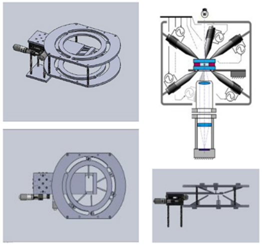


Figure 2: Final CAD illustration of mechanical mounting assembly to microscope [2]

Figure 3: Singular tweezer wrapped with magnetic wire on mount

System Functional Diagram

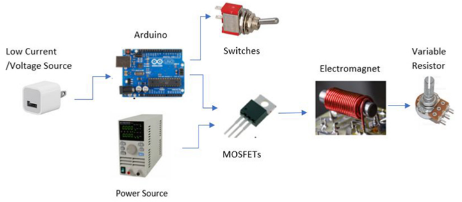


Figure 4: Schematic of Full Project Design with Mechanical Potentiometers

Magnetic Field Simulation

- Simulation done using Ansys Maxwell 3D
  - 1 yolk modeled (3 electromagnets)
  - 500 coil wraps
  - 1 amp running through each
- Color gradient represents field strength
- Directional pull in center represents the direction of paramagnetic bead movement

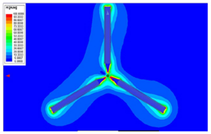


Figure 5a: Magnetic field strength of one yolk

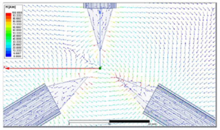


Figure 5b: Magnetic field strength with directionality vectors of one yolk

Methods

Magnetic beads were placed under the IX73 microscope in suspension. Movement of the beads due to applied magnetic forces or Brownian motion was recorded with a CCD camera. Post-process analysis through MicroManager and ImageJ allowed us to measure the displacement and time the bead moved and the Stokes equation was used to determine the magnetic force on the bead.

$$F = 6\pi\eta r v$$

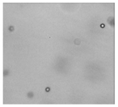


Figure 6: Magnetic Beads under a Microscope

Calibration Results

Calibration of 1 Tweezer in Different Media

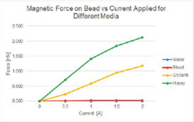


Figure 7a: Force vs Current of One Tweezer

Figure 7a example data shows the dependence on current for increasing magnetic force as a function of viscosity. With a maximum current of 2A, we should be able to achieve forces in the nN range.

Figure 7b example data shows the change in bead displacement with the change in current as a function of viscosity. This relationship, with further iterative testing, can help to develop a feedback loop system that would control the current input to each tweezer.

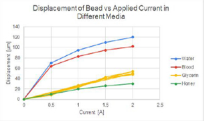


Figure 7b: Displacement vs Current of One Tweezer

Calibration of 6 Tweezers

To begin, the inductance in each tweezer is calculated:

$$L = \frac{N^2 \mu_0 \mu_m A}{l}$$

From here, the magnetic field generated can be calculated using the superposition of the six magnetic fields generated by the tweezers:

$$B = \sum_{i=1}^{6} \frac{\mu_0 q_i}{4\pi r^2} \cdot u_i$$

This allows us to calculate the force on the bead:

$$F = \nabla\left(\frac{1}{2}\frac{3V}{\mu_0}\left(\frac{\mu_b - \mu_0}{\mu_b + 2\mu_0}\right) \cdot B^2\right)$$

For the purpose of these calculations, the distance the bead traveled from center was 50 µmeters in the positive x and y directions. For movement along the positive y-axis, tweezers 1 and 5 were turned off. For movement along the positive x-axis, tweezers 1 and 6 were turned off. [3,4]

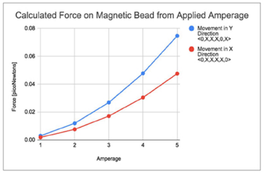


Figure 8: Calculated Force on Magnetic Bead from Applied Amperage ranging from 1-5 amps

Conclusions and Future Work

Conclusions

- A hexapole system be used to manipulate the magnetic forces in 3D
- This project can be achieved with a small budget

Future

- Complete calibration of one tweezer with mechanical potentiometers
- Complete calibration of six tweezers with mechanical potentiometers
- Complete calibration with DigiPots
- Develop feedback control loop