# Design and Construction of a Self-Replicating Milling Machine

Julian Leland
ENGR 90, Spring 2012
Advisor: Prof. Faruq Siddiqui

Hello everybody; thank you all for coming. My name is Julian Leland, and today I'm going to be presenting my E90 – the design and construction of a self-replicating milling machine.



## Presentation Outline

- Introduction to Project/Motivation
- Design Process
  - Definition of Specification and Function
  - Frame Design
  - Linear Motion Systems Design
  - Spindle and Power Systems Design
- Construction
- Performance & Conclusions

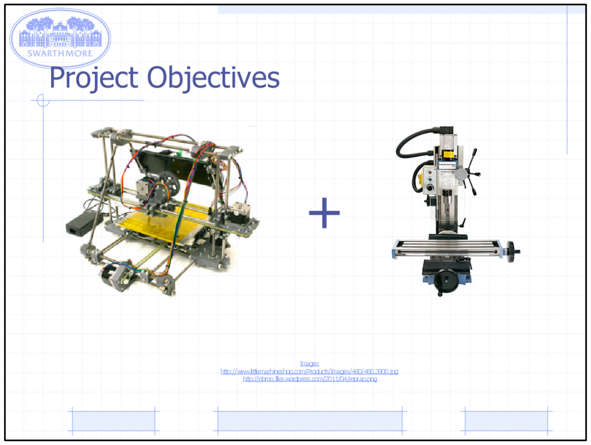
Briefly, I'd like to outline my presentation today.

First, I'm going to introduce my project, and explain why I think it's worth pursuing.

Second, I'm going to describe the process I went through to design this machine, focusing on these four major sub-tasks I had to complete.

Third, I'll talk a little about the construction and assembly processes.

Finally, I'll discuss where the machine is now, how close it comes to achieving my design objectives, and talk about avenues for future work.




• In recent years, small, affordable, digital rapid fabrication tools like 3D printers (see above) have made desktop manufacturing a buzzword, even outside of hobbyist and maker communities

  • One major aspect with SOME OF THESE MACHINES is "self-replication" – idea that if you have one of these machines, you can build all the parts that you can't just buy off the shelf to build another.

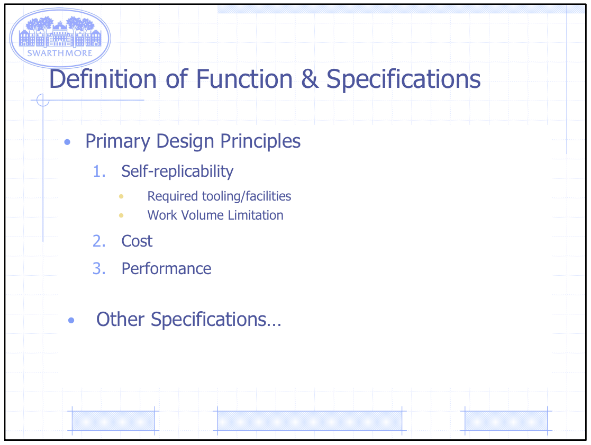
• Most of these tools are either 1) additive manufacturing tools (3D printers), 2) non-contact subtractive (plasma cutters), or 3) light-duty contact subtractive (wood routers)

  • **Nothing addresses the need traditionally filled by milling machines – working of metals at reasonably rapid rates while still maintaining cut precision measurable in .001"**
  • Currently available small milling machines are expensive (upwards of $600 w/o CNC functionality), limited in their functionality, and often of poor quality – finally, cannot self-reproduce.

• **Goal of this E90**: Design and construct a 3-axis machine tool, which can mill basic materials including mild steel and can create all parts that can't be easily purchased which are needed for its construction.

  • Work volume of 6" x 6" x 6"
  • No advanced machining processes
  • Comparable in cost to its competitors ($500-$700)
  • Intended for CNC use






The first step in the design process was to fully define the machine's mechanical specifications and intended function.

Three primary design principles were defined at the beginning of the project, to serve as a compass for selecting between competing design goals

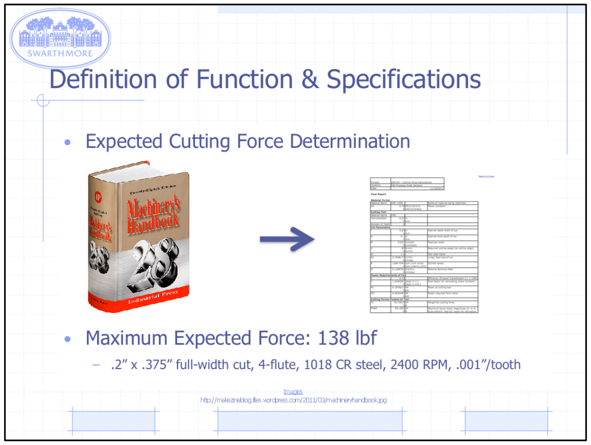
• Self-replicability: a user should be able to create an exact copy of the machine, using only a preexisting machine as well as basic hand tools/measuring equipment. This statement has a lot of ramifications.

  • No advanced manufacturing processes – no casting, scraping, grinding or welding
  • No fancy metrology equipment – intended to only require 3' scale, 6" dial calipers, combination square and shim stock.
  • All precision-manufactured parts must fit within the machine's work volume (6" x 6" x 6") – if they cannot, they must be designed for compliance (e.g slots instead of holes to allow for more generous manufacturing tolerances).

• Cost: More time- or manufacturing- intensive design options should be selected over more costly design options.

• Finally, the performance goals stated earlier – capable of light milling in mild steel – should be achievable

In addition to these basic principles, a number of other aspects of the machine were outlined, including the basic geometry of the frame, the machine's kinematic type, the positioning ability of the machine, the required translation rates of the machine, the materials to be used in the machine, and the maintenance and repair requirements of the machine.



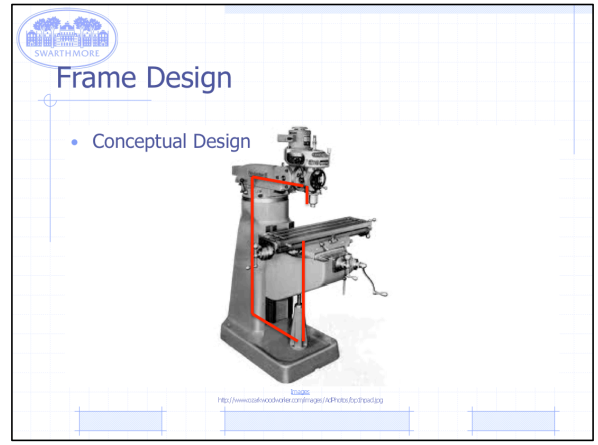

In order to fully define the performance goals of the machine, as well as to give myself loads to use for design purposes, I had to determine the maximum expected cutting load.

I developed a method based off of information in Machinery’s Handbook and a variety of other sources to estimate maximum cutting force experienced by 2-, 3- and 4-fluted end mills for specified cut geometries, feed/speed combinations and materials.

I programmed this into a spreadsheet, and simulated a variety of cuts. I found that the maximum expected cutting force was 138 lbf, for a .2”  by .375” full-width cut in 1018 steel, at 2400 RPM and with a feed of .001” per tooth. I then applied a factor of safety of 1.5 to this expected load, leading to my expected design load of 200 lbf.

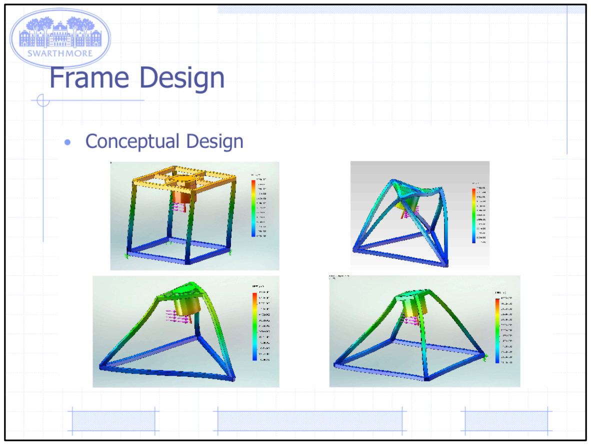
With this design load, I stipulated that my machine should be able to perform a .125” x .1” full-width cut in 1018 steel without experiencing total error motion greater than .001”






With the machine basically outlined, I turned my attention to my first major design task - designing the frame of the machine.

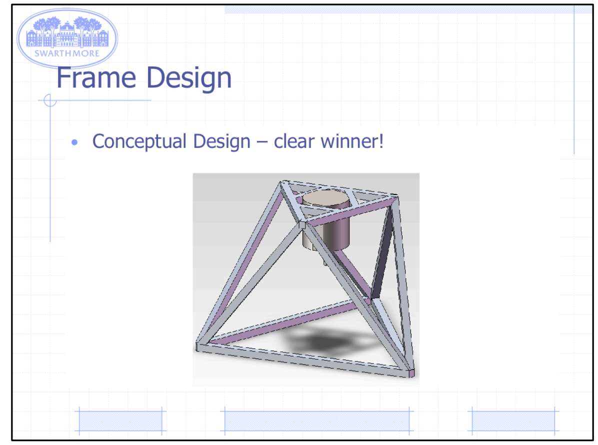
Most milling machines rely on a C-frame design. Although this design allows for easy operator access, all of the frame members are cantilevered off of each other – prone to flexure.




I instead decided to opt for a closed frame. This allows greater flexibility in design, and typically yields better dynamic and static performance. Additionally, since I'm intending for my machine to eventually be CNC controlled, I don't care as much about accessibility.

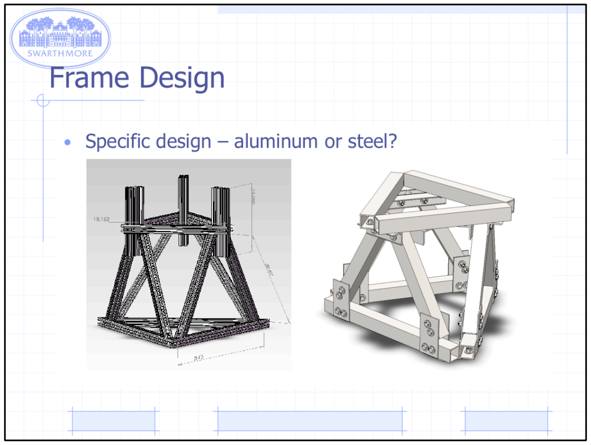
I developed a number of concept "test frames" in Solidworks and simulated them under static loading conditions. Each frame was designed to fit a certain "work volume cube" within it, and used identical frame members to isolate the "innate stiffness" of the design.






A winner quickly emerged – what I'm calling a double tetrahedral frame.

This frame design proved to be an order of magnitude stiffer than the other designs I'd come up with. It also allows one "long" axis – basically, parts can protrude through one of the triangular side frames to allow long parts to be machined.

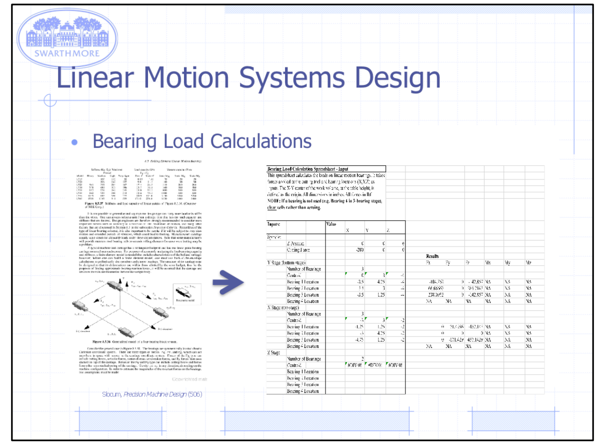



I then moved on to the specific design of the frame.

I developed models of the frame using two different construction materials: 80/20 aluminum extrusion framing, and standard hollow steel section with structural bolted connections.

As you can see, I ultimately elected to go with the steel. My reasons for this included:
• the lower cost of the steel – initial estimates showed it would be significantly less expensive than the aluminum (although this would later prove to not be completely accurate).
• greater dynamic and static performance of the steel. Simulations showed that the steel frame was significantly stiffer than the aluminum, and was also more vibration-resistant due to its greater weight and natural damping characteristics.



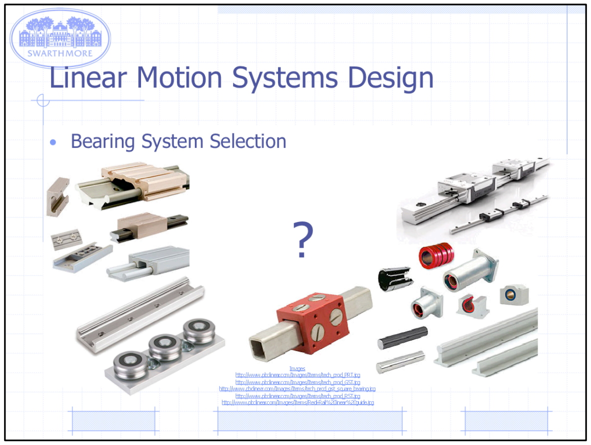



The second major design phase of my project was the design of the linear motion systems – the bits that slide back and forth within the machine.

Although I briefly entertained exploring non-Cartesian motion systems – for example, combined rotary and linear motion systems - I ultimately elected to stick with the tried-and-true stacked linear motion systems for X, Y and Z motion.

Before I could select a bearing system, I needed to know what sort of forces I could expect at my bearings. Working from a derivation by Dr. Alex Slocum, I developed a spreadsheet which would approximate the reaction forces in 4-, 3- and 2-bearing carriage systems given a point load at any point in 3-space.

This spreadsheet not only allowed me to determine what kinds of loads I could expect at my bearings, but also allowed me to evaluate the relative performance and cost tradeoffs between using the different bearing systems – more bearings produces lower loads on individual bearings, but increases cost.

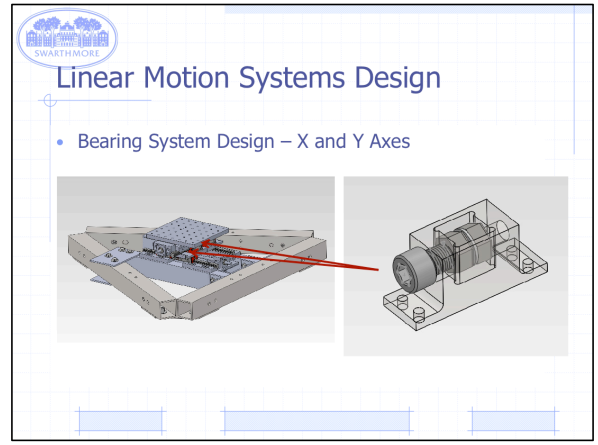



Because of time constraints and manufacturing difficulty, I elected to purchase a premade bearing system rather than design one from scratch.

The variety of bearing systems commercially available is incredible, ranging from simple sliding element systems to “drawer-slide” caster systems to sophisticated recirculating ball-bearing carriage systems.

Ultimately, I selected a recirculating ball-bearing system. These are the standard among both hobbyist and industrial machines: they are extremely stiff, very low friction, and resistant to impact loading/oscillating loads (which frictional bearing systems are not). However, they are highly sensitive to mounting misalignment, and are EXTREMELY expensive.

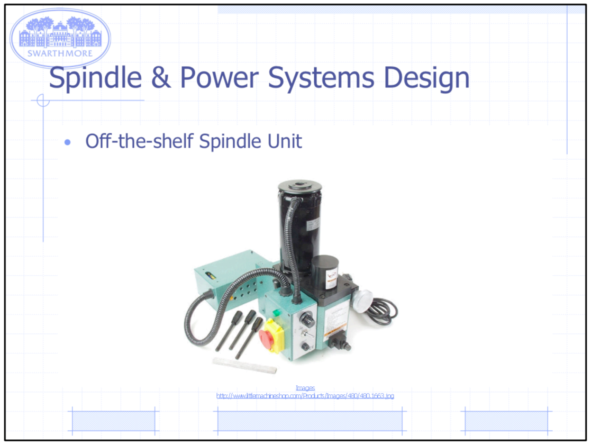





I designed the X and Y bearing systems in Solidworks. To accommodate the high mounting precision requirements of the linear rail system I had selected, all precision components were required to fit within the work volume of the machine – i.e. be no greater than 6” in any direction. Additionally, leveling screws and slots were used to allow for compliance in assembly, to prevent internal strains from being developed by the machine.

I also designed a lead screw drive system based around a 3/8”-10 Acme threaded rod with a backlash-reducing nut system. I elected to use standard-, rather than precision-grade Acme hardware for cost reasons. The lead accuracy – the distance traveled per amount turned – of the precision and standard grades are the same, and the lower quality thread fit of the standard grade thread is accounted for by the backlash-reducing nut.

The lead screws are singly supported, using two angular contact bearings in a DF configuration. This allows for slight angular misalignment, but produces high axial stiffness.



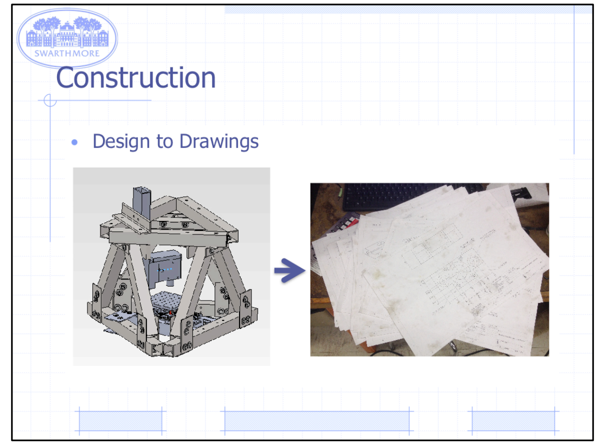

The final design task in this project was the design of the spindle and power systems.

Early on in the project, I investigated a variety of options for the spindle and power system, including off-the-shelf units, engraving spindles, and self-designed spindles. Unfortunately, spindles are among the highest-precision components in a machine tool, and typically are hardened and ground.

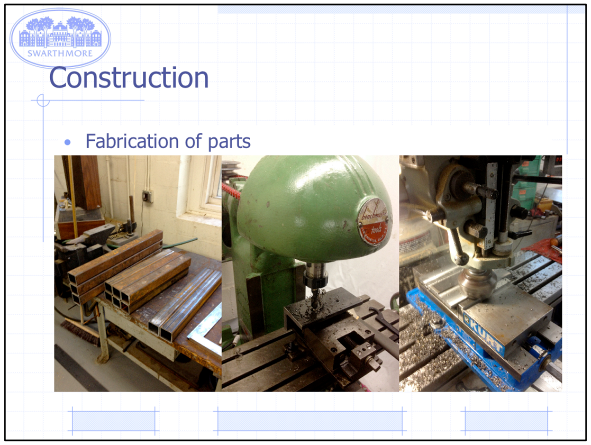
Consequently, I elected to use an off-the-shelf unit. The most cost-effective option I was able to find was a combined spindle and motor unit used in a variety of benchtop milling machines. It incorporates variable speed control and uses R8 collets.

I also selected to use the dovetail-mount column that this spindle unit is designed for, which simplified attachment of the spindle. It incorporates a rack-and-pinion gear giving Z-axis motion.





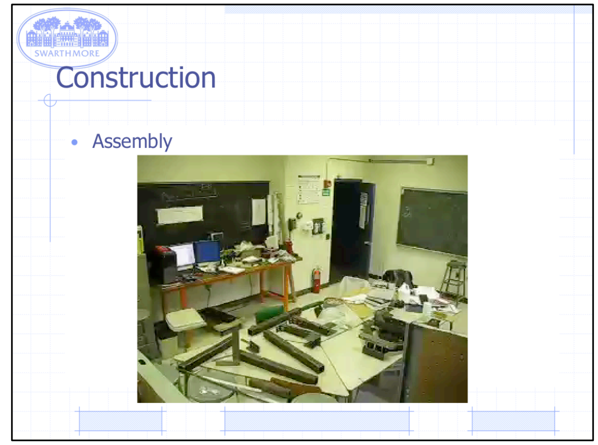

All told, this machine requires 94 machined pieces, 37 of which are unique. I transferred my Solidworks parts to paper drawings, and began machining.




Fabrication took a long, long time. I didn't keep close track of the hours I spent in the shop, but I would estimate it at roughly 200-250 hours of machining time.

All machining was done either in the Swarthmore machine shops, or at my house in Washington, DC. To simplify the fabrication process, I used the full capabilities of the machines I was using – I didn't limit myself to a 6" x 6" x 6" work volume.





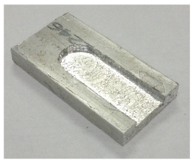

Assembly took surprisingly little time, considering the amount of time required to machine the parts. I completed assembly in a period of roughly 12 hours.

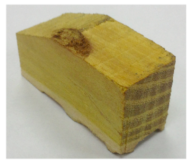
The majority of this time was spent attempting to level the X and Y axes. This proved to be an extremely difficult process, and one which is still not completed to my satisfaction - I'm intending to go back and realign the axes, to make sure that the bearings don't fail.

Assembly was easily completed using basic hand tools – box wrenches, socket wrenches, hex wrenches and hammers. I did use a precision level and square for some alignment tasks – however, these could be replaced with a high-quality combination square or carpenter's level.

## Performance

- Cutting Performance





- Work Volume
  - Much larger – 6” x 6” x 12”

So, does it work?

In short…kinda.

Although no quantitative measurements of cutting performance have been made, the samples I’m passing around now, some of which you can see here demonstrate the machine’s cutting performance.

• The wooden block is osage orange, a particularly hard and fibrous wood. The machine has no problem making cuts in this material.
• The aluminum bar shows the machine’s performance under both end- and side-milling conditions. As you can see, chatter is clearly a serious problem – indeed, the machine was beginning to chatter so seriously it started to loosen some of the screws in the stage. There is believed to be some loose component that is the root source of this chatter – it is being investigated now.
• The stainless steel bar shows that the machine is capable of executing basic drilling operations.

The work volume wound up actually exceeding the specified limit in the Z direction, yielding a total volume of nearly 6” x 6” x 12”



## Performance

- Other Goals
  - Total cost - <$1,100!
    - Including student discounts, tax exempt, etc…
  - Self-replicability – still unclear
    - Further investigation required after machine has been re-aligned.

There are a number of other metrics beyond cutting performance which can be used to evaluate the performance of this machine

• Cost: The total cost for raw materials, fasteners and parts, not including shipping costs or tooling costs, came to approximately $1,100. Additionally, this amount is not reflective of the true cost to the average consumer – many of these items were purchased using educational discounts, or with Swarthmore’s tax-exempt status.

• Self-replicability: With the exception of possibly 2 parts, this machine is theoretically self-replicable – all parts can be machined within its work volume. However, since it has yet to be determined that the machine can mill mild steel with reasonable accuracy, it cannot be said conclusively if the machine is capable of self replication.

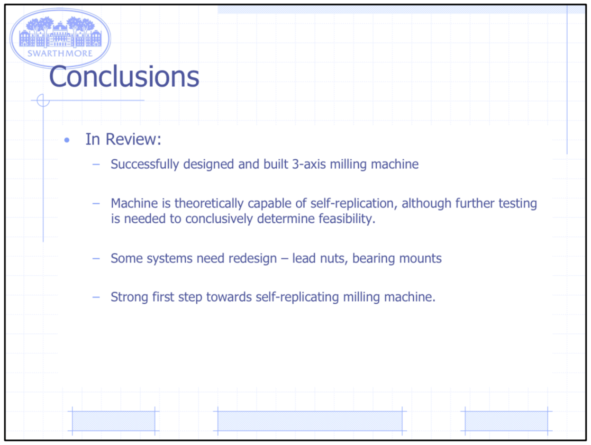
# Conclusions

- Immediate Improvements/Future Work
  - Tighten all bolts
  - Re-aligning XY Carriage (especially Y axis)
  - Redesign lead nuts
    - Use bronze nuts
  - Rebuild spindle (has been dropped on its head, literally)



# Conclusions

- Design Improvements
  - Design spindle, linear motion systems to reduce cost
  - Redesign X axis mounting system to reduce misalignment
  - Redesign Z axis to use custom linear motion system – take better advantage of frame stiffness
  - Develop a better method for aligning/leveling X and Y axes



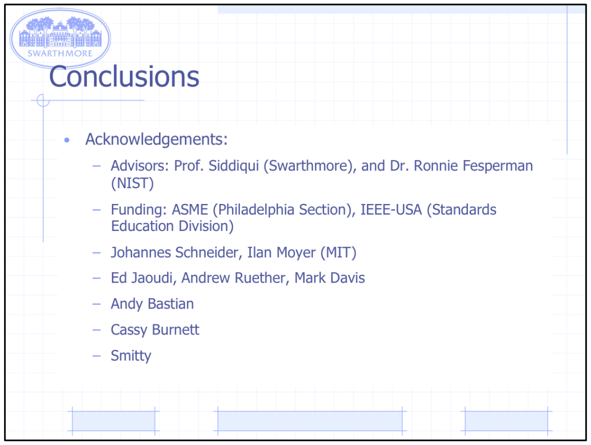

In review, I have:

• successfully designed and built a 3-axis milling machine, which has been demonstrated to be capable of milling and drilling wood and aluminum, although not yet mild steel.

• This machine is theoretically capable of self-replication, but more testing will be needed to conclusively determine this.

• A number of systems within the machine need redesign, but overall, this is a strong first step towards developing a truly self-replicating milling machine.






Finally, before I close, I'd like to thank some of the many people who made this project possible.
• First, I'd like to thank Professor Siddiqui, who was my faculty advisor for this project, as well as Dr. Ronnie Fesperman at the National Institute of Standards and Technology, who also advised me.
• I would also like to thank the Philadelphia Section of ASME as well as IEEE-USA, who generously provided funding for this project.
• I would like to thank Ilan Moyer and Johannes Schneider at MIT for their consultation and for materials they provided.
• I would also like to thank Ed Jaoudi, Andrew Ruether and Mark Davis for technical assistance.
• I would like to thank Andy Bastian for consultation and 3D printing services
• I would like to thank Cassy Burnett for her patience and help
• Finally, but certainly not least of all, I would like to thank Smitty. This machine would not have been built without his unending patience and assistance, and I would have never thought to pursue this project without his introducing me to the machine shop, and teaching me over the past four years.

SWARTHMORE

# Questions?

Works Cited:


- Beer, F, E. Johnston, J. DeWolf, and D. Mazurek. *Mechanics of Materials.* New York, NY: McGraw-Hill Higher Education, 2009.
- Beitz, W., and K.-H. Küttner, . *Dubbel Handbook of Mechanical Engineering.* Translated by M. J. Shields. NY: Springer-Verlag, 1994.
- Budynas, R, and J. K. Nisbett. *Shigley's Mechanical Engineering Design.* Ninth Edition. New York: McGraw-Hill, 2011.
- Industrial Press. *Machinery's Handbook.* 28th. New York: Industrial Press, 2008.
- Ito, Y. *Modular Design for Machine Tools.* NY: McGraw-Hill, 2008.
- Kennametal Corporation. *End Milling Horsepower Calculations.* 2012. http://www.kennametal.com/calculator/end_milling_hp_calculations_in.jhtml (accessed April 12, 2012).
- Lingaiah, K. *Machine Design Databook.* 2nd Edition. NY: McGraw-Hill, 2003.
- Schneider, Johannes. "Mechanical Design of a Desktop Milling Machine for Fabrication in an Introductory Machining Class ." Senior Thesis, Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, 2010.
- Slocum, Alexander H. *Precision Machine Design.* Englewood Cliffs, NJ: Prentice-Hall, 1992.
- Weck, M. *Handbook of Machine Tools.* Translated by H. Bibring. Vols. 1, 2. NY: John Wiley & Sons, 1980.