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14. ABSTRACT

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We also completed and delivered two kits and instructional materials to the install sites. The electronics kit uses the Othermill to make circuit boards, and the mechanics kit uses the MENTOR2 laser cutter to make basic machine

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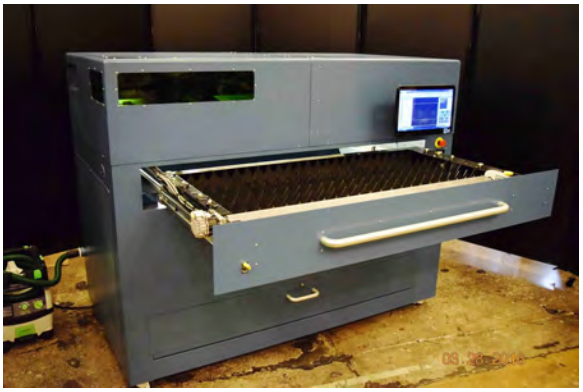
Abstract

The MENTOR2 FieldWork team at Otherlab completed the design, production, and installation of three metal-cutting laser cutters. The completed laser cutters are installed at MARMC in Norfolk, Virginia, at SOCOM in Tampa, Florida, and at Otherlab in San Francisco, California.

We also completed and delivered two kits and instructional materials to the install sites. The electronics kit uses the Othermill to make circuit boards, and the mechanics kit uses the MENTOR2 laser cutter to make basic machine parts. Both kits are designed as introductions to the machines, and to basic principles of electromechanical design.



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Statement of the problem studied

The goal of the DARPA Manufacturing Experimentation and Outreach 2 (MENTOR2) program was to “improve defense readiness by improving the secondary and post-secondary education of those who are trained to utilize, maintain, and adapt high technology systems in low technology environments.” Towards this end, we proposed developing a laser cutter capable of cutting metal that was field deployable, easy to install and use, and low-maintenance. Our approach was to enable more high tech solutions to in-field maintenance.

In addition, MENTOR2 also sought training materials that would turn ordinary military recruits into MacGyver. Towards this end, we developed curriculum materials that could be build with the help of our metal laser cutter, and a small desktop mill for making electronic parts. Combined, our electromechanical introduction was meant to be an integrated solution to part of the problem.

Summary of the most important results

From a machine design point of view, we were able to bend the cost curve of these kinds of machines significantly. By designing to maximize performance while trying to minimize cost, we were able to design a number of components in-house that would have been quite expensive to purchase off the shelf -- in particular, the cutting head and capacitive head sensor for the laser. As predicted, the cost of fiber lasers dropped over the course of this project, which enables future machines to be even more cost effective. We also were able to design demonstration software as proof-of-concept for getting sheet and tube jobs onto the machine.

On the training materials side, we were able to complete kits that introduce a number of important ideas -- both to introduce concepts of engineering, as well as demonstrate some of the construction ideas for building using a desktop mill for circuits and a metal laser cutter for mechanics. Further, we were able to incorporate a few of the design ideas from the laser cutter itself into the curriculum.

What follows is a summary of the design that was completed, broken down by Focus Area and deliverable number from our Statement of Work.

Focus Area 2: Prototyping Tools

A driving use case for our laser cutter is in-field repairs, such as in a portable military shop shown in Figure 1. Our machine is designed to fit into a small container, with its footprint of 74”L x 40”W x 56”H. It runs on a single 110V/20A wall outlet, but is easily converted to 220V for overseas use. For assist gas, it needs only clean (oil-free), dry (moisture-free), 150psi shop air at 3 cubic feet per minute, making it possible to use with an oil-free portable air compressor and dryer. Both the SOCOM and MARMC lasers were installed with such a compressor/dryer setup, while Otherlab uses house air. The diode-based fiber laser has virtually no moving parts, and is very robust. We designed the machine to also be robust and very low maintenance.

Figure 1: Portable military repair shop

The full laser cutting system is comprised of a number of sub-systems. Functionally, they are the cutting head, the X-Y gantry, the rotary, and the enclosing chassis. In addition, there's the electronics, wiring, and power supplies to electrify the machine, as well as the motion control hardware and software to control it. The laser itself is a commercial IPG 150W laser that can be pulsed at 10% duty cycle to 1500W. The laser is produced by a collection of diodes, combined together and delivered via fiber optic cable.

2.1 Cutting Head

An important first step was for us to design our own cutting head, which is itself composed of a number of sub-systems — Figure 2 breaks out the pieces. The QBH connector connects in the laser fiber. The optics first straighten and focus the beam. The capacitive head sensor (CHS) uses the nozzle as one half of a capacitor, and the circuit board sends an electrical signal back to the motion controller. The air is needed because metal laser cutting is really a melt-and-blow process. The entire head is moved up and down by the Z-axis stepper motor.

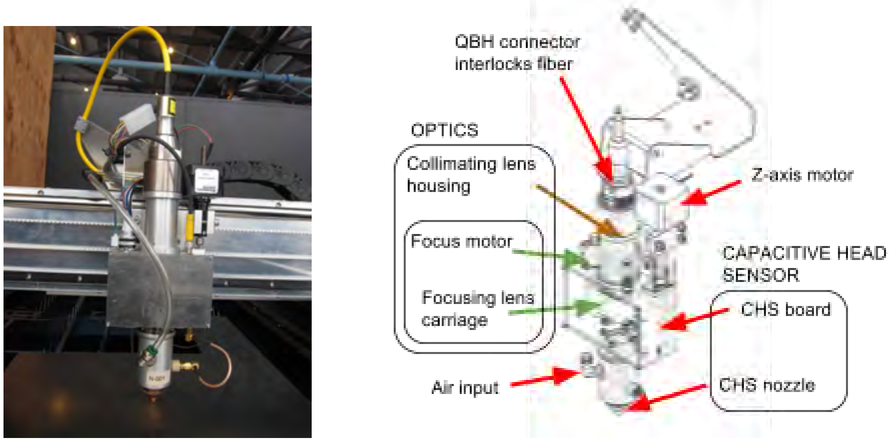


Figure 2: The completed cutting head (left), and the subsystems that comprise it (right).

<u>Optics</u>: In the optic subsystem, the collimator lens straightens the beam out after it leaves the fiber (where it is diverging), and the focusing lens brings it down to a spot. Using a 60mm collimator and 125mm focusing lens, we can expand the 50µm beam coming from the fiber up to 104µm (see Figure 3). We designed for 100µm to balance the need for concentrating the energy from the laser with the need for a wide-enough gap for the air to blow the metal out.

We also designed the focusing lens carriage (identified in Figure 2, and seen in Figure 3) to be motorized, so we could change the focus within the material being cut. For instance, with thicker materials, it makes a difference whether the focus is on the top surface, bottom surface, or middle.

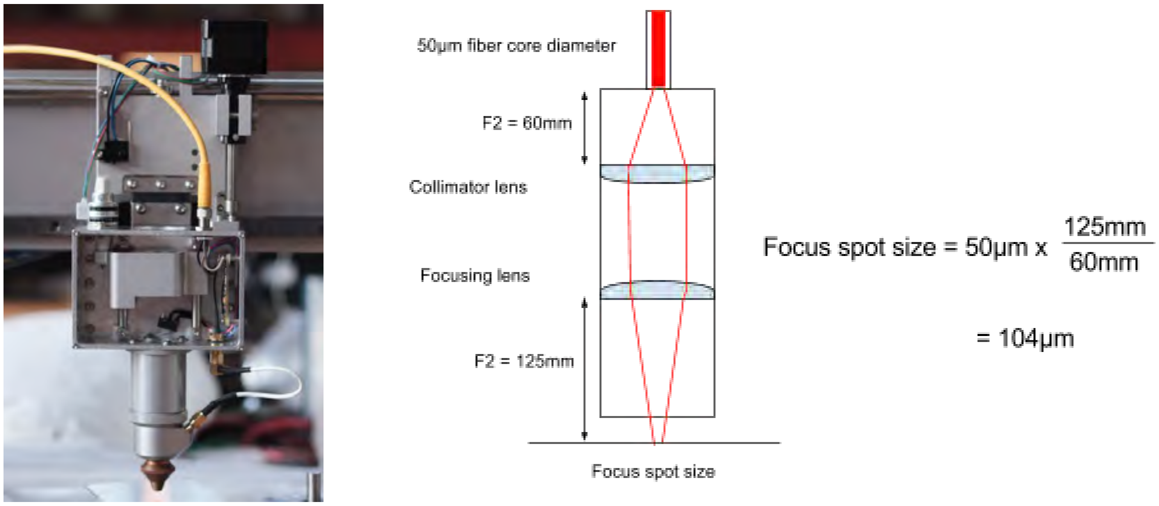


Figure 3: The focusing lens carriage (left), and the optics design (right)

<u>CHS</u>: The CHS uses the nozzle on the cutting head as one plate of a capacitor, and the metal being cut as the other plate (connected through the drawer to ground). A custom circuit measures the capacitance between the nozzle and metal, and sends the signal back to the motion controller to maintain a constant, programmed distance (interpreted as a function of

capacitance). The schematic and subsystems are shown in Figure 5. Each of the small circuit boards are outputs from the Electronics Kit (see 3.2), meant to show how these smaller units can make up a real-world device. The final board is shown in Figure 4.

Figure 4: CHS circuit board, as produced for use in the machines

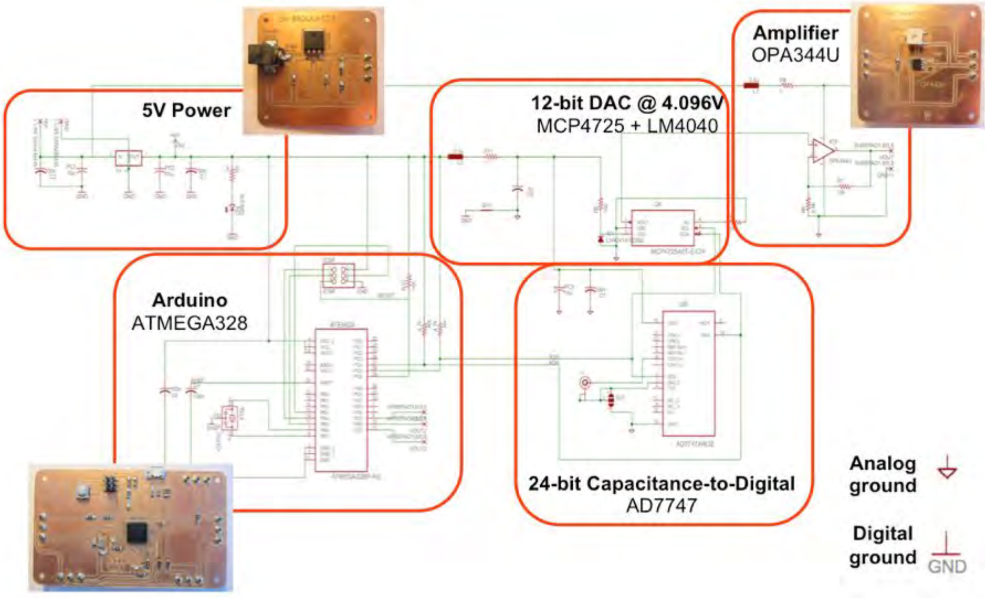


Figure 5: CHS schematic, by subsystem, with teaching boards overlaid

2.2 Two-axis cutter

The two-axis cutter, seen in Figure 6, moves the cutting head along the X-axis (long) and Y-axis (short). The entire Y-axis is cantilevered, meaning it is secured to a linear rail and driven by a motor along the back, while the front is simply supported by a bearing running along a metal dowel. This simplified design reduces the cost of having a second motor to drive the front, without sacrificing accuracy (measured at 0.001”/linear foot, with 0.0005” repeatability).

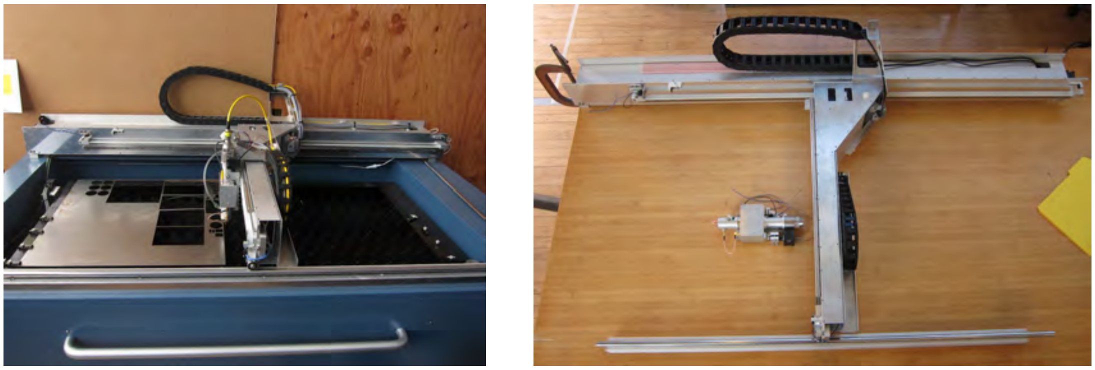


Figure 6: Two-axis cutter, installed (left) and alone (right)

<u>X- and Y-axis motors</u>: The Y-axis is direct driven with a straightforward pulley and timing belt design. The belt starts and ends at the cutting head, and the teeth on the belt fit into grooves in the pulley to eliminate slipping. The motor then can precisely locate the head by moving the belt.

The X-axis is an interesting design, where the belt runs over a pulley attached to the motor, and instead of the belt moving, it is the motor that runs along the belt. This is also a simplifying design, using the timing belt as a track. As a result, both the X-axis and Y-axis motors are located on the cantilevered Y arm, along with the cutting head. This increases the mass of the arm, which we account for in the specification of the X-axis motor.

2.3 Rotary cutter

One of the key features of our machine is the integration of a rotary tube cutter, for both round and square tubes. There are a number of solutions for round tubes, since it is basically just mapping the Y-axis to the angle of the rotary. For square tubes, it is a more complex path to be able to get around the corners as the tube rotates. The rotary is pictured in Figure 7.

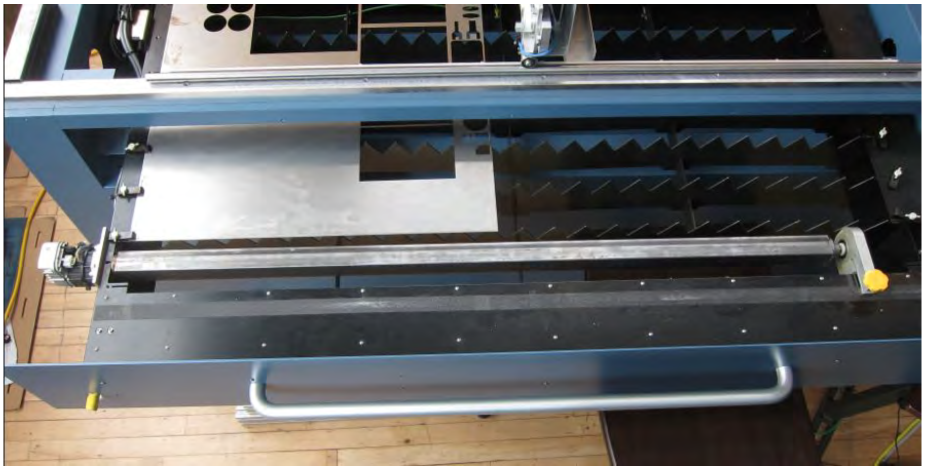


Figure 7: Rotary tube cutter installed in front of drawer

Idler system: Figure 8 shows what is mounted on the underside of the front of the drawer. There is a linear guide that the idler carriage is connected to, along with a rotary encoder for enabling the motion controller to know where the idler is to avoid hitting it. A proximity sensor alerts the machine when the carriage is in the fully retracted position, which is needed when homing the X and Y axes, since the machine doesn't yet know where the axes themselves are.

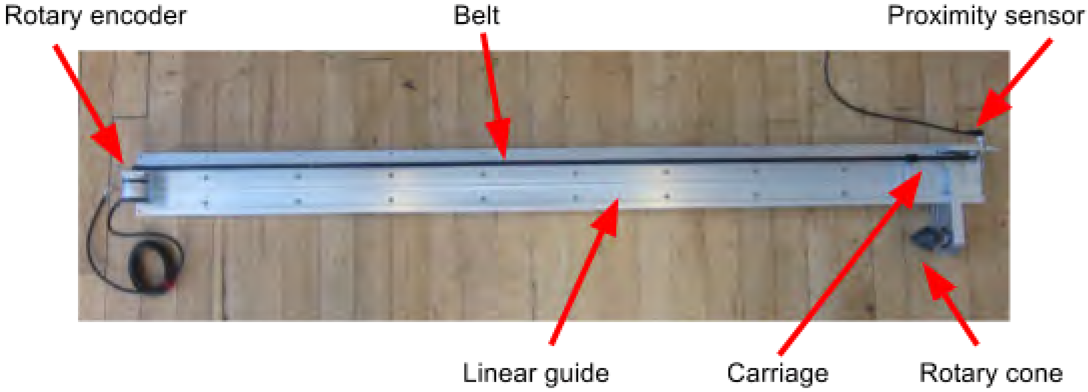


Figure 8: Rotary idler positioning system

Cones: The rotary axis is direct driven by a servo motor, with a support cone attached. The idler also has a support cone, but connected to a bearing on which it spins. The drive cone is grounded to enable the CHS to work. A mounted square tube, and a drawing of the support cone, are pictured in Figure 9.

The drive cone has a "flag" built in that a second proximity sensor can detect for homing. The cone holding part is designed with four symmetric flat sections, to help fixture square tubes. It is not the optimal solution, since a square tube can be poorly seated on either cone, which messes up alignment of the tube to the cutting head. In future revisions, we are investigating a clamping chuck for grabbing the tube from the outside rather than supporting it from the inside.

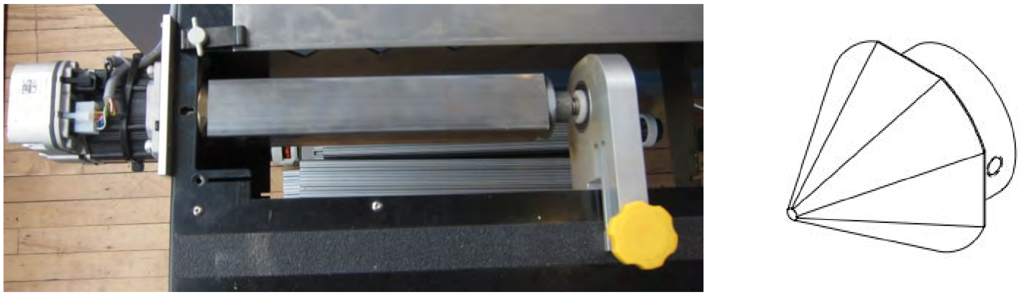


Figure 9: A short square tube mounted in the rotary (left), supported by cones (right)

Tuning: The servo motors can be auto-tuned -- they will run through a sequence of starts and stops and use the feedback from the motor itself to adjust its own settings based on the inertia of the load. Since the rotary handles tubes of different diameters (between 0.5” and 1.5” square or round), and different lengths (up to 50” long), the inertia of the load varies considerably. We were able to manually tune the motors to a reasonable setting so that it works across a wide range of tubes. This was less of a problem on the X and Y axis motors, since their inertia doesn’t change with each job.

Chassis

The chassis is required to house the above subsystems. We designed a Class 1 laser machine, meaning the laser is fully enclosed, with no danger to people during operation. We decided on a drawer-load system towards this end.

Drawer: The bed is 25” x 50”, which is slightly oversized from a 1/4 of a U.S. (imperial) standard 4’x8’ stock material. The oversize is meant to also accommodate a 1/4 of a metric sized 2500mmx1250mm sheet (~98”x49”). The machine is also wired to easily convert to 240V for use in foreign countries. We integrated the rotary into the drawer, as can be seen in Figure 10, making both easy to load.

There is a small design issue with the current drawer. As you can see in the figure, the drawer slides are connected directly to the bed. This means that when the drawer is closed, it is in the position it will stay in during cutting. Unfortunately, it is not 100% repeatable to go back to the exact same position with every drawer open and close. The left drawer slide does lock in and out, and the locking gives somewhat better repeatability (and is also on the side with the cutting bed origin).

To fix this, we could make the bed independent of the drawer, and move it to a known, exactly constrained position before cutting. This could be done with kinematic couplings, which is also one of the activities in the Mechanics Kit (see section 3.1).

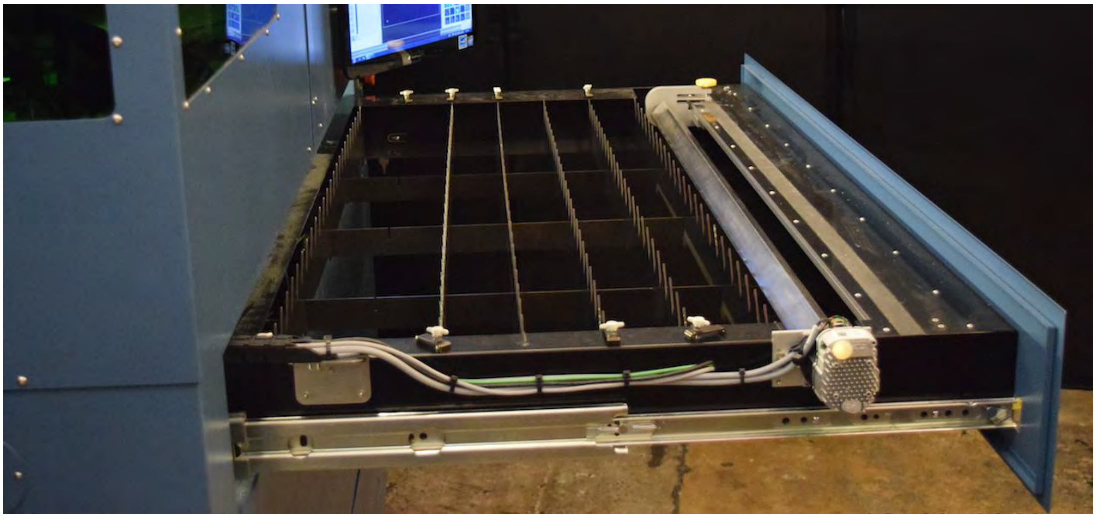


Figure 10: Side-view of drawer with integrated rotary

Laser and Controls

Laser safety interlock: We are using the OEM version of the IPG laser, which means we are responsible for all of the circuitry that prevents the laser from accidentally turning on at any point, and for making sure the Class 1 interlocks are all connected. Figure 11 shows a schematic view of the interlock circuit we designed.

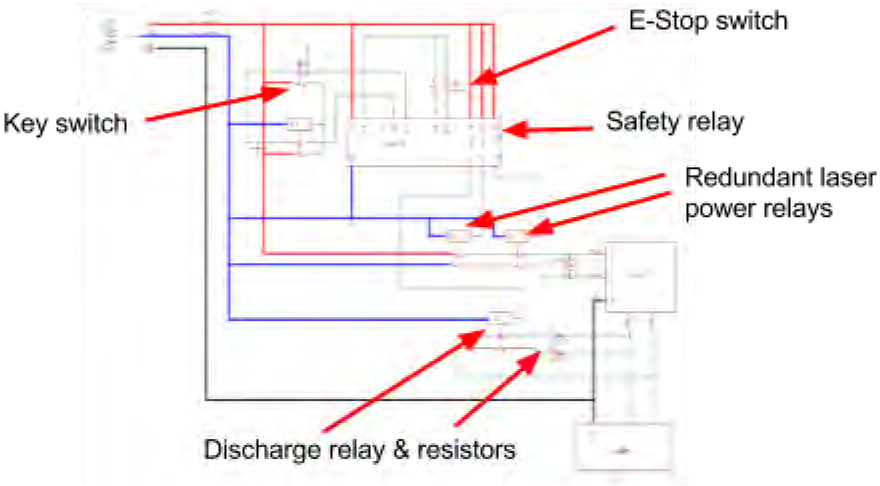


Figure 11: Schematic for laser power safety interlock circuit

The sequence for turning on the machine is to release the E-stop if it’s closed, since the safety relay won’t work with the switch engaged. Then turn on the key switch, which signals to the safety relay to close the redundant laser power relays. The key switch also opens the discharge relay, which is normally closed. When the safety relay turns off, the discharge relay will close, and the discharge resistors will dissipate remaining energy in the laser power supply.

Motion Controller: We decided to use an ExtraTech motion controller, which is an OEM product that reduced our technical risk, after investigating the TinyG open-source controller used in the Othermill. We met with Alden Hart, the force behind TinyG, and explained our needs: a rotary axis, CHS feedback, and “laser power control” to change the laser’s power as the acceleration changes. He recommended against using TinyG.

The Extratech board has a variety of inputs and outputs, and besides running the motors, it also interfaces to the buttons and lights on the machine. It has a direct connection to the laser to control its settings such as frequency and power, as well as to turn it on and off appropriately (the “laser power control” mentioned above).

Extratech also controls the gas regulator. It can control the pressure output between 0 and 130psi. The machine requires 150psi oil-free (“clean) and moisture-free (“dry”) air. It can also use other compressed gases for different cutting properties -- oxygen to cut hotter (and faster and thicker), nitrogen and argon for shielding the cut. An “assist” gas is necessary to blow the melted metal out of the cut, so having choices, including relatively low-cost shop air, is useful, especially for the field.

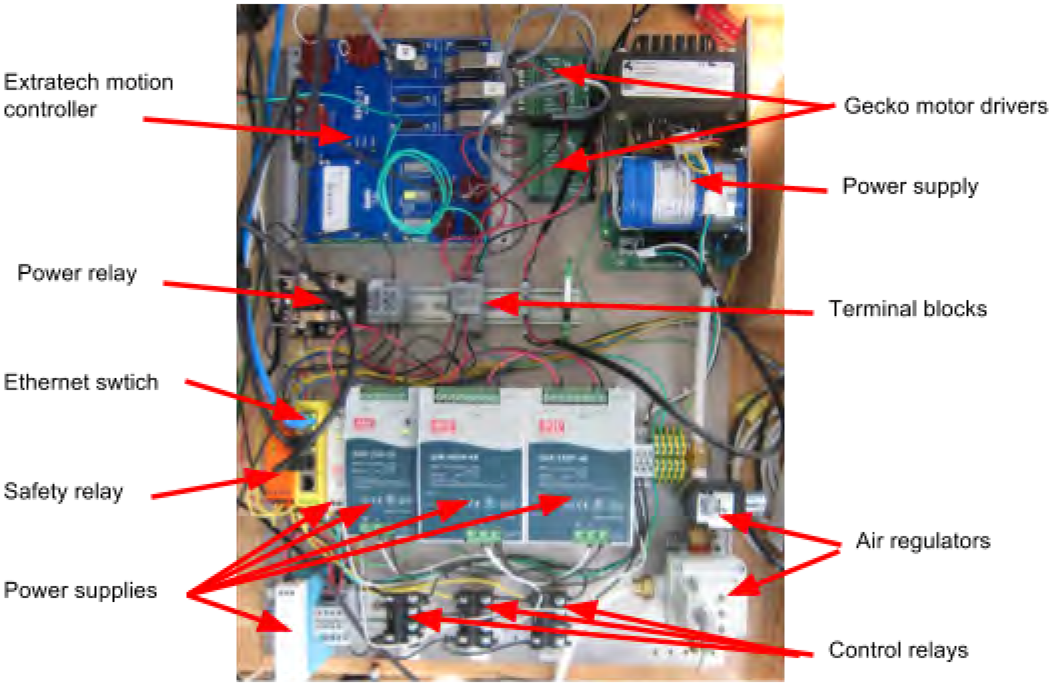


Figure 12: Finished power and control plate

<u>Human Machine interface (HMI)</u>: The HMI is also purchased from Extratech, and allows us to perform basic functions such as homing, jogging the axes, and setting processing parameters for different materials. It also can take in a DXF file and turn it into the cut file needed. It is not traditional G-code, but rather it is written in a dialect of the Forth programming language called Micro Cito, which allows real-time modifications during running. Figure 13 shows a screenshot of the HMI software called Job Manager, and the physical interface we designed with the key switch from the safety power interlock, indicator LEDs, and buttons required to start the job, or pause or stop.

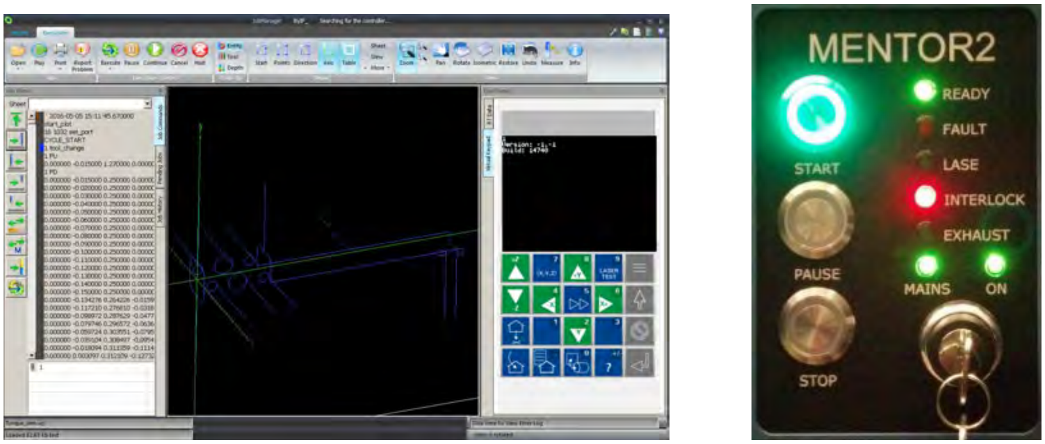


Figure 13: Job Manager software (left), and physical control interface (right)

Software

We were not funded to develop software explicitly. But given that the laser is a computer-controlled machine, at the MENTOR2 kickoff meeting we were given permission to allocate some of our prototype budget towards software development.

TubeCAD: We were able to get a rudimentary CAD program written that allows a 2D sketch to be converted into 3D tubes, with intersections calculated. It also allows the joints to be given tab/slot fixturing connections, and gussets to be automatically added. See Figure 14.

Figure 14: TubeCAD turns a sketch into tubes, with slot/tab connections and gussets optional

The software is functional, but unfortunately rather buggy. It crashes, and often causes Windows to stop responding while calculating some change. The tubes can be exported, but only stacked up to fit on a single tube instead of broken out by individual piece, and the same is true for the gussets. Still, it is a useful demonstration, and performs the intersection calculations as required.

DXFWrapper: Another package we developed allows a flat DXF file to be wrapped around a tube, specified through a series of options in the left sidebar. An imported DXF can be aligned to the 2D representation of the tube, and scaled or stretched to fit, but ideally would match the tube dimensions exactly. A complication can arise for square tubes in that the corner radius of square steel tubes can vary between 1 to 3 times the wall thickness, for both ASTM A500 cold-rolled and A513 hot-rolled square tubes. Since the perimeter of the tube includes this variation, the wrapping of the DXF can also vary greatly between the screen and the tube.

We included a way to change the corner radius in DXFWrapper, but it still requires exact length to be in the DXF, and the matching tube to be loaded for cutting. Ideally, a future version wouldn't have to use unwrapped DXFs at all, relying instead on solid models with parametrically configurable properties like corner radius. A screenshot is in Figure 15.

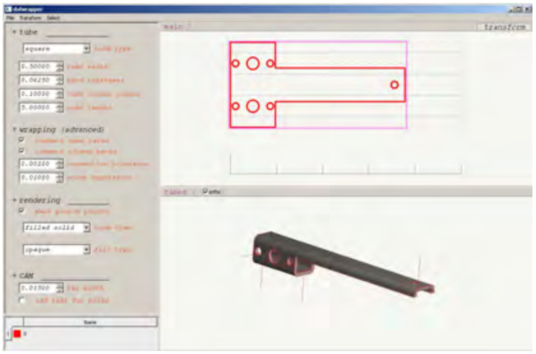


Figure 15: DXFWrapper software wraps a flat DXF file around a tube, and exports a cut file

Software workflow: The overall workflow for machine tools continues to be a pain point for users. For 3D, it usually requires either buying and learning an expensive CAD package. For 2D, it might mean creating an image in a program like Inkscape or DraftSight, which are both free, and not using any geometry that isn't supported by the machine tool. In the future, doing an end-to-end workflow makes sense to try overcoming big compatability issues. We would still want to be able to import standard formats like STEP and DXF, but we would also prefer a simple way to create tube and sketch geometry that can use the laser cutter like a simple printer.

FabCam: As part of a No-Cost-Extension for this project, we did additional development on what we hoped would be a more robust software solution for producing files for the machine. We worked with a vendor on this solution. Unfortunately, their progress has been slower than anticipated, and as of the conclusion of the MENTOR2 contract, finished software has not been completed. We are continuing to work on improving it, and will release it -- and future software upgrades -- to the installed test sites.

Figure 16 shows the work-in-progress version as of March 2017. The software can import a DXF, and allows pieces to be assigned the processes of either Cut, Engrave, or Raster, with the colors corresponding to the process. It can also import a DXF that represents an unwrapped tube, and rewrap it, similar to DXFWrapper. But it is not yet in releasable format.

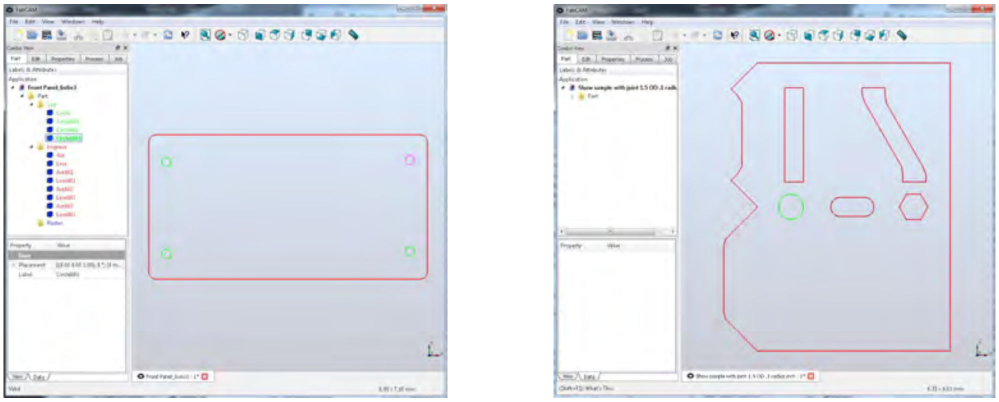


Figure 16: FabCam software as of March 2017. Left: 2D Sheet. Right: 3D Tube (unwrapped).

Improved HMI: Also as part of the No-Cost-Extension, we began work on a new HMI that would run on an embedded Linux machine with a small touchscreen. The goal is to further reduce the cost of the machine by eliminating the need for purchasing Job Manager from Extratech, and also eliminating the need for a full Windows PC to run the machine. Figure 17 shows screenshots.

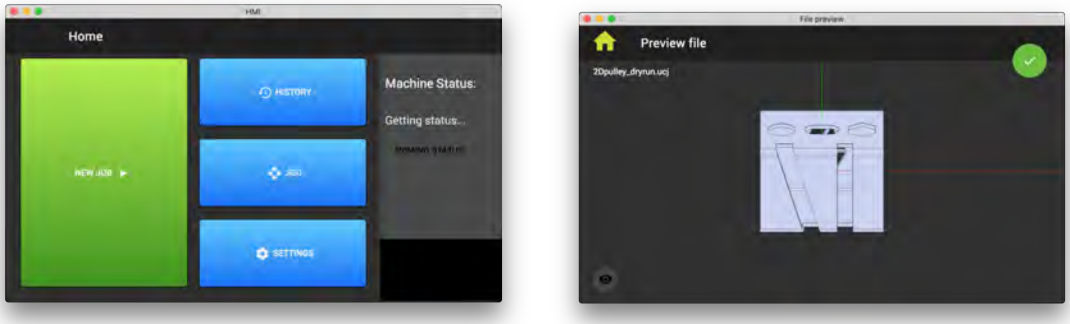


Figure 17: Improved HMI, with home screen (left) and job preview (right).

2.4 Mill

The Othermill has been a commercial product since 2013. We purchased three -- two for our test sites, and one for in-house use. The Navy also ordered several more to put onto vessels in mid-2015. Additional Othermills were purchased to put into three mobile fab-lab trailers in 2016. The mills are precise, easy-to-use thanks in part to the dedicated software (see Software Workflow above), and great at milling small objects, including surface-mount electronics. They are so compact that they fit in tight spaces, such as shown in Figure 18 at MARMC. It is on top of a bookshelf, with the monitor mounted on the wall above. This is a good example of how CNC tools can go mobile.

Figure 18: Othermill installed at MARMC on top of a shelf (about as small a space as possible)

2.5 Support and improvements

The machines were installed at the test sites in May 2016. We went out for installation and training over the course of a week, visiting both sites. We went to SOCOM first, where the machine had been unpacked from the shipping crate seen in Figure 19. They were still in the process of moving into a new building, an old auto repair shop that had never been properly wired with a ground wire on the AC electrical circuit. As a result, they didn't have air conditioning, or their new air compressor up and running. We spent some time making the small air compressor and dryer we supplied work, since the fittings we supplied were not correct. Training then progressed slowly, in part due to the heat of Tampa without air conditioning. Still, by the end of the second day, they felt comfortable with the machine and workflow.

Figure 19: Laser cutter installed at MARMC (left), and the shipping crate at SOCOM (right)

We next went to MARMC. The sailors had previously engaged with the FabLab training program, and were eager to customize their machine. By the end of the first day, they had used the Roland vinyl cutter to create "The Cookie Monster" name and image, seen in Figure 17. The training at MARMC went smoothly, and they made it through the initial box (sheet metal) and swept bend (tube) tutorial projects fairly quickly. They are seen on the MARMC demo table in Figure 18. We did not do any of the mechanical breadboard kit with the sailors, but we did create a reference version for them, seen in the middle of Figure 20.

Figure 20: Products from our instructional materials on the demo table at MARMC

They immediately wanted to start doing their own projects. By the end of the second day, there were two impressive projects completed, both seen in Figure 21. The split keyring was done by a sailor cutting a round tube, an improvement on a keychain we had provided with a USB flash drive that was not as robust as this one. The engraving was done using an existing DXF file that had to be cleaned up for use on our machine. Both of these projects demonstrated the ease of use of the laser cutter and engraver, including the tube cutter.

Figure 21: MARMC custom produced parts – split ring (left) and engraved plaque (right)

Since the May training, several other projects have been completed. One is a switch cover replacement. Through the FabLab training, they had modeled and 3D printed a version, seen in Figure 22. With the laser cutter, the part was redesigned to be cut from a piece of square tubing, making it a potentially longer-term replacement than the plastic. It could also be made from sheet metal and bent into shape. The tube allows multiple copies to be cut from the same tube, in the same cut if desired.

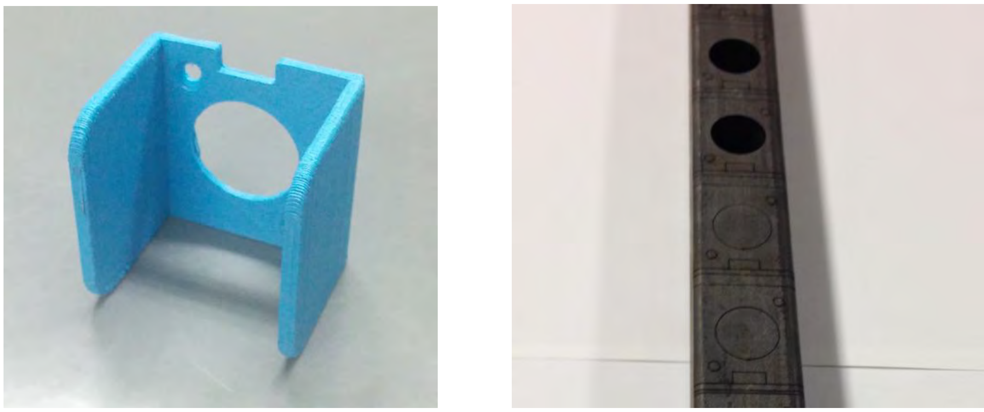


Figure 22: A switch cover 3D printed (left), now cut from square tube (right)

Figure 23 shows additional brackets that have been made from sheet metal. On the left are brackets for restraining the computers kept under the desks in the FabLab. We are not sure what the bracket on the right is for, but was submitted by the FabLab's manager Tim van Arsdale.

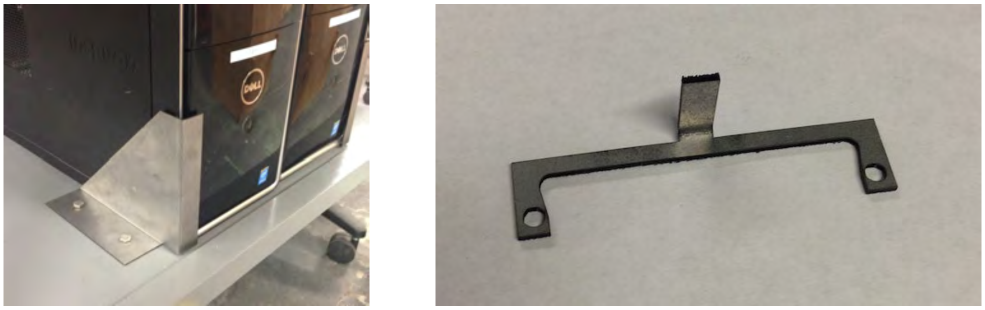


Figure 23: Two more brackets cut and bent at MARMC

Figure 24 is a test cut of the MARMC logo done on the laser cutter, as well as a finished logo plate affixed to a podium created in the MARMC FabLab. While not a repair part, it shows the versatility of the tool, and also the ease of cutting detailed parts at high resolution. The user wrote, “Overall I was very impressed with the accuracy of the small features. I made a smaller version of the logo that is about 6" wide and all of the details cut beautifully.”

Figure 24: Laser cut MARMC logo for a podium

Support updates: While installing the machine at MARMC, a potentially serious issue was discovered. The nozzle is supposed to detect when it touches metal by measuring zero capacitance. We observed that in one instance, the nozzle not only touched metal while moving the Z-axis down, but it kept moving and actually lifted up the cantilevered Y-axis! This had the potential to seriously damage the machine. We weren't sure if the issue was with the nozzle and a bad connection, the settings on the CHS board, or with the Extratech controls. As a result, we mailed a replacement nozzle to both sites, along with a new CHS board, and updates to Extratech to limit the range of motion of the Z-axis.

We also got feedback from MARMC that the raster function wasn't working properly. It wasn't turning on, and it wasn't drawing the image in the place expected. We sent update software, along with instructions, to both sites to implement.

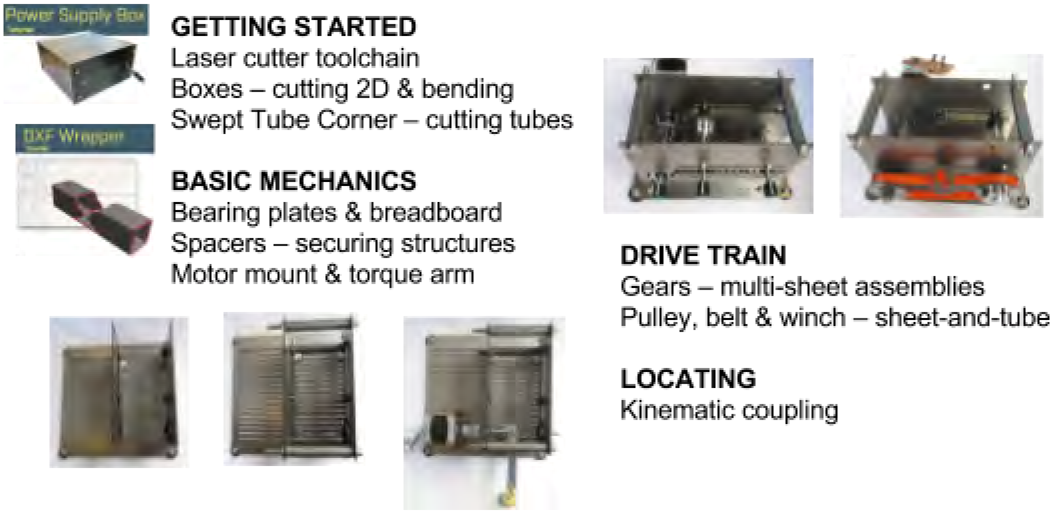
As these test sites continue to use the machine, we will continue to support them for the duration of the contract and beyond as much as possible. We also greatly look forward to seeing what other projects they come up with.

Focus Area 3: Kits and MOOCs

Our charge was to create kits and instructional materials as a MOOC (Massively Open Online Course) to support training of military recruits to become like "MacGuyver," able to engineer a solution to any problem in the field, on the fly. We chose to focus on the basics of mechanics and electronics, to supplement what other groups in the cooperative agreement of MENTOR2 would be providing.

3.1: Mechanics kit

For mechanics, we designed the course with some initial projects to get familiar with sheet and tube cutting, and the workflow in general. We wrote up step-by-step tutorial for making a box out of bent 2D sheets, and a demonstration bend in a square tube that would be too costly to do without some kind of CNC cutter. The covers of these tutorial can be seen in Figure 25, as part of the whole course overview.



GETTING STARTED
Laser cutter toolchain
Boxes – cutting 2D & bending
Swept Tube Corner – cutting tubes

BASIC MECHANICS
Bearing plates & breadboard
Spacers – securing structures
Motor mount & torque arm

DRIVE TRAIN
Gears – multi-sheet assemblies
Pulley, belt & winch – sheet-and-tube

LOCATING
Kinematic coupling

Figure 25: An overview of the mechanics kit projects and lessons

From there, the course has students build up a mechanical breadboard piece by piece, first by cutting the breadboard and bearing plates, then some spacers, a motor mount, torque arm for exploring the torque of the motor, and some transmission elements, and finally a demo kinematic coupling made from a single round tube. The construction techniques for designing with sheets and tubes come largely from an Instructable by Charles Guan, "How to Build Your Everything Really, Really Fast."[1] The mechanical breadboard idea comes from a curriculum that was archived for MENTOR2 called Electromechanical Technology (see section 3.5).

The kits themselves, seen in Figure 26, are a collection of tools and hardware, including a small vise-mounted bending brake, rivet nut installation tool, pliers, and a collection of starter metal sheets and tubes. We delivered the materials to both sites in May, and the instructions in August after finishing the writing and revising of the materials.

Figure 26: Material included in the mechanics kits, as delivered to two test sites

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[1] http://www.instructables.com/id/How-to-Build-your-Everything-Really-Really-Fast/

There are a number of possible future improvements to be made to the mechanics kit. For one, it would be nice to include more “exact constraint” or kinematic design principles into the entire kit, and not just as a demo at the end. Towards that end, the breadboard could be much less flexible than it is now, and pieces could be located more precisely with fine adjustments built in.

It would also be interesting to partner with universities to implement lab-like equipment. For example, an MIT master’s thesis from the early 2000s developed a number of hands-on labs for introductory solid mechanics that could be adapted to the laser cutter.[2] Creating a library of instructional materials for metal-cutting lasers is a long-term goal.

And although CAD design was outside the scope of what we thought we could accomplish with these training materials, it would be useful to curate best-practices for CAD, along the lines of Resilient Modeling Strategy.[3] It would also be nice to incorporate finite element analysis, based on introductory materials such as Cornell’s simulation materials.[4]

3.2: Electronics kit

The electronics kit takes a subsystem approach, grouping essential components that work together instead of focusing on the components much themselves. The boards are single-sided with surface-mount components, to reduce their complexity in making and assembly. It allows us to engrave names, schematic symbols, formulas, and other relevant information onto the copper. Usually when designing a through-hole board for novices, stuffing the board is quite difficult, since there is no guidance as to where the components go from the blank side. In our approach, we also tried to lay out the board so it corresponds to the schematic diagram, making the components recognizable, and the functionality more obvious, in a way it might not be if the board is optimized for space or other non-educational goals.

The outline of the course is given in Figure 27. The boards are electrically connected through stacking pins, usually with a 5V, Ground, and Signal pin present. The course starts with easier but essential boards, such as the 5V regulator for providing power to a circuit without requiring batteries, and light bulbs that play the part of resistance in series and parallel.

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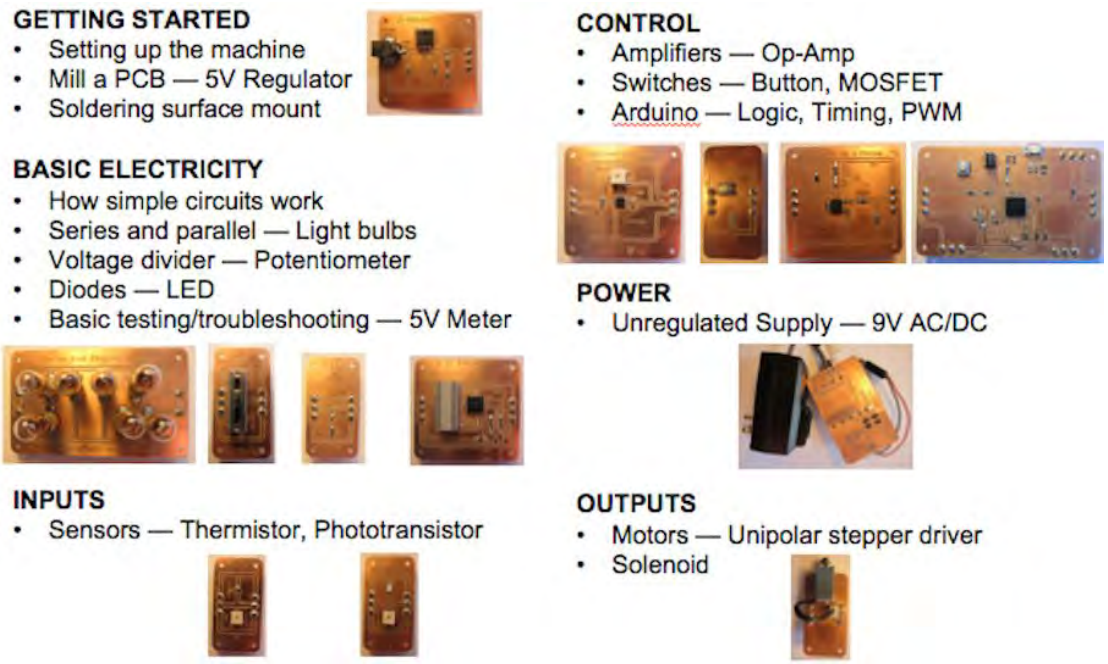
[2] https://dspace.mit.edu/handle/1721.1/16803

[3] http://resilientmodeling.com/

[4] https://confluence.cornell.edu/display/SIMULATION/ANSYS+Learning+Modules



GETTING STARTED
- Setting up the machine
- Mill a PCB — 5V Regulator
- Soldering surface mount

BASIC ELECTRICITY
- How simple circuits work
- Series and parallel — Light bulbs
- Voltage divider — Potentiometer
- Diodes — LED
- Basic testing/troubleshooting — 5V Meter

INPUTS
- Sensors — Thermistor, Phototransistor

CONTROL
- Amplifiers — Op-Amp
- Switches — Button, MOSFET
- Arduino — Logic, Timing, PWM

POWER
- Unregulated Supply — 9V AC/DC

OUTPUTS
- Motors — Unipolar stepper driver
- Solenoid

Figure 27: An overview of the electronics kit projects and lessons

More complex circuits, such as the 5V Meter, require soldering of finer IC pins. The Arduino clone is the most complex and difficult board, but comes towards the end of the boards after a significant amount of soldering practice. The unregulated power supply is the most dangerous, in that it interfaces to mains electricity.

The boards are modeled in part on LittleBits, a commercial toy that has a similar sub-system approach to construction, where boards can be remixed to create new functional systems. It is also based on System Alpha, a 1980s U.K. electronics curriculum that produced similar kinds of boards for teaching electronics.

Figure 28 shows the electronics kits as delivered to the two test sites. it includes all of the necessary parts to build five sets of the boards, on the assumption that some of the boards will be messed up, and that at least one complete set will be obtained from these materials. Additional kits were purchased by the Navy to go on the ships with the Othermills, and to go into the Navy trailers supplied by TechShop.

Figure 28: Material included in the electronics kits, as delivered to two test sites

Videos would make a useful supplement to the course, to show the dynamic nature of electricity. There are some simulation images included in the course materials. These could be used to complement videos of the boards themselves. Additional boards would also be useful for expanding the range of systems that can be made.

3.3: Case studies

We incorporated a few “case study” ideas into the electronics and mechanics kit instructions. For example, during the discussion of the belts and pulleys in the mechanics kit, a section describes the similarity to the belt and pulley system on the Y-axis, as seen in Figure 29.

Figure 29: Example from the mechanics kit instructions relating concepts to the machine

As part of archiving, we put the Engineering Case Library from the American Association of Engineering Education (ASEE) onto the Internet Archive. See Section 3.5 for more info.

3.4: MOOC integration

Initially our goal was to host a MOOC on mooc.org, a site that was to be hosted by Google, supporting an instance of edX for anyone to use. That was announced in 2013, and as of today, it is still not a functional platform. We investigated other platforms, such as Canvas, which is what SRI chose after having trouble installing their own local instance of edX. All materials were segmented for MOOC loading. DARPA suggested that, given the distribution of machines by the Navy into austere environments such as ships and trailers, as well as the non-Internet connected MARMC base, that it would make more sense to just have the materials on a CD instead of an online platform.

For assessment, we created a series of questions to be asked after training, mostly related to content ideas from the courses. These questions were approved by the Georgia Tech IRB process, as well as the Army review process, and were ready for our training in May. At the training sites, since SOCOM wasn't ready with their power, and MARMC was more interested in trying their own projects, we decided to not give the questions, and instead have appended them to the instructional materials.

3.5: Archiving

Four educational resources were identified, collected, and archived on the Internet Archive. The Naval Personnel (NAVPERS) instructional manuals from the 20th century are all public domain, since they were developed by the U.S. Government. The Electromechanical Technology Series was also in the public domain, as per the copyright statement in each book. Permission was obtained to archive the Engineering Case Library, originally developed at Stanford and taken over by the American Society for Engineering Education. And a somewhat long permission process ended with full permission to archive the Physics of Technology series, which was developed by a number of different groups in the 1970s.

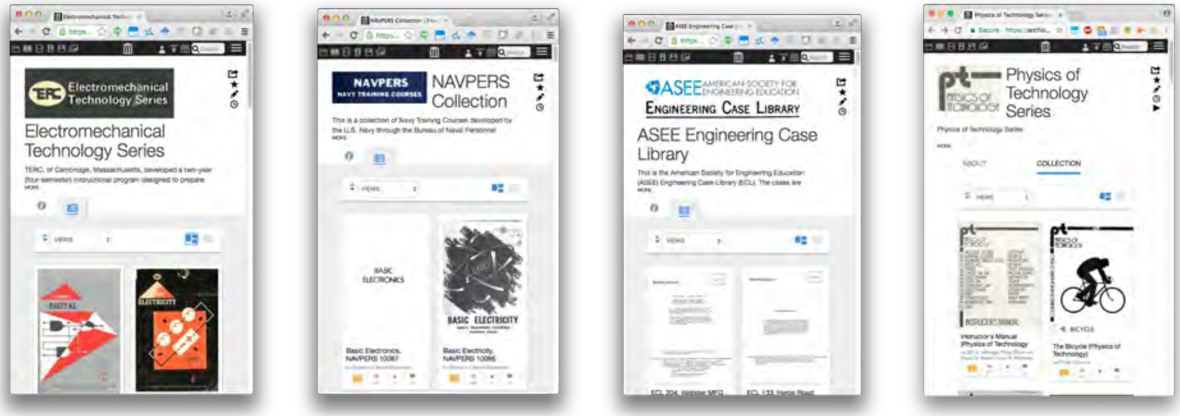


Figure 30: Collection pages for the archived materials on the Internet Archive

All four collections are now uploaded to the Internet Archive, as can be seen in Figure 30. As of June 2017 the items in the three collections besides Physics of Technology (recently uploaded) have been viewed over 70,000 times:

- 18,949 for Electromechanical Technology[5]
- 27,089 for NAVPERS[6]
- 24,739 for the ASEE Engineering Case Library[7]
- No data is available yet for Physics of Technology[8]

These kinds of materials helped with development of the educational materials for this project, and will continue to support interested people well into the future. The appendix has a full list of the titles and URLs for all documents archived.

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[5] https://archive.org/details/electromechtech&tab=about
[6] https://archive.org/details/navpers&tab=about
[7] https://archive.org/details/engineeringcaselibraryasee&tab=about
[8] https://archive.org/details/physicsoftechnology&tab=about

Appendix / Bibliography

Physics of Technology Series

Instructor's Manual https://archive.org/details/PhysicsOfTechnologyInstructorsManual
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Automobile Collisions. : https://archive.org/details/AutomobileCollisions
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The Multimeter□ https://archive.org/details/TheMultimeter
Photodetectors□ https://archive.org/details/Photodetectors
The Pile Driver□ https://archive.org/details/ThePileDriver
The Power Transistor https://archive.org/details/ThePowerTransistor
The Pressure Cooker□ https://archive.org/details/ThePressureCooker
The Slide Projector□ https://archive.org/details/TheSlideProjector
The Solenoid□ https://archive.org/details/TheSolenoid
The Spectrophotometer□ https://archive.org/details/TheSpectrophotometer
The Stroboscope□ https://archive.org/details/TheStroboscope
The Toaster https://archive.org/details/TheToaster
The Torque Wrench https://archive.org/details/TheTorqueWrench
The Transformer   https://archive.org/details/TheTransformer
The Bicycle https://archive.org/details/TheBicycle

Electromechanical Technology Series

Electromechanisms / Motor Controls:
https://archive.org/details/ElectromechanismsMotorControls
Electromechanisms / Devices: https://archive.org/details/ElectromechanismsDevices
Mechanisms / Drives: https://archive.org/details/MechanismsDrives
Mechanisms / Linkages: https://archive.org/details/MechanismsLinkages
Unified Physics / Fluids: https://archive.org/details/UnifiedPhysicsFluids
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Electromechanisms / Automatic Controls:
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NAVPERS

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ECL 80: Fracture Of A Marine Gear: https://archive.org/details/ECL-80
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ECL 87: Design Of A Creme Lite Mixer: https://archive.org/details/ECL-87
ECL 88: A Case Study Designing A Transformer: https://archive.org/details/ECL-88
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ECL 91: The Support And Alignment Of The Stanford Linear Accelerator: https://archive.org/details/ECL-91
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