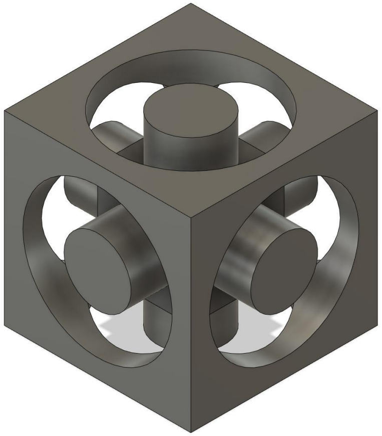
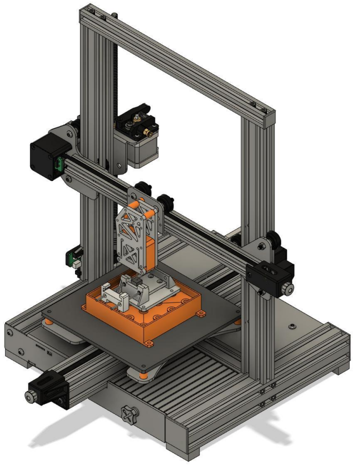
Democratization of Metal Fabrication Through a Novel Electrochemical Machining Process

Engineering: Electrical, Mechanical and Robotics

Logan Brown, Grade 11





ABSTRACT

Metal parts are the foundation of modern technology. Unfortunately, machining, the primary process used to manufacture metal parts, is difficult and costly, especially for high-strength metals and complex shapes.

To make machining more cost-effective, I created a **novel 3-axis CNC machine** that utilizes electricity and saltwater to dissolve away material in a process called electrochemical machining (ECM). This process involves **no cutting forces**, and therefore does not need the same level of strength and rigidity as a conventional CNC machine. Furthermore, the ECM process exhibits **no tool wear**, allowing tools to be used indefinitely without being replaced, leading to **reduced tooling costs**. My machine is **10 times cheaper** than the least expensive conventional machines.

Since the mechanical properties of the material being machined have no effect on the ECM process, it can make parts out of almost **any conductive material,** even materials that are extremely difficult or impossible to machine conventionally, like hardened steel, tungsten carbide, and nickel-based superalloys. This process can make use of **extremely small tools** like **needles** and **wires** to make fine parts that would be destroyed by the forces and tool wear involved in other machining processes.

My ECM machine can produce complex parts out of carbon steel with tolerances within 0.2mm. My machine also **completely recycles** its electrolyte using a **novel filter design** that costs **less than twenty dollars** and has **no moving parts**, which is not possible using existing techniques. This makes the machine more **sustainable** and **environmentally friendly** by reducing waste produced.

INTRODUCTION

One of the most important processes in manufacturing is machining. Machining is a process where material is progressively removed from a workpiece to form it into a desired shape. Machined parts are found everywhere, and form the basis of all industries. The process typically used to machine parts, known as conventional machining, consists of the mechanical removal of material by cutting off pieces of the material using a sharp object moving at high speed. Because conventional machines have to withstand the forces involved in mechanical material removal, there are strict limitations on their minimum size and cost. The cheapest machines available capable of cutting soft metals like aluminum can only cut relatively simple shapes and cost $3,000 - $10,000. Machines that can cut harder materials and more exotic shapes are significantly more expensive. The prohibitively high cost of conventional machining restricts access to machining at multiple levels, ranging from members of the general public trying to make consumer-level items, to companies and researchers attempting to do aerospace research.

Fortunately, there are alternative processes to remove material non-mechanically, thereby lowering cost and increasing capability. One such process is electrochemical machining (“ECM”). When two pieces of metal are placed in a conductive solution, and a voltage is applied between them, a current will flow, causing the surface of the anode (positive electrode) to disintegrate in a process known as anodic dissolution. Electrochemical machining utilizes localized anodic dissolution to remove material. This process can machine almost any conductive material with no cutting forces and very little heat. Commercially, ECM is used to make medical and aerospace parts, but these machines are extremely expensive ($800k+), and require a custom tool for every part to be machined.

My project is a desktop sized ECM machine that uses a small tool moving in three axes. This allows for arbitrary parts to be created using a single universal tool or set of tools rather than a custom tool for every desired part. The machine can cut carbon steel at depths upwards of 4mm, and with a tolerance of 0.01-0.4mm depending on the dimension and operation. As part of my development of this machine, I designed a custom control board PCB, designed and manufactured a peristaltic pump and, created a novel filtration system capable of continuously removing waste from the electrolyte stream. I also wrote my own firmware to control the entire system.

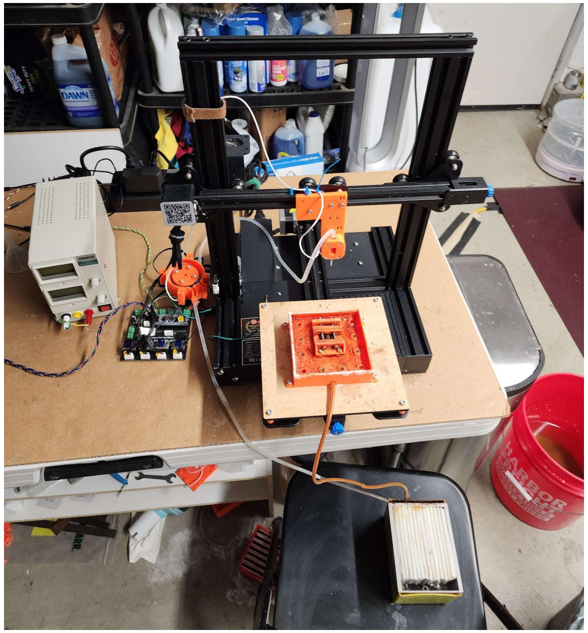
MATERIALS

Materials

- Lead screw driven linear actuator
- Stand alone stepper motor driver
- Arduino nano
- Ender 3 V2 for Gantry
- Custom PCB Main board
- Peristaltic Pump
- Silicone tubing
- Custom 3d printed parts
- Custom laser cut parts
- Low carbon steel stock
- Sodium Bicarbonate
- Sodium Chloride
- Distilled Water

Equipment

- Laptop (for CAD, programming, and operating the machine)
- 3D printer for parts manufacture
- Glowforge Laser Cutter for parts manufacture



Machine setup

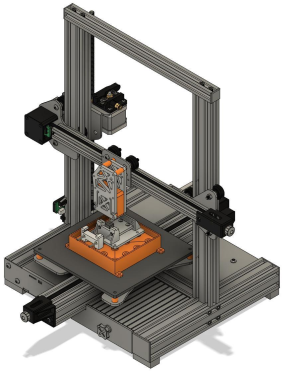
Programming

ENGINEERING PROCESS

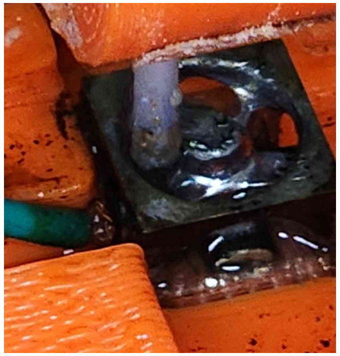
System Overview

The system consists of 4 primary sections:

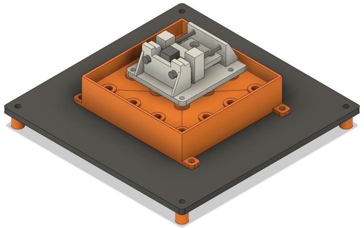
- **Machine**
- **Pump**
- **Filtration**
- **Control system**



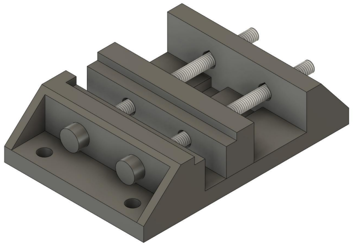
The machine



Machining in progress



Electrolyte tray with work holding vise

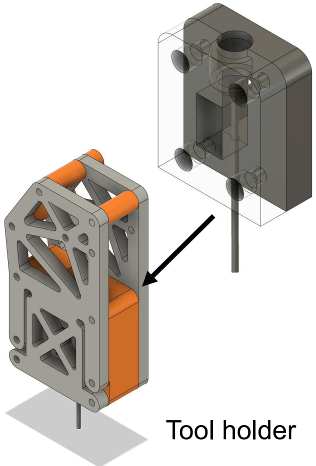


Custom work holding vise

The machine is the device that holds and cuts (machines) the material, consisting of:

- **The gantry from an Ender 3 V2 3D printer.**
- **A custom 3D printed work holding and electrolyte collecting tray.**
- **A 3D printed tool holder.**
- **The tool.**

The tool is a flat hollow stainless steel needle inside a PTFE tube for insulation. This insulation prevents over machining by the sides of the tool as it goes into the material. During operation, a voltage is applied across the interelectrode gap, causing a current to flow and material to be removed. The control system uses the gantry to move the end of the tool in the desired path. This rapidly produces metal hydroxides which can bind to the electrodes preventing further machining. Electrolyte is pumped through the needle into the interelectrode gap flushing away these waste products. The contaminated electrolyte flows into the work tray and drains into the filter. The dirty electrolyte passes through the filter producing clean electrolyte, and the metal hydroxide contaminates are left inside of the filter. The clean electrolyte is then pumped back through the machine and the cycle repeats.



Tool holder

ENGINEERING PROCESS (Con'd)

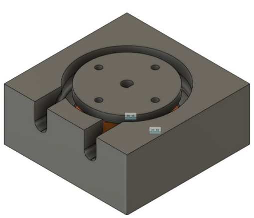
Pump

A critical component of the ECM machine is the electrolyte pump. Existing pumps are expensive and difficult to modify and did not meet design requirements.

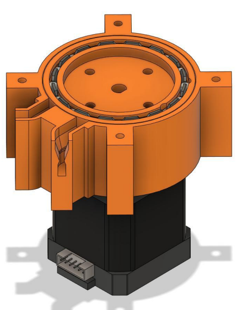
- Pump must withstand corrosive electrolyte.
- Easy to control flow rate or pressure in software.
- Achieve high pressure to drive electrolyte through a small needle.
- Inexpensive to produce and maintain.
- Easy to modify and change properties.

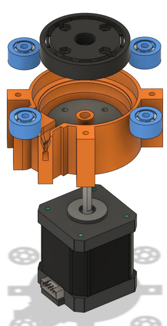
I designed and built my own peristaltic pump. More than 10 iterations were needed to meet all design criteria.

Final Pump Design



Early Pump Iteration



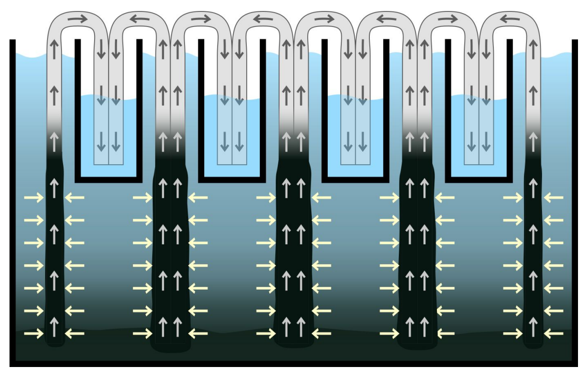


Final Pump Design Exploded View

Filtration

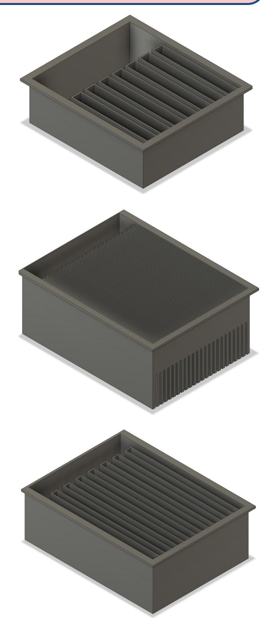
ECM uses electrolyte at a rapid rate which cannot be reused without filtration. Iron hydroxide slurry also passes through and/or clogs most filters, making filtration difficult. To solve this, I created a filtration system that can continuously filter electrolyte slurry without clogging.

- Continuous filtering of electrolyte slurry without clogging.
- High flow rate to supply machine continuously. (16 l/h)
- Easy to clean and maintain.
- Inexpensive to produce, operate, and replace. (< 20$)
- Has no moving parts.



Electrolyte filtering diagram

My filtration system uses capillary action to siphon clean electrolyte out of a large waste container leaving behind insoluble impurities. The filter consists of a filtrate bin and a waste bin. The filtrate bin has an array of siphons allowing resulting in a large filtration surface area.



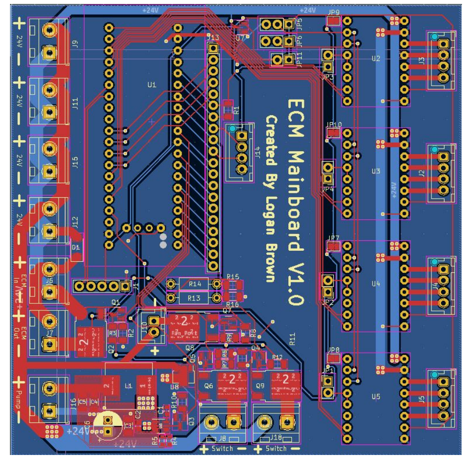
Filter design iterations

ENGINEERING PROCESS (Con'd)

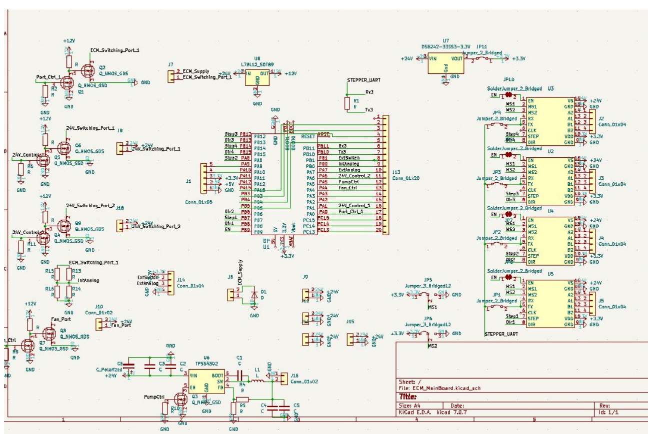
Control System

Repurposing a 3D printer control board was impractical due to a lack of programming access to some ports on the microcontroller. Because of this, I designed my own control board PCB using KiCAD.

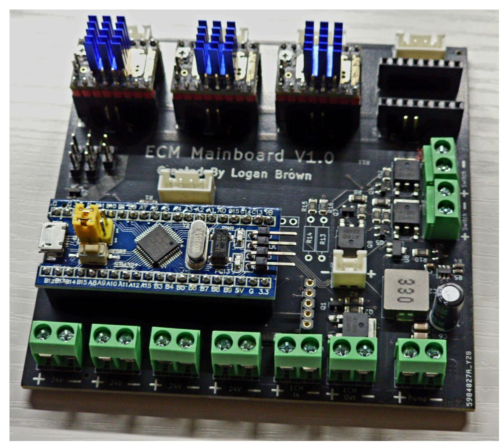
- Has most of the features present on existing control board.
- Added swappable microcontroller board
- Added swappable stepper motors drivers.
- Added electronics for toggling power to the interelectrode gap
- Added voltage sensing for conductive homing.



Custom PCB control board design



Schematic for the custom control board



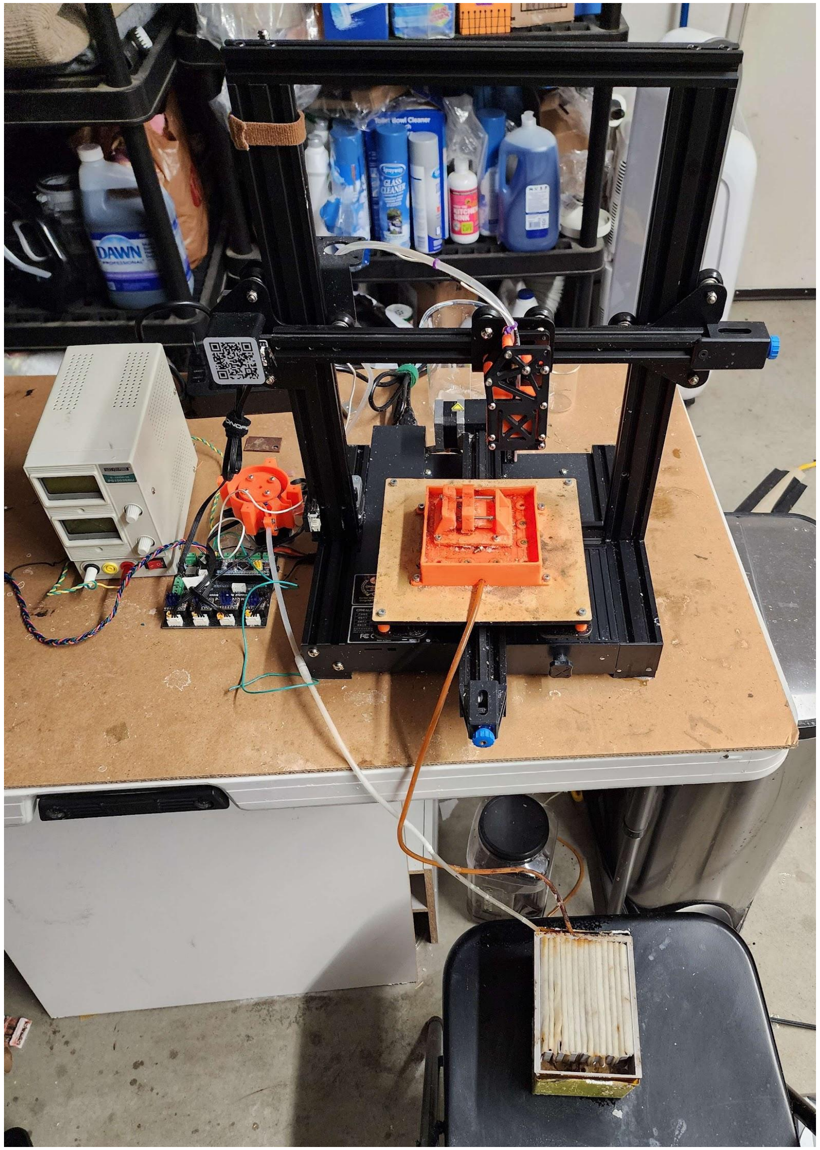
Final Assembled Board

Machining process (Firmware)

1. The tool moves down slowly until it makes contact with the workpiece. On contact a complete circuit is detected by the microcontroller using circuitry on the control board. This process is known as conductive homing.
2. The tool then traces the cutting path. If it makes contact with the surface, it moves up. This ensures the tool is at the highest point of the surface.
3. The tool then moves up slightly to provide a small gap between the workpiece and the electrode.
4. Power is applied and the tool follows the path again, with electrolyte flowing. This removes a thin layer of material along the path.
5. This process is repeated until the desired depth into the material is reached.

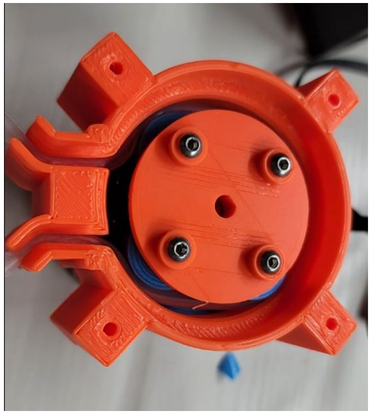
RESULTS (Machine)

Final Machine

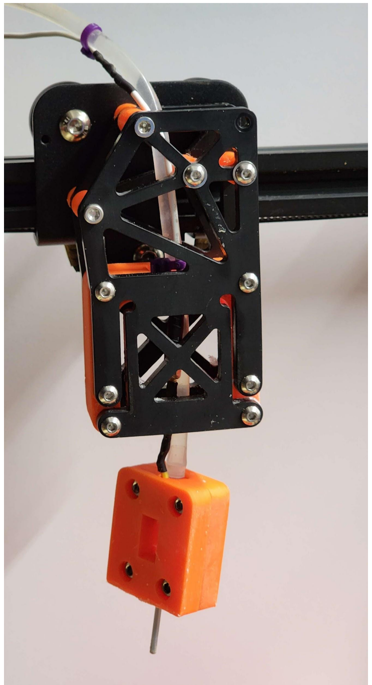


Final Filter Design

Assembled Pump



Tool Holder



RESULTS (Machining)

Final Production Part

Process Parameters

Voltage: 15.8V max
Current: 3A max

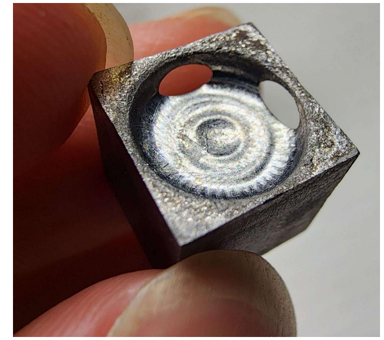
Target Interelectrode gap: 50µm
Feed Rate: 1.5625 mm/s

Tool diameter (without insulator): 1.65 mm
Tool diameter (with insulator): 2.00 mm

Electrolyte concentration: 5.13 M NaCl
Maximum Pump Flow Rate: 266 mL / min
Maximum Filtration Rate: Testing limited by maximum pump speed; at least 266 mL / min

Material Removal Rate

Predicted MMR: 2.2 mm^3 / (A min)
Predicted Peak MMR: 6.6 mm^3 / min
Actual MMR: 1.6 mm^3 / min
Mean Current (from MMR): 730 mA



Machining Test

Target diameter: 8.50 mm
Actual diameter:
8.52 mm - 8.80 mm
Note: Hole is tapered

Target depth: 1.7 mm
Actual depth (center): 1.7 mm
Actual depth (edge): 1.62 mm

Volume: 99 mm^3
Machining time: 60 min

Surface Finishing Test

Cutting results progression

DISCUSSION

- The machine can successfully produce high precision steel parts with tolerances within 0.3 mm. This is comparable to the tolerances achieved with a comparable FDM 3D printer.
- The machining process does not apply any cutting forces to the part or tool meaning that intricate parts can be machined without a risk of the part or tool being destroyed by the cutting forces.
- At a price of around **$300**, the machine is approximately **10X less expensive** than the least expensive conventional machines capable of machining aluminum let alone steel.
- The machine is capable of **completely recycling** its electrolyte using a filter that **costs less than $20** and has **no moving parts**, which is not possible using current techniques. This makes the machine more more sustainable and environmentally friendly while still remaining accessible at a small scale.

CONCLUSION

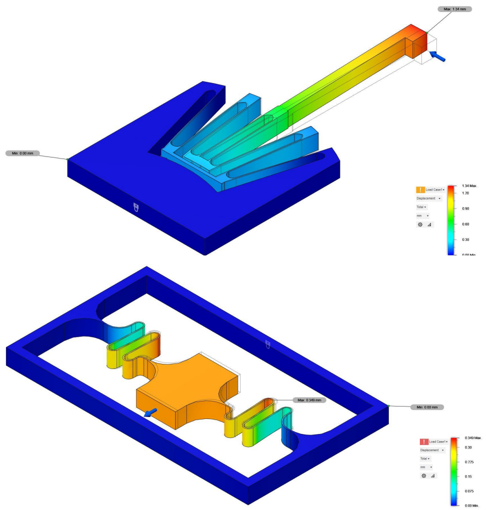
Future Improvements

This project has significant room for future improvement. Below is a list of some ways the project can be improved in the future

- Increase maximum voltage and current of power supply to improve speed
- Increase size of the filter for higher flow rate through the system
- Increase the maximum flow rate through the pump to use bigger tools
- Add temperature control to the electrolyte system to increase machining rate and repeatability
- Redesign the tool holder to allow easy tool swapping
- Create larger tools for a higher material removal rate
- Create a wire based tool to make thin cuts quickly and precisely
- Add more axes to the machine to make more complex parts
- Add additional failsafes to detect tool crashes, electrical shorting, and other faults
- Create a pulsed power supply to enable PECM to improve dimensional accuracy
- Try using a sodium nitrate based electrolyte to improve dimensional accuracy
- Redesign work holder to improve work holding accuracy

Applications

- Production of replacement parts, particularly in developing or underdeveloped countries where replacements aren’t readily available.
- Production of parts to create industrial infrastructure.
- Prototyping parts that need high thermal or mechanical strength.
    - Internal combustion engine
      Jet and rocket engine research
    - Other aerospace components
- Production of medical equipment
- Space colonization
    - Low mass and no consumables
- Production of delicate metal flexures and tools.



delicate metal flexure designs

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