Mechatronics and Robotics Engineering Technology

ROBT 4491: Mechatronics Project

Final Project Report: Servo-Controlled 3D Printer

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Acknowledgments

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ABSTRACT

This project involved the implementation of Teknic ClearPath CPM-SDSK-2310P-EQN servo motors and a Duet 2 ethernet control board to create a 3D printer using a CoreXY kinematic system. The project was requested by Stephen McMillan, Program Head of Manufacturing Technology at BCIT.

The main structural components, as well as some electrical components, were sourced from an existing CoreXY frame from a previous mechanical engineering project. These components included the frame, with Y and Z axis limit switches; the aluminum CoreXY gantry system without belts; the Z axis, driven by a traditional Nema17 stepper motor and gearbox; a PanelDue touchscreen interface; and the 120V AC bed heater, interfaced to the controlboard via a solid-state relay.

The scope of this project was for a team of two mechatronics students to research and design a system to interface the ClearPath servos with the existing control board; additionally, several mechanical components of the printer, such as the CoreXY belt system, needed to be repaired in order to get the machine running again. Once operational, the high precision and torque of the ClearPath servos was expected to achieve a high level of print quality and maintain accelerations of 1g – approximately 9810 mm/s^2.

Before interfacing the motors with the full system, a single ClearPath servo was tested on a linear test axis, to represent a single axis of a simple 3D printer. To start, this motor was controlled over USB through Teknic's ClearPath MSP software, where the motor ran through an automatic tuning program to "learn" about the system it was attached to. Following tuning, the motor was able to be jogged along the axis at specified speeds, and it would display information such as velocity, acceleration, and positioning error on a mechanical oscilloscope interface within the software.

At the same time as the initial motor tests, research was done on the Duet 2 Ethernet control board and the best way to interface it with the motors. It was found that external motor drivers 10 and 11 could be configured within the Duet firmware to output step, direction, and enable signals at logic signal levels of 3.3V. These were the exact signals required for external operation of the ClearPath servos; however, the servos required logic levels of 5-24V.

To solve this problem, an external I/O level shifter PCB was designed. This board contained six basic MOSFET amplifier circuits: one amplifier for each step, direction, and enable signal across the two external motor drivers. These amplifiers took in the 3.3V signals from the Duet driver pins and amplified them up to a 24V level, which was provided by an "always on" fan header on the Duet.

The Duet was then interfaced to the ClearPath I/O pins through the amplifier PCB via a 10-pin ribbon cable from the Duet, and a Molex Mini-fit Jr cable to the ClearPath motor. G-Code commands were then sent over USB to the Duet, which were converted to the appropriate signals to control the ClearPath servo. This test was successful in achieving the desired 1g of acceleration, but failed to produce smooth motion due to a conflict between the autotuning procedure and a belt deformation on the axis.

Two of the ClearPath motors were then mounted to the full system with a 3D-printed mount designed in CAD. A new carriage plate to mount the hotend, X axis limit switch, and attach to the belt system was waterjet-cut out of 1/4" aluminum for rigidity. New belts were then added to the gantry system to enable motion. After interfacing all required subsystems to the Duet board, control was tested through the Duet Web Interface (DWI).

To successfully print at high speeds and accelerations, a strong cooling system was needed to ensure plastic was fully cooled before a layer was finished. It was suggested by Stephen McMillan that a compressed air cooling system should be implemented. Stephen provided a 3D-printed air duct system that attaches to the hotend. The cooling system regulates compressed air down to between 15-40 psi,

and transmits it to the duct system via 1/4" pneumatic tubing. Flow control is currently controlled manually by the operator through an on/off valve, and a regulator.

Performance of the printer was measured through visual and dimensional evaluation of several test prints, including a calibration cube, a 3D benchy, and a spiralized vase. The calibration cube helped to determine the correct steps/mm for each of the printer axes, resulting in around 319 steps/mm for X and Y axes, and 8000 steps/mm for the Z axis. The printer was found to be accurate within approximately 0.1 mm. The 3D benchy and spiralized vase prints helped to evaluate cooling performance, which was able to successfully keep up with the print speeds. Depending on the size of the print, it was found that setting the air pressure to about 30 psi after the first couple of layers was optimal.

At the end of testing, the printer was found to have the following specifications:

- 50000 mm/s^2 acceleration on travel.
- 10000 mm/s^2 acceleration while printing.
- 500 mm/s maximum travel velocity.
- 250 mm/s maximum print velocity.
- 319 pulses/mm of resolution on the X and Y axis.
- 8000 pulses/mm of resolution on the Z axis.
- 300 x 300 x 300 mm^3 build volume.

Going forward, the 3D printer will be returned to the posession of the Mechanical Engineering department under the care of Stephen McMillan. The printer will likely be provided to mechanical and mechatronics programs as a capstone project where further upgrades will be performed. Some ideas for future upgrades and work include the following:

- Replace CoreXY drive with a crossed-gantry drive.
- Automated compressed air control from the Duet.
- Replace the Z axis with a more stable solution to mitigate vibration of the print bed.
- Tool changing or multi-extruder capability.
- IMU on gantry/tool with Klipper or future ReRap firmware for full closed loop position control.
- Standalone network connection over BCIT Ethernet so you don’t need to connect directly to a laptop.

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1 INTRODUCTION

This project was requested by Stephen McMillan during the spring 2022 semester at BCIT as a capstone project available for the Mechatronics department. The plan was to have two Mechatronics students build and interface electrical components to create a 3D printer with improved acceleration and quality over a previous model. It was suggested that this team would determine the best method to interface Teknic ClearPath servo motors with an existing control board to achieve the improved performance. An arbitrary goal of 1g (9810 mm/s^2) of acceleration was chosen as a target to help measure performance.

This document covers an overview of the system as well as the subsystems, which are the computer, Duet 2 Ethernet control board, user interface, drive system, homing system, hotend, heated bed, and part cooling. Following the system overview, this document discusses how each system was implemented and verified through the timeline of the project, and discusses evaluation of performance as a whole.

2 SYSTEM OVERVIEW

The 3D printer in this project implements an old CoreXY frame. This frame has been refitted by Adam Rogers and Mason Kury from the Mechatronics program. The new printer uses two ClearPath CPM-SDSK-2310P-EQN servo motors controlled by a Duet 2 Ethernet board to drive the CoreXY frame. The high-performance servos and Revo Hemera extruder are used to push the system to its limits.

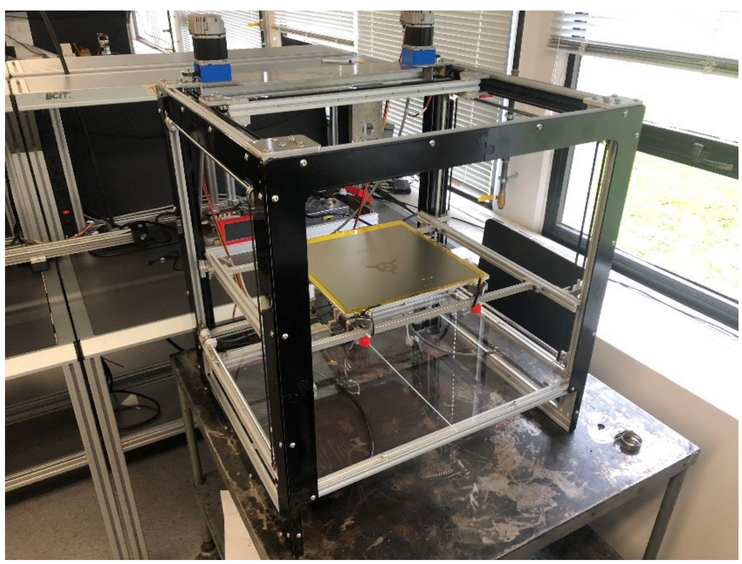

Figure 1: Full picture of the 3D printer.

The previous student 3D printer project used stepper motors with a CoreXY system, causing the printer to be slow, imprecise, and lacking position feedback. By implementing a solution using ClearPath servos that have incredible precision and torque the limits, the speed and quality of prints can be greatly increased. Due to the closed-loop design of servo motors, this also prevents the printer from losing track of position; this saves prints from the potential of failure due to layer-shifting. The system was originally desired to operate with 1g (9810 mm/s^2) of acceleration, but can currently operate at over 5g.

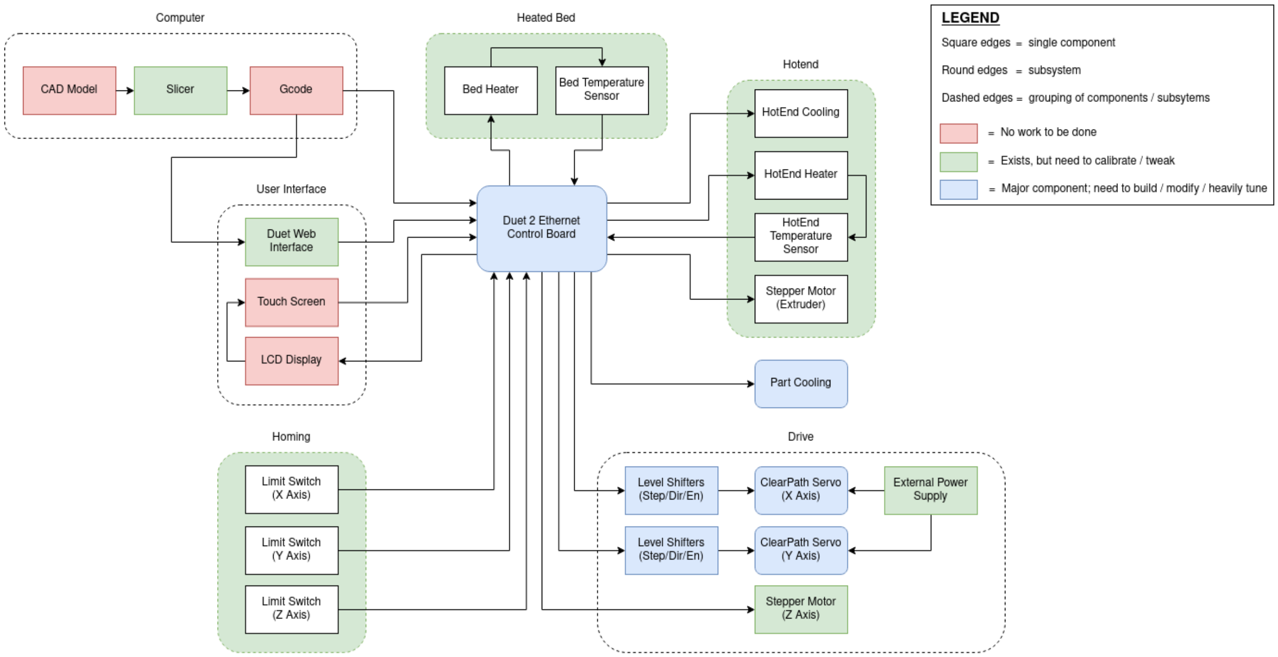

Figure 2: Block Diagram of 3D printer System, showing scope of work for the project

The system overview will cover the following subsystems in detail:

- Computer
- Duet 2 Ethernet control board
- Drive
- Homing
- Hot End
- Heated Bed
- Part Cooling

2.1 COMPUTER

A normal desktop computer serves mainly to slice 3D CAD models into G-Code, but also provides a medium for the web portion of the user interface. The computer runs the popular Cura slicer configured with all necessary settings to slice CAD models into G-Code compatible with the Duet 2 control board. The G-Code can then be uploaded to the printer through the Duet web interface over Ethernet, or directly through an SD card and the PanelDue touchscreen interface. Only settings involving the print itself are modified through Cura; settings regarding limits of printer motion or configuration of other hardware are set in firmware and may be modified and loaded through the web interface.

2.1.1 Connecting Over Ethernet

Note: this guide is for Windows 10 and will look different if you are using a different OS.

1. Access your network control panel. This can be found by pressing Win+R, typing "ncpa.cpl" without quotes, and pressing enter.
2. Locate the Ethernet port you're using and go to properties.
3. Turn sharing off if it is on and then go to properties under IvP4.
4. Select Use IP and enter: "192.168.1.200" your mask should be "255.255.255.0".
5. Open a window from your preferred search engine and search "192.168.1.169".
   - This is the IP address of the Duet board when this report was written, and may change in the future.
   - See Appendix A for comands to check this address and change it if needed.
6. Enter "BCIT" with no quotation marks when prompted to enter a password.
   - this is the password that was configured when this report was written, and may change in the future.
   - This password is configured in G-Code in "config.g" on the Duet's SD card.

2.1.2 Connecting Over USB

Note: this guide is for both Windows and Linux users, and has been specifically tested on Pop!_OS.

To connect over USB to send G-Code commands, you need to use a terminal program of your choice, capable of serial communication. For Windows users, you might consider using PuTTY. For Linux users, PuTTY will also work, but CuteCom is a great alternative with a nice user interface.

1. Open your chosen terminal application.
2. Choose "serial" as the connection type.
3. Select the port of the Duet 2 Ethernet board:
   - For Windows users, you can find this port in the device manager under COM ports; the port should be labelled as a Duet board.
   - For Linux users, finding the port is distro-dependant so you will need to determine the process for your system. If no other devices are connected to your computer, the board is likely connected to /dev/ttyACM0, or similar.
4. Set the baud rate/speed to 115200.
5. Ensure the interface is set to use 8 data bits with 1 stop bit.
6. Ensure the mode is set to Read/Write.
7. Enter "M115" to the input bar and press enter. This command will return the firmware version, along with other useful information if the connection is working properly.
8. If step 7 was successful, you are now connected and can send G-Code commands over USB.

For other useful G-Code commands, please see Appendix A.

2.2 Duet 2 Ethernet Control Board

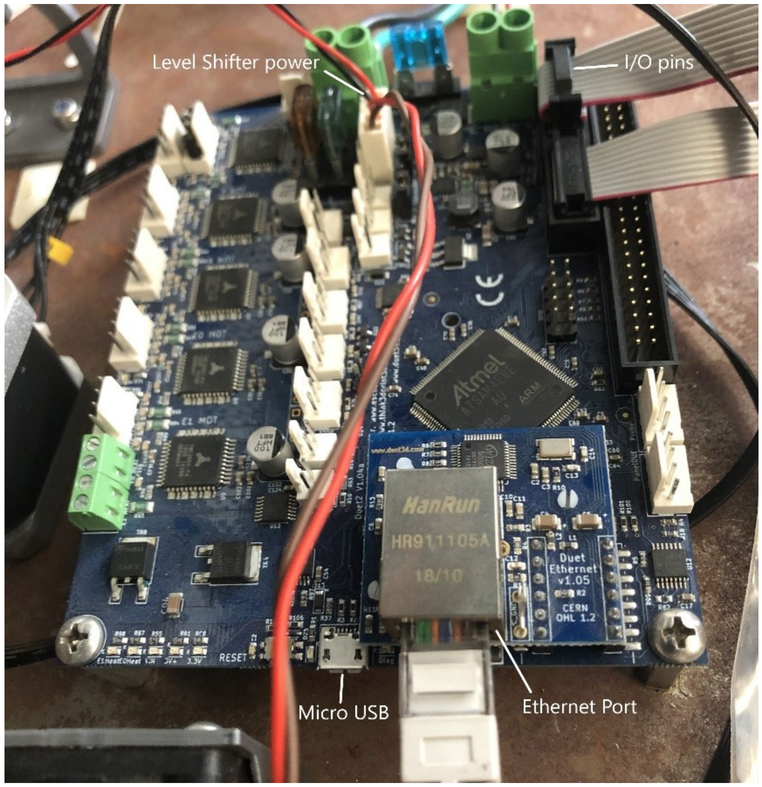

Figure 3: Duet 2 Ethernet board.

The Duet 2 Ethernet control board is the heart of the printer system, and ultimately its own subsystem: everything talks through this board. All settings regarding hardware (motion limits, how temperature is handled, etc.) are configured within the Duet's firmware. G-Code is loaded onto the Duet board through the web interface, or an SD card. The Duet is responsible for executing G-Code commands by sending out all necessary signals for motion and temperature to the connected subsystems.

The Duet 2 is configured to output its motion signals on drivers 10 and 11, which are intended for use with external stepper motor drivers. Instead of the usual four stepper motor signals that feed directly to the coils of a stepper motor, these drivers output step, direction, and enable signals at a 3.3V logic level. These signals can be configured with G-Code commands (see Appendix A, M569) to set the minimum pulse widths, as well as setup and hold times, according to the specs of the drivers/motors these signals are connected to.

2.2.1 I/O Level Shifter Schematic

The ClearPath SDSK servo motors happen to take in those exact same step, direction, and enable signals to update their position setpoint; however, they require a higher logic voltage between 5-24V. The chosen solution to this problem was to design and fabricate a level-shifter board that runs six basic MOSFET amplifiers -- one for each of the three signals on the two drivers -- to bring the 3.3V signal up to the voltage provided by a fan header. Currently, the fan headers are set to output the Duet's V_{in} signal, which is 24V for this setup. This is due to the 24V requirement of all components on the E3D Hemera Revo hotend.

Our schematic and PCB designs are shown below.

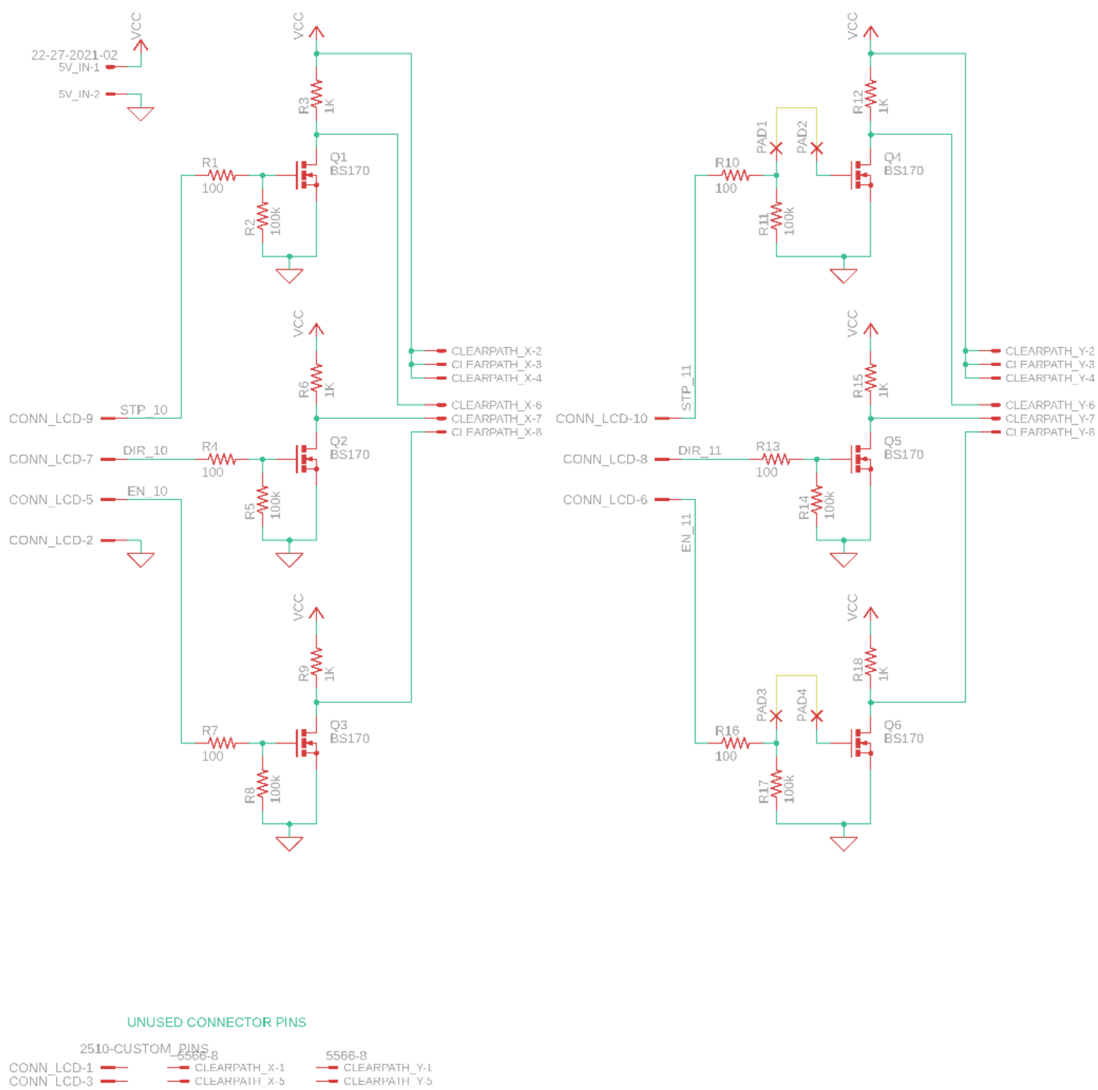

Figure 4: Autodesk Eagle schematic of level shifter circuits from Duet driver pins to ClearPath IO pins

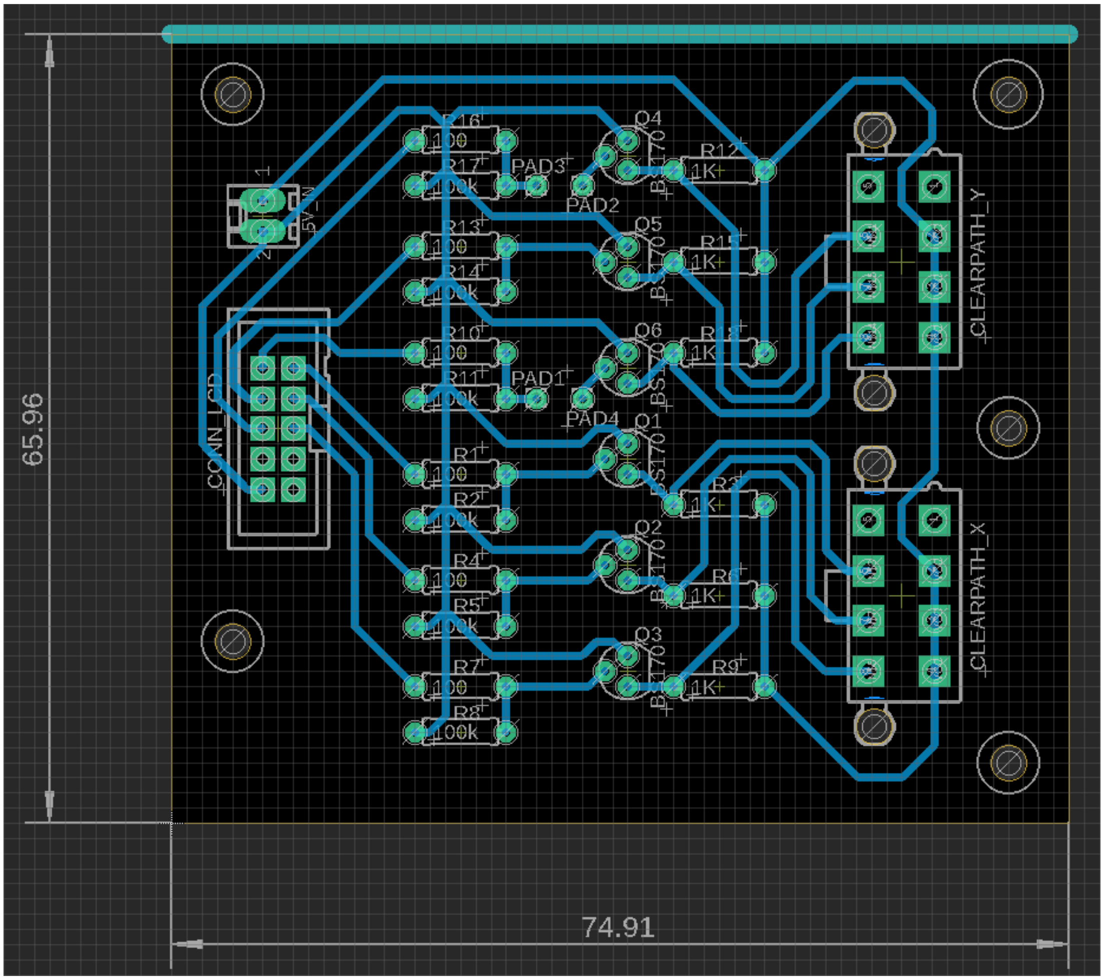

Figure 5: Autodesk Eagle top view of board layout showing bottom traces and component footprints

2.3 User Interface

The user interface subsystem is a grouping of everything allowing the user to interact with the printer. It consists of the Duet Web Interface (DWI) over Ethernet, as well as an LCD/touch screen unit mounted on the printer itself called the PanelDue. Some settings can be configured through the touch screen on the fly, while almost all settings directly related to the printer system can be configured through the web interface, including loading new firmware. A print job can be started by loading G-Code through the web interface, or by connecting an SD card and using the PanelDue menu system.

For guides on navigating the DWI and PanelDue, please refer to Appendices D and E, respectively. In those sections, the two interfaces are covered in much greater depth and include some tips on troubleshooting.

2.4 DRIVE

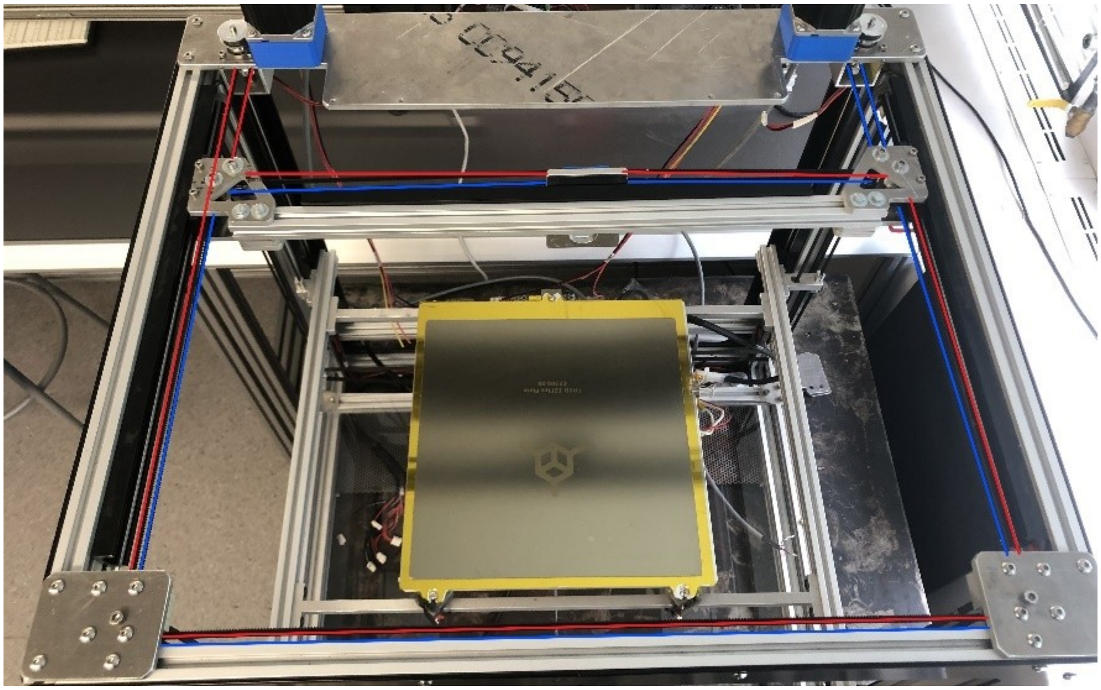

Figure 6 CoreXY drive. Top belt is shown in red and the bottom belt is shown in blue.

The drive subsystem consists of two ClearPath SDSK servo motors set up in a CoreXY configuration, and a traditional stepper motor that drives the Z axis. The right and left motors work to move the CoreXY mechanism that supports the gantry, while the Z motor utilizes several belts to move the bed vertically as layers are completed on a print.

The traditional Z axis stepper motor can be powered directly through the Duet and its 24V power supply, while the torque requirements of the ClearPath motors demand an external 75V power supply, solely dedicated to them. All motors are ultimately controlled via step and direction, but this is already done for the Z axis internally within the Duet board. XY step, direction, and enable signals must go through an external level-shifting circuit to bring the Duet's 3.3V logic signals up to 5-24V; the rest is handled by the ClearPath servos' internal systems.

2.4.1 ClearPath SDSK Servo Motors

ClearPath SDSK servo motors are configured through a Micro-USB connection using a laptop or PC. Once connected, ClearPath MSP 2.0 software can be used to configure and monitor the motors. Any time the mechanical system a ClearPath motor is attached to is changed, the autotune program must be run again through the MSP. When configuring a ClearPath motor for this project, ensure it is in "step/direction" mode. Certain ClearPath models may not have the "step/direction" mode available; in that case, select "pulse burst" mode for similar functionality.

The servos are powered from a 75V power supply connected to the V+ and GND power pins.

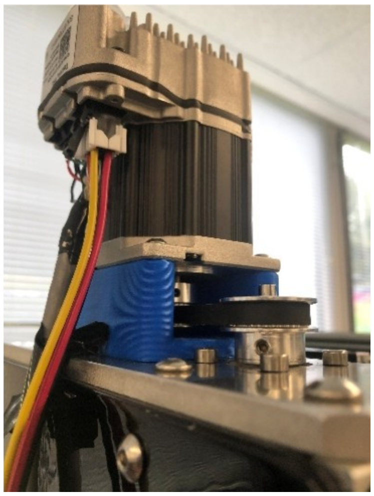

Figure 7: ClearPath CPM-SDSK-2310P-EQN

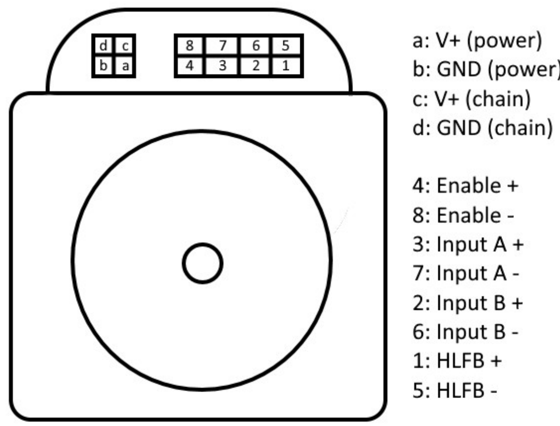

Figure 8: ClearPath servo pinout

Notes:

- The servo cannot be powered from the chain connections. These connections can only be used as outputs to chain other servo power connections together, and cannot be used as a power input.
- The enable pins cause the servo to become active at which point it will begin holding its position and responding to inputs.
- Input A and B are used for direction and step inputs respectively using the step/direction or Pulse Burst modes.
- HLFB was not used in this project and can be left disconnected.

Since this project evolved to completely repurpose the full frame of the existing CoreXY printer, a method to mount the ClearPath servos in place of the previous Nema 17 stepper motors was needed. The previous design had implemented a large waterjet-cut aluminum plate that allowed for mounting the Nema 17 motors on its underside, and still allowed enough room for future tool-changing capability. The ClearPath servo motors use a frame equivalently sized to replace Nema 23 motors, which are larger, meaning they can't be mounted on existing Nema 17 screw holes. Additionally, the larger overall size of the ClearPath motors meant they couldn't fit underneath the existing plate without interfering with gantry motion or the potential for tool-changing.

The chosen solution was to design a mount that screwed in to the existing Nema 17 mounting holes and provided a larger mounting footprint for the Nema 23 frame of the ClearPath servo motors. Since the motors only take on a rotational load, having them mount pointed down, raised from the top of the existing plate did not provide any disadvantages under normal operating conditions. This mount also allowed enough space internally to use larger and smaller sprockets connected via a small belt to the CoreXY mechanism in order to change the gear reduction if needed.

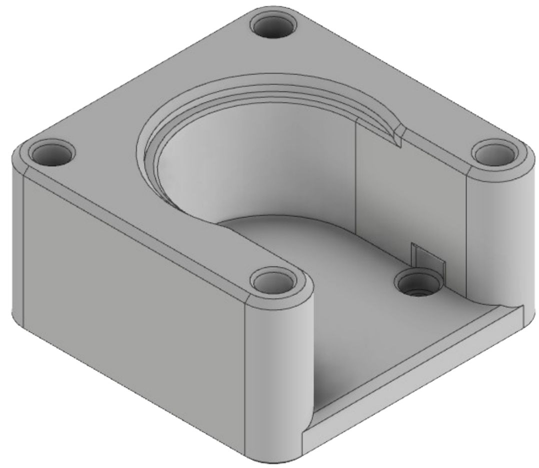

Figure 9: Isometric view of CAD design for ClearPath mounting adapter

2.4.2 SERVO POWER SUPPLY

Figure 10: Teknic IPC-5/350/500-Watt DC Power Supply

The power supply for the ClearPath servos is an IPC-5 DC power supply. It’s a 75-volt power supply and connects to both servos power connections. It requires a 120V AC wall plug to function.

Note: The power supply must be mounted upright with an inch of clearance above and below the supply to prevent overheating.

2.5 Homing

The homing subsystem is comprised of 3 limit switches – one for each axis – and G-Code algorithms stored within the Duet's firmware for homing the machine. It is critical that the machine knows where the (0,0,0) position is so that absolute movements can be made within the print volume.

On this system, the Z axis will overshoot the '0' position for more repeatable accuracy; because of this, it cannot be homed independently and must be homed using the 'all axis' option. On some machines, homing also includes determining the mesh shape of the bed to improve first layer performance; this feature was not implemented on this machine.

2.6 Hotend

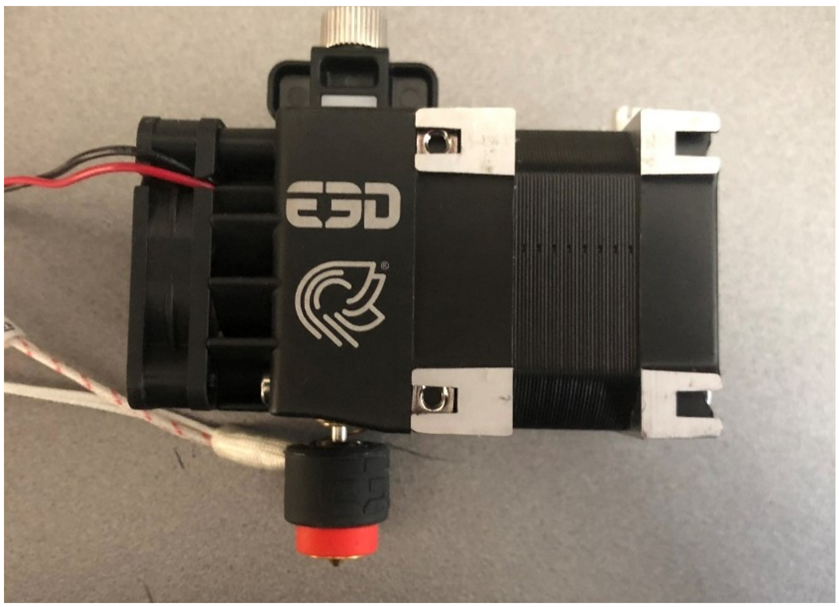

Figure 11: Side view of the E3D Revo Hemera integrated hotend assembly

The hotend is the main subsystem that allows a 3D printer to print. In this application, the hot end includes the heater, heatsink, heat break, cooling fan, nozzle, thermistor, and extruder motor, integrated together.

The heater and thermistor form a closed-loop control system with the job of maintaining the desired nozzle temperature set by the Duet board.

The extruder is the driving force behind feeding plastic filament into the hot end so it can melt.

The heatsink and cooling fan ensure that the plastic filament doesn't melt prematurely before entering the melt zone, as close to the nozzle as possible. It was found that the auto PID tuning of the extruder wasn't able to handle the temperature changes from extrusion so it had to be manually tuned.

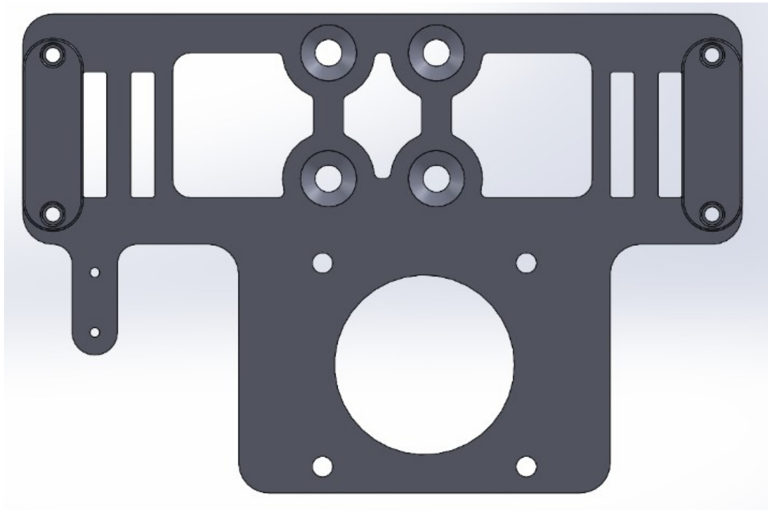

Figure 12: CAD model of carriage plate

The hotend is mounted to the gantry system using a water-jet cut plate, along with the X axis limit switch. It’s designed so that the belts will go through the far slot and loop back around through the closer slot to mesh with itself. Two 3D-printed clamps mount to the edges of the plate to lock the belts in place.

2.7 Heated Bed

A heated bed isn’t required for a 3D printer, but generally ensures that materials (especially those that are more exotic) stay secured to the bed and do not warp while printing. The heated bed subsystem is simply comprised of a large planar heater, and a thermistor to form a closed-loop temperature control system connect to the Duet with the goal of maintaining a set temperature.

On this system, the bed heater is a Keenovo 120V AC silicon heater, attached to the underside of the bed. Mains power is switched by a solid-state relay, triggered by the Duet 2 Ethernet's bed heater signal. Because this bed is so powerful, heating in only minutes, PID control is possible instead of the traditional bang-bang method. After auto-PID tuning, it was found that 70-75 degrees Celsius was ideal when printing with MG Chemicals PLA filament.

2.8 PART COOLING

Part cooling is critical to ensuring the extruded filament returns back to a solid state as soon as possible; this increases print quality, and allows for the printer to run faster. Most printers utilize centrifugal blower fans mounted on the hot end to direct air flow onto the part as filament is extruded, but the cooling solution chosen for this project is a compressed-air subsystem, separate from the Duet.

The use of compressed air provides massive air flow potential, with all weight used to create air flow mounted externally, away from the printer. Air travels through pneumatic tubing to a duct system, which mounts on the tool to add very little weight. The extra air flow ensures that the printer is not limited on the speed it can print due to extruded plastic not cooling fast enough.

Generally, the pressurized air should remain off for the first and second layers, and then the regulator should be set to 15-40psi based on print geometry for optimal performance. A small on/off flow control valve is present to allow easy shutoff of air flow during the first layers.

Thank you to Stephen McMillan for designing and printing the air ducts used to in this cooling system.

Figure 13: Compressed air regulator, pressure gage, control valve, and adaptor

Figure 14: Early version of compressed air duct that attaches to hotend assmebly

3 SYSTEM VERIFICATION

Operation of the ClearPath servos and duet board were tested using a linear axis to develop the motion system. This linear axis was approximately 1 metre long, and utilized a smaller ClearPath IO motor in pulse burst mode for its drive. As outlined earlier, ClearPath IO pins function the same for pulse burst mode as they do for normal operation for SDSK series motors. This allowed for initial testing of the fabricated level-shifting PCB, and to prove that the desired speeds were achievable.

Once the full system was assembled and printing, performance was measured through visual and dimensional evaluation of sevaral test prints. By measuring a calibration cube model, the printer was found to be accurate within around 0.1 mm, and cooling was found to be sufficient through printing some more decorative models.

3.1 SYSTEM OPERATION

This section discusses the methodology used when designing and testing each portion of the project. Each portion of communication between the Duet 2 board and ClearPath servo motors was verified before assembling the full system. Problems encountered throughout the process and the chosen solutions are also discussed.

3.1.1 VERIFYING DUET EXTERNAL DRIVER CONFIGURATION

An Analog Discovery 2 was used as an oscilloscope to measure the output of the step and direction pins on the Duet board. These pins are external driver outputs from drivers 10 and 11, which are configured through firmware to have the appropriate pulse widths and frequency, according to the ClearPath specifications.

3.1.2 INITIAL SERVO TESTS ON LINEAR AXIS

During initial development, a single ClearPath servo was connected to a linear axis to learn the basics of operation. This was used to develop the position control drive, and to see how the velocity and acceleration could be pushed to their limits.

At lower speeds there was an issue where the linear axis would begin to perform jerky motions. It is believed that this was due to the linear axis belt being slightly deformed, resulting in a poorly tuned system; however, the linear axis was ultimately quite useful to experiment with the ClearPath and MSP software, and the concept of 1g acceleration was verified.

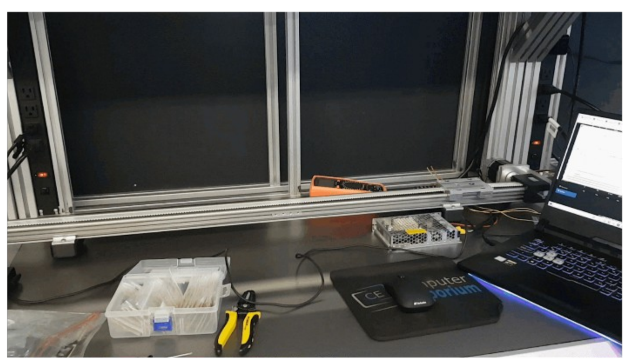

Figure 15: Linear axis setup used for testing

3.1.3 Bridging Duet Communication to ClearPath IO

Once the ClearPath servo was functioning on the linear axis using the MSP's software control, the next step was to drive the servos using G-Code from the Duet board. Step and direction signals were provided from the Duet external driver pins, but the Duet is only able to output at a 3.3V logic level. The ClearPath I/O requires a logic level between 5-24V. The chosen solution was to design a level-shifter board to transform the output signals to higher voltages.

3.1.4 SDSK Tests on CoreXY Drive System

After the initial drive development using the linear axis, the ClearPath servos were adapted to work in the CoreXY frame. This involved creating mounts for the servos and configuring the Duet board to work in a CoreXY kinematic system; this requires both motors to work together to move a single axis. This was configured in the "config.g" file through the Duet Web Interface.

Once configured, basic motion tests were performed. It was found that the minimum pulse width of the Duet was hit at speeds of just over 500 mm/s; changing the system to have a coarser XY resolution would be required to achieve higher speeds for the same minimum pulse width.

3.1.5 Verifying Other Subsystems

The hot end and bed heater have auto PID tuning so running that and then testing the printing led us to find that the bed heater is fine with the auto PID tuner but the nozzle should be manually tuned for a more robust performance as the auto tuner was weak to disturbances. The limit switches connections were tested and then a homing routine was created.

Both the hot end and bed heater have PID-tuning capability. Reprap firmware provides an autotuning feature that can be run through G-Code commands. This method was found to work for the bed heater, but ended up being too weak for the hotend to keep up with the compressed air cooling system. The solution was to PID-tune the hotend heater by hand, increasing overshoot and steady-state oscillations, but forcing the hotend to remain at the set temperature with cooling active.

Limit switch connections were also verified via the onboard LEDs provided on the Duet board; when a switch is pressed, the corresponding LED lights up to show that it is working. Once the limit switches were verified, homing macros were written in G-Code and stored as "homeall.g," "homex.g," and "homey.g" in the DWI's system files; "homez.g" does not contain any code, as homing the Z axis individually would result in a collision with the bed.

Note: The ClearPath servos are very strong and will have no trouble bending the brass extruder if homing is configured incorrectly. At the time of writing this report, all homing routines are safe should not be able to cause damage to the printer.

3.1.6 Verifying Full Printer Operation

Once all the subsystems had been verified, the print quality of the system was tested. Some common issues and solutions that were found included:

- Gaps/breaks throughout print:
  - increase cooling
  - lower speeds.
- Warping:
  - increase cooling
  - increase bed temperature (if on first layer)
  - lower speeds.
- Layer shifting/overshoot/uneven walls:
  - re-autotune ClearPath servos.
- First layer not sticking:
  - ensure bed is level
  - clean off build surface
  - decrease cooling during first layer
  - increase bed temperature
  - increase nozzle temperature during first layer
  - lower speeds during first layer.

3.2 Performance Metrics

The printer was tested using a 3DBenchy and simple vase model to see the quality of the prints being produced. The benchy provided an excellent overview of the motion parameters that needed tuning, and the vase helped to get the cooling right.

The whole process involved a lot of trial and error due to the huge number of variables at play, so few metrics were quantifiable; but, the dimensions of a 20x20x20 mm^3 calibration cube were able to be measured to determine the proper steps/mm resolution for each axis.

The remainder of evaluation was done by judging visual defects that occurred during prints.

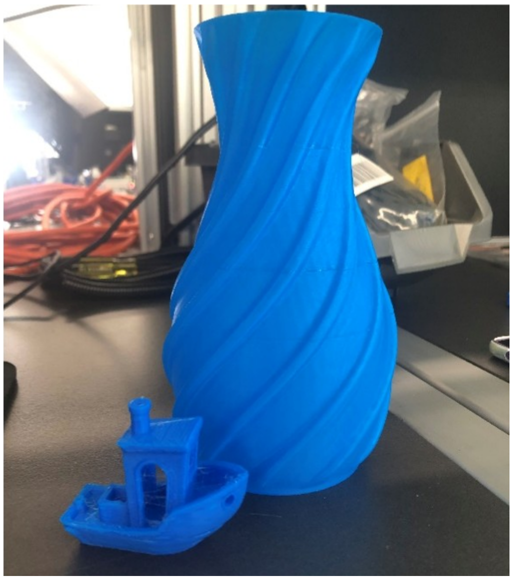

Figure 16: Example of print quality for working printer

4 PROJECT SUMMARY

This purpose of the project was to build and interface the electrical components to create a 3D printer with improved acceleration and quality over a previous, more traditional model. The desired specifications set at the project start were met and exceeded. Upon finalization of the project, the machine will be returned to the Mechanical Engineering department at BCIT under the care of Stephen McMillan. In the following years, the machine may be provided to mechanical and mechatronics programs as another capstone project, where further upgrades can be implemented.

4.1 SYSTEM SPECIFICATIONS

The current relevant specifications for the printer are:

- 50000 mm/s^2 acceleration on travel.
- 10000 mm/s^2 acceleration while printing.
- 500 mm/s maximum travel velocity.
- 250 mm/s maximum print velocity.
- 319 pulses/mm of resolution on the X and Y axis.
- 8000 pulses/mm of resolution on the Z axis.
- 300 x 300 x 300 mm^3 build volume.

4.2 RECOMMENDATIONS FOR FUTURE WORK

Some ideas for future teams that decide to work on this project include the following:

- Replace CoreXY drive with a crossed-gantry drive.
- Automated compressed air control from the Duet.
- Replace the Z axis with a more stable solution to mitigate vibration of the print bed.
- Tool changing or multi-extruder capability.
- IMU on gantry/tool with Klipper or future ReRap firmware for full closed loop position control.
- Standalone network connection over BCIT Ethernet so you don’t need to connect directly to a laptop.

5 CONCLUSION

The original goal for this project was to interface ClearPath servo motors to an existing 3D printer frame that utilized a CoreXY kinematicc system. It was required that ClearPath servos capable of 1g of acceleration and an extruder capable of keeping up with the drive were sourced. These components had to be interfaced with an existing Duet 2 Ethernet control board.

The main issues that were faced involved receiving necessary parts on time; the defined project timeline allowed for expected periods of delay, but some of these could have been avoided with better planning. Luckily, through the use of 3D-printed components, most portions of the project had extremely quick turnaround times, making up for lost time with shipping other components.

Once printing began, several ways of improving print quality without sacrificing speed were found, including:

- adjusting the compressed air cooling system
- servo tuning
- using better-quality filament
- calibrating the resolution of the axes
- and using a larger diameter nozzle.

With the project completed, it is safe to say the design requirements were exceeded. The printer can move at accelerations of 50000 mm/s^2 (which is over five times the initial requirement of 1g) with travel speeds of up to 500 mm/s, and print speeds of up to 250 mm/s. It is currently capable of printing a 3D benchy in under 17 minutes, with the motors capable of going over four times faster.

Overall, this machine is currently over four times as fast as the average printer and has the potential to go even faster. With the potential upgrades mentioned in section 4.2, this printer could be able to compete with some of the record-holding printers from around the internet. Speed aside, with some further tuning this machine will be able to produce high quality, dimensionally accurate mechanical parts much faster than a normal printer.

Appendix A: Useful G-Code Commands

The following G-Code commands may be helpful if manual, lower-level debugging of the system is required, or if you are setting up a new system with similar components for the first time.

M584 X10 Y11
- Selects the X and Y motors to use drivers 10 and 11, which output step, direction, and enable signals at logic 3.3V.
- These signals are wired to our level-shifting board and connected to the ClearPath motor IO pins, and are required for operation.
- See Appendix C for a wiring diagram, showing the external driver pins on the Duet 2 Ethernet.

M569 P10 S1 R1 T5:5:1.5:0
- Sets driver 10 to have an active-low enable signal, drive forward, and configures pulse timings.

M569 P11 S0 R1 T5:5:1.5:0
- Sets driver 11 to have an active-low enable signal, drive forward, and configures pulse timings.
- **PLEASE NOTE:** driver 11 must be active-low due to a firmware bug. Additionally, if motor direction is not correct, you must use the Teknic MSP software to reverse the direction, as this bug removes the ability to reverse direction with the M569 command.

M203 X<x feedrate> Y<y feedrate> Z<z feedrate> E<active tool feedrate>
- Sets the maximum feedrate for the specified axes in [mm/min].

M204 P<print acceleration> T<travel acceleration>
- Sets the default acceleration for print and/or travel moves in [mm/s^2].

G92 X0 Y0 Z0 E0
- Manually tells the duet that the current position is the (0,0,0,) home point, and allows manual movement by G-Code without properly homing.
- Very useful for debugging.

G1 X<pos [mm]> Y<pos [mm]>
- Manually performs print speed movment to the specified position.
- Absolute move, unless you have specified otherwise in G-Code (for relative moves).

M552 (no arguments)
- Returns the current status of the network connection.
- Value returned includes configured IP address, and actual current IP adress.

M552 S0
- Brings down the network interface.
- **Send this before configuring a new IP address.**

(continued on next page)

M552 S1 P0.0.0.0

- Brings up the network interface.
- Configures the Duet to use a dynamic IP address assigned to it by the connected network.

M552 S1 P<static IP address>

- Brings up the network interface.
- Configures the Duet to use a static IP address.
- **Ensure this static IP address does not conflict with an existing device, or the network will reassign the Duet with an IP different from the specified address.**

Appendix B: Torque Calculations

Below is the data from the spread sheet used to calculate the inertia of the components. Parts were estimated as rectangles cylinders and point masses. Actual measurements were gathered from a CAD model of a cross gantry model assuming parts to made of aluminum. Calculations were performed prior to switching to CoreXY model, as such only one axis was considered.

	Total			Total Reflected			Total Motor
Total Reflectec	0.001569608		Gears + Belt	8.5095E-06		Motor	1.829E-05
Gear reduction	1		Axis + Shaft	8.15924E-05		Gears	3.4038E-06
Total Motor	2.16938E-05		End Tool	0.001479506		Motor Shaft + Belt	0
			Inertia	0.001569608		Inertia	2.16938E-05
Inertia	0.001591302						
				Majority Gears			Motor Gear
Torque	0.156106706		Mass	0.02082		Mass	0.02082
(oz-in)	22.10658287		Radius	0.0146		Radius	0.0146
			Inertia	2.219E-06		Inertia	2.219E-06
			Actual Inertia	1.7019E-06		Actual Inertia	1.7019E-06
				Main Belt			
			Mass	0			Motor Belt
			Radius of Pully	0.0146		Mass	0
			Inertia	0		Radius of Motor Pulley	0.0146
						Inertia	0
			Actual Inertia	0			
						Actual Inertia	0
				X axis			
			Mass	0.18			Motor Shaft
			Offset	0.0146		Mass	
			Width	0.01485		Radius	
			Height	0.0084		Inertia	0
			Inertia	4.36624E-06			
			Offset Inertia	4.2735E-05		Actual Inertia	
			Actual Inertia	4.253780E-05			
				Yaxis			
			Mass				
			Length				
			Width				
			Inertia	0			
				End Tool			
			Mass	0.388			
			Offset	0.06			
			Radius	0.0146			
			Inertia	1.479506E-03			
				Drive Shaft			
			Mass	0.844			
			Radius	0.00701			
			Inertia	2.07371E-05			
			Actual Inertia	1.942870E-05			

Figure 17: Inertia calculations spreadsheet.

Appendix C: Duet 2 Ethernet Wiring Diagram

Below is the wiring diagram for the Duet 2 Wifi/Ethernet control board from the Duet3D website; the board used in this project was specifically a Duet 2 Ethernet board. The most important signals mentioned throughout this project can be within the 10 pin ribbon cable connector toward the bottom right of the diagram, labelled "Stepper Channel 10 & 11 (Label: CONN_LCD)."

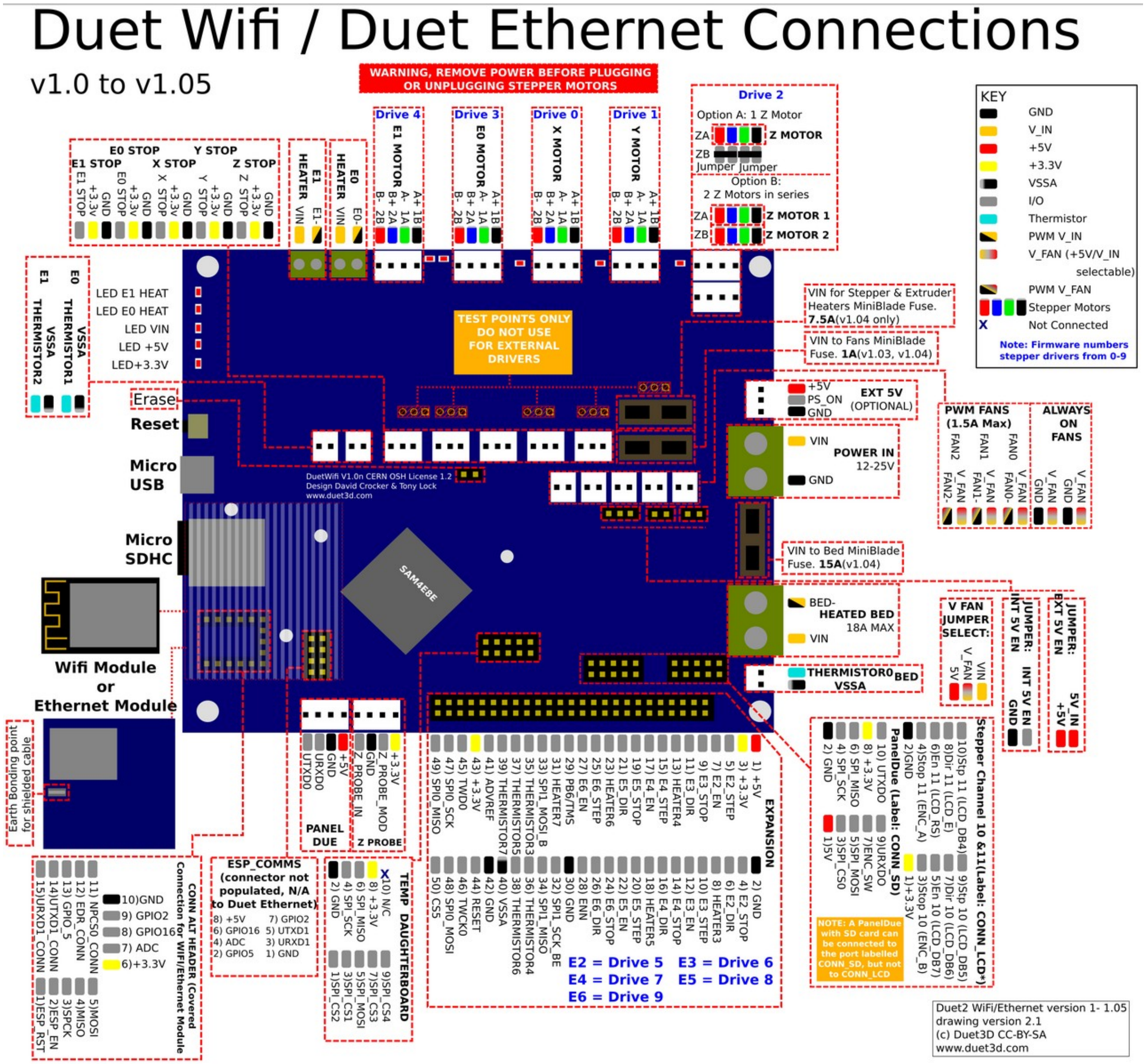

Figure 18: Wiring diagram for Duet 2 Ethernet control board

Appendix D: A Tour of the Duet Web Interface

The Duet Web Interface (DWI) is the main unique feature present on the Duet 2 Ethernet board. This interface is hosted by the Duet board, and available to other machines over its Ethernet connection. It is accessed directly via the configured IP address, as described in section 2.1.1.

After successfully connecting to the DWI, you will likely want to home the machine and adjust heater temperatures. Most of this common functionality is present on the "Dashboard," which you can access through the menu on the left side of the screen. If this menu is not present by default, click the three lines in the top left corner.

On the "Dashboard," you can home the machine through the "Home All" button, or home an individual axis with its respective button. The interface displays a message when an axis is not homed, and will not let you move an axis until it is homed. All homing routines are safe and do not need to be executed in a specific order; however, the Z axis cannot be homed individually, as the gantry needs to move out of the way of the bed to avoid collision with the nozzle. There is no code present in the Z homing routine, and therefore no danger of accidentally causing a collision. Pressing the "Home Z" button has no effect, which is intended. After the required axes are homed, the printhead can be jogged by pressing the appropriate buttons in rows next to the home buttons; these command buttons are labelled in millimetres.

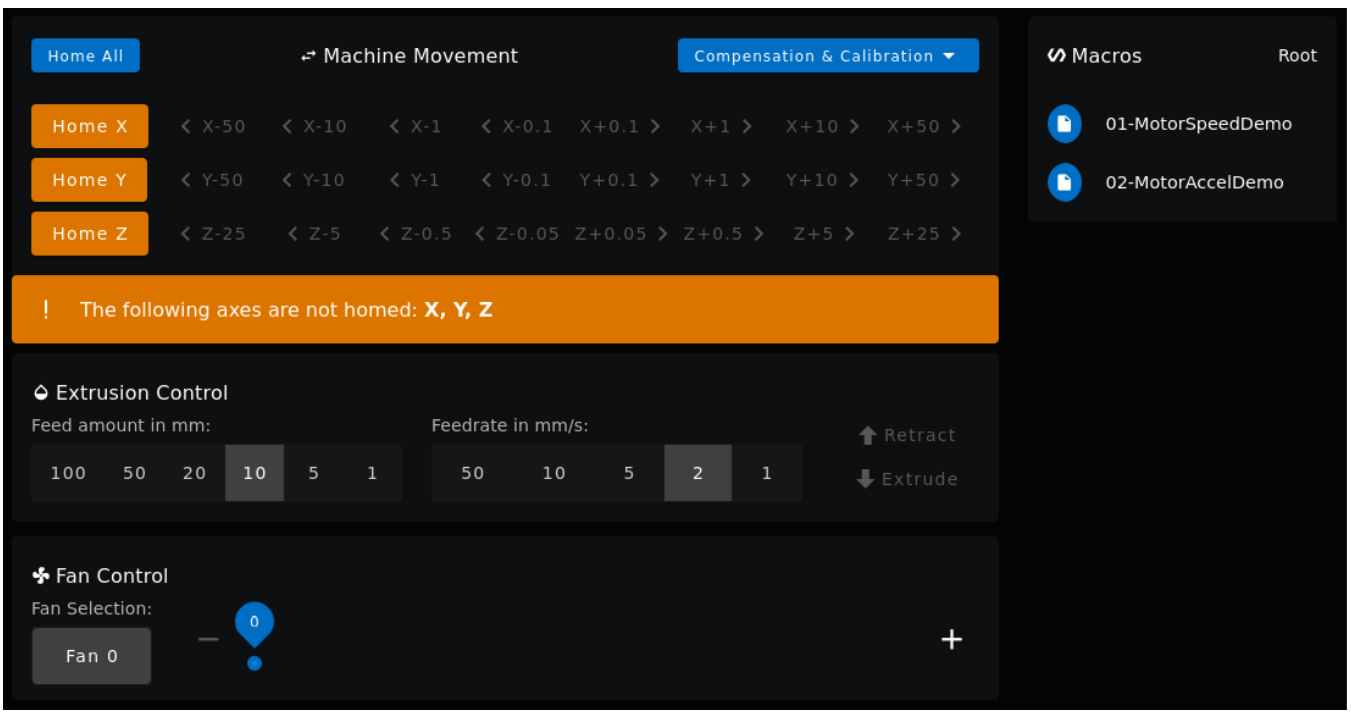

Figure 19: Main printer controls present on the "Dashboard" within the DWI

Temperature can be set and monitored through the "Control Heaters" section on the "Dashboard." A heater's temperature can be set by entering a number in the appropriate box, and then clicking the name of the heater to cycle it to the "active" state. When "active," a heater will match the temperature set in the "active" box, and "standby" will cause it to match the temperature set in the "standby" box. The heater's temperature will be displayed under "Current," and it will also show on the "Temperature Chart" graph.

To extrude filament manually, the hotend heater will first have to be heated, the name of the tool must be selected to make it the active tool, and then extrusion can be achieved through the controls in the "Extrusion Control" section. If the DWI prevents you from clicking the "Retract" and "Extrude" buttons, ensure the current tool has been selected as "active" by clicking the name of the tool, and that it is heated to an appropriate temperature for extrusion.

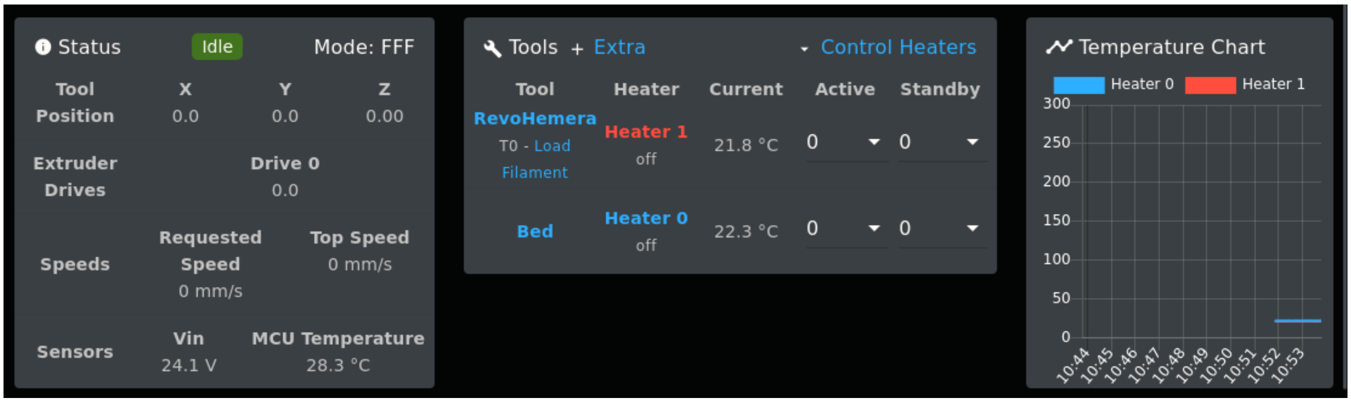

Figure 20: Main printer status indicators present on the "Dashboard" within the DWI

G-Code files for prints can be uploaded by navigating to the "Jobs" tab, and clicking "Upload G-Code File(s)." A job can then be started by clicking on the uploaded G-Code file and confirming the start of the job. A job can be monitored on the "Status" tab, which contains all necessary information about the current print job, and several controls useful for tweaking the current print. Among the most useful are "Z Babystepping," to adjust the distance between the nozzle and the bed mid-print, and the "Speed Factor," which lets you quickly adjust the multiplier of all speeds in the current print.

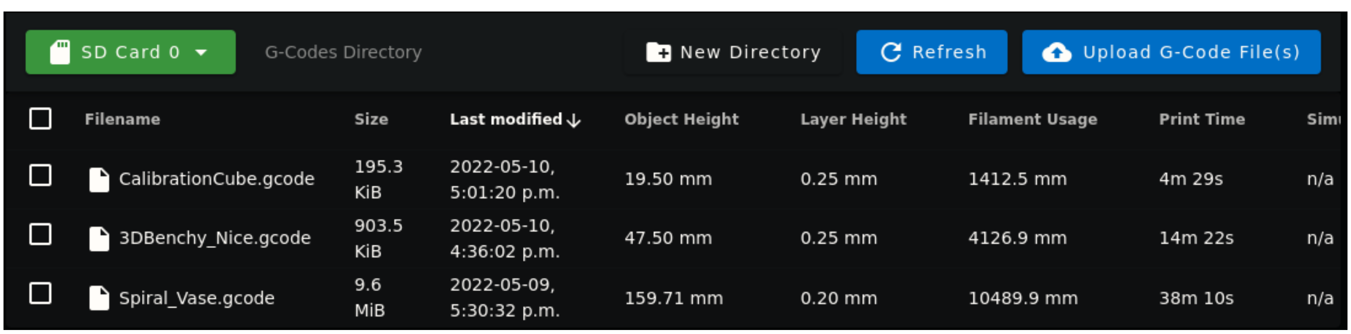

Figure 21: Job select section within the DWI

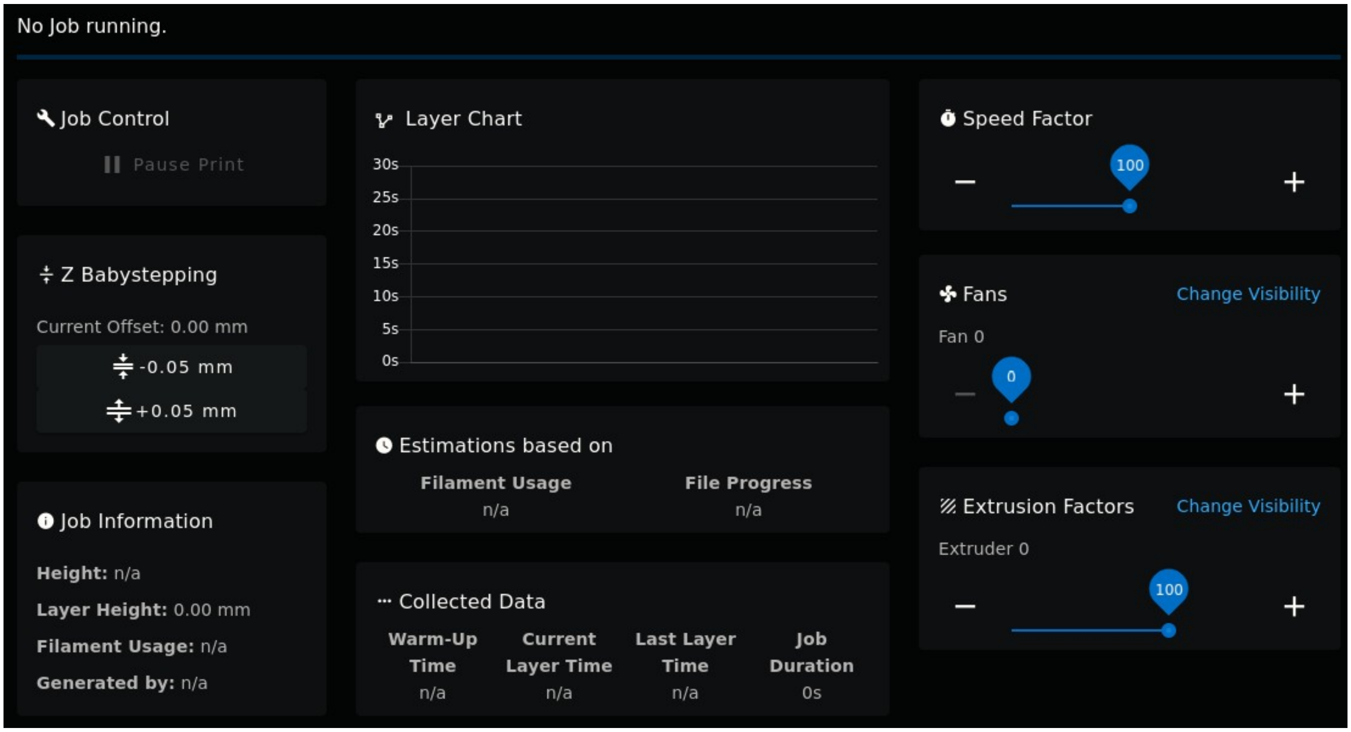

Figure 22: Job status menu within the DWI

Manual G-Code commands can be sent via the "Console," or through the text bar present at the top of almost every screen within the DWI. Manually sending G-Code commands may be more useful in some cases such as levelling the bed than using the main "Dashboard" controls. If sequences of commands are commonly used, you may combine the commands into a G-Code file and upload it as a macro under the "Macros" tab; macros can be run by clicking the file name and confirming to run the file under the "Macros" tab, or on the small menu present on the right side of the "Dashboard" controls section.

One of the most important features of the DWI is the ability to edit system configuration files without touching the SD card. G-Code to configure heaters, motors, network, and more are present in "config.g" under the "System" tab; all commands present in this file are run each time the Duet 2 Ethernet board is started. If you want to configure offsets defined when homing the machine, edit the appropriate lines in the "homeall.g," "homex.g", and "homey.g" macros. As mentioned before, "homez.g" does not contain any actual code at the time of writing this report, and should not be modified unless changes are made to the machine that require the Z axis to be individually homed. The appropriate lines to modify offsets on are noted in the comments within the homing macros.

Firmware can also be uploaded through the DWI; since this process changes from version to version, please search up the appropriate method for the current firmware.

Appendix E: Using the PanelDue Interface

The PanelDue is a handy touchscreen interface mounted to the front of the printer between the slide-out drawer and the plexi-glass floor of the printer base; though all functionality is possible through the web interface, the PanelDue may be convenient when a laptop or computer isn't handy, depending on where the printer is set up. The screen visible on startup shows the printer name in the top left, printer status in the top right, numbers describing the temperature of various interfaced heaters, buttons for homing the axes, and buttons to navigate the other pages of the interface.

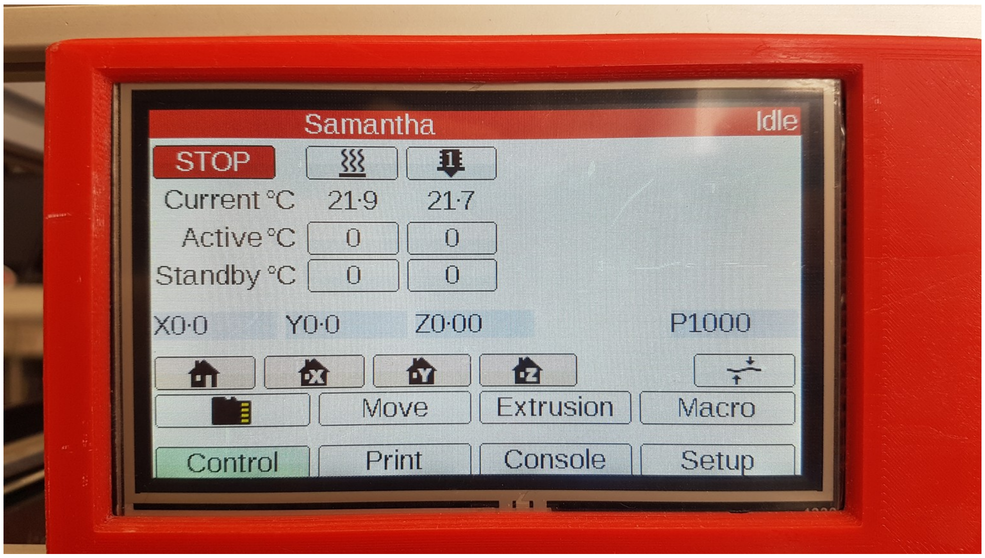

Figure 23: PanelDue "Control" menu visible after startup

If you plan to manually jog the printer around, the first thing you will want to do is home the axes. This can most effectively be done by pressing the home button, which has an image of a house on it. There are several home icons with letters corresponding to the individual axis it homes, and one without letters that homes all axes at the same time. All homing routines are safe to use without any risk of crashing, so you may decide which axis/axes you want to home based on the situation.

Once the appropriate axes are homed, you may press the "move" button, which will open a popup menu. Plus and minus buttons with numbers represent positive and negative distances to move in millimeters should be visible and available for each axis. Press the desired button once to move that distance.

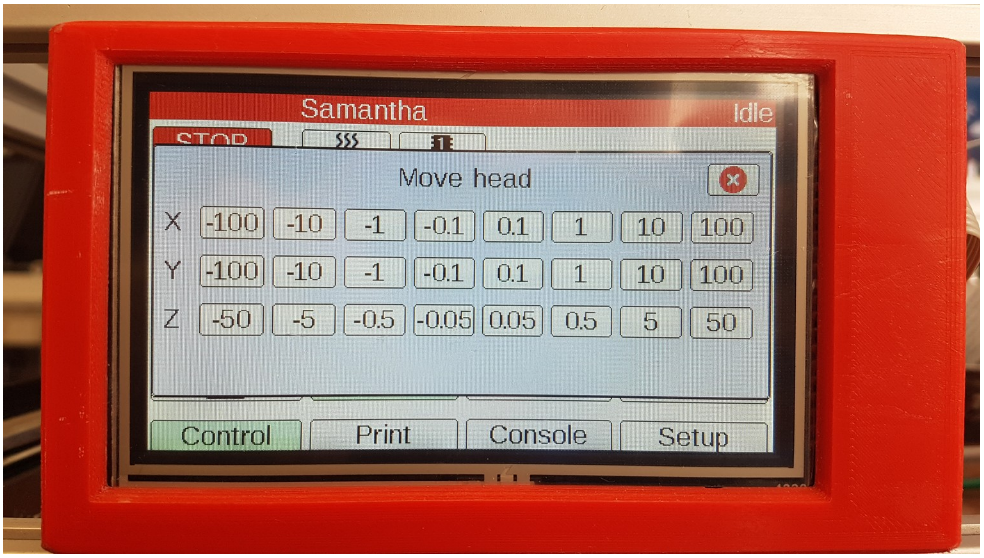

Figure 24: PanelDue "Move" menu used to manually jog printhead

On the main "control" screen that is visible on startup, there should also be buttons for heating and changing the status of any heaters that have been interfaced to the Duet 2. Pressing these buttons will open another popup menu, and you will be presented with more buttons to increment/decrement the set temperature of the selected heater. Once you have entered the desired active or standby temperature, press the set button to command the heater to go to that temperature. To cycle the status of a heater between "off," "active," and "standby," press the icon corresponding to the desired heater; in the image below, pressing on the rectangle with heat lines will cycle the heated bed status, and pressing the nozzle with the number 1 will cycle the status of the single hotend heater.

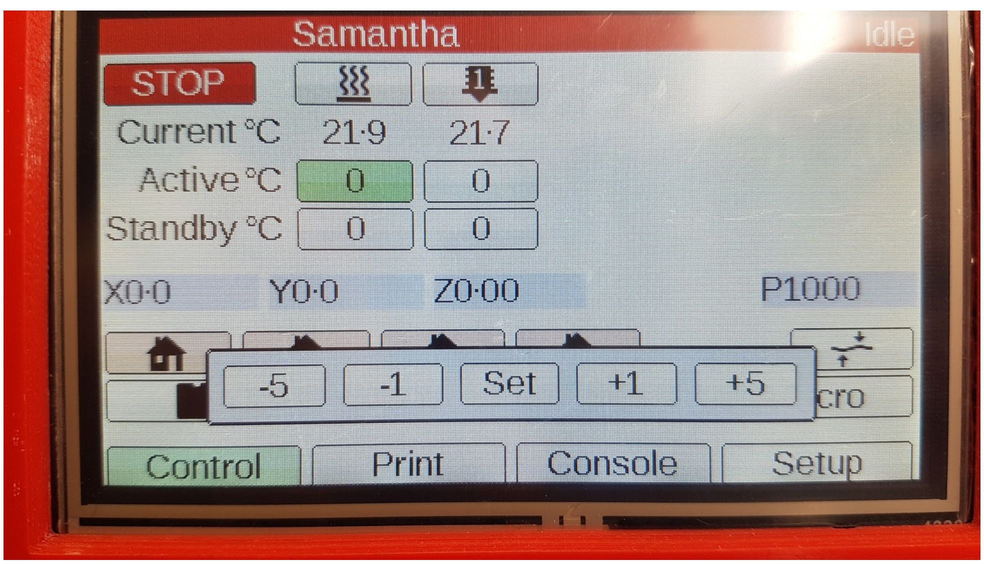

Figure 25: PanelDue popup to set temperature

Additionally, you may trigger any macros that have been saved to the Duet through the "Macro" menu, or start print jobs. G-Code for print jobs can also be loaded via an SD card plugged into the PanelDue by pressing the icon with the SD card, and confirming the file you would like to print. This job can then be monitored through the "Print" menu. You also have access to a miniature terminal, and several other useful tools through the PanelDue.

If you are having trouble communicating with the PanelDue, ensure the baud rate in the "Setup" menu is set to 57600.