Overview

2.72: Elements of Machine Design **is a hands-on machine design course which makes heavy use of a hardware project to achieve many of its unique learning objectives. In light of the COVID-19 pandemic and shift to remote learning, the standard hardware project is no longer tenable. The 2.72 course staff have developed an alternative project which achieves most of the hardware-based learning objectives while being compatible with the remote-learning model. The proposed project uses hardware "kits," sent individually to students, to achieve these goals. This document summarizes the new remote-learning project, including the contents of the hardware kits, planned learning milestones, and mitigations for potential safety concerns.**

2.72 via Remote, Hardware-Based Learning

2.72 teaches machine design competency in six areas:

1. Analysis
2. Deterministic design
3. Fabrication
4. Machine characterization
5. Machine optimization/calibration
6. Coupled relationships between areas 1-5.

These learning objectives are usually met via a hardware project (desktop lathe) with strict performance requirements, as hardware is necessary to develop these real-world competencies. The recent COVID-19 pandemic has necessitated a shift in MIT pedagogy which most dramatically impacts hardware-based courses. The at-home hardware project proposed herein aims to preserve the hands-on practical learning component which has become a core feature of 2.72.

Students would receive a hardware kit which includes:
1. An inexpensive, hobby-grade CNC engraving machine
2. A metrology kit including various measurement tools
3. Raw material for use with the CNC engraver

The unit cost per kit, including shipping, is ~$225 per student (26 kits total).
The total cost falls within the remaining allocated course budget.

Learning objectives (4-6) will be achieved via a set of modules planned around the kit hardware. Modules will include: assembly and basic operation of the CNC engraver, calculations to predict performance, the planning and execution of characterization experiments to measure real-world capabilities and limitations (of both the measurement tools and the engraver itself), analysis of experimental results, and recommendations for potential design improvements.

The course will culminate with two technical reports addressing the CNC engraver's structural characteristics (rigidity, vibrations, etc) and the machine's repeatability performance (precision). Results from the modules will be incorporated here. Students will summarize their overall results including discussions of the machine's claimed vs. measured capabilities, calibration and setup improvements that can be made without the need for any new parts, and justification of proposed design changes / improvements which would utilize new or different parts.

The staff understands that there is some inherent risk involved in sending hardware to students' homes; thus we have all tested the machine, identified potential risks, and generated countermeasures for potential safety risks. The details of the testing, risks, and countermeasures are covered in the Safety Considerations section.

VEVOR 3018 CNC Engraver

Source: https://www.amazon.com/dp/B08425BG33/

2.72 Hardware Kit Contents

Below is a complete list of the materials that would be sent to each students, along with a link to our purchasing spreadsheet which has links to each specific item

Item Description	Justification and Planned Use
CNC Engraver Kit	A low-cost CNC engraving kit to be used as the basis for several activities
Fish Scale (Force Gauge)	Apply known loads to the machine. Used in conjunction with displacement sensor for stiffness characterization
String	To be used with fish scale - tie a loop around machine component, and pull
Dial Test Indicator (DTI) with mount	Enables measurement of fine motion errors and small displacements, e.g.: runout, backlash, min. motion increment, deflection, axis alignment, etc
Safety Shield	To be securely placed in front of the machine to protect the user from any potential flying debris
Safety Glasses	Eye protection
Plastic Calipers	General purpose measurement of lengths, depths, and offsets
Raw Material: Plastic	Acrylic sheets for engraving - 4"x6"x2mm (5 pack for running multiple tests)
Link to full list of parts & materials: Link to parts list for 2.72 send-home kits	

Safety Considerations

The 2.72 course staff has assessed the potential safety risks inherent in sending this hardware to students' homes; during spring break the staff ordered, assembled, and stress-tested these machines, and for each possible safety risk identified, we have developed one or more countermeasures for risk mitigation.

General precautions and considerations

There exist inherent concerns about having students potentially working alone with these desktop CNC engravers; the staff reasoned that the working alone policy has in the past been relaxed for CNC machines which pose minimal safety risk, specifically 3D printers – this machine is in essence a hobby 3D printer with a different tool mounted on the head (an engraving head instead of a plastic extruder). In the course of our testing we have deemed that this machine is as low-risk (lower in some regards) than the desktop 3D printers which are ubiquitous around campus.

As a general safety precaution, the kit includes safety glasses, and a large sheet of 1/32" polycarbonate (1 foot by 2 foot) sheet to be used as a safety shield in front of the machine. Students will be instructed to bend the shield such that it wraps fully around the front of the machine. Furthermore, each student must complete the online EHS course ***"EHS00485w - Introduction to Shop Safety Rules"*** and send confirmation of completion to course staff before being greenlit to receive a machine kit. This web course teaches how to safely work in and around machines in the various machine shops and makerspaces on campus. Although this project is remote, the course content regarding safety precautions and personal protective equipment make it highly relevant to this at-home project. As a further general precaution, we are asking students if they feel uncomfortable with setting up and running the machine, the staff is able to walk them through the process via teleconference software.

The staff has created a checklist that the students are to keep with the machine, to be referenced when powering up the machine, when beginning an engraving session, and when powering down the machine. This is similar to the practice around campus of keeping a sheet at every machine with a checklist for basic safe machine operation and tips for ensuring successful operation. The checklist is as follows:

- Startup procedure
  - Safety glasses on
  - Check for trip hazards
  - Check that engraving table is clear
  - Check for entanglement hazards - all hair tied back, hoodie strings tucked in
- Before beginning an engraving session
  - Check that safety shield is in place
  - All others without PPE must clear the room
  - Check that workmaterial is clamped snugly in place
  - Check that engraving tool is held firmly in place
  - Run the cut "in air" first by shifting Z upwards by 6 mm
  - Double-check toolpaths - is the minimum Z move appropriate?
  - Double-check path home - is the toolpath starting from the correct place?
- Shutdown procedure
  - Move toolheard clear of table; allow about 25-50 mm of Z clearance, position head roughly in the center of the work volume
  - Power down the control board
  - Unplug the power transformer

Specific potential safety hazards

In the course of testing the machine at our homes over spring break, we identified several potential safety hazards that require countermeasures:

- Pinch points
- High spindle speeds and vibrations
- Potential for flying debris

In addition, several of our concerns were deemed to be non-issues after stress testing

- Electrical hazards and power draw
- Securing the machine
- Debris build-up

Details and countermeasures are as follows:

1. Potential Pinch Points

This machine is driven by leadscrews and therefore presents the possibility (however unlikely) that fingers could get caught between a solid point on the machine and a leadscrew-driven moving component. **To mitigate this risk, we are first disallowing students to physically interact with the machine in any way while it is running. As a further precaution, we require that students implement a torque limit on each of the leadscrew motors such that all motions could be safely stopped by hand (i.e. the machine cannot overpower its operator).** This is accomplished by physically adjusting a potentiometer on the motor control board (meaning, the torque limit cannot be inadvertently overridden in software). This low torque limit permits the machine to perform its engraving functions while remaining "stoppable" by the user.

2. Vibrations and High Spindle Speeds

The engraver, as designed, may demonstrate excessive vibrations when operated near its maximum spindle speed (10,000 RPM). Although it has not been observed in the staff's testing, such vibrations could potentially shake parts loose and fling them away from the machine. **To mitigate this risk:**

- **Maximum spindle speed will be reduced to 2,000 RPM (down from 10,000 RPM). This is enforced via a machine configuration file provided by course staff.**
- **The provided polycarbonate shield must be curved as instructed and placed in front of the machine**
- **The user must wear safety glasses at all times when working on the machine**.
- **If others are present in the room (e.g. interested parents), they must wear safety glasses and must remain a generous distance away from both the machine and its operator.**
- **Persons under 18 years of age may not be present in the room at any time while the machine is connected to wall power.**

3. Potential for flying debris

The potential for flying debris is present in any machine that exerts forces to perform its function - an engraver encounters very low forces compared to a traditional cutting process. To minimize the forces involved, **we are restricting the students to only cut acrylic that we send as part of the kit**. Despite this, there still exists the possibility of a student machine user potentially crashing the machine due to a bad setup and sending debris flying. We mitigate this risk at multiple levels:

1. The “pre-flight” checks included in the checklist we’re asking the students to run through before doing any engraving
2. The motor torques are being limited, making it less likely that a crash will actually break a tool
3. We require the students to have the polycarbonate sheet safety shield in place along with safety glasses on

Minor issues

Several issues that we deemed to be non-issues are described as follows:

- Electrical hazards and power draw
  The machine plugs into a standard 120 V outlet via a 120 W charger similar to what would be used for a laptop. During stress testing one of our staff plugged in the transformer into a standard 6-outlet surge protector that was already full of other standard household office electrical equipment (lamp, router, printer, laptop, monitor, etc) and did not observe any ill effects
- Securing the machine
  During stress testing we ran the machine at the highest spindle RPMs, and despite uncomfortable levels of vibration, we did not notice the machine being able to shift around; the machine’s weight was enough to hold it in place. Combined with the fact that the staff is limiting the spindle speed to a fifth of its maximum value, we deem this not to be a problem.
- Debris build-up
  Engraving produces dust; clean up can be performed with a brush and dustpan or a vacuum.

Conclusions

Thank you for taking the time to review this document. We expect the safety review may be an iterative process as this is the first time 2.72 is being attempted in an at-home format. Please email questions or concerns to the course TAs:

Aaron Ramirez (aeram00@mit.edu)
Charlie Wheeler (wheelerc@mit.edu)