Model Magnetic Force Microscope

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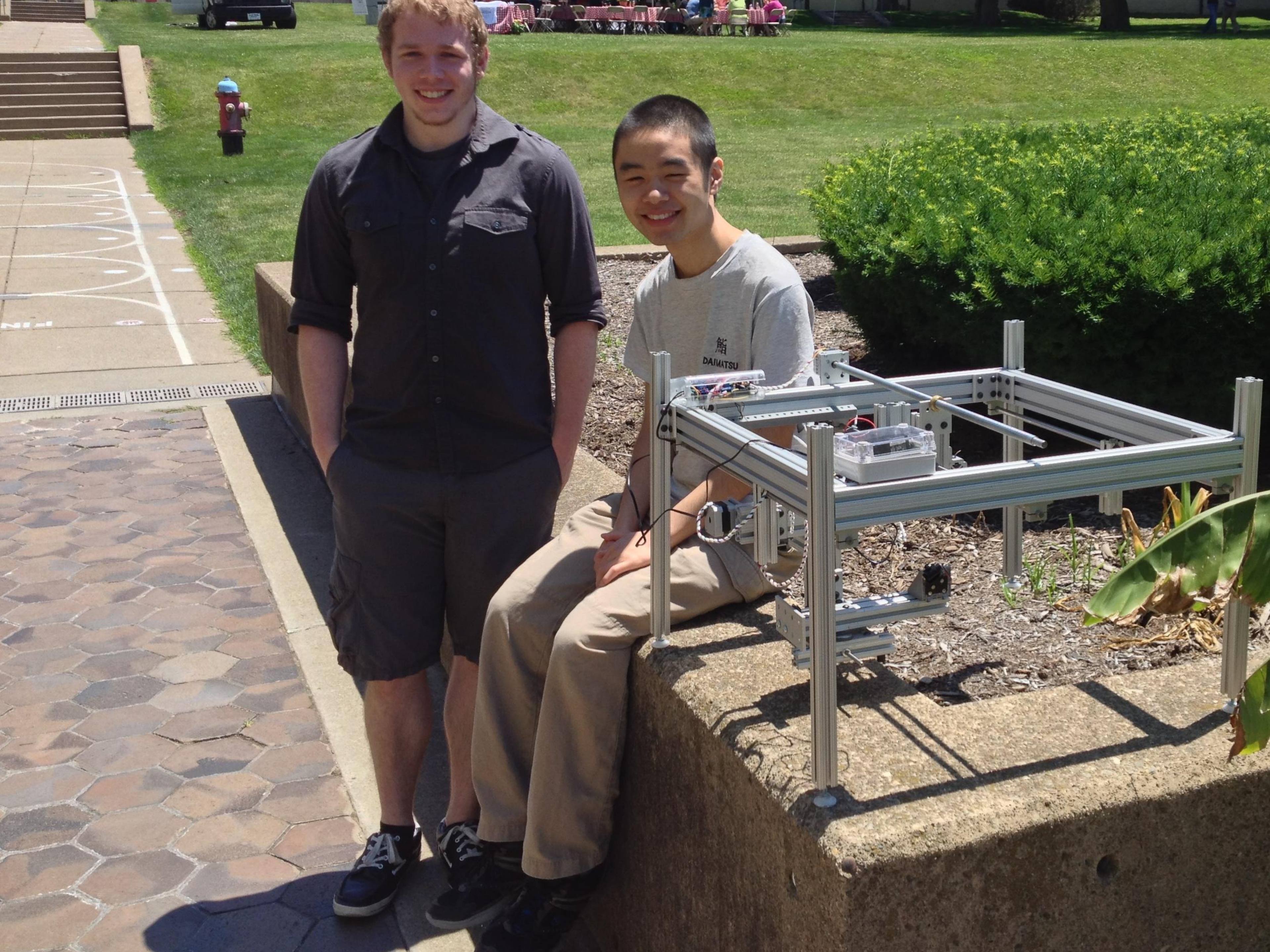
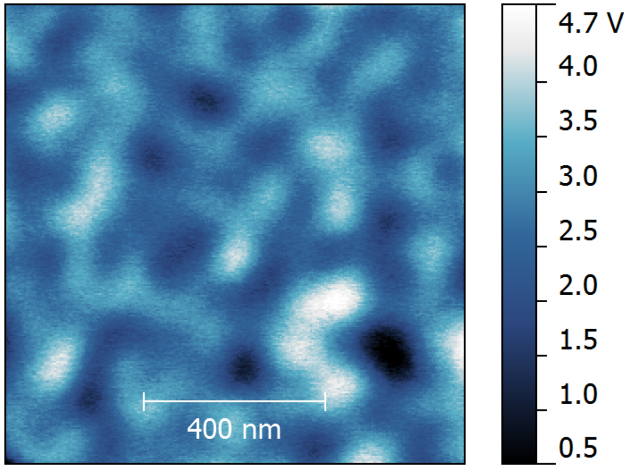

DAIMATSU

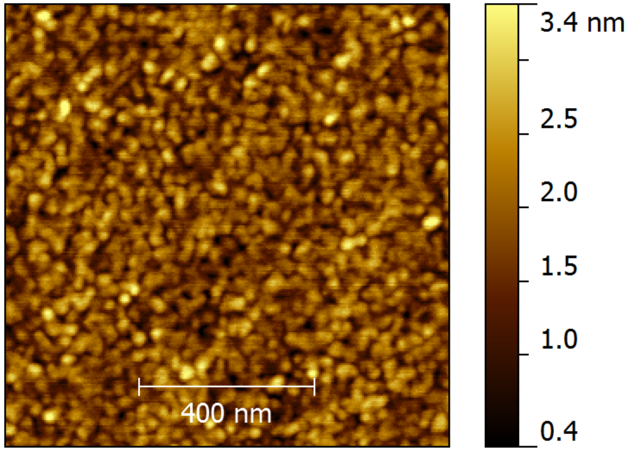
Magnetic Force Microscopy

- Type of scanning probe microscopy, variant of atomic force microscopy
- Scan magnetic tip over a given surface
  - Image magnetic stray field
  - Resolutions on the order of 10 nm

Magnetic Force Microscopy

- On first pass, obtain information about topography (right)
- On second pass, use topographical information to maintain constant height and gather data that reveals information about magnetic properties of the sample (i. e. magnetic domain structure, grain boundaries) (left)





Scan of Iron Platinum; image credit: Stephan Piotrowski

Motivation

- MFM is widely used to study nanoscale magnetization patterns
- MFMs are usually very complicated to look at and understand

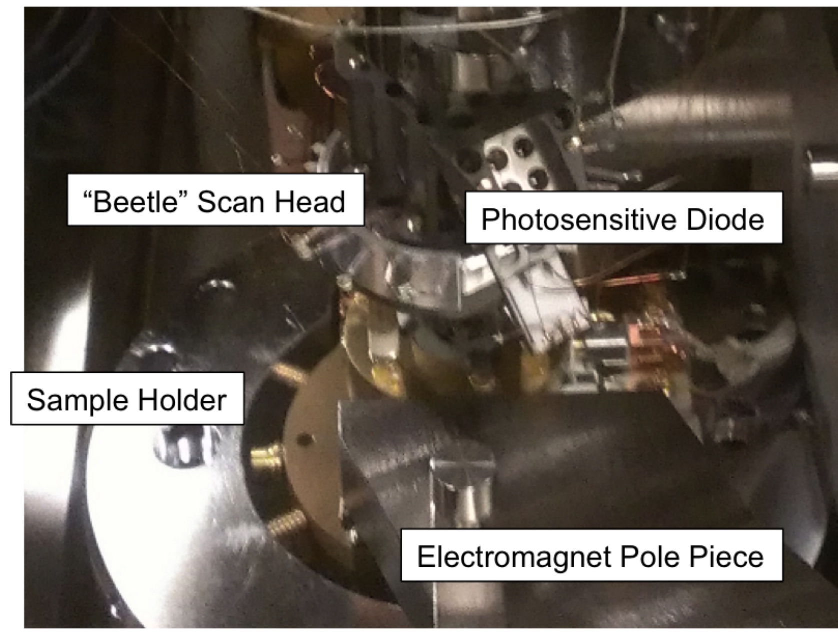
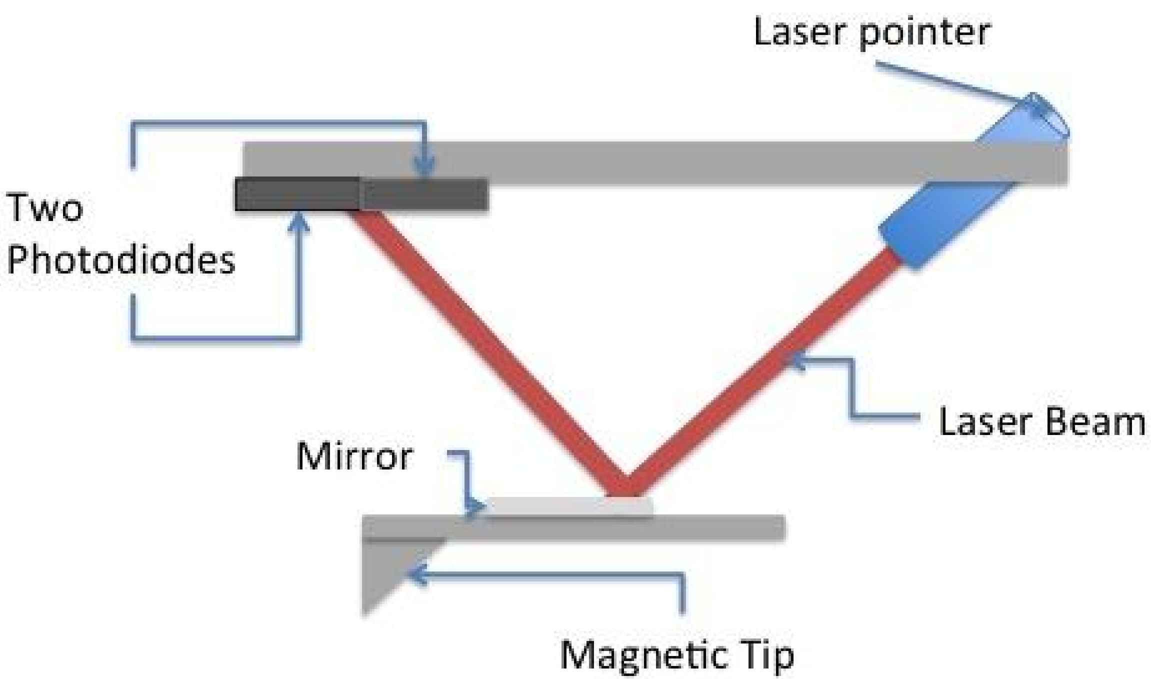


image credit: Stephan Piotrowski

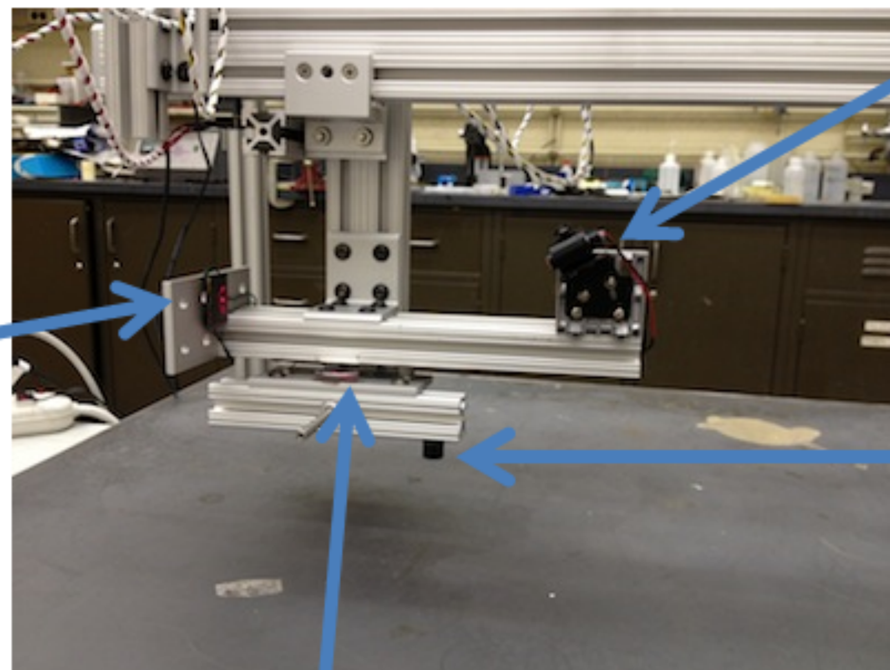
Motivation

- This project allows for easy demonstration
  - Clear view of key components
  - Easier to understand underlying physics

Motivation

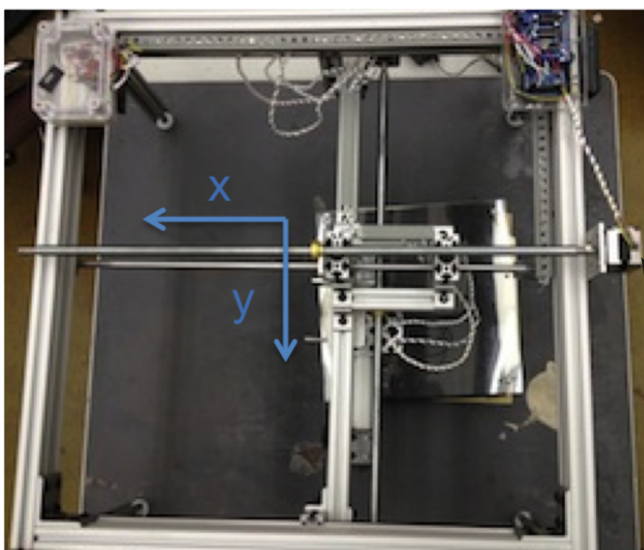

Laser pointer
Two
Photodiodes
Laser Beam
Mirror
Magnetic Tip

Motivation



Mechanics

- Cantilever scanned over given surface
- 2 movement axes
- Stepper motors control motion
  - Accurate control to within 1/2000 inches



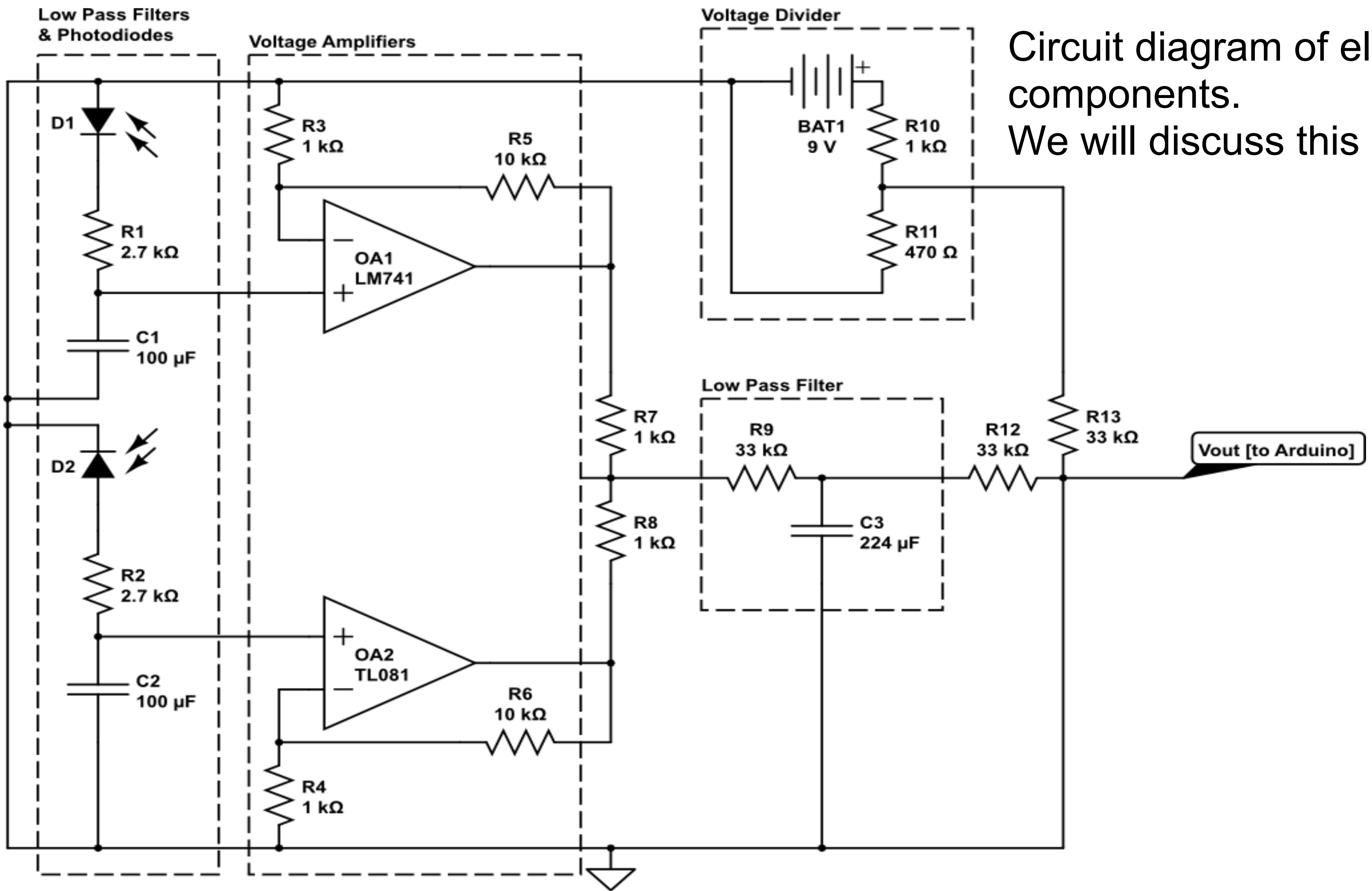
Top view of model MFM

Stepper Motor

Mechanics

- Magnet on tip repulsed/attracted by magnetic force exerted on it by the sample
  - Tip approximated as point dipole
  - $F_{dip} = (m \cdot \nabla)B$
  - m is the dipole moment of the tip, B is the magnetic field due to the sample at the position of the tip
- Tip height determined by position of laser spot reflected off mounted mirror

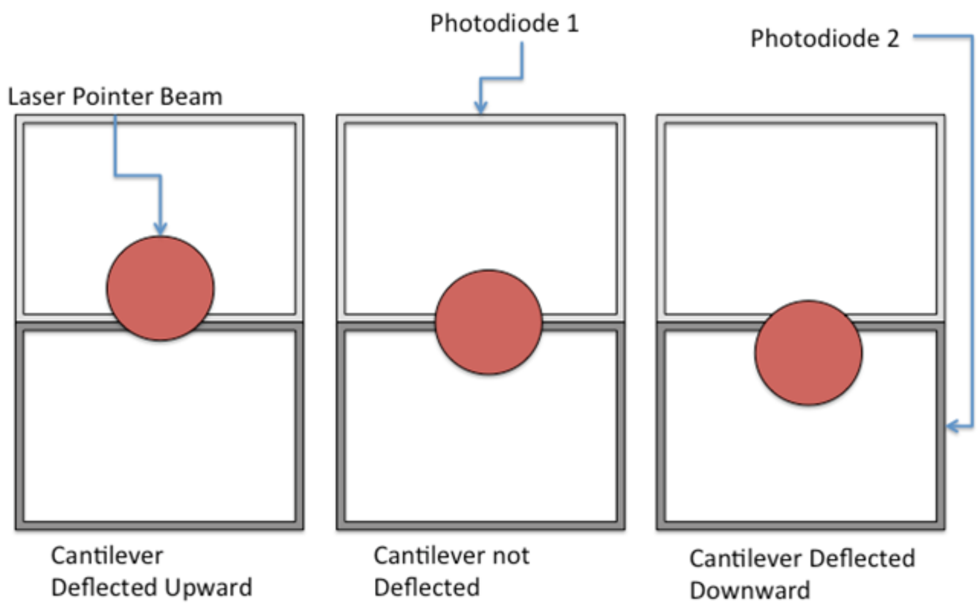
Detector & Circuitry



Circuit diagram of electronic components.
We will discuss this piecewise

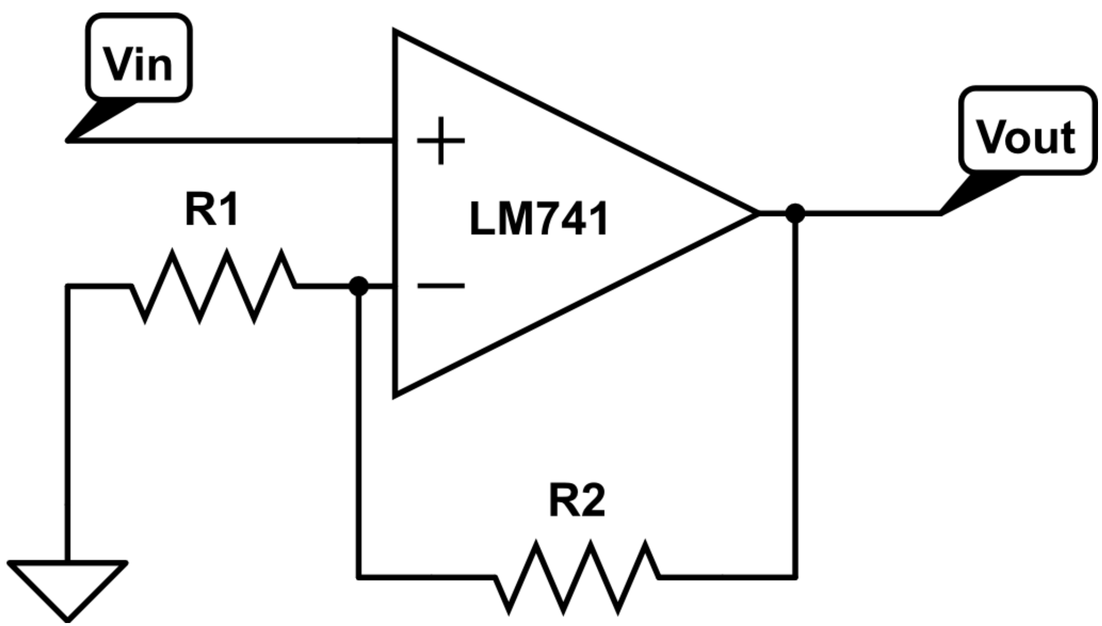
Detector

- Split Photodiode Detector
  - Voltage on each diode related to area of laser dot hitting it
  - More of laser hitting it, higher voltage



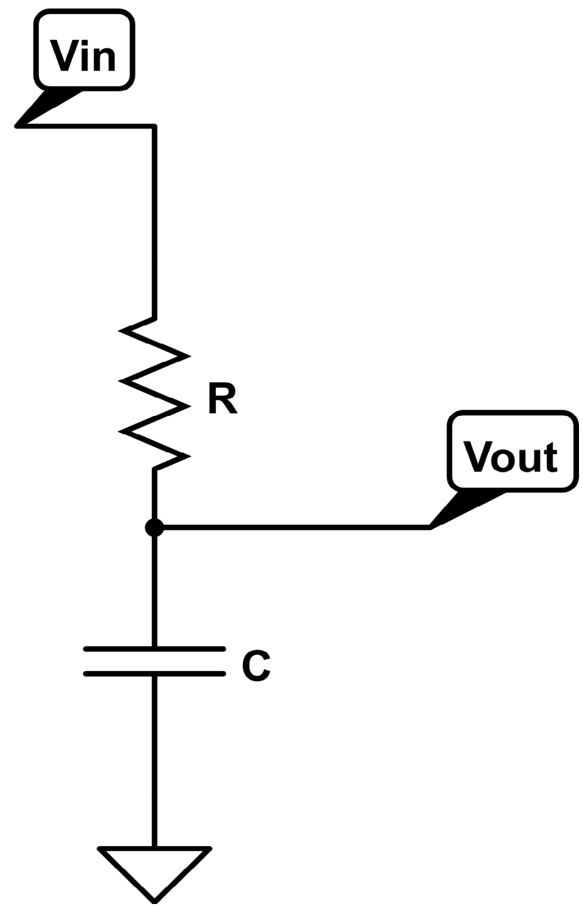
Circuitry

- Photodiodes outputted to voltage amplifiers
- Amplified voltages are subtracted
  - Can determine position of laser dot on detector from resulting voltage



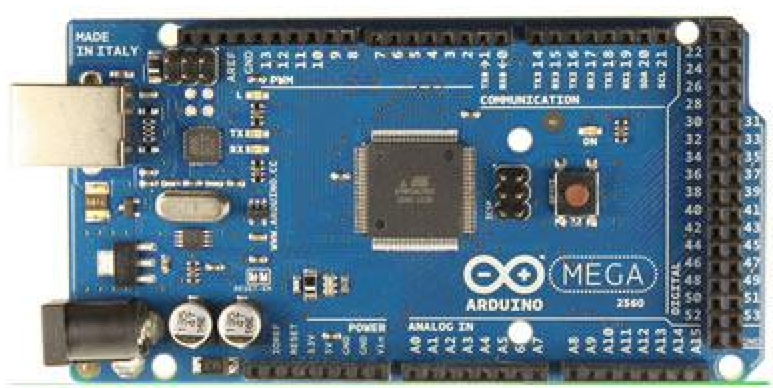
Circuitry

- Run signal through low-pass filters
  - Remove noise [60Hz] from overhead lighting
  - Impedance ["resistivity"] of capacitor:
    - $R_c \cong |Z_c| = \dfrac{1}{\omega C}$



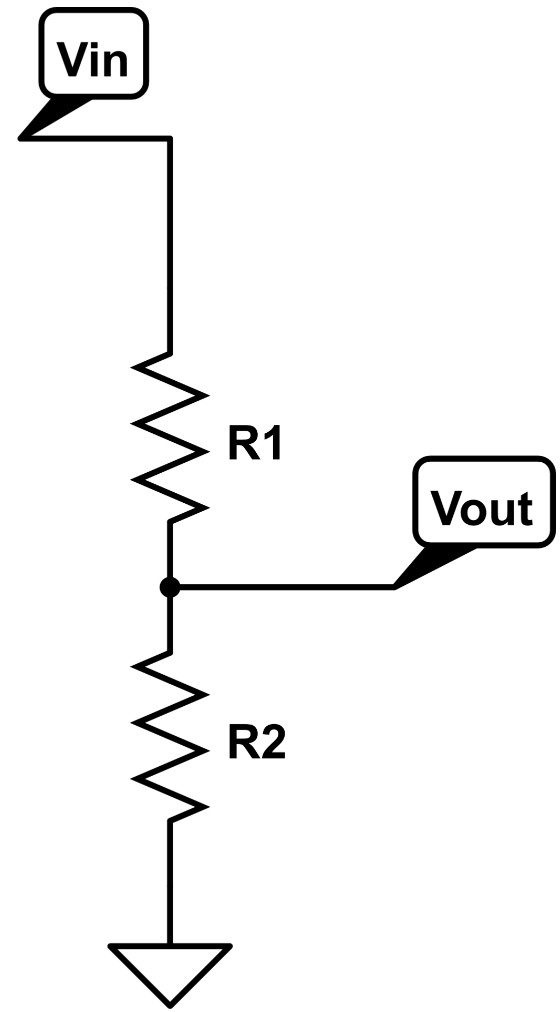
Circuitry

- Arduino detects output voltage using analog electronics
    - Detects voltages from 0 to 5V in 5 mV increments



Circuitry

- Use voltage divider
  - Offset output by adding appropriate voltage
  - Keep output voltage between 0 and 5 V
  - $$V_o = \frac{R_2}{R_1+R_2} V_{in}$$

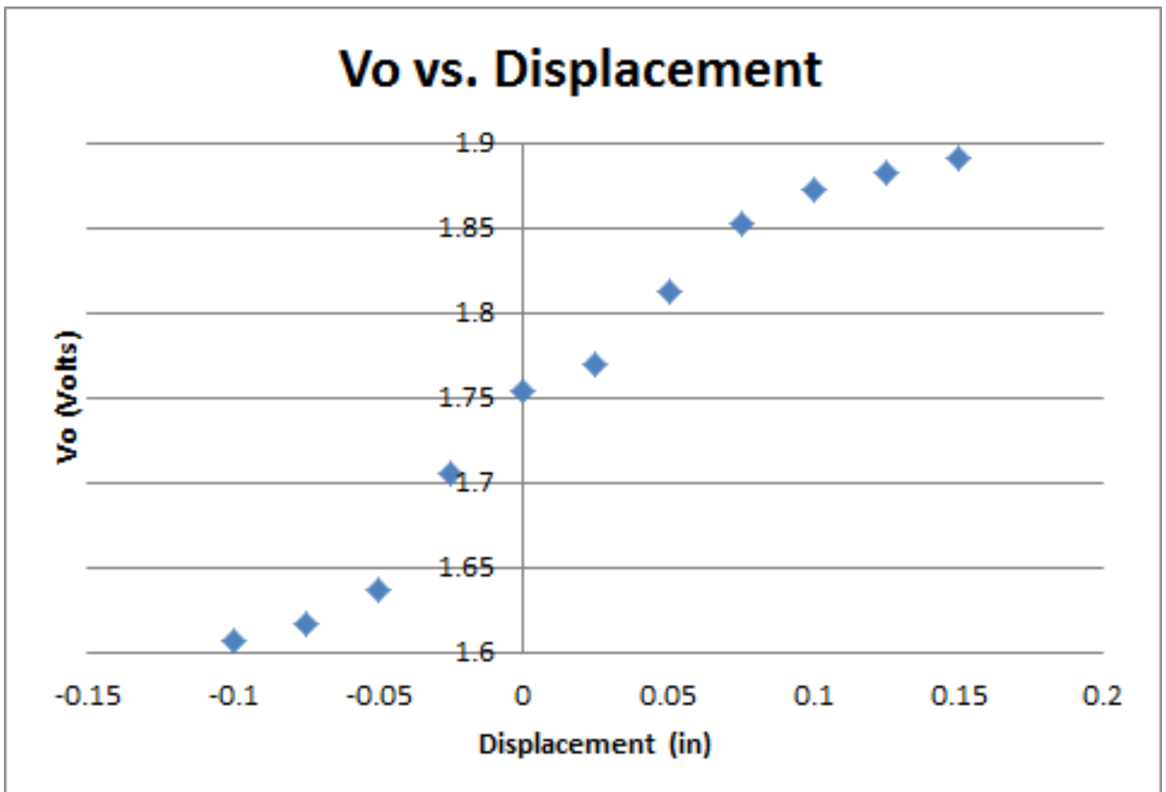


Calibration

- arctangent relationship between output voltage (Vo) to laser dot displacement (d) [1]
- Yields: $Vo = \arctan(1.6103*d + 0.6518)$
- Inverted: $d = (0.621)\tan(Vo) - 0.405$

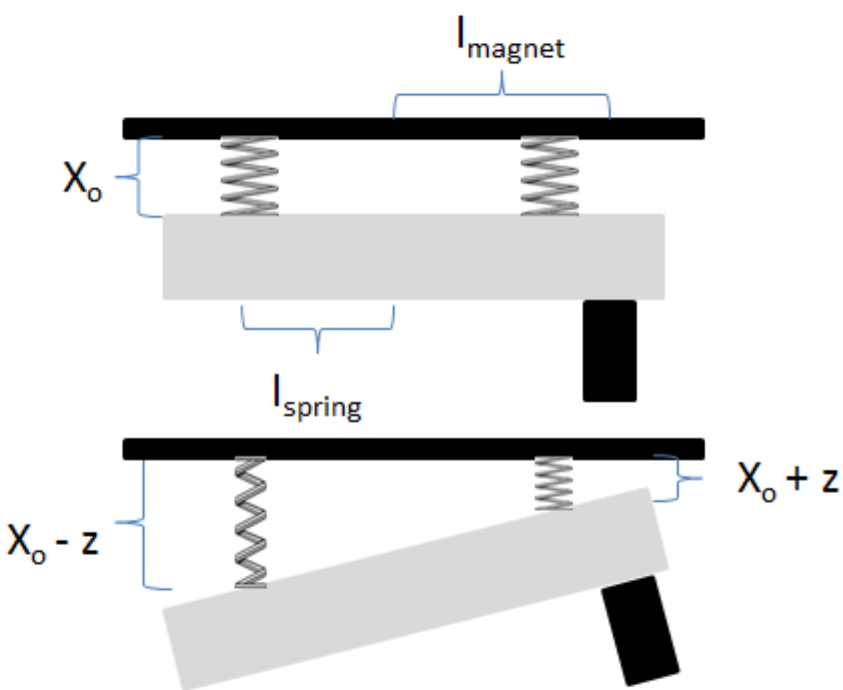
Calibration

- Graph output voltage of photodiodes against known displacements of the laser spot



Data Analysis

- Force can be computed using deflection height and spring constant from a torque conservation argument

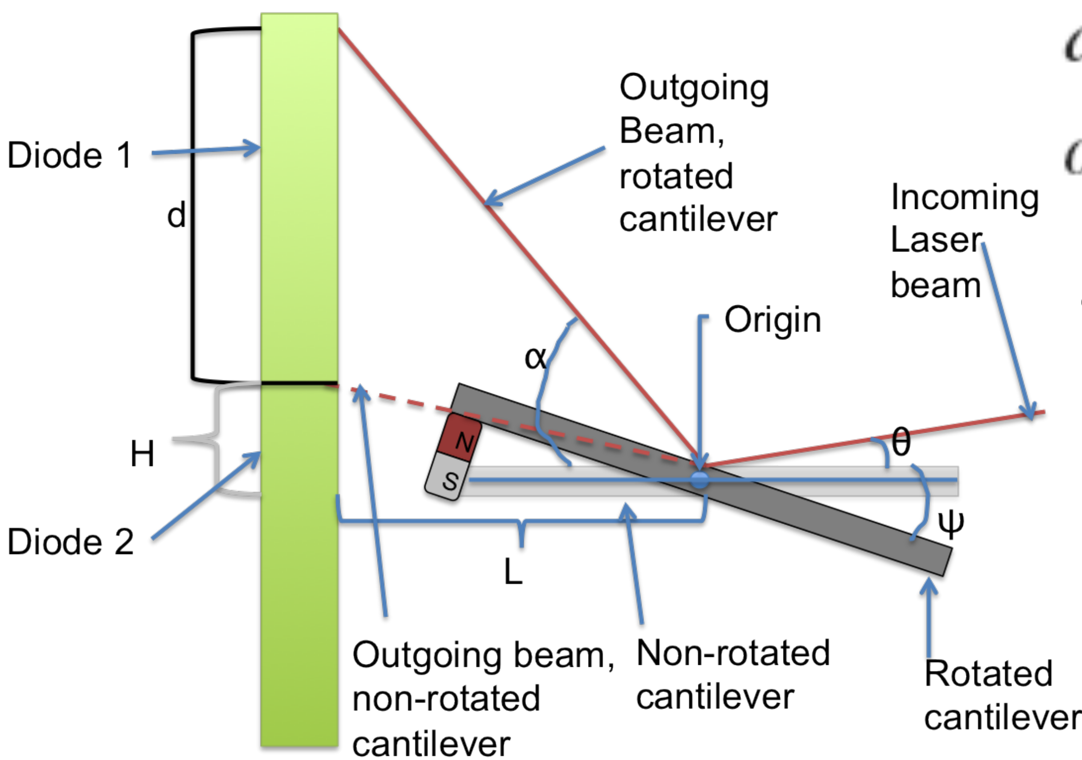


$$\boldsymbol{F}_{on\ tip} = \frac{l_{spring}}{l_{magnet}}(2k\boldsymbol{z})$$

But we have to find z from the data that we have: voltage output from the split photodiode detector

Data Analysis

- Relate laser displacement to deflection angle



$$d = (L+x)\tan(\alpha)+y-H$$

$$\alpha = \theta+2\psi$$

H is the vertical displacement of the equilibrium dot position from the origin (axis of rotation)

(x,y) is the position of the contact point of the laser relative to the origin

Data Analysis

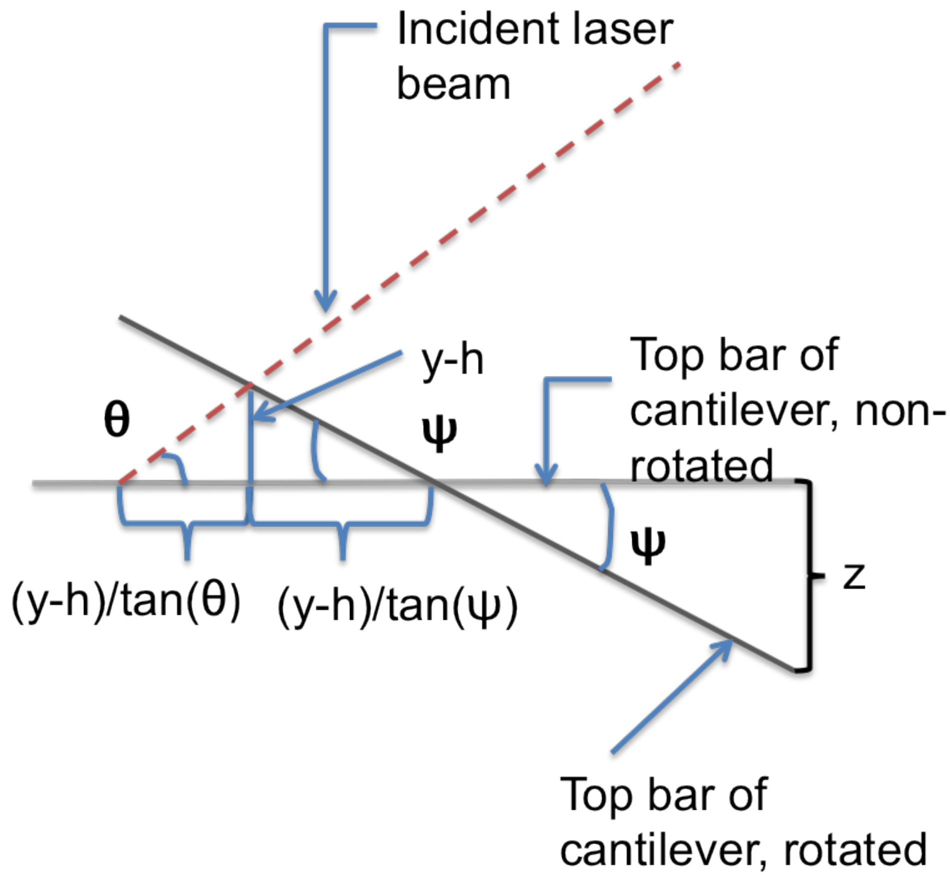
Noting that points on the top bar of the cantilever are constrained to move on a circle about the axis of rotation of radius h, we have

$$x = \frac{(\sec\psi - 1)}{\tan\psi + \tan\theta}h \qquad y = \frac{(\tan\theta\sec\psi + \tan\psi)}{\tan\theta + \tan\psi}h$$

using our result from the previous slide, and taylor expanding our solutions for x and y to second order yields:

$$\psi = \frac{L \pm \sqrt{L^2 + h(h - H - d + L\ \tan\theta)}}{h}$$

Data Analysis



- Using a similar triangles argument finally yields the deflection height z as:

$$z = \tan(\psi)[l_{spring} - \frac{y-h}{\tan(\theta)} - \frac{y-h}{\tan(\psi)}]$$

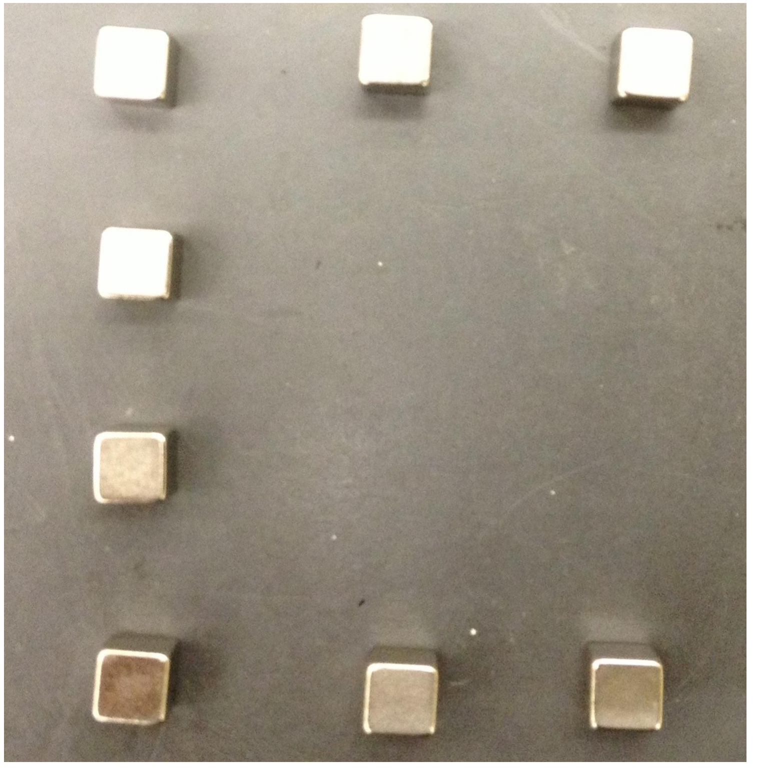
- If we so desired, we could substitute our expressions for psi and y into the previous expression to have z as a function of d, where theta, h, L, and l are fixed parameters

Putting it all together...

- Scan across sample
- Pass photodiode output through circuit to obtain readings [in volts]
- Convert voltage to compression of springs
- Use compression to calculate force on tip
- Now we have to do something with the data...

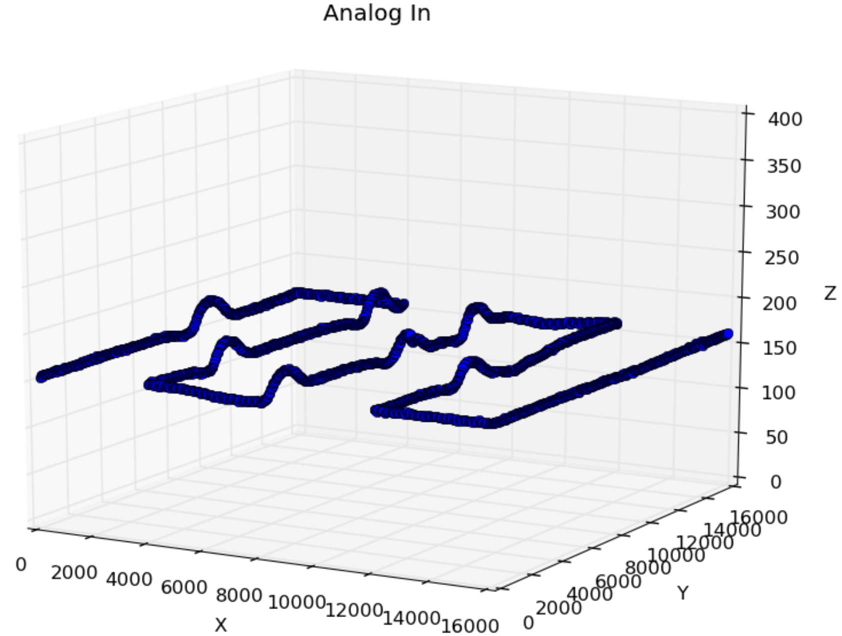
Graphing Software

We would like to be able to represent magnetic sample patterns that we construct, like this one



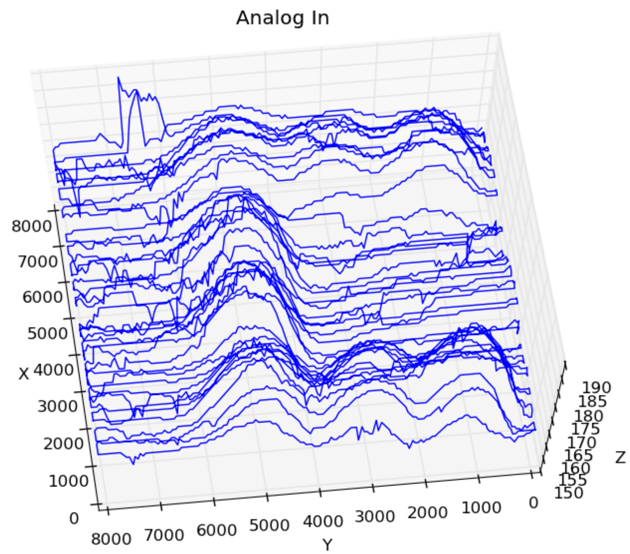
Graphing Software

- Data is taken in discrete line scans
  - Image of large line-spacing data:



Graphing Software

- We would like to see a continuous surface
  - First improvement: high scan density
  - We get a much clearer picture
  - Still discrete lines, and hard to interpret



Graphing Software

Next Improvement [2]:

- Partition the region in which the data lies into a grid of square cells
- Ideally we would be able to solve a matrix equation, Ax=b, for a coordinate vector at every point
- It is usually the case that there are more vertices in the grid that there are data points, in which case the problem will be underdetermined

Graphing Software

- solve minimization problem instead:
  - Seek to minimize $\|\boldsymbol{Ax} - \boldsymbol{b}\|^2$
  - called residual
- We would also like to find a way to give preference to smoother solution surfaces
- Add a regularization term to the minimization problem that biases towards smooth solutions
- This particular algorithm works by enforcing gradient equivalence across nearest-neighbor cell boundaries

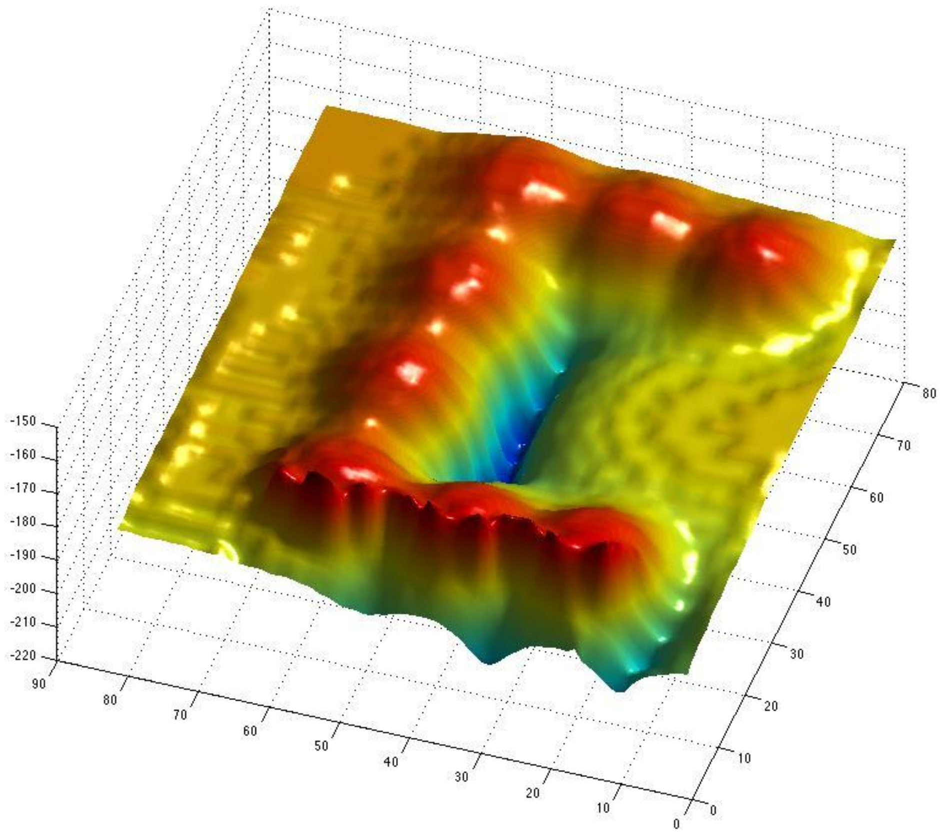
Graphing Software

- Use an iterative solver to find a vector x such that

  $$\|\boldsymbol{Ax} - \boldsymbol{b}\|^2 + \|\boldsymbol{\Gamma x}\|^2$$

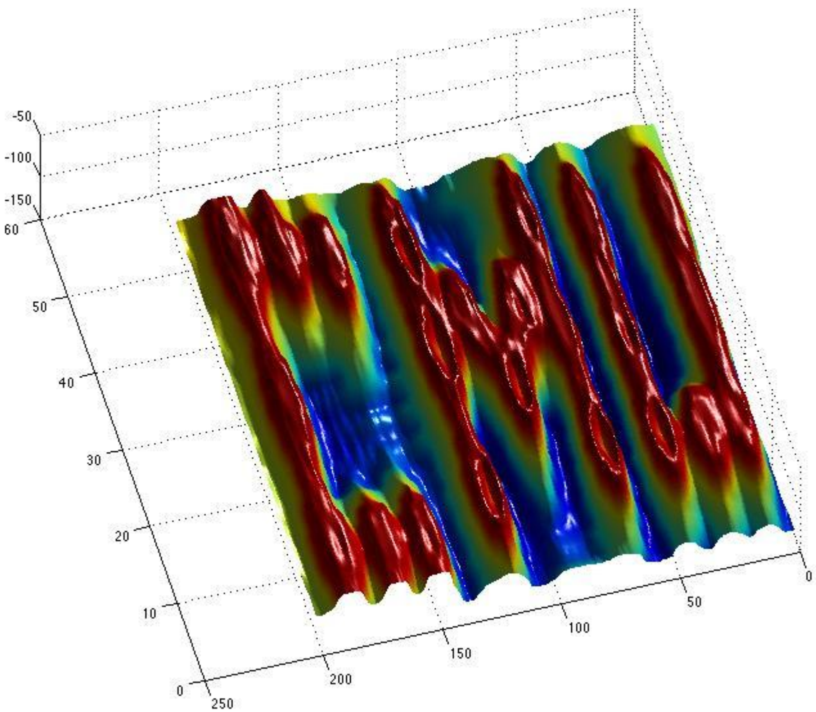
  is minimized
  - Gamma is our smoothness operator
  - Multiplying the regularization term by a scalar works to increase or decrease the smoothness of the output surface depending on the magnitude of the scalar relative to unity

Graphing Software

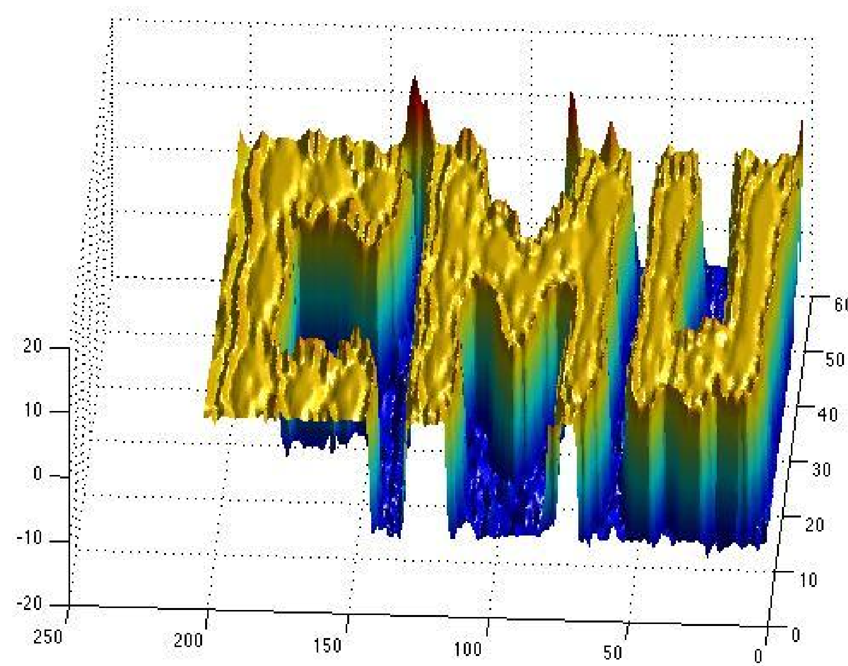


This method gives much nicer, more readable visualizations of data

Results: Magnet CMU



Analog In (1 unit/4.9 mV) vs xy



Force (N) vs xy

Possible Sources of Error

- Non-exact equilibrium alignment
  - deflection in opposite directions result in different positions
  - gives difference of +/- 5 mV on input
  - About 1.6% of the input range
  - This error accounts for small noise on the equilibrium plane

Possible Sources of Error

- Vibration during movement
  - non-smooth motor movement causes vibrations
    - smoother movement mode doesn't provide enough torque
  - gives difference of +/- 10 mV on input
  - About 3.3% of the input range
  - More noticeable during x-movement, during which very few measurements are taken (in our data, between .5% and 2%)

Future Work

- Improving resolution & reducing error
- Modelling new types/modes of scanning probe microscopy
    - Topographic measurements
    - Conductive atomic force microscopy
        - Gain information about electric, as opposed to magnetic properties of sample (i.e. current-voltage characteristics, conductivity)

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References

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Images

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