University of Manchester
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Project Report 2012

Improving the Makerbot 3D Printer

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Abstract

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Personal 3D printers allow anyone to manufacture complex physical objects on demand with minimal skill and effort. The Makerbot Cupcake CNC is a low cost, easy to build 3D printer with a wide community of users. Though relatively capable, the machine is held back by its primitive control electronics and microcontroller.

New electronics based around a more powerful ARM microcontroller were produced along with new firmware to control the printer. The system was built on the widely used FreeRTOS and uses the μIP TCP/IP stack allowing a clean, easily extended design to be implemented.

The new system improved the print quality achievable by the printer thanks to improved timing accuracy. Additional sensors also allowed the printer to act with increased independence.

Supervisor: Alasdair Rawsthorne

Acknowledgements

Thanks are due to my supervisor, Alasdair Rawsthorne, who has been both supportive and helpful throughout every stage of the project. Also, many thanks to Dave Bowden who constantly supplied me with all manner of tools and components at short notice throughout. Finally, thanks too to my parents and girlfriend who've been kind enough to put up with my ranting and assist with proof-reading while working on this report.

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Chapter 1

Introduction

3D printing is a manufacturing process where computer models of objects are automatically reproduced in a physical form [JE12]. Figure 1.1 shows an example of a complex 3D printed object. Various 3D printing technologies exist, some of which have gained a number of hobbyist-friendly implementations. In this project, a number of refinements to the popular Makerbot Cupcake CNC 3D printer were made to improve its performance.

In this chapter the applications of 3D printing are examined followed by an introduction to the Makerbot and the improvements made by this project.

1.1 Applications

3D printing technologies allow complex objects, including complete mechanisms, to be easily manufactured based on digitized designs in one go with a single piece of equipment. Various materials are used including metal, various plastics, resins and even sugar [Can12].

Rapid prototyping is an obvious application where the flexibility to quickly manufacture a wide range of objects extremely valuable. For example, Boeing are using 3D printing to reduce the tooling cost and speed up prototyping its aeroplanes [Sta12].

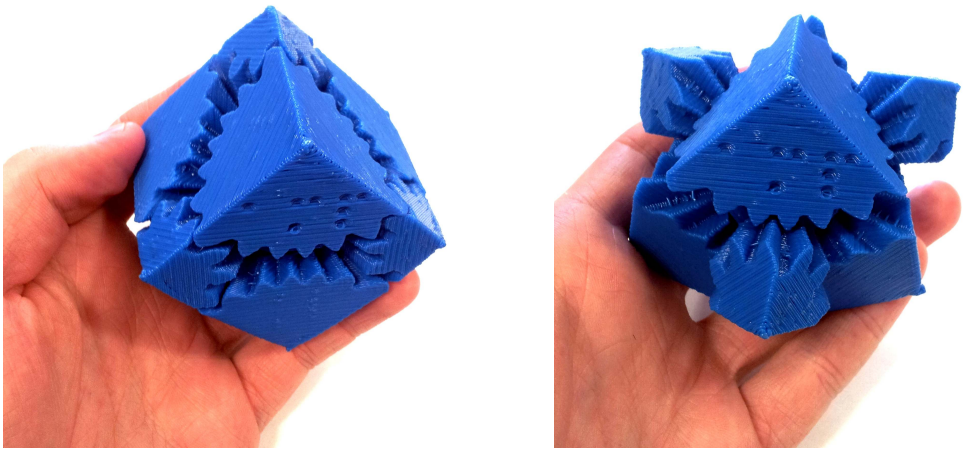


Figure 1.1: 3D printed 'Gear Cube' produced by the printer upgraded in this project

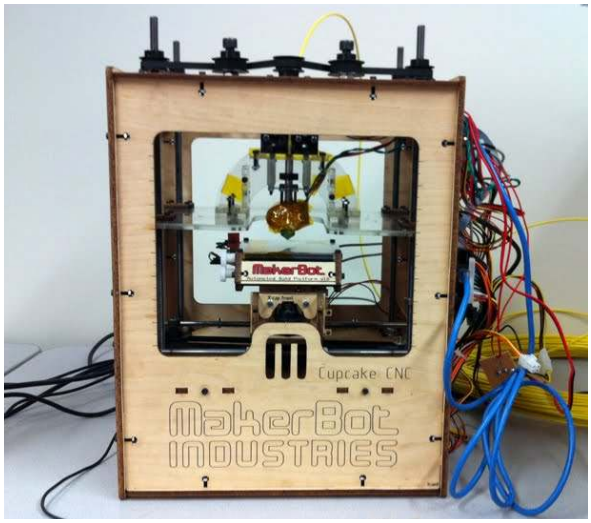


Figure 1.2: Unmodified Makerbot Cupcake CNC (photo by Rayshobby [Pro12])

Because there is no tooling cost associated with changing a design, custom manufacturing is also possible. This has applications both for personalised goods and more recently in the manufacture of bespoke medical implants [Mar12].

The cost of entry-level 3D printers has recently become much lower with DIY devices such as the RepRap costing between $300 and $620 to build [She12, Rep12f]. This has helped grow communities such as Thingiverse where people share their designs for printable objects with the goal of making physical things as easily accessible as any other digital media [Ind12d].

1.2 Makerbot

The Makerbot (figure 1.2) is an open source, DIY 3D printer which can produce plastic objects up to 10cm × 10cm × 13cm in size. It consists of a moving platform onto which an 'extruder' melts plastic filament and deposits a thin strand of plastic (figure 1.3). Objects are produced by moving the platform underneath the extruder and to form layers of plastic which are stacked one on top of each other until the complete shape is formed. Figure 1.4 shows how a cone (A) might be sliced into layers (B) and how each layer might be printed (C).

Software running on a computer handles the process of slicing a 3D model and generating the list of movements required to print it out. A simple microcontroller on the Makerbot receives this list of instructions and generates the carefully timed electronic signals needed to drive the printer's components.

1.3 Project Motivation and Goals

The Makerbot, while a very capable machine, has many limitations in its hardware, electronics and firmware. In this project the control electronics and microcontroller are the primary area for improvement. The existing system has trouble with complex designs

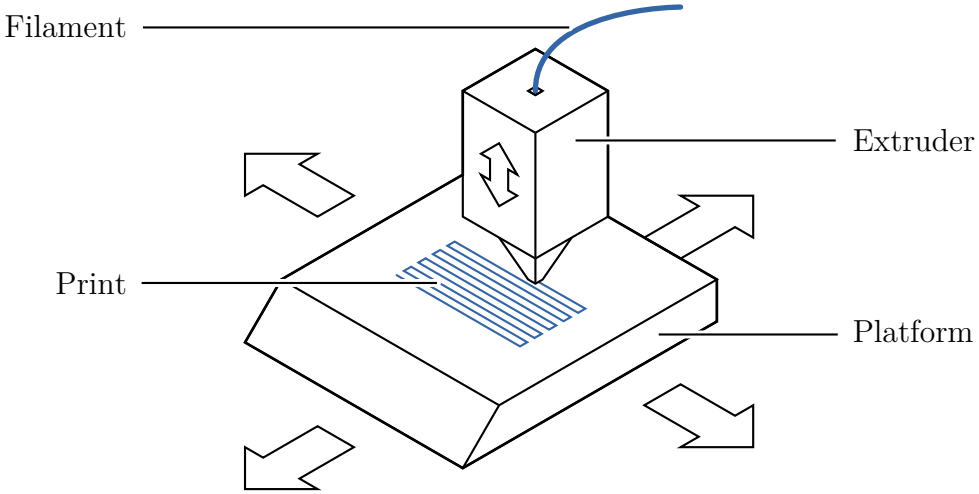
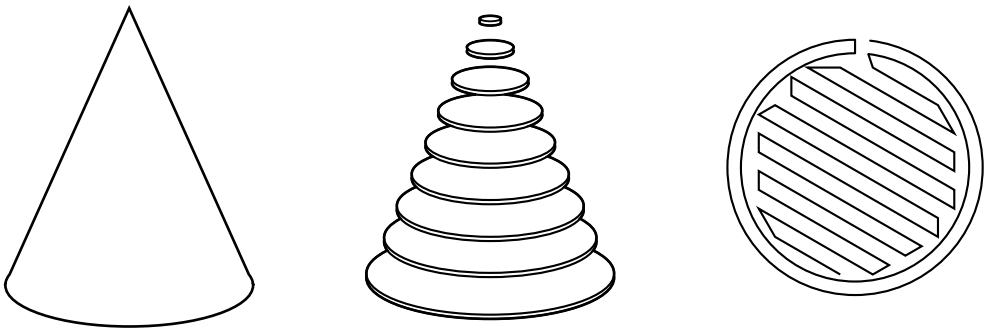


Figure 1.3: Makerbot key components



(A) (B) (C)

Figure 1.4: Slicing a 3D model into layers to be printed

where dense sequences of instructions exceed the microcontroller's limited resources and slow serial interface. The electronics are also a complicated configuration of several circuit boards using crude mechanical relays. Finally, the printer does not have sensors to indicate the positions of the platform and extruder requiring the platform to be carefully positioned before prints. This is a time consuming and error prone task which also means that the printer can't detect mechanical errors during printing.

In this project, each of these three complaints are addressed by the following primary project goals:

Simplify control electronics Produce a single board which contains all required components using only reliable solid-state parts.

Improve performance Upgrade to a more powerful microcontroller and develop new firmware to exploit the resulting improvements in speed and communications capabilities.

Add sensors for platform and extruder movements End-stop sensors at the end of each axis of movement will be added to allow the system to position itself.

1.4 Report Outline

This report first discusses the background of the project covering 3D printing and the technologies selected for the project. In chapter 3 the design of system is proposed followed by details of the implementation in chapter 4. Chapter 5 describes how the system was tested and evaluates the new system's performance. Finally, chapter 6 concludes the report and describes opportunities for future work following on from the project.

Chapter 2

Background

In this chapter the background of the project is described. The principle components of the Makerbot are discussed in more detail followed by a description of the tasks carried out by the firmware required to drive them. Afterwards, the ARM based 'Mbed' microcontroller used in this project is introduced along with the 'FreeRTOS' operating system.

2.1 Makerbot

The Makerbot Cupcake CNC used in this project is the first generation of a series of printers based on the RepRap 3D printer [Ind12a]. The RepRap, and consequently the Makerbot are open designs which are freely available for use and modification.

In this section, the primary components of the printer are described followed by the electronics, firmware and microcontroller that drives them.

2.1.1 Printer Components

The printer can be broken down into three major components, the axes along which the machine's components can move, the extruder which melts the plastic and the platform itself on which the design forms. Each of these are described below.

Axes of Movement

There are three axes of movement in the Makerbot. Two horizontal axes along which the platform can travel, the X- and Y-axes, and one vertical axis along which the extruder is moved, the Z-axis.

The X and Y axes move along rails and are belt driven by a stepper motor. The Z-axis moves up and down four threaded rods which are connected together via a belt and driven by a single stepper motor. When the threaded rods turn, the extruder is moved by the screwing effect of the rods.

Stepper motors allow precise movements to be made. In contrast with simple DC motors which turn electrical energy into continuous movement, stepper motors turn energy into discrete 'steps' of movement.

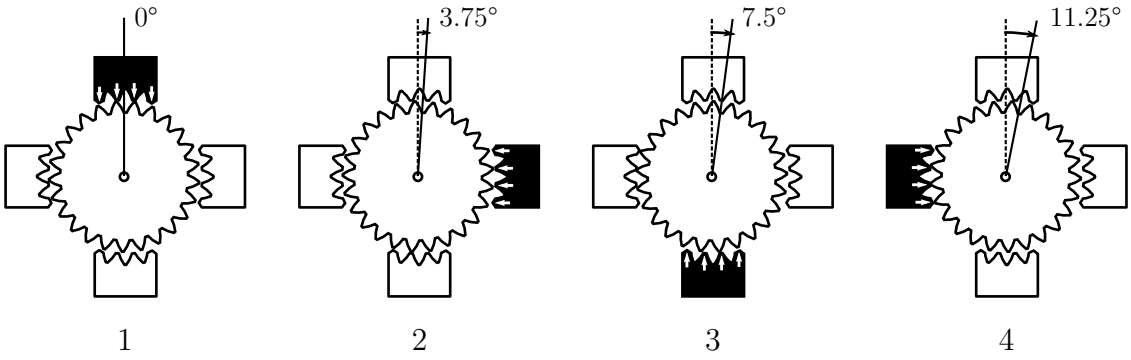


Figure 2.1: Stepper motor operation

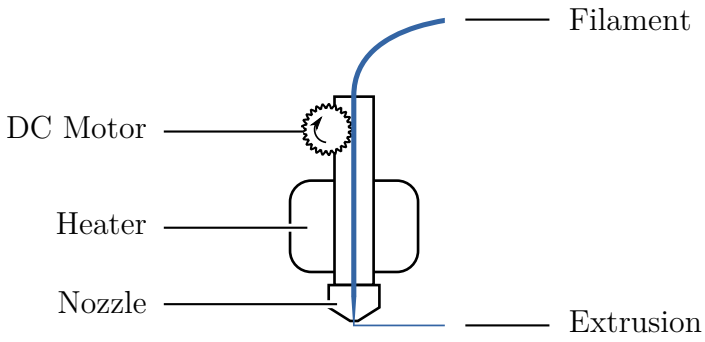


Figure 2.2: Extruder components

A simple stepper motor consists of four toothed electromagnets and a toothed magnetic central rotor. By turning on each electromagnet in sequence, the teeth of the rotor are moved to align with the energised electromagnet causing a single step of movement to be executed (an example is given in figure 2.1) [Inc12].

By controlling these steps, the motor's rotation and speed can be exactly controlled. Stepper motors lack active feedback mechanisms and rely solely on the motor successfully completing every step. This assumption does not hold if the motor is unable to provide enough torque (turning power) to move its load. As a result, the motors used by the printer are designed to be powerful enough to reliably provide the torque required so that sensors are not needed to judge the position of the system.

Extruder

The extruder uses a simple DC motor and gearbox to force a filament of acrylonitrile butadiene styrene (ABS) plastic, the material from which Lego® is made, into a heater and out of a fine nozzle (figure 2.2). A temperature sensor is installed in the heater allowing the temperature to be carefully controlled to ensure an even flow.

Platform

The platform contains a heated build surface which helps prevent prints warping and this also improves the adhesion of the print to the build surface.

The build surface is also a conveyor belt powered by a small DC motor and gearbox. It is used to eject printed objects after printing completes allowing continuous printing operations.

2.1.2 Electronics

The Makerbot is controlled by the RepRap's generation 3 electronics [Rep12c]. These consist of:

Motherboard This circuit board hosts an 8-bit microcontroller which communicates with a computer via a custom serial interface and controls the printer's operation.

Extruder Controller This circuit board hosts a second small microcontroller along with electronics for the extruder's motor and temperature sensor. The extruder controller communicates with the motherboard via a custom RS485 interface.

Relay Board This circuit board contains a mechanical relay for turning each of the two heaters on and off. The relay board is driven by the extruder controller using simple digital signals.

Stepper Motor Driver ($\times 3$) Circuit boards which produce the high-power signals required to drive the stepper motors. These boards are connected to the motherboard via a simple digital interface that abstracts away many of the electrical and timing difficulties driving a stepper motor.

2.1.3 Microcontrollers

The electronics use a pair of Arduino-compatible microcontrollers to drive the printer. These devices have a fairly minimal 8-bit instruction set, limited amounts of memory (4KB of RAM) and a very limited set of options for high-speed communications. A faster microcontroller capable of faster communication and command processing is needed to solve the performance problems described in §1.3.

2.1.4 Firmware

The firmware on the microcontrollers is responsible for two main tasks: receiving print data from a computer and producing the signals required for printing. The signals produced have strict 'real-time' timing requirements and so to meet these, specialised timing hardware within the microcontroller must be used.

3D printers typically receive print data in the form of G-code files [Rep12b]. G-code is the *de facto* standard for controlling computer numerical control (CNC) machines such as 3D printers, laser cutters and lathes. The language is human readable and defines step-by-step instructions for machine actions such as 'move to (X,Y,Z)' or 'enable heater'.

The RepRap generation 3 firmware on the motherboard uses a custom serial protocol to communicate with the host computer. This protocol is designed to be simple for the microcontroller to use and, as well as various diagnostic features, contains a compressed version of G-code.

2.1.5 G-Code

G-code is assumed to execute on an abstract 'G-code machine'. The machine consists of 26 numeric registers named 'A' to 'Z'. A G-code instruction consists of a set of register assignments after which the machine executes a specific action based on the contents of its registers.

Some registers may be reset to an 'undefined' state before each instruction allowing the machine to identify when a register is written. For example, the 'G' and 'M' registers are used to specify what type of action should occur and, if not cleared, it would be impossible to determine which register contains the action required.

Each register accepts either a floating point or integer value, for example the 'G' and 'M' registers only accept integer action numbers while 'X', 'Y' and 'Z' are floating point and accept coordinates.

For example, when the instruction `G1 X10 Y-15 Z0.3 F3000` is encountered, the following register values are set:

F: 3000 **G:** 1 **X:** 10 **Y:** -15 **Z:** 0.3

In this example, the action is 'move to' as determined by the 'G' register. The 'X', 'Y' and 'Z' registers determine where to move and 'F' determines the speed. If this is followed by `M104 S225` then the following registers will be set:

F: 3000 **M:** 104 **S:** 225 **X:** 10 **Y:** -15 **Z:** 0.3

Note that the 'G' register has been undefined but the others have remained. In this example, the action is determined based on the 'M' register to be 'set extruder temperature' and the 'S' register determines the temperature. 'X', 'Y', 'Z' and 'F' are ignored. Finally, if `G1 Z0.6` is encountered the following registers are set:

F: 3000 **G:** 1 **S:** 225 **X:** 10 **Y:** -15 **Z:** 0.6

Once again the machine determines the action to be 'move to' and moves to the position defined by 'X', 'Y' and 'Z' at the speed in 'F', ignoring the 'S' register. Because the values of 'X' and 'Y' have not been changed, the machine will move only the Z-axis.

2.1.6 Support Software

The G-code used by the printer is generated from 3D models using an open-source tool called Skeinforge [ske12]. Skeinforge is typically used as part of ReplicatorG, a graphical user interface for preparing and printing 3D models [rep12a]. ReplicatorG can also handle the translation of G-code into the compressed format used by the RepRap firmware. Other less mature tools, such as Slic3r, are available but less frequently used.

2.2 ARM & Mbed

As well as high-performance processors designed for phones, ARM also design the Cortex-M series of microcontrollers. For this project a Cortex-M3 based 'Mbed' microcontroller was chosen to replace the pair of existing 8-bit microcontrollers [Sem12b]. The reasons for the suitability of this choice are justified in this section.

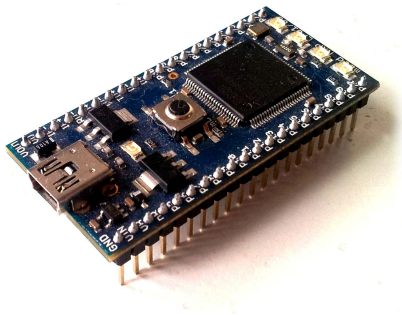


Figure 2.3: Mbed microcontroller

2.2.1 Mbed

The Mbed is a small microcontroller prototyping board centred around the NXP LPC1768, ARM Cortex-M3 based microcontroller (figure 2.3). It has has four debugging LEDs, a USB port for loading programs various input/output facilities including facilities for attaching an Ethernet port. The pins on the device expose these input and output capabilities and fit into standard 0.1" spaced circuit boards and prototyping breadboards.

The Mbed provides a USB flash drive-like interface. This interface is used to program the device by simply copying a binary file onto it. This mechanism is used to support the device's unusual choice of purely web-based official development tools. Web-based development was not ideal for this project and an alternative solution is discussed in §4.2.1 allowing conventional development tools to be used.

2.2.2 NXP LPC1768

The LPC1768 microcontroller behind the Mbed provides the ARM Cortex-M3 processor with various useful peripherals. It runs at up to 100MHz and has 32KB of ram [NXP10]. While still a seemingly tiny amount compared to even a modest smart phone, this is a large amount for a microcontroller without the overhead of running a fully-fledged general purpose operating system and associated software.

The chip contains various peripherals such as hardware timers, analog interfaces and, importantly, fast Ethernet support. These timers will, as with the previous microcontrollers, be vital for driving the electronics properly. Analog inputs are also needed to interface with the electronics. Ethernet support will allow the microcontroller to quickly receive detailed print data over the network.

As well as these features, ARM devices are widely used and boast mature, open-source development tools making it an ideal choice for expanding the open-source Makerbot design.

2.3 Real-Time Operating Systems

The firmware consists of various complementary parts (such as communication and control), which are easily managed with the use of an operating system. Due to the absolute

timing and performance requirements FreeRTOS, a real-time operating system (RTOS), was selected.

2.3.1 Differences With Non-Real-Time Systems

Real-time operating systems, like other operating systems, provide a scheduler which allows multiple processes to run as if simultaneously. It also provides facilities for communicating between these processes. Unlike regular operating systems, an RTOS can provide exact timing guarantees. They are also generally targeted at microcontroller development with tight resource constraints and without the need for extra hardware such as a memory management unit (MMU).

2.3.2 FreeRTOS

FreeRTOS is a widely used, open-source RTOS designed for use with a range of microcontrollers, including many Cortex-M3 based devices [fre12]. The two key features provided by FreeRTOS are 'tasks' and 'queues' which are described below.

Tasks

A system built on FreeRTOS can be structured as several tasks executing in parallel. Tasks are similar to processes or threads on a conventional operating system with each task having its own set of registers and a stack.

Because the microcontroller can only run one task at once, the FreeRTOS uses preemptive scheduling to approximate this behaviour where the current task is periodically interrupted by a timer (preempted) and a different task put in its place. If tasks are switched fast enough, they appear to run simultaneously.

Tasks may be given different priorities and can be suspended until events such as a timer expiring or a hardware resource becoming available occur. The timing of the operating system's actions can be guaranteed allowing real-time systems to be developed.

Queues & Mutexes

To provide synchronisation and communication between tasks, FreeRTOS provides a queue structure. Queues are defined which allow data to be inserted or removed with a first-in-first-out (FIFO) access scheme.

These queues can be used safely by multiple tasks simultaneously without race conditions and so are ideal for inter-task communication. Because of this safety, they also form the basis for standard parallel programming constructions such as semaphores and mutexes.

When accessing a FreeRTOS queue a task may become blocked, for example, when adding an item to a queue that is already full. FreeRTOS can provide timing guarantees on timeouts waiting for these functions to complete. It also allows a task's priority to be temporarily raised when resumed after a blocking call, ensuring it is scheduled as soon as possible, reducing the delay before any new data is processed.

Chapter 3

Design

The 3D Printing system can be divided up into three main parts as shown in figure 3.1. These major components and their requirements and design are described in the following sections.

This project is principally focused on the development of the firmware and electronics used by the printer. In particular, the process of generating 3D models and G-code as well as mechanical operation is out of the scope of the project. The printer hardware and off-the-shelf, open source tools provided by the Makerbot project will be used for these purposes.

3.1 Firmware

The microcontroller firmware will consist of three main components running on top of the FreeRTOS operating system. The first will be the μIP network stack for communication with the computer software. The second, is a G-code processing pipeline which will translate G-code into an appropriate sequence of commands to drive the electronics. The third component is a driver interface for the various Mbed peripherals.

In this section, each of these components is examined followed by a brief discussion of the safety requirements of the system.

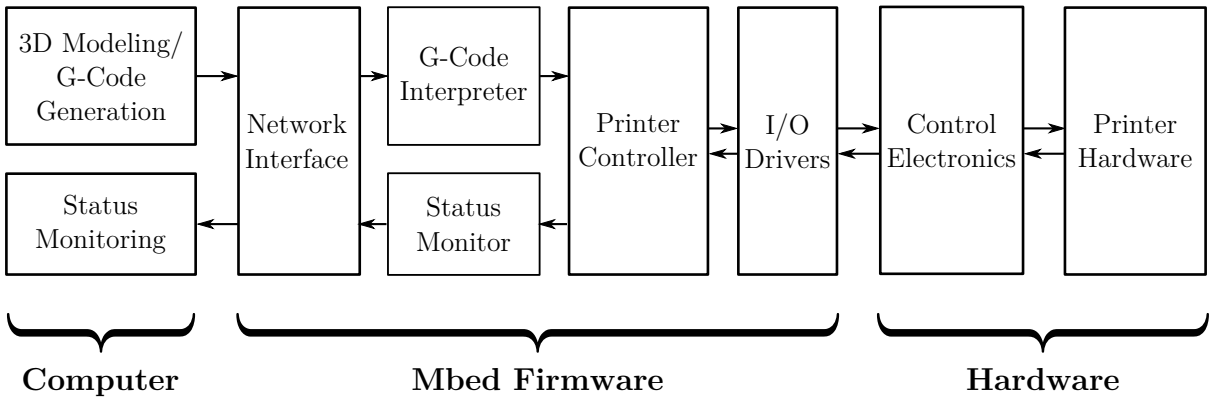


Figure 3.1: High-level diagram of overall system architecture.

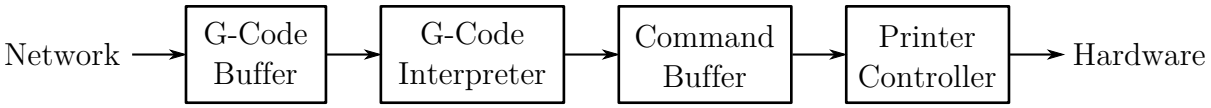


Figure 3.2: G-code processing pipeline

3.1.1 Network Interface

The firmware will provide an interface for streaming G-code to the printer and an interface for querying the printer's status. This will be done via a network interface primarily to increase the bandwidth of the connection with the computer.

The G-code interface should be a simple open port which accepts G-code streams and feeds them into the pipeline without the need for specialised software on the sending computer. It will need to support flow control as the rate at which the printer is able to accept G-code instructions will vary depending on what instructions are being executed. For example, while waiting for heaters to warm up, no instructions are executed but during complex movements, many instructions are executed in rapid secession. The interface must also be reliable because a missed, corrupted or out-of-order G-code instruction would cause potentially dangerous results. TCP offers both reliable communication and flow control mechanisms and is implemented in μIP making it an appropriate choice for this task[1].

The status querying interface should be kept minimal and human readable. A `telnet` compatible interface should be created.

3.1.2 G-code Processing Pipeline

The main task of the firmware is to process incoming G-code from the network and to control the printer appropriately without stalling. A pipeline architecture (figure 3.2) was selected where G-code from the network is buffered before being interpreted and converted into low-level commands. The low-level commands are placed in another buffer and then executed in sequence to drive the printer.

In order to reduce stalls due to data processing between commands, space is exchanged for computation time by keeping all command arguments in formats directly used by the printer in the low-level commands. For example, distances should be represented as an integral number of steps and not floating point millimetre values.

At the start of the pipeline, the effect of network latency should be minimised by allocating a large G-code buffer giving the network longer to respond to changes in the rate of command execution before the buffer drains.

Finally, by assigning a high priority to the printer controller the delay between a command completing and another starting is minimised. This minimises the error introduced during very short bursts of extremely detailed movements.

[1]Some G-code implementations have error checking and retransmission mechanisms built in but these are poorly specified and designed for use with serial connections.

3.1.3 G-code Interpreter

Though existing G-code interpreters are available they are generally tightly integrated with the control logic they were designed with and not easily used standalone. G-code implementations also vary widely with 3D printers but generally only a require a very small subset of the language features. As a result, a small G-code interpreter will be implemented for the required subset of G-code.

3.1.4 Drivers

In order to interface with the electronics and facilitate accurate timing, various peripherals on the Mbed will be used requiring supporting driver code. In particular, the following features will be needed:

General-Purpose Input/Output (GPIO) Allows digital, TTL (Transistor-Transfer-Level), signals to be produced and read from the pins on the microcontroller. For example, stepper control and end-stop signals.

Analog Input Read analog signals from the electronics, for example, readings from temperature sensors.

Timer Used to produce interrupts at precisely timed intervals to allow stepper control signals to be generated.

Watch-dog Timer To ensure fail-safe behaviour, a watch-dog timer can be used to reset and power down the system in the event of software malfunction.

3.1.5 Safety

The system must behave safely in the event of a software failure and should be interruptible by a user at any time. The system must also start up in a safe state so that unintentionally powering on the machine cannot result in dangerous behaviour. Readings from the system must also be sufficiently accurate that they do not mislead the user about the system's safety.

3.2 Electronics & Hardware

New electronics are required to replace the motherboard, relay and extruder boards. As well as this, electronics and hardware must be added for the proposed end-stop sensors. The requirements for these parts are described below.

3.2.1 Stepper Control

The printer's three primary axes are controlled by stepper motors which require complex circuitry to drive them. Off-the-shelf RepRap stepper motor drivers (figure 3.3) will be used as in the existing electronics [Rep12h]. The boards connect to the stepper motor and power supply and provide a TTL control interface. They also provide a connection

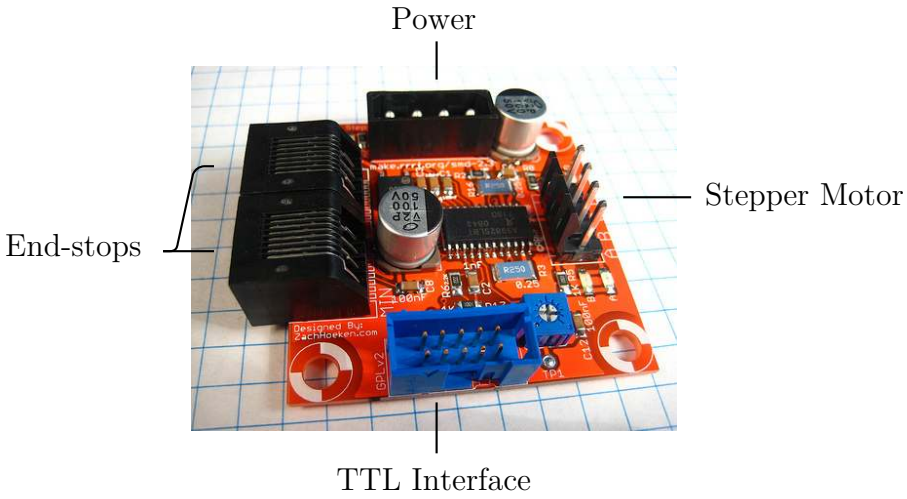


Figure 3.3: Stepper controller board with connections labelled (photo [Rep12g])

for two end-stop sensors to be attached (the output from which they passively forward back through the TTL interface).

The enable, direction and step signals from each stepper board must be driven by the microcontroller's GPIO pins.

3.2.2 Heater & DC Motor Control

The heaters and motors both require large amounts of current at 12 volts to run. This far exceeds the output capabilities of the GPIO pins on the Mbed so a circuit will be needed to switch the power for these devices.

Previously, mechanical relays were used to control the heaters but instead a solid-state solution should be sought to allow the possibility of varying heater power.

3.2.3 End-stops

By adding end-stop sensors on each axis, the axes can be accurately and consistently positioned at the start of a print job. Electronics compatible with the interface exposed by the stepper controller board will be required.

Optical end-stops have been selected as the Makerbot has pre-drilled mounting holes at the end of each axis for mounting them. Optical end-stops are also non-contact and so do not disrupt the movement of the axes.

Chapter 4

Implementation

This chapter describes the implementation of the system in detail. First the electronics produced are described and followed by an explanation of the firmware which drives them. Finally, safety considerations and a brief discussion of the development methodology used is presented.

4.1 Electronics

Two circuits were produced, one which hosts the Mbed and the electronics needed to drive the heaters, motors and temperature sensors and another which provides an interface between the end-stops and stepper controller boards.

The main board hosts the Mbed, electronics for controlling heaters and motors, reading from temperature sensors and connections for the stepper controller boards (figure 4.1). A second board is used for the end-stop electronics as these parts may be replaced separately from the main electronics and connect via the existing stepper controller interface. The completed system, as installed in the printer, is shown in figure 4.2 with the major components labelled.

To keep the system easy to build requiring readily available tools, 0.1" spaced electronics were used throughout. These are easy to work with using only a standard soldering iron and basic tools. Components of this size can also be used for prototyping with a solderless breadboard.

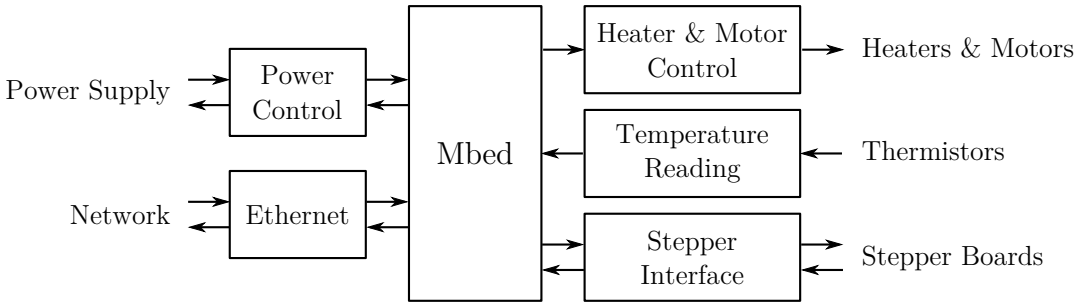


Figure 4.1: Components of the main board

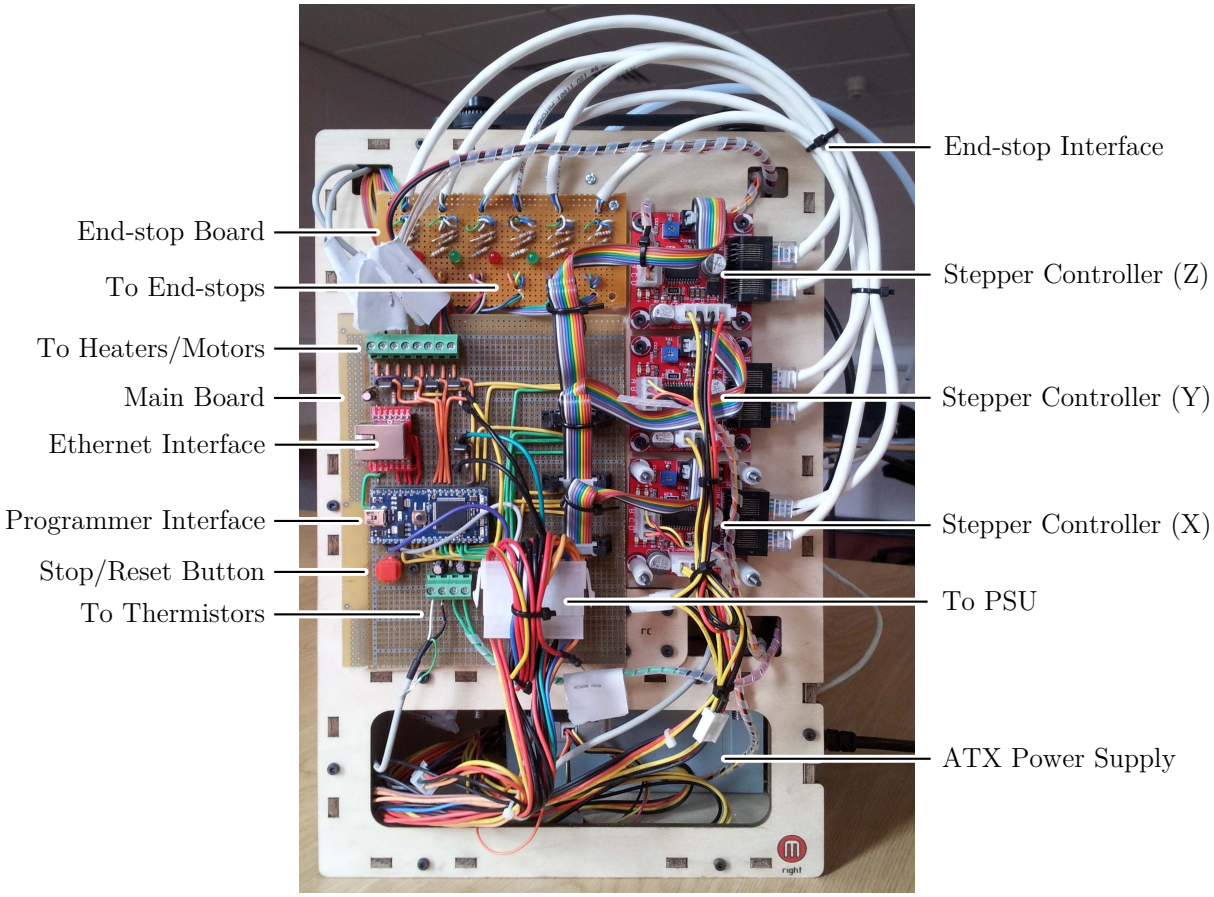
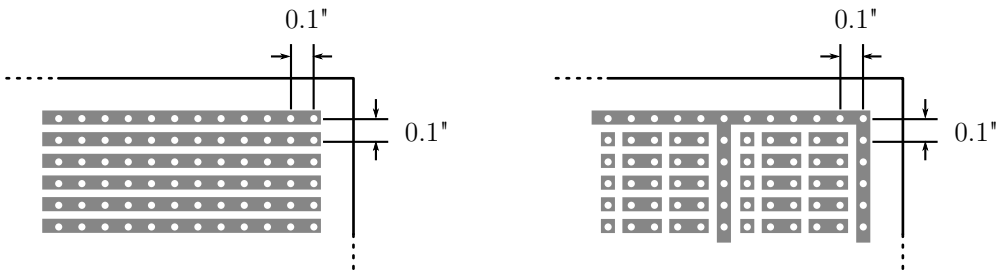


Figure 4.2: Electronics installed with key components labelled



(A) Strip Board (B) DIP Board

Figure 4.3: Types of prototyping board

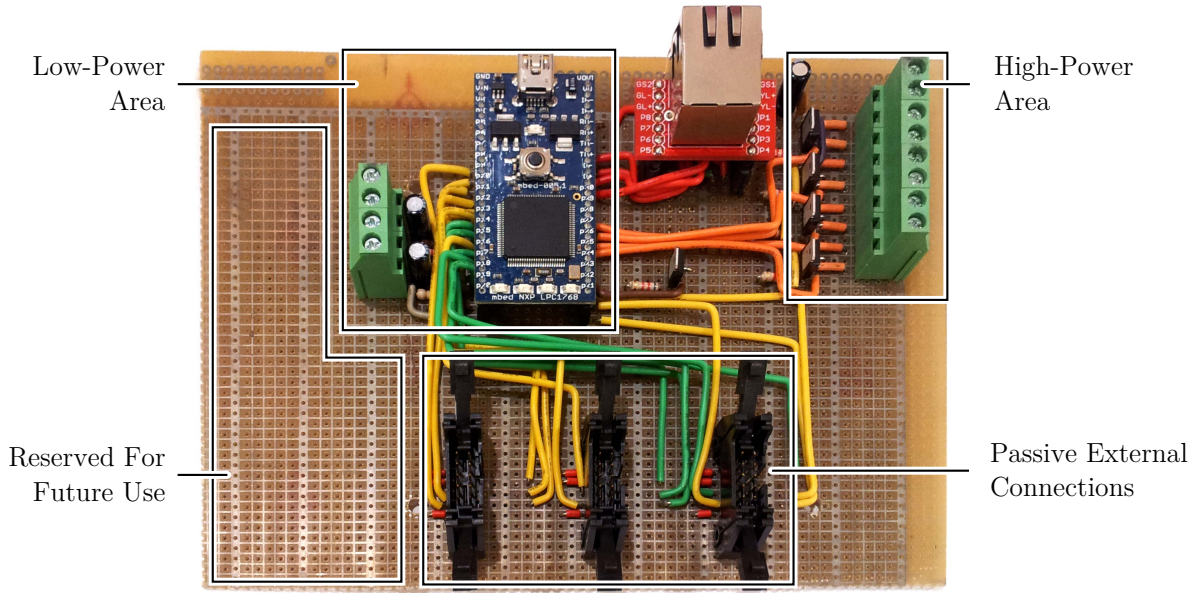


Figure 4.4: Top-level layout of main board (reset button and power connections not shown)

4.1.1 Layout & Board

A prototyping board designed for working with DIP (Dual In-line Package) components such as the Mbed was selected (Figure 4.3(B)). Conventional strip board (4.3(A)) is not ideal for these components as it would require many connections to be cut between the columns of pins.

The main board contains electronics for both low-power systems such as the Mbed and high-power systems such as the heater and motors and electrical interference between these parts must be minimised. The high and lower power parts have been kept physically separate on the board (figure 4.4), each with their own power supply connections. The board also has a continuous track covering the whole board which can be connected to ground (known as a ground plane), helping reduce noise [Sil06].

A full circuit schematic and pin-out for the board is given in Appendix C.1.

(A) Physical Appearence (B) Symbol

Figure 4.5: Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

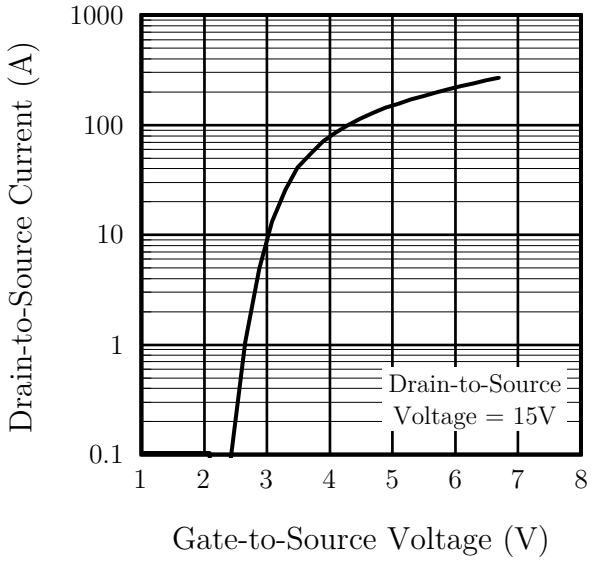


Figure 4.6: IRLU8729PbF Typical Transfer Characteristics (reproduced from 'Fig 3', [Int09])

4.1.2 Heaters & DC Motors

The heaters and DC motors in the extruder and platform operate at a higher voltage and are considerably higher-current than the microcontroller can provide on its output pins. To control these a transistor can be used. Transistors act like a switch which allows high-power components to be switched on and off using only a small current from the Mbed. An IRLU8729PbF MOSFET (Metal Oxide Field Effect Transistor) was selected as it can switch large loads up to 58A with very little on-resistance (reducing energy wastage through heat) [Int09].

A MOSFET has three connections called the gate, drain and source (Figure 4.5). When the voltage between the gate and source is 0V, no current flows from the drain to the source. As the voltage between the gate and drain are increased, the current allowed to flow increases rapidly when it passes a certain threshold (Figure 4.6). By connecting the gate to a pin on the Mbed and the source to ground, a large current from a device such as a heater or motor attached to the drain can be switched.

The behaviour of a MOSFET when the gate is left floating (disconnected) is generally undefined and can damage the component. When the Mbed powers on, its output pins

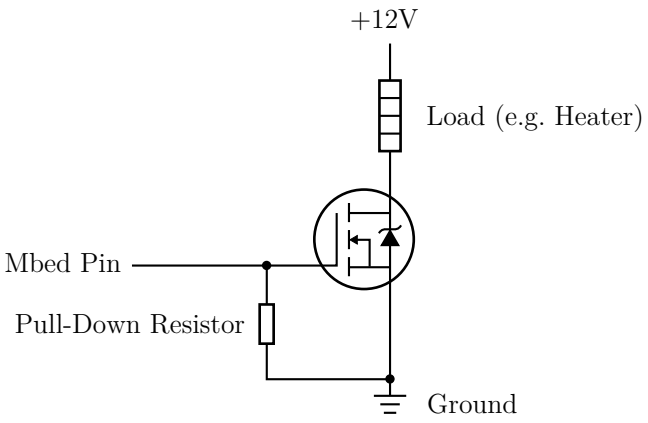


Figure 4.7: Example MOSFET circuit with pull-down resistor

default to a floating state which could cause a MOSFET to unexpectedly switch on or become damaged. To prevent this happening the gate is connected to ground via a resistor. When the output pin is floating the gate is pulled to 0V by the resistor. When the output of the pin is not floating, the gate is pulled to that voltage overriding the pull-down resistor. A high resistance value is used so that the Mbed can easily override the pull-down resistor. Figure 4.7 shows the circuit used to control the two heaters and two motors using a MOSFET and pull-down resistor.

When driving motors, a 'flyback diode' is usually used to prevent a voltage spike occurring when the power is removed from the motor. This voltage spike is caused by the magnetic field in the motor's coils collapsing. This is not included in the circuit as the MOSFETs used already contain an appropriate diode.

It should be noted that this circuit does not allow the motors to be driven in both directions as this is not needed by the printer. If this was required, a more complex circuit (such as an H bridge) would be needed.

4.1.3 Thermistors

To measure the temperature of the heaters, thermistors are used. The resistance of a thermistor changes non-linearly with temperature and can be modelled using an equation derived from the Steinhart-Hart Equation [SH68]:

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{\beta} \ln\left(\frac{R}{R_0}\right) \tag{4.1}$$

Where T and R are the current temperature and resistance of the thermistor, T_0 and R_0 are the temperature and resistance at a reference temperature and β is a characteristic constant for the device available in the data-sheet.

Using the Analog-to-Digital converter in the Mbed, voltages, but not resistances, can be read directly. As a result, a potential divider (figure 4.8) is used to produce a measurable voltage which is proportional to the resistance to measure it indirectly. A reference voltage V_{ref} is placed across two resistors, R_1 and R_2, and the voltage between

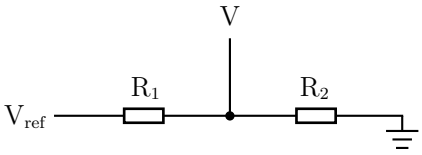


Figure 4.8: Potential divider

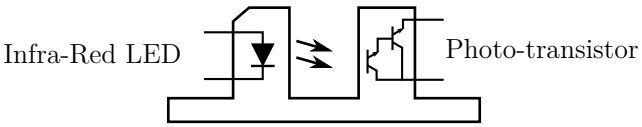


Figure 4.9: Photo-interrupter with a photo-transistor in a Darlington pair

them at V is measured. The relationship between these variables is

$$V = V_{\text{ref}} \frac{R_2}{R_1 + R_2} \tag{4.2}$$

Thus, if the thermistor is placed as R_2, the resistance can be calculated using

$$R_2 = V_{\text{ref}} \frac{R_1}{V - V_{\text{ref}}} \tag{4.3}$$

The value of R_1 was chosen to evenly spread the voltages from the expected range of thermistor resistances over the full range of 0 to V_{ref} volts. This maximises the utilisation of the analog to digital converter available over the temperature ranges used.

Using (4.1) and (4.3) with a potential divider circuit will allow the temperature of the thermistor to be measured.

4.1.4 Stepper Motors

The stepper controllers chosen accept TTL signals and connect via a ten-pin insulation displacement connector (IDC). An IDC socket was placed on the board and the pins connected directly to the Mbed and ground plane as required.

4.1.5 End-stops

Optical end-stops consist of a photo-interrupter containing an infra-red LED and a photo-transistor arranged across a gap (Figure 4.9). Photons from the LED activate the photo-transistor allowing current to flow but, when the gap is blocked, the transistor is switched off and no current flows.

Due to problems sourcing the interface boards for the end-stops, a circuit was built which is compatible with the stepper-controller interface. $+5V$ and ground are provided and a TTL logic signal is expected by the interface. To ease debugging, an indicator LED was also added which is lit when the end-stop is unobstructed.

The LED in the photo-interrupter is driven via a current-limiting resistor and the signal output and indicator LED are connected through the photo-transistor. A pull-down resistor is used to pull the signal to ground when the photo-transistor is powered off.

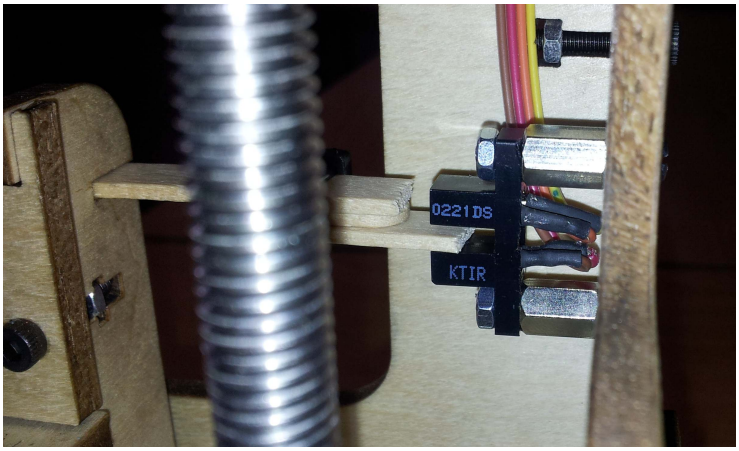


Figure 4.10: Photo-interrupter endstop being interrupted by the X-axis

The circuitry is placed on a board with cables running to each end-stop (shown mounted in figure 4.10) and to each of the CAT-5 sockets on the stepper controller boards. Strain-relief is included so that the connections are not damaged if the cables are caught in the machine. A circuit diagram is provided in appendix C.2.2.

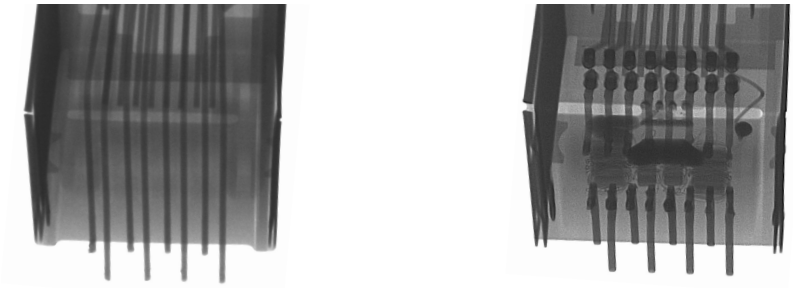
4.1.6 Power

The printer uses an ATX power supply unit (PSU) commonly found in desktop computers. A 20-pin connector containing both power and various control signals for the power supply (see table 4.1) is used to power the main board.

Signal	Colour	Notes
Ground	Black	
+3.3V	Orange	±5% Tolerance (Unused)
+5V	Red	±5% Tolerance
+12V	Yellow	±5% Tolerance
-12V	Blue	±10% Tolerance (Unused)
Power Good	Gray	Signal asserted when all voltages are correct and stable
+5V Standby	Purple	Power available at all times (Max 2A)
+3.3V Sense	Brown	Unused
Power On	Green	Active-Low signal pulled up to +5V

Table 4.1: 20-pin ATX Connector Signals[Int04]

The Mbed is connected to the 5V standby supply allowing it to remain connected to the network and power on the system on demand. The maximum power consumption of the Mbed is 200mA, well within the ratings of the ATX specification [Sem12b]. The Mbed's on-board regulator provides a regulated 3.3V supply used by the Mbed and the low-power electronics attached to it. The 3.3V supply from the PSU is not used because the regulator in the Mbed offers a cleaner supply which is always available.



(A) Without Magnetics (B) With Magnetics

Figure 4.11: X-ray of RJ45 sockets with and without integrated magnetics [Lom12]

To allow the PSU to be turned on by the Mbed, the power on signal is attached to a GPIO pin. Because the Mbed is a 3.3V logic device a MOSFET is used to connect the 5V Power On signal to ground (thus turning on the Power Supply) using the 3.3V signal from the Mbed.

4.1.7 Ethernet

Ethernet requires relatively complex circuitry to drive it. With the exception of the Ethernet magnetics, this is provided on-board the Mbed. A jack containing the magnetics (figure 4.11) was used to complete the system.

4.2 Firmware

In this section the firmware for the Mbed is described, starting with the infrastructure required for development on FreeRTOS on the Mbed and then moving on to the major components of the system. Finally the safety precautions taken and the tools and development practices used are outlined.

4.2.1 FreeRTOS on the Mbed

The Mbed is designed for use with a web-based IDE and compiler [Sem12a]. This system is not appropriate for use in the project as the process of uploading code to be compiled is laborious and the compilation options restricted.

The CodeSourcery G++ None-EABI toolchain includes a GCC ARM cross-compiler, linker and LibC compiled for various ARM based microcontrollers. It was selected over closed-source alternatives because it has a large community of users and produces good quality code.

An unofficial port of FreeRTOS for the Mbed is available designed for the CodeSourcery toolchain. It provides a base FreeRTOS configuration with a demonstration μIP based web server as well as other simple operating system demos. Also included are headers for the ARM Cortex Microcontroller Software Interface Standard (CMSIS) which defines a common interface for ARM Cortex microcontrollers [ARM12]. Finally, headers defining macros and pointers for all control registers in the Mbed are included.

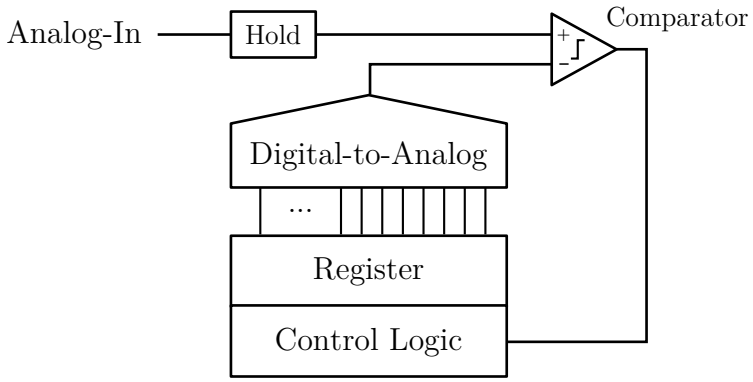


Figure 4.12: Successive-approximation analog-to-digital converter

Appendix E.2.2 contains specific compilation instructions for the final system with the CodeSourcery toolchain.

4.2.2 Temperature Control

To drive the two heaters an active-feedback loop is used where input from a thermistor is used to drive a heater via a MOSFET. The following subsections describe how analog values are read by the Mbed and the theory and operation of the feedback loop that controls the heaters.

Analog Input

The Mbed includes a 12-bit successive-approximation analog-to-digital converter (ADC) for reading analog values [NXP10]. The ADC uses a digital-to-analog converter and a comparator to binary search for an approximation to the analog value while the input is held constant (figure 4.12). Once an appropriate number of iterations of the binary search have been carried out, the value in the register is returned [Max01].

The ADC sampling process takes at least $5\mu s$ or approximately 500 CPU cycles therefore the CPU can carry out another task while the ADC process takes place [NXP10]. Though an interrupt is provided when the ADC completes (as well as a direct memory access (DMA) facility), this was not used. Instead, a slow-poll is used where the task reading from the ADC is suspended for a time typically adequate for ADC operation. The temperature sensors are sampled at an extremely low rate (around 2Hz) and latency is not important as changes occur very slowly. This system is very simple to implement with negligible overhead.

Heater Control Loop

A naïve controller could simply turn on the heaters whenever the temperature drops below some target temperature or 'set point' and then off when it was met or exceeded. This type of controller can cause the temperature to overshoot and fall below the set point as the heating and cooling of the system is not immediate. Instead a proportional-integral-derivative (PID) controller is used which can control heaters which takes into

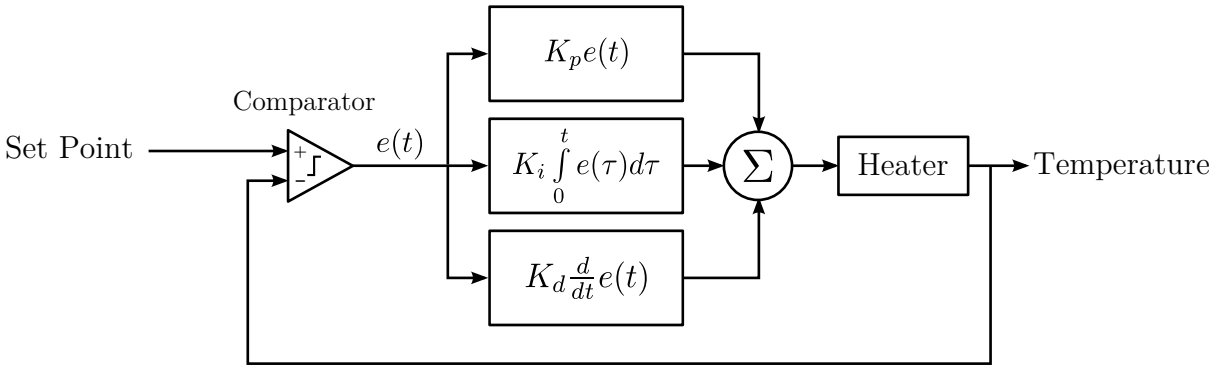


Figure 4.13: PID heater controller schematic

account such behaviours. PID controllers are widely used where a process which is not completely understood must be controlled [Ben93].

Figure 4.13 shows a schematic of the PID controller used in the system. At time t the comparator calculates the error, $e(t)$, between the actual temperature and the set point. A value is calculated from this error using a factor proportional to the error, the error accumulated over time (integral) and the error's rate of change (derivative). These factors are weighted by the constants K_p, K_i and K_d respectively and the result used to control the heater. The three weights must be chosen manually to produce sensible behaviour. §5.5 discusses how these values were selected.

The value calculated could be used to control an analog output or PWM[1] or a threshold value used to decide whether a heater is on or off ('bang-bang' control). Bang-bang control was used as the previous electronics proved this method to be adequate.

The PID control loop is executed in its own task twice a second when each temperature is read and the heaters switched on and off as appropriate. Executing the loop more frequently would not be useful because of the slow rate of change in the system. Doing so would also be costly due to floating point calculations being carried out in software.

4.2.3 Stepper Control

To drive the stepper controllers, accurately timed pulses must be produced to cause the stepper motors to move at the correct speed. These pulses also need to be coherent between motors so that the three axes can move simultaneously to plot straight paths.

Principle of Operation

Before each movement begins, a periodic timer is set based on the frequency at which steps must occur and is used to toggle the step signal. This is used instead of Bresenham's line algorithm to simplify implementation [Bre65]. Since expensive floating point calculations are required for value conversion into machine units, the additional calculation introduced is not significant. During each timer tick only cheap integer operations are required.

[1]Pulse width modulation (PWM) is a method of approximating analog outputs by rapidly switching a signal on and off with a varying duty-cycle. This is cheap to implement in hardware and avoids inefficiencies in MOSFETs when only partially driven.

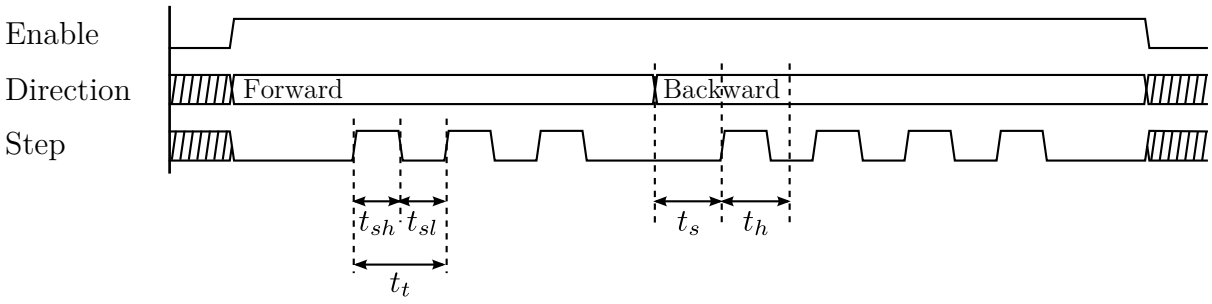


Figure 4.14: Stepper control signal wave diagram

Period	Meaning	Timing Constraint
t_{sh}	Step high	$\geq 1\mu s$ [All09]
t_{sl}	Step low	$\geq 1\mu s$ [All09]
t_s	Setup time	$\geq 200ns$ [All09]
t_h	Hold time	$\geq 200ns$ [All09]
t_t	Step time	$\geq 757\mu s$ (Experimentally determined)

Table 4.2: Stepper timing constraints

Timing Constraints

The stepper controller boards are based on an Allegro A3982 stepper controller which defines additional timing requirements. Table 4.2 gives the timing constraints for these signals. Figure 4.14 shows an example waveform with three forward steps followed by four backward steps. On the positive edge of the step signal the direction is sampled and the motor is stepped.

The motors in the printer add an additional timing constraint, t_t, due the limit on how often they can step defined by the mechanical properties of the printer. This is important because the faster the stepper is driven, the less torque is available and so the stepper may miss steps and fail to move.

Timer Requirements

If a stepper is set to run at its maximum speed, steps will be 757μs apart meaning that the signal must be toggled every 379μs. Therefore the output signals may change at up to 1.32kHz.

FreeRTOS provides timing guarantees for scheduling arbitrary delays within tasks. Unfortunately, this uses the system timer which ticks at 1kHz which is far too low for the frequencies such as those discussed above.

According to the Nyquist-Shannon sampling theorem a frequency of fHz can only be generated by a timer running at $> 2f$Hz. This means the timer resolution must be above 2×1.32kHz $= 2.64$kHz [Sha49]. Figure 4.15 shows 'aliasing' caused by trying to reproduce a signal at $\frac{2}{3}$ ($> \frac{1}{2}$) the frequency of the timer where whole cycles are missing in the output.

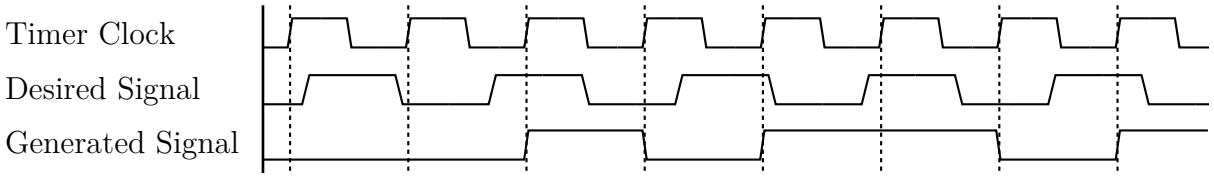


Figure 4.15: Nyquist-Shannon sampling theorem example with high-frequency signal

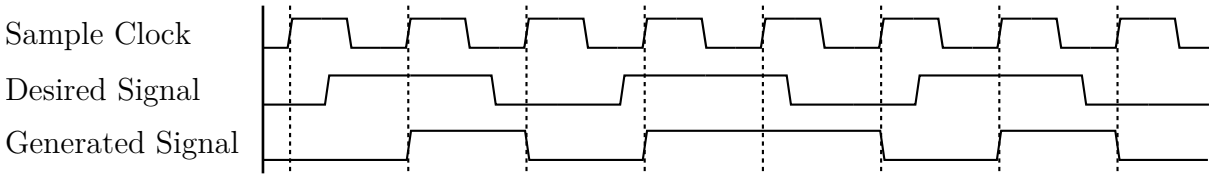


Figure 4.16: Example of sampling artefacts

The effect of sampling artefacts can cause further inaccuracies. Figure 4.16 shows a signal below $\frac{1}{2}$ of the sampling frequency displaying such artefacts. In the worst case when sampling at fHz, a signal change may be $\frac{1}{f}$s late. Therefore, increasing the sampling frequency decreases the error introduced by such artefacts.

High print quality depends on smooth, even steps, as a result, the timer resolution must be not only above 2.64kHz due to the Nyquist-Shannon sampling theorem but also be high enough to reduce sampling artefacts to an acceptable level. If errors due to artefacts are to be reduced in the worst case to, for example, one-hundredth of the step period then a frequency of 264kHz is needed.

Increasing the speed of the system timer to such a frequency would make the overhead of the scheduler unacceptable and so the FreeRTOS timer cannot be used. Instead a hardware timer which interrupts the microcontroller causing a light weight interrupt service routine (ISR) to run will be needed.

Because the Mbed only provides a limited number of hardware timers, just one is used to control all three steppers. As each stepper may not be in phase, the time between signals being produced for each stepper can become very small, even when the step period is large. This is another example of a sampling artefact where the resulting errors are at worst $\frac{1}{f}$s for a timer running at fHz. Because the timer is already sufficiently fast to make such errors insignificant, no extra precision is required when sharing a timer.

The timers provided on board the Mbed consist of a register comparator and counter which is incremented by the system clock after being passed through a clock divider (figure 4.17). The timer was configured such that when the counter matches the value in the register, the counter is reset and the CPU is interrupted. The timer was configured to run at 1MHz which exceeds the 264kHz requirement calculated above with some additional margin.

The ISR for the timer interrupt determines for each stepper, whether its step signal should be toggled and calculates how long until another interrupt is required. The timer compare register is updated, the ISR returns and normal program execution resumes.

GCC generates approximately 100 instructions for the ISR taking an estimated 250 cycles to execute[2]. Assuming the CPU executes one instruction per cycle at 100MHz the

[2]Estimate based on informal analysis of the generated assembly code

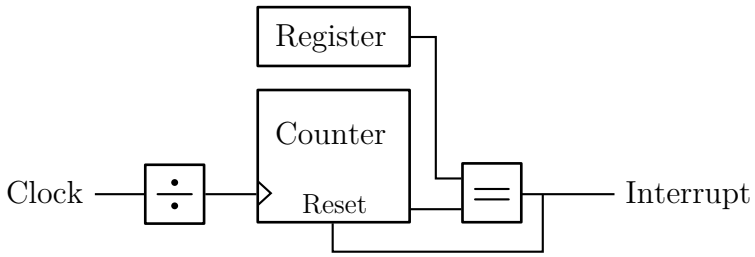


Figure 4.17: Mbed timer architecture

amount of CPU time used by the ISR in the worst case can be calculated as follows:

$$\text{Overhead} = \frac{\text{Interrupts Per Seccond} \times \text{ISR Cycles}}{\text{Cycles Per Seccond}} = \frac{(1.32 \times 10^3) \times 250}{100 \times 10^6} = 0.33\% \quad (4.4)$$

This design results in very little overhead in the system but provides very accurate signals to the stepper motors.

Usage

An API is provided which allows a number of steps in a given direction with a specified period to be sent to a stepper motor. To allow sequences of coherent movements to be made, a method which blocks until all steps have been completed is also provided. This method uses a semaphore which is released by the ISR when all steps have been completed. This is also used to temporarily give a higher priority to the controlling task during which time the next sequence of steps can be started immediately.

4.2.4 G-Code Interpreter

In this subsection there is a discussion of the selection of G-code features implemented by the system. Following this, the implementation of the parser and interpreter is described.

Feature Subset Selection

G-code interpreters support a large variety of features ranging from comments and instructions which return data to error checking. As well as various language features, the actions available and their precise behaviours differ.

To keep the system as simple (and fast) as possible, only features and actions required to support the output of Skeinforge's G-code generator were implemented. The resulting language simply supports comments and writing to registers. The syntax supported is given in Backus-Naur Form (BNF) in appendix D.1.1.

Actions (and their treatment of registers) were also selected based on the output of Skeinforge and include:

- Unit selection
- Calibration
- Movement

- Motor control
- Power control
- Temperature control
- Delays

A complete description of the actions supported is given in appendix D.2.

Parsing

The G-code subset supported is very simple and so a small parser was implemented by hand rather than using a standard parser generator such as GNU Bison. Such tools also generate code that is not optimised for running on a microcontroller in a real-time environment and would have been time consuming to learn.

A simple state machine was built which parses and executes the G-code setting and reading registers as described in §2.1.5. When unexpected characters or register values are encountered a flag is set and the parser continues from the next character or instruction.

Once each instruction is parsed and the register values set, the values are converted into machine units. For example, movements are converted into relative movements measured in stepper motor steps and speeds converted into step periods measured in timer ticks. These low-level commands are then added to the command buffer to be executed by the printer controller.

4.2.5 Printer Controller

The printer controller uses a FreeRTOS queue in a high priority task to buffer low-level commands from the G-code interpreter. The controller consists of a simple loop which executes each command requiring minimal processing. As a result, this task spends most of its time blocked waiting for actions to complete but responds quickly when required.

4.2.6 Network Interface

The network interface consists of two services built on the μIP stack: a G-code transmission interface and a status monitoring interface. μIP provides a simple API for sending and receiving data over TCP and UDP within applications built within its protosocket and protothread frameworks [Dun06].

Protothreads are extremely lightweight threads using cooperative multitasking implemented in pure C. These threads do not preserve registers or variables during blocking phases of execution and use minimal system resources. Protosockets are a simplified UNIX-style socket interface built on protothreads. These libraries are designed with extremely low-power microcontrollers in mind. As a result, only a minimal application is implemented within the μIP framework which passes data from the network immediately to the other parts of the system.

The G-code was initially implemented using TCP but a bug in μIP's flow control implementation meant an alternative implementation was required and built on UDP. The two protocols are outlined below along with an additional TCP interface used for reporting the system's status.

TCP G-code Interface

The TCP G-code interface consists of an open port listening for connections. Once connected a client simply sends the G-code to the printer and disconnects when finished. Telnet or net-cat (`nc`) can be used to send G-code files to the printer, for example

```
nc 192.168.3.100 1818 -q 0 < model.gcode
```

Where `model.gcode` is the file to send and `193.168.3.100` is the IP of the printer.

As the G-code subset supported does not support return values, nothing is returned by the printer.

UDP G-code Interface

Unfortunately, as discussed in §5.3, the TCP implementation in μIP is incorrect. Due to time constraints this was not fixed during the project. Instead a UDP based protocol was implemented.

UDP provides a facility for sending datagrams containing a small amount of data to a remote host. These datagrams are not guaranteed to arrive or to arrive in the order they are sent. They do include a checksum and so if a datagram arrives it can be safely be assumed to be intact. Finally no flow-control mechanism is provided (excess packets are silently dropped). They are, however, lightweight and a good base for building custom protocols.

UDP alone cannot be used to send data to the printer and simple protocol has been built on top which provides a communications channel which is

- Reliable
- Unidirectional
- Order-guaranteed
- Flow-controlled

Figure 4.18 shows the format of datagrams sent between the printer and sender. Datagrams are sent to the printer which contain a sequence number and a payload whose length can be calculated based on the datagram's size (contained in the UDP header). The sender then waits for a response from the printer containing the same sequence number and a window size. The printer will only respond if a datagram with an appropriate sequence number is received discarding out-of-order datagrams. If a response with a matching sequence number is not received by the sender within a short timeout, the datagram is retransmitted. This mechanism facilitates reliable, in-order transmission.

The window size returned by the printer is used for flow control and is the amount of space in the G-code buffer or the maximum datagram size (whichever is smallest). The sender may send up to this amount of data to the printer in its next datagram ensuring the printer is always sent as much data is it can deal with. If the G-code buffer becomes full then the window size will become zero the sender must poll the printer until the window size becomes non-zero.

§5.3 discusses the performance and practical implications of this protocol and the full specification is given in Appendix F.1.

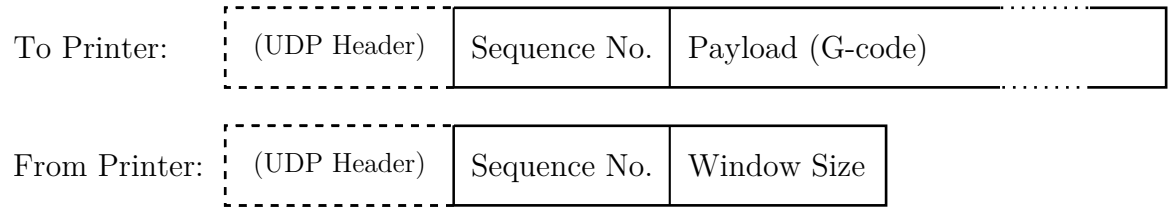


Figure 4.18: UDP G-code Sender Datagram Format

Status Interface

A simple Telnet-compatible TCP interface (listening on port 2777) was implemented that can be used to request the contents of various status and debugging variables. As flow control was not necessary, the TCP implementation in μIP is adequate for this purpose.

The interface listens for keywords separated by white space and responds with tab separated data compatible with GNU Plot. For example:

```
tmp
22523 22500 0 11800 12000 1
```

The command `tmp` requests current temperature information. The response contains the current temperature, set point (target) and whether the heater is on or off for the extruder and the platform. Temperature readings are given in degrees Celsius multiplied by 100. This is due to the version of LibC provided with the CodeSourcery tool chain not supporting printing of floating point values.

A utilities for using the status monitoring facility are described in the next section and full documentation for the protocol is given in Appendix F.2.

4.3 Utilities

Two utilities for interacting with the printer were written in Python. The first, a client implementing the UDP G-code transmission protocol and, the second, a utility for conveniently monitoring the printer status. These utilities are part of the `makebed.py` command.

For example, the following command will stream the G-code contained in `cube.gcode` to the printer:

```
makebed.py send cube.gcode
```

While print jobs are running the status information can be requested or polled. For example:

```
makebed.py get temperature
```

Additionally, a simple wrapper, `makebed_live.sh`, is provided written in Bash using GNU Plot to plot various pieces of printer status information in real-time (figure 4.19).

Usage information for the utilities can be found in Appendix E.3.

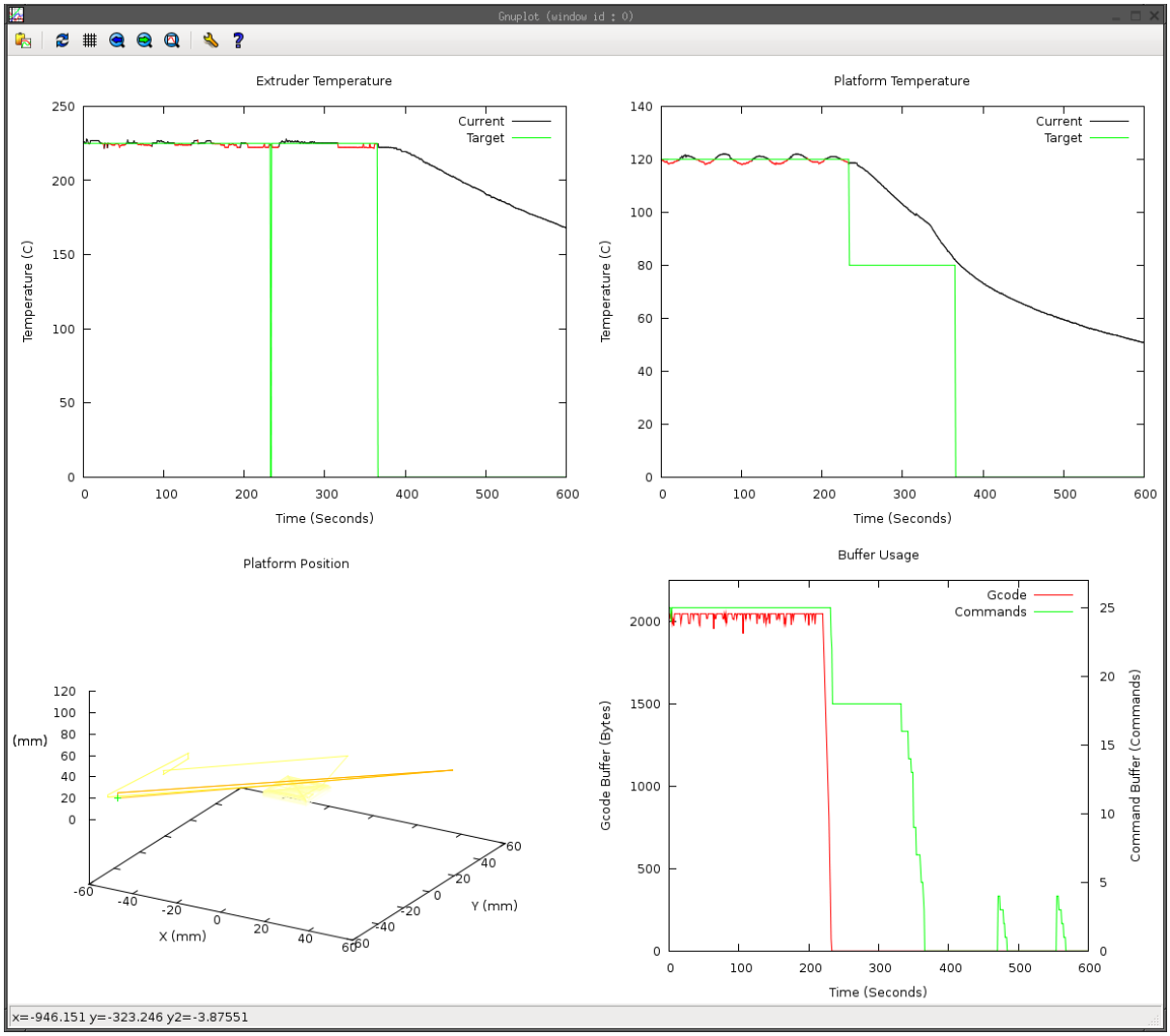


Figure 4.19: `makebed live.sh` screen shot

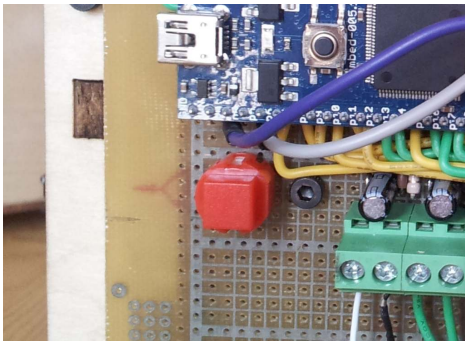


Figure 4.20: Emergency stop/reset button

4.4 Safety

Because the system contains heaters and moving parts, safety was a major consideration when implementing the system. This section outlines the key features used to ensure operation is as safe as possible including human-interaction features and fail-safe design.

4.4.1 Heater Indicator LEDs

The two heaters each use an indicator LED on the microcontroller to indicate when the heaters are powered on. This enables an operator to easily and safely check the state of the heaters during operation.

4.4.2 Power-on Behaviour

On power-on, the PSU is not turned on and so the heaters and motors do not receive power. The only way to start the heaters is to open a new connection to the printer and send the required PSU and heater instructions. This design means that if the printer is powered on unintentionally it will not do anything unsafe. It also means that resetting the printer has the effect of putting it into a safe state where an explicit action is required to restart it.

4.4.3 Stop Button

The electronics connect the Mbed's reset pin to a larger and easier to press red button (figure 4.20). Because of the safe power-on behaviour and indifference to software failures this button can always put the system into a safe state.

4.4.4 Watchdog Timer

The most safety critical software process is that of the heater controller. If this routine fails for any reason the heaters may become stuck powered on. As over-heating is not as obvious to the operator as for example, a jammed axis, this is a particularly dangerous fault.

To catch such faults the Mbed includes a hardware watchdog timer (WDT). The WDT contains timer which, upon timing out, resets the system. The WDT must be 'fed'

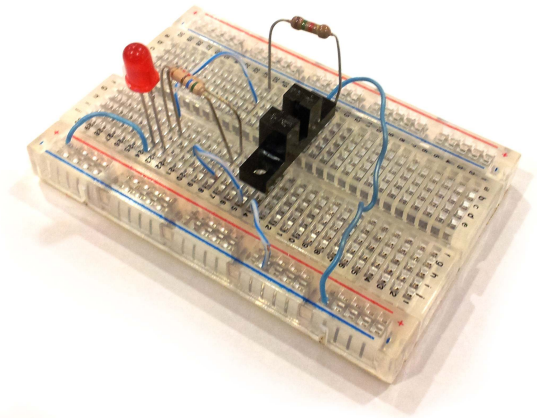


Figure 4.21: Breadboard with a prototype end-stop circuit

(reset) periodically to prevent it resetting the system. To feed the WDT specific values must be loaded in the correct order into a control register. This mechanism can catch bugs which cause the routine to jump to a random location, block for an excessive period or otherwise become corrupted.

The heater controller loop executes at 2Hz and the WDT is fed at the end of each iteration of the control loop. The WDT is set with a timeout of two seconds meaning that it should never come close to a timeout except in the event of a control loop has failure or the system resources have somehow become saturated.

After the WDT has reset the system it enters a safe state where the heaters do not have power and are allowed to cool safely.

4.5 Methodology & Tools

In this section the methodologies used for the implementation of the system are discussed followed by the choice of languages and development tools and why they were selected. Finally the methods used to debug the firmware running on the Mbed are described.

4.5.1 Methodology

Development followed an iterative, bottom-up process where components were built, tested and then integrated into the system as a whole.

Prototyping was used heavily in the development of the electronics. The major parts of the circuit were initially prototyped on a solderless breadboard and powered by a bench power supply (figure 4.21). In these prototypes, different components could easily be swapped in and out of the design and measurements easily taken with the system running at different voltages.

The UDP protocol was also initially prototyped using a high level language (Python) allowing quick development and testing. Some parts of the prototype were subsequently modified and used as part of the off-printer client software.

4.5.2 Languages

The firmware was written entirely in C. As well as a mature compiler and manufacturer-provided header files, C strikes a good balance between the availability of sensible abstractions and providing low-level access to the underlying hardware. Thanks to a policy of manual, static memory management no garbage collection or dynamic memory allocation was required which helps make system performance more deterministic.

The off-printer utilities are written primarily in Python and include a wrapper shell script written in Bash. These languages provide very high levels of abstraction simplifying and accelerating development. The performance costs incurred by using such languages are not relevant on a modern PC for the simple tasks required and so represent a good fit for the project.

4.5.3 Version Control

To track changes and keep snapshots of the project's code, Git was used for version control [git12]. Git provides facilities for quickly comparing versions of code. It also allows experimental copies or branches of the code base to be created and independently modified. Useful changes can be made in their own isolated branches and easily be merged back into the main version of the system. Changes can also be quickly reverted. These features allowed new ideas to be created and tested without fear of irreversibly altering the system.

4.5.4 Debugging

Microcontrollers are typically debugged using a JTAG (Joint Test Action Group) interface which allows the microcontroller to be paused, stepped and examined during program execution. Unfortunately the Mbed does not expose this interface and so all debugging must be carried out through the input/output facilities provided.

The port of FreeRTOS used included a demonstration web server which was modified during the first iteration of firmware development to allow program variables to be exposed through this interface. Eventually the demonstration code was removed and the status interface described in §4.2.6 was put in its place providing equivalent facilities. Both interfaces allowed internal variables to be polled, examined and graphed on a PC.

As well as the firmware itself, its interactions with the network also required debugging. To do this Wireshark, a network analyser was used. This allows the individual packets sent and received by a computer to be monitored, filtered and examined. It also includes protocol specific features such as protocol checking and protocol-specific statistics.

Chapter 5

Testing & Evaluation

As the system was built, the individual parts were unit-tested extensively before integration into the rest of the system. Integration tests were then performed followed finally by a series of full system tests. This strategy meant testing was a continuous process throughout the implementation and identified bugs early.

In this chapter the tests carried out during development are described along with an evaluation of the results. Each section describes the tests a major component of the system was subjected to concluding with an evaluation of the system's overall performance.

5.1 Electronics

The major components of the electronics were prototyped and tested on a breadboard with the use of a multimeter. The higher power components, such as the heaters and motors, were initially disconnected or tested with low-power test loads until the circuit was deemed to be correct. Once connected, these components were then tested under operational loads with careful supervision to ensure that they functioned correctly and that the current flowing through each part of the circuit was as expected. The tested circuit designs were then soldered together on circuit boards where the connections were first tested for continuity and checked for short circuits before performing integration tests on the system.

Overall the electronics performed well and no problems caused by electrical noise generated when switching high-power loads were observed. The parts of the system which were found to exhibit unexpected behaviour are outlined in the following subsections.

5.1.1 MOSFETs

The MOSFETs were able to switch on the heaters and bring the system from room temperature to operating temperature within 10 minutes, matching the performance of the previous system as expected.

After an extended period of being powered on, the MOSFETs became hot running at around 50°C. The data sheet for the IRLU8729PbF MOSFETs states that the operating temperature range is from -55°C to 175°C and so this temperature is safely within operational limits.

5.1.2 End-stops

Printed plastic paddles were originally planned as the triggers for use with the end-stops. Unfortunately, acrylonitrile butadiene styrene (ABS) plastic used by the Makerbot is transparent to the infra-red wavelengths used by the opto-interrupters and so this material is unsuitable. The design was changed to instead use wooden craft 'lollipop sticks' which fit into pre-cut slots in the Makerbot and easily trigger the opto-interrupters.

5.1.3 ATX PSU

Some ATX PSUs require a certain load on all provided voltages in order to power up properly [Rep12e]. While a large load is drawn on the 12V line by the heaters and motors, the 5V line only powers the Mbed which draws little power. The result of this is that the 12V line attached to the heaters only provided 9V and so could not warm up to the required temperature.

A resistor can be added to the 5V line to draw extra current and fully power up the PSU [Rep12e]. Due to time constraints an alternative PSU was used which did not feature this behaviour rather than modifying the circuit. With the new PSU, all voltages met their specified requirements.

5.2 FreeRTOS

The availability of the FreeRTOS port made it extremely easy to integrate into the project. FreeRTOS itself provided the right balance of features and performance for the project. The operating system did not place restrictions on the use of low-level system registers and simply provided preemptive multitasking and some atomic operations as required.

The operating system was initially tested for timing accuracy using a frequency probe attached to an I/O pin toggled by a simple demonstration program to ensure the system was behaving as expected. This test yielded a mismatch from the expected frequency which was found to be an incorrect definition of the system clock speed in a FreeRTOS header file. Once fixed the system ran as expected running the included demo and test programs as defined. No further issues were found during the course of the project.

5.3 μIP & Networking

Various tests were conducted on the μIP stack during the project, concentrating on performance and correctness of the features used. This section discusses these tests and concludes with an evaluation of μIP's suitability for the project.

Wireshark was used to monitor the packets sent between the Mbed and computer where it became apparent that every packet from the Mbed was being duplicated. After ruling out network problems as the cause, the bug was traced down to the Ethernet driver provided by the demo. The driver duplicated every packet sent to the network (including IMCP Ping Requests, figure 5.1). As well as wasting bandwidth, if a TCP packet acknowledgement (ACK) from the Mbed was to be delayed in the network, retransmission

```
$ ping 192.168.3.100
PING 192.168.3.100 (192.168.3.100) 56(84) bytes of data.
64 bytes from 192.168.3.100: icmp_req=1 ttl=64 time=0.364 ms
64 bytes from 192.168.3.100: icmp_req=1 ttl=64 time=0.385 ms (DUP!)
64 bytes from 192.168.3.100: icmp_req=2 ttl=64 time=0.175 ms
64 bytes from 192.168.3.100: icmp_req=2 ttl=64 time=0.195 ms (DUP!)
64 bytes from 192.168.3.100: icmp_req=3 ttl=64 time=0.195 ms
64 bytes from 192.168.3.100: icmp_req=3 ttl=64 time=0.212 ms (DUP!)
64 bytes from 192.168.3.100: icmp_req=4 ttl=64 time=0.179 ms
64 bytes from 192.168.3.100: icmp_req=4 ttl=64 time=0.195 ms (DUP!)
^C
--- 192.168.3.100 ping statistics ---
4 packets transmitted, 4 received, +4 duplicates, 0% packet loss, time 3000ms
rtt min/avg/max/mdev = 0.175/0.237/0.385/0.081 ms
```

Figure 5.1: Ping responses being duplicated by the μIP driver

will result in four duplicate ACK packets. This causes the sending computer to retransmit and incorrectly adjust its expectations of the network connection when the packets are eventually received [Sch12]. This behaviour is one factor that can prevent TCP flow control from functioning correctly.

The packet duplication behaviour is often added to μIP implementations to work around problems caused by μIP only allowing one packet to be sent at a time [Mai]. Modern systems (such as Windows and Linux) will allow several packets to arrive before acknowledging them all at once, saving bandwidth reducing the effect of network latency. This delays the transmission of the next packet by μIP as it waits for the ACK. By duplicating each packet, the receiving computer is forced to immediately send an ACK as, from receiver's perspective, a duplicate packet may indicate that the original packet was delayed in the network and the sender did not receive an ACK in time in this case because the receiver had never sent it. As a result the receiver sends the ACK immediately allowing μIP to send the next packet.

Though this wastes bandwidth it reduces the wait between each packet being sent and in practice dramatically increases the bandwidth available when sending data from the Mbed to the computer. Disabling this work-around means sending multiple-packet bursts of data to a computer is more time consuming but removes a barrier to flow control being used successfully. The only data sent from the Mbed are status responses which are small enough (around 30 bytes) to fit in a single packet. Disabling packet duplication, in favour of removing a barrier to proper flow control, is a good trade off.

Unfortunately, problems with flow control persisted with no improvement after disabling packet duplication. With the duplicate packets removed, the traffic became clearer. To enable flow control, TCP sends a window size with each packet representing the amount of data the receiver is able to receive. μIP reports a constant window size until the method `uip_stop()` is called when the window size is set to zero and any further packets received are discarded. The zero window message is resent until `uip_restart()` is called and the old window size is restored. A packet is then sent to the computer to

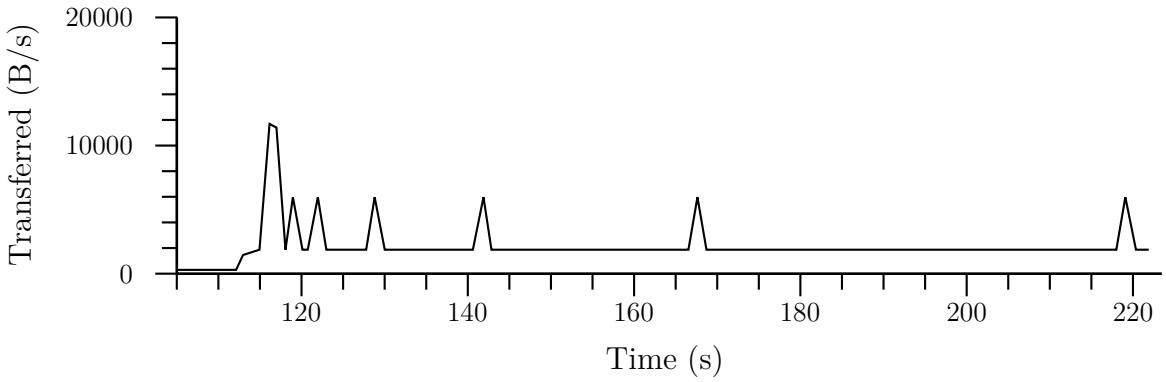


Figure 5.2: Exponential back-off by computer when μIP flow-control used

request data transfer to continue.

To test this mechanism, a program was written which produced a long sequence of small movement G-code instructions. This causes the buffer to initially fill up and then be constantly kept topped up by the computer while being restrained by flow control. The actual behaviour of the connection (shown in figure 5.2) shows the buffer is initially filled (the first spike) but then the sender waits an exponentially growing period until it starts filling the buffer again regardless of when the window size is made non-zero.

By inspecting the packets sent and received, the window size is always obeyed by the computer but the packet announcing the window size becoming non-zero appears to be ignored as transmission is not immediately resumed. Wireshark's protocol checker did not report any errors and comparison with the known-working implementation of TCP flow control in Linux did not reveal any obvious differences. Unfortunately further study did not yield a diagnosis for the problem. Due to the time constraints imposed by the project TCP had to be dropped for G-code transmission in the project.

5.4 Temperature Readings

The temperature readings depended on correct values being read from the analog inputs and on correct calculation of the temperature based on these readings. Consistency of readings is important, reading temperatures close to the actual value, however, is relatively unimportant. This is because the temperature is fairly uneven within the heated components of the printer and so it is difficult to define a 'correct' reading. The actual temperature values used during printing are calibrated manually and so the absolute temperature in °C is not significant.

To test analog input, a selection of resistors with known values within the range of values the thermistor could exhibit were tested. As well as breadboard testing, the test was repeated on the final circuit board as the screw terminal used to connect the thermistors could also be used to connect a test resistor directly.

When converted to a resistance using (4.3), the values read were found to be within $\pm 2\%$ of the resistor value as read by a multimeter (a difference which is accounted for by the fact that a second resistor with a $\pm 5\%$ tolerance is used in the potential divider).

To test that temperatures were being correctly calculated, an infra-red thermometer (figure 5.3) was used to take reference temperature readings from the extruder and plat-

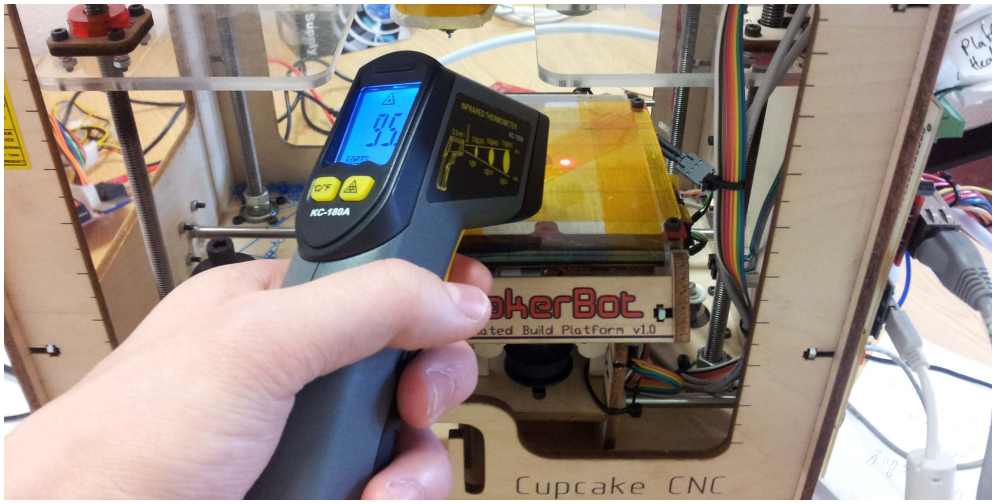


Figure 5.3: Checking platform temperatures using an infra-red thermometer

form. The heaters were turned on and readings were taken every minute as the extruder and platform heated up and then every five minutes for half an hour as it cooled down. The tests were repeated multiple times alongside other experiments, each time with similar results, to ensure consistency. These values were then compared against the value calculated using (4.1).

The radius of the area measured by the thermometer becomes larger as it is moved further away from the target. Because the temperature across the platform and extruder vary greatly depending on location, the thermometer was placed close to the centre of the extruder nozzle and the centre of the build platform where the thermistors reside.

The temperatures recorded for the extruder were within ± 1°C below 100°C but rose to around $+8 \pm 1$°C around 220°C (normal operating temperature).

The platform temperatures were initially incorrect by ± 10°C or more. This was caused by a simple connection error. Once the problem was corrected, readings followed a similar pattern to the extruder (up to the 125°C the platform is designed to operate at).

The results above represent adequate performance for the task of maintaining a desired temperature and also show that the temperatures read are close to their real values such that an operator can safely tell from a temperature reading that the device is unsafe to touch. The error at high temperatures may be a result of not being able to use the thermometer to measure the internal parts of the extruder where it is hottest.

5.5 PID Control

The PID controller has three constants (K_p, K_i and K_d) which must be manually tuned to yield sensible system performance. An optimal system has oscillations in temperature that are as small as possible.

PID controller tuning is a non-trivial problem for which automated solutions are either highly specialised or unavailable. Heuristics exist such as The Ziegler-Nichols method for selecting good values which work in many cases and require human interpretation [ZN42].

Constant	Extruder Value	Platform Value
K_p	5.143	7.0
K_i	0.0612	0.342
K_d	108.0	36.0

Table 5.1: Generic PID controller constants for a Makerbot [Ind12c]

The Makerbot wiki suggests values (given in table 5.1) which yield adequate performance on many printers [Ind12c]. After selecting these values the printer's performance was monitored both while idle and during printing and the size of the oscillations were measured. Performance was similar in both states (with the exception of a temperature jump in platform temperature at the start of printing caused by molten plastic being extruded on top of the thermistor). Oscillations were $\pm 2°C$ for the extruder and platform. Due to time constraints, further improvements in tuning could not be achieved. Though this is greater than the $\pm 1°C$ recommended, print quality was not adversely affected.

5.6 Stepper Control

The amount of plastic deposited at a given point during a print is dependent on the rate at which the plastic is extruded and also the rate at which the platform moves. The accuracy of the timing (combined with the mechanical properties of the machine) determines the platform's rate of movement and thus the print quality.

The stepper control system consists of code for producing accurately timed steps and code for coherently moving the stepper motors. These two parts were tested separately as described in the following subsections.

5.6.1 Timing

To ensure timing accuracy, the three stepper signals were driven at a combination of frequencies with a frequency probe attached to the step pin. These tests were generated initially using a program on the microcontroller (so that the system was not under any load) and then using G-code sent over the network interface while other requests were being made (to place the system under reasonable load).

The frequencies measured were exact to within the accuracy of the probe (four significant figures) for all tests.

5.6.2 Stepping

To test that steps happened coherently, with sequences of steps correctly spaced apart, the system was connected to the printer and circles were plotted. The circles are made up of short, continuous line segments where the relationship between the movements on each axis varies. Once again, the test was initially conducted using a test program running on the Mbed and then by G-code sent over the network. The number of segments the circle was divided into was increased from 30 to $3,000$ and the speed set to 330mm/minute and 3300mm/minute to test slow and fast movements.

The performance of the system was measured by visual inspection of the movement and circles plotted by attaching a pen to the extruder. The time taken the plot the circles was also measured using a timer on the Mbed to see if the processing overhead between each segment caused significant drift. Above around 100 segments the circles drawn appeared smooth and at low and high speeds the overhead after 20 circles had been plotted at each speed and resolution was less than the 1ms resolution of the timer. Finally, to ensure that steps were not missed, the system was moved to a known point between tests and this did not drift after all tests had completed.

5.7 End-stops

The endstops were tested under various lighting conditions to observe the effect of external lighting on the opto-interrupters. The following lightings conditions were tested:

- Ambient strip lighting
- Ambient halogen lighting
- Ambient incandescent lighting
- Ambient natural light
- Direct halogen lighting
- Direct incandescent lighting
- Darkened room

Testing consisted of blocking each opto-interrupter by moving the printer axes so that the end-stop is triggered and observing the digital value read by the Mbed and the state of the debugging LED. Under all but the direct lighting conditions the correct value was read and the debugging LEDs were either completely off or completely on. Under direct lighting, especially incandescent lighting, the state read by the Mbed for some end-stops became stuck due to external light shining into the opto-interrupters. In these cases the debugging LEDs did not become completely 'off' indicating that the opto-interrupter was being only partially triggered.

Though these results suggest that the end-stops cannot be used under direct lighting from halogen or incandescent bulbs, the system was found to perform well outside these conditions. Although not tested due to unfavourable weather conditions, direct natural light may also have caused similar problems. While these restrictions are unfortunate, they are not unreasonable and still allow the system to be used in practice.

5.8 Buffer Utilisation

To ensure that the printer pipeline did not stall during print jobs, the G-code and low-level command buffers were monitored during the execution of various test jobs. If buffer

underruns occurred or poor buffer utilisation was observed, it could indicate a performance issue in the G-code interpreter, network interface or their interaction with the operating system.

The utilisation of each buffer along with a counter for the number of underruns experienced by the command-buffer were logged while various G-code files were sent to the printer. Most testing was carried out during the system testing phase but the following synthetic tests were also used.

Circle plotting with low detail This test ensured that, given a sequence of slow G-code instructions, the printer keeps all buffers reasonably full and that the network interface can cope with small, infrequent bursts of data.

Circle plotting with high detail This test ensures that, given a constant sequence of fast G-code instructions, the printer keeps all buffers reasonably full and that no underruns occur during busy periods.

Circle plotting with high detail and pauses This test ensures that given a sequence of fast G-code instructions separated by pauses (where the buffers filled and the network interface paused) the transmission can quickly restart after the pause.

In all tests the buffer levels were generally above half full in the worst case. In a small number of instances the underrun counter was triggered but no effect on the printer was observed. These underruns may have been the result of FreeRTOS not allocating enough resources to the G-code interpreter until the low-level command buffer emptied (but while the G-code buffer was still full). Once the G-code interpreter was allowed to execute, printing would have continued immediately resulting in the unobservable pauses observed.

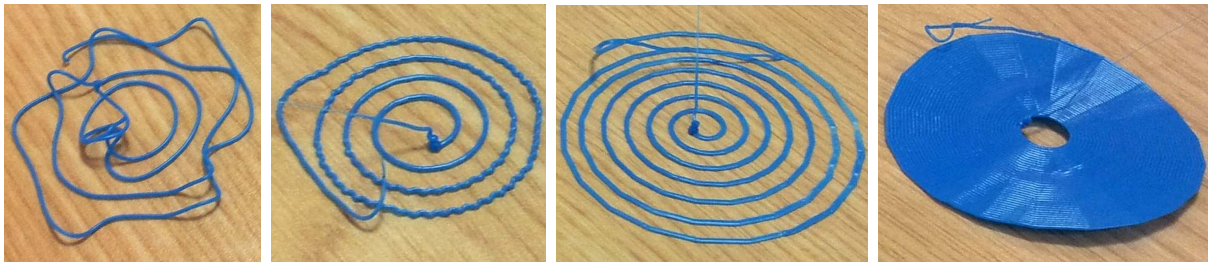
5.9 System Testing

The system was tested as a whole to assess its performance in both printing synthetic benchmarks as well as printing real-world objects. These tests also aided in calibration of the G-code generator (Skeinforge). The synthetic tests allow the printer's performance to be objectively measured while real objects show the real-world performance of the printer in its intended application.

5.9.1 Synthetic Tests

As a simple test of using all of the printer's components coherently, the circle plotting test was modified to produce spirals and the heaters and extruder enabled. Figure 5.4 shows samples of the output of these tests:

(A) The extruder was moved at a safe distance from the platform to ensure that all components move coherently but without the risk of the extruder colliding with the platform or blocking the nozzle of the extruder.



(A) (B) (C) (D)

Figure 5.4: Synthetic 3D printer tests for basic calibration

Figure 5.5: Bad print of the test in figure 5.4(D)

(B) As in (A) but the extruder is moved closer to the platform to test that the system can safely operate close to the platform and that the plastic adheres properly (and then is properly detached when ejected).

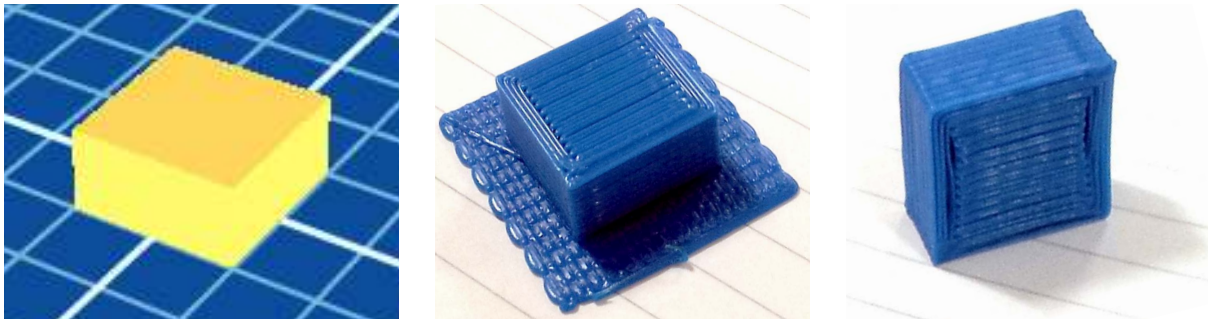
(C) A larger spiral was printed to test that the plastic adheres closer to the (colder) edges of the platform and that warping due to temperature changes during the print, does not cause problems.

(D) The winding of the spiral was tightened to test that the plastic adheres to itself and the platform and that warping does not cause the print to fail. Figure 5.5 shows a print where the spiral was printed too loosely and it did not adhere to itself.

These prints were repeated, varying the platform temperature, Z-axis position (height) and the tightness of the spiral until the tests performed as described above. These tests ensure that the printer is capable of operating all its major components coherently in order to produce printed object.

To test the system with G-code generated by Skeinforge, a simple 3D model of a cuboid (Figure 5.7 (A)) was printed. This print yields a cuboid of known dimensions and used to check calibration settings for Skeinforge and assess the printer's performance.

Figure 5.6: Digital callipers being used to measure test cuboids



(A) (B) (C)

Figure 5.7: Test cuboid model (A) print from Skeinforge G-code before raft removal (B) and after raft removal (C)

The cuboid was initially printed on top of a thick 'raft' of plastic (used to ensure an even printing surface) and then separated using a chisel.

The dimensions of the cuboids were checked using a pair of digital callipers (figure 5.6) to ensure that the printed object is of the correct size. The Makerbot wiki claims that 0.1mm resolution is possible on a correctly tuned machine and this requirement was met by most of the printed cuboids [Ind12b]. In a small number of cases, the Z-axis of the printer did not move the required amount due to the mechanism jamming, a known problem with the Makerbot design [Jet12]. As a result, these prints were of the incorrect height but were otherwise correct and the problems not attributed to the firmware.

5.9.2 Test Objects

To test the printer's ability to produce useful objects, various objects were printed including objects with moving parts or near the print size limits of the printer. These tests check the system's ability to deal with large and complex loads. A selection of printed test objects is provided in Appendix B.

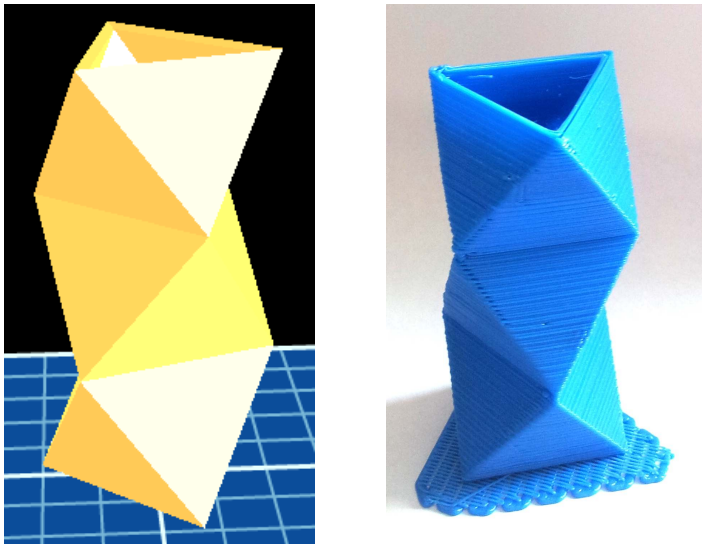
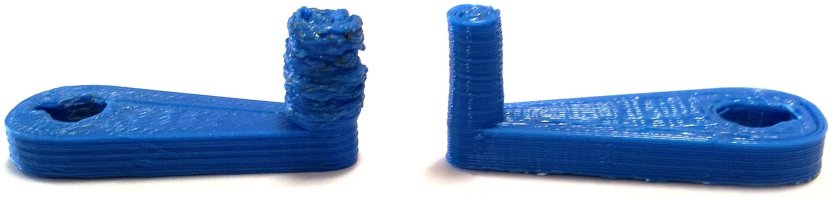


Figure 5.8: 3D printed vase with detailed corners



(A) (B)

Figure 5.9: 3D printed Z-axis handle comparison of old (A) and new (B) electronics

Detailed Prints

Prints with detailed areas were used to test that the system could process the larger density of G-code at the required rate and also to ensure that steps were not missed during printing.

For example, figure 5.8 shows a vase which yields very short line segments while printing the corners of the shape. The previous electronics would not be able to process this design fast enough and would skip instructions causing steps to be missed. With the new electronics no buffer underruns or printing problems occurred during a run featuring a large version (shown) and a smaller version containing finer detail.

Figure 5.9 shows an object which has a small cylindrical handle printed with the old and new electronics. With the old system, the G-code was not processed fast enough resulting in the printer stalling and depositing extra plastic. The new system was able to process the same amount of G-code without stalling.

Figure 5.10 shows a pair of herringbone gears printed with the old and new electronics. (A) and (B) show how the new system is able to produce rounder circles due to better timing accuracy. (C) and (D) show the effect of improved timing accuracy on the teeth of the gears.

Figure 5.10: 3D printed herringbone gear comparison of old (A) & (C), and new (B) & (D) electronics

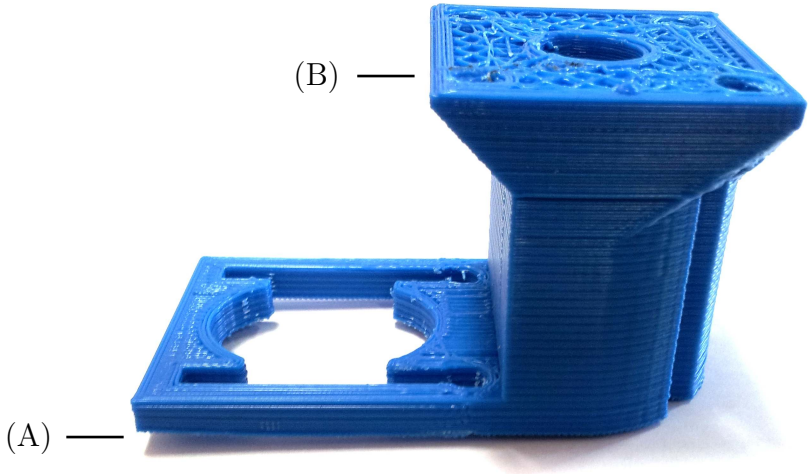


Figure 5.11: Failed large print showing warping (A) and a collision with the extruder (B)

Large Prints

Large prints stress the printer and electronics for long periods and can reveal missed motor steps or instructions. The previous system had frequent issues printing large test objects due to skipped instructions or steps and is a particular area for improvement.

Of the large objects printed, only one failed to print (figure 5.11). This was due to the object warping (A) and then becoming detached from the platform during the print causing the tip of the extruder to rip the object off the platform (B). Unevenness in the temperature of the object during printing is the cause of this distortion. This is partially caused by unevenness in the temperature of the build platform. Unfortunately, this is a problem with the printer's design which is not addressed in this project.

Raftless Printing

Though the first prints were completed on top of a raft, it was later disabled. This reduced print time, improved print quality and allowed intricate designs such as combs to be printed where removal of a raft would damage the design (figure 5.12).

Many objects were reprinted using raftless printing and performance was generally

Figure 5.12: Folding ‘butterfly comb’, printed without a raft

similar with the exception of larger designs. These experienced greater warping without the support of the raft and thus were more prone to failure due to the extruder hitting the object.

Chapter 6

Conclusions & Future Work

In this chapter, the outcomes of the project are compared against the initial goals and future work is suggested based on lessons learnt and the limitations the project.

6.1 Project Goals

The three project goals have each been addressed within the project and in this section the degree to which they have been met is discussed.

6.1.1 Electronics Replacement

The new electronics functionally replace all the features of the old electronics and have proved reliable in testing. With a single board the system is also a lot simpler than the previous three boards (removing the need for a custom communications protocol and extra microcontroller). Though not quite as polished as a printed circuit board (PCB), it offers the possibility of future expansion.

The solid state MOSFETs, used for heater control, have performed well with the silent operation notable over the previous system. They also allow the possibility of variable power controls for the motors and heaters with only software changes.

The only notable issue remaining is its compatibility with certain ATX PSUs. Despite the simplicity of the fix, time was not available to implement and test the change. Future work should aim to address this issue.

6.1.2 Microcontroller Improvements

The choice of using the Mbed microcontroller proved overall to be a good decision. It provided all the hardware required in a small, easily integrated package. The device was also fast enough to host the printer software providing a major improvement over the old system. Unfortunately, the lack of exposed debugging facilities significantly hindered development in some areas. For example, with JTAG debugging facilities available, adding a new networking stack may have been possible within the project time scale.

The firmware written for the Mbed proved to be an improvement over the previous system making more detailed prints possible due to improved system performance and

communications. It is also far more modular in design making expansion and experimentation feasible. The print quality achieved by the printer is now largely consistent with the constraints of the hardware itself rather than inadequacies of the firmware or microcontroller.

FreeRTOS proved a good choice of operating system as it provided a reliable multi-process environment. It also didn't place any restrictions on development allowing straightforward code for interacting with the low-level features of the Mbed.

μIP, though the best option within the constraints of the project due to its simplicity, wasn't especially well suited to the task. The flow control problem greatly diminished the utility of the stack by forcing the development of a custom protocol. As well as this, the API it enforces (requiring protothreads and protosockets) is likely to make future expansion of the network interface difficult due to its heavy restrictions in the name of unneeded performance savings. Future changes to overcome these problems are discussed in §6.2.1.

The stepper and heater control systems developed, though relatively naïve, proved performant and improved on the old system. Possible future improvements are described in §6.2.4.

Overall, the improvements made to the microcontroller and firmware were successful and have had a positive effect on the performance and future expandability of the printer.

6.1.3 End-stops

Though susceptible to glitches under direct lighting, the end-stops developed functioned correctly and allowed automatic calibration of the axis positions as required. They also obey the standard interface used by other Makerbot end-stops meaning future modifications may make use of standard designs.

The need to build a control circuit rather than using pre-made PCBs resulted in another circuit board on the printer reducing some of the simplicity gained from simplifying the main electronics. The CAT-5 cables used to connect the board to the rest of the electronics are also bulky, especially considering that only a single signal wire is used within each 8-core cable.

Due to time limitations, the end-stops were only used for positioning. Though not used to their full capability, the end-stops provide a valuable improvement to the printer's operation. Other uses for the sensors and a fix for the ambient lighting issues are described in §6.2.2.

6.2 Future Work

There are many possible avenues of future work which would either strongly complement the project or build directly on the system. The most interesting of these possibilities are presented below.

6.2.1 Network Interface

The interface used to interact with the printer is an important part of the system as it is both user-facing and performance critical. Unfortunately, while adequately performant,

the interface built falls short in other areas and these issues are deserving of further work.

G-code Interface

No job control, security or multiple-user support is provided by the G-code interface of the printer. Each of these shortcomings restricts the printer to networks of trusted users who are able to collaborate to manually schedule print jobs. Future work might build upon conventional printer interfaces, for example integrating with the central Unix printing system (CUPS), to provide a more polished user experience.

Network Stack

Due to the limitations and bugs in μIP an alternative stack such as lwIP could be used [Dun12]. This would provide a higher level, FreeRTOS-integrated network interface and, with its better tested flow control features, would enable TCP to be used for G-code transmission. This improved interface could also allow changes to the network interface to be significantly cleaner to implement.

Web Interface

The Mbed is powerful enough to generate and host dynamic web pages as demonstrated by the FreeRTOS web server demo. A web application for control and monitoring of the printer via a web browser could make the printer significantly easier to use by not requiring specialist software.

6.2.2 Endstop Support

To eliminate problems caused by lighting, a more advanced system could be implemented. The infra-red LEDs in the opto-interrupters could be rewired such that they are pulsed, the photo-transistor's signal is then checked by the microcontroller for the presence of these pulses. External light sources are unlikely to contain matching pulses and so the system can be sure of the origin of the light passing into the photo-transistor.

As well as this, the end-stops could be used for safety to detect when the axes have moved outside their operating area unexpectedly. This could help prevent damage to the printer and ensure safer operation when G-code with unreachable coordinates are used or mechanical failures occur.

6.2.3 G-Code Support

The subset of G-code supported by the printer is limited to that produced by Skeinforge. To allow other tools to be used for G-code generation and also to allow more features of the printer to be exposed, the G-code support could be extended.

6.2.4 Firmware Improvements

Two major improvements could be made to the firmware to better account for the mechanical properties of the printer. These are outlined below.

Complex stepper control systems take into account the properties of stepper motors and do not step at a constant rate. Instead, the speed is increased and decreased gradually making use of the increased torque available at low speeds during acceleration and deceleration. Such behaviours unfortunately also require more precise control of the extruder as the amount of plastic required throughout each line segment would vary with the speed of movement.

The heaters could potentially respond more appropriately if variable amounts of power could be supplied (rather than just 'on' and 'off'). This requires PWM support to be added and changes made to the PID controller. PID controllers for variable power systems often require complex additions to function correctly and require careful set up.

6.2.5 Mechanical Improvements

As well as the aspects focused on in this project, many improvements could be made by modifying the printer's mechanical components. This work is the focus of many hobbyists and organisations with improvements in further generations of the Makerbot design building on these ideas. Porting promising ideas from other printers could provide valuable improvements in performance complementing the improved control of the printer achieved in this project.

6.3 Final Conclusions

The limitations of the network interface are probably the most significant but, with some modest restrictions, are not fatal. Future work in this area could address these limitations and explore possibilities for network printing with 3D printers.

Overall, the project has been a success with the performance and extensibility of the printer being improved. As shown in appendix A, the printer is usable and follows essentially the same usage pattern as other 3D printers.

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Appendix A

Example Printing Workflow

The following appendix contains a walk-through of the complete process of designing and printing an object from scratch. The process begins with the production of a 3D model of the design. The next step is to convert the model into G-code instructions and send them to the printer. A description is then given of the key phases of the printing process. Once the print is complete, the printed object is ready after a small amount of cleaning if required.

A simple cuboid is used as an example throughout as the process of designing complex 3D models is not the focus of this report. The cube will measure 20mm wide, 20mm deep and 10mm tall.

A.1 3D Modelling (OpenSCAD)

There are many programs available for 3D modelling but in this example OpenSCAD is used. Other tools may be used provided that they can export models in the widely used Standard Tessellation Language (STL) file format which is accepted by the G-Code generation software shown in this example. Alternatively, ready-made models in STL format can be downloaded from websites such as Thingiverse [Ind12d].

OpenSCAD is a constructive-solid-geometry modelling tool that takes descriptions of 3D models as text and outputs them as STL files [CW12]. In order to define the cube model we specified, the following code is used:

```
cube(size=[20,20,10]);
```

Typing this into the OpenSCAD GUI allows you to see a rendered version of the object by choosing 'Compile and Render' from the 'Design' menu (figure A.1). The object can be exported to an STL file ready for G-code generation by choosing 'Export as STL' from the same menu.

A.2 G-Code Generation (ReplicatorG & Skeinforge)

Once an STL file has been produced, G-code for printing the model must be generated. ReplicatorG provides a more user-friendly front-end to the Skeinforge G-code generator [rep12a]. Skeinforge relies on a calibrated printer profile to guide its decisions. A profile

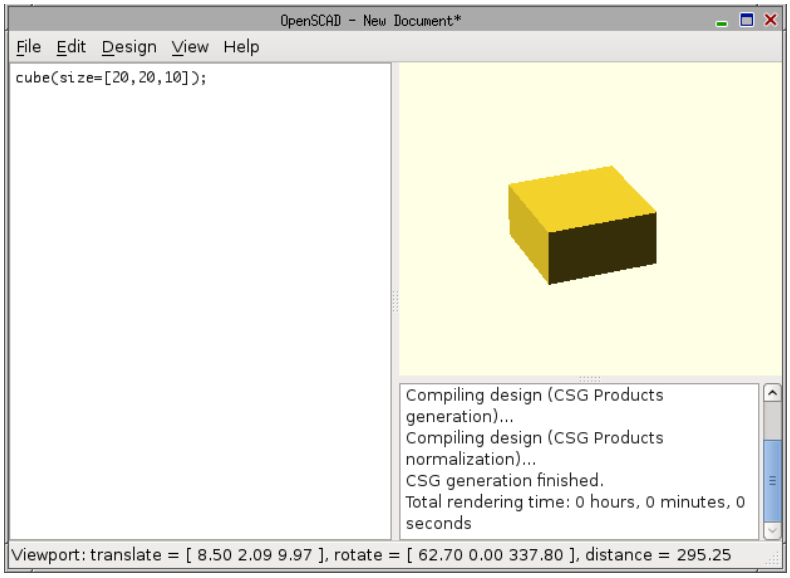

Figure A.1: OpenSCAD showing a cube model compiled and rendered

was produced compatible with ReplicatorG 27 and Skeinforge 35 as part of the project which must be copied into

`replicatorg-0027/skein_engines/skeinforge-35/skeinforge_application/prefs`

Once ReplicatorG has been started, the STL file from the previous step is loaded using 'Open' from the 'File' menu (figure A.2). Once loaded, the model should be positioned centrally on the platform using the tools on the right of the preview. Clicking 'Move' provides features to 'Center' the model and 'Put on Platform' to ensure the model is not printed in mid-air.

Once the model is correctly positioned, the G-code is generated using the 'Generate GCode' button. A dialogue will prompt for a profile to be selected, 'SF35-cupcake-ABP-raftless' should be used (figure A.3). This process can take some time for complex models. A `.gcode` file is produced containing the printer data in the same directory and with the same name as the STL file.

A.3 Status Monitoring

To monitor the printer during a print, a utility called `makebed_live.sh` is provided which shows heater temperatures, extruder position and buffer usage. It is helpful to have this open during a print to monitor the progress of the heating and cooling stages as well as to check for buffer underruns.

Figure 4.19 (page 40) shows the utility in use during a print.

A.4 G-Code Streaming

Before any G-code is sent to the printer, the printer should me moved to its 'home' position (figure A.4). This can be done manually by hand or automatically by sending a

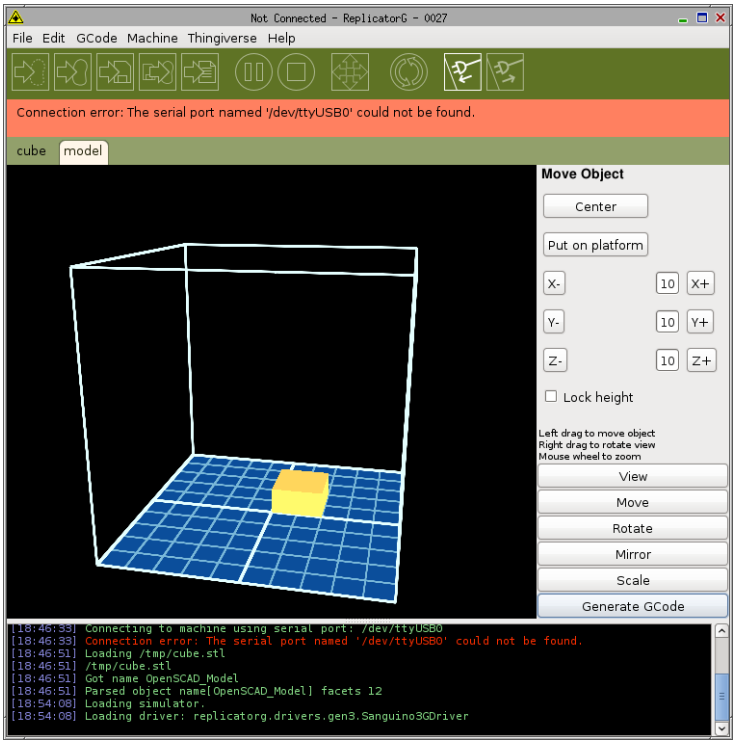

Figure A.2: ReplicatorG GUI showing a cube model loaded

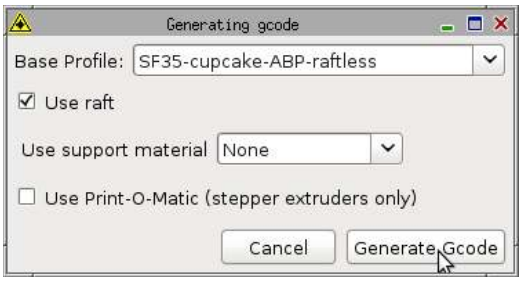

Figure A.3: Skeinforge profile selection dialogue

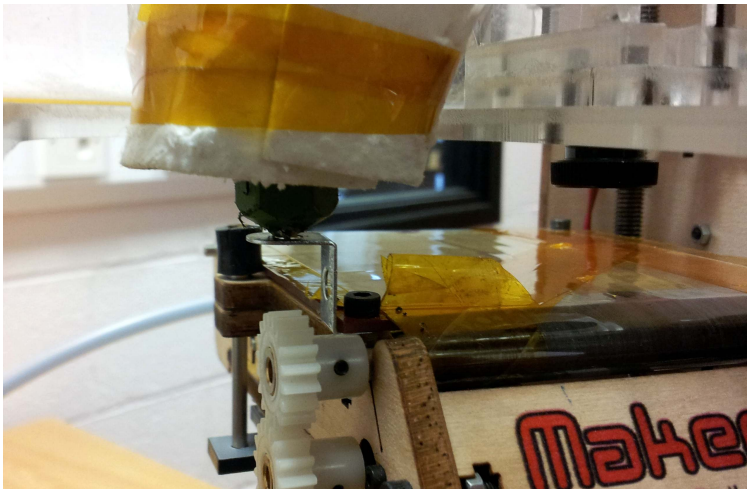

Figure A.4: Extruder placed in the homing bracket

G-code file to the printer containing automatic homing instructions[1].

The `makebed.py` utility is used to stream a G-code file to the printer:

```
makebed.py send cube.gcode
```

This command will block until all print data is sent to the printer.

Complete documentation and safety advice for using `makebed.py` to send files to the printer is provided in appendix E.3.2.

A.5 Printing Process

The G-code generated by Skeinforge profile created in this project goes through several phases during a print. Each of these is described in the following subsections.

A.5.1 Warm Up & Self-Clean

The printer first enables the platform and extruder heaters setting the temperatures to 120°C and 225°C respectively. Next, it moves the extruder to the heating position, to the left of the platform and in front of the rubber cleaning peg. The printer then stays in this position until both heaters are up to temperature (taking around 10 minutes).

Some plastic may ooze from the extruder during heating leaving an unknown quantity of plastic in the extruder's heating chamber. Before printing, the extruder is refilled with plastic and any excess wiped off against the cleaning peg (figure A.5).

A.5.2 Printing The First Layer

Once everything has heated up and the extruder is free of excess plastic, a rectangle is drawn on the platform which surrounds the area the object will be printed in. This allows the operator to check that the print will fit on the platform and to allow manual

[1]See appendix D.3.5 for an example of such an automatic homing G-code file.

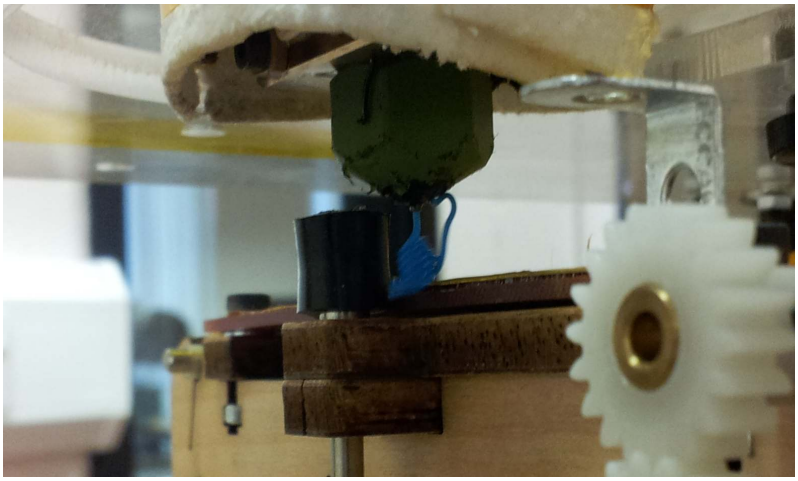

Figure A.5: Extruder extruding plastic during a self-clean

Figure A.6: First layer being printed

adjustments to the height of the extruder to ensure that it is at the correct distance from the bed.

It is critical that the distance between the extruder and platform is correct during the printing of the first layer. If it is too far, the plastic will not adhere to the platform and will not accurately produce the shape required. If it is too close, the plastic printed will not fit under the extruder causing the printed object to get caught on the extruder as it moves around during the print.

Adjustments should be made by turning the adjustment handle on the Z-axis during the printing of the border. The border will be discarded after printing and so mistakes can be corrected while it is produced.

Once the border is drawn, the extruder prints out the first layer of the object (figure A.6). This is done at a slower speed than other layers allowing more plastic to be deposited producing thicker lines helping the print adhere better to the platform.

A.5.3 Main Printing Phase

During this phase, the model is printed layer by layer. Each layer is usually printed first by drawing three solid outer 'shells' and then filling in the centre. Layers near the top and bottom of the model are filled completely to produce a solid finish. Layers inside the model are filled with a hexagonal 'fill pattern' (figure A.7). The fill pattern is not visible

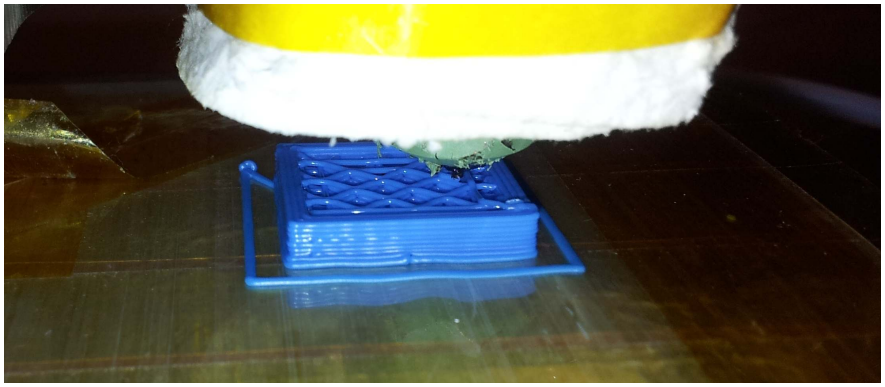

Figure A.7: Fill pattern being printed

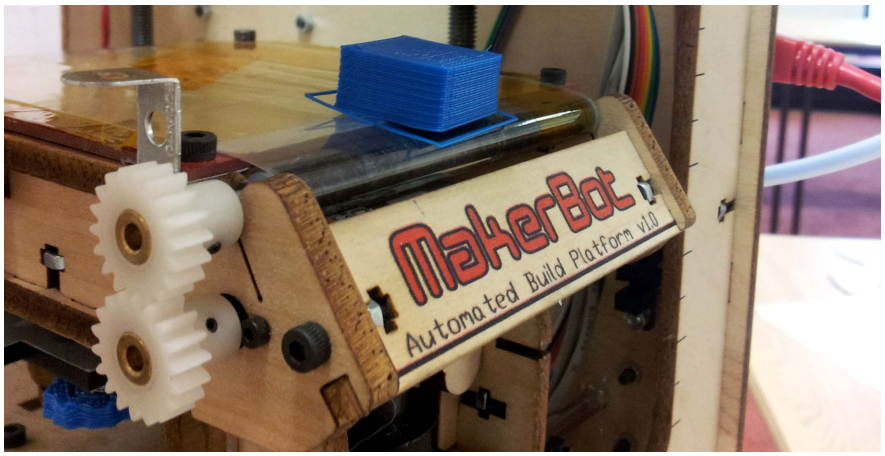

Figure A.8: Finished cuboid being ejected

when the object is completed. It is used as it significantly reduces the time and plastic required to fill objects while still retaining strength.

The cube takes about 8 minutes to print.

A.5.4 Cool-down, Eject and Self-Clean

Once the print completes, the platform is cooled down to allow the object to solidify completely. This takes around 2 minutes.

When the object has cooled, the platform conveyor is activated and the object is peeled off the platform and deposited in front of the printer (figure A.8).

As plastic oozes out of the extruder after the print completes it must once again be cleaned using the same process as the start of the print.

Finally, the printer returns to the home position and the heaters and power supply turn off. If another print job is started at this point, the extruder will still be hot but the platform, having cooled slightly, will need to be partly reheated before the print can begin. Many prints can be run successively in this way with no human intervention unless a print fails.

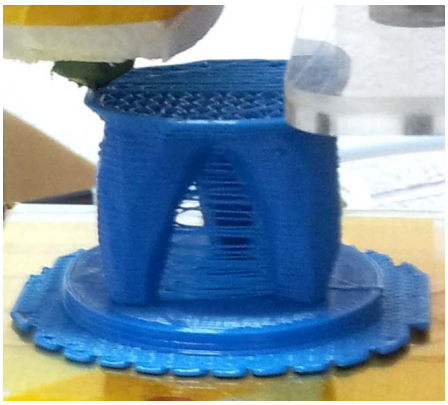

Figure A.9: Strings of plastic left during printing requiring manual removal

A.6 Final Print

Once the printer ejects the object it will still be hot and may still be slightly soft in some places. Care should be taken when handling the object until it has fully cooled.

The border printed at the start can be snapped off and the process is complete. For more complex models, strings of plastic left during printing (figure A.9) may also need to be removed using a knife.

Appendix B

Example Prints

This appendix shows a representative selection of the objects that were printed as test cases during system testing. All designs printed were downloaded from Thingiverse or included as part of ReplicatorG.

B.1 Intricate Prints

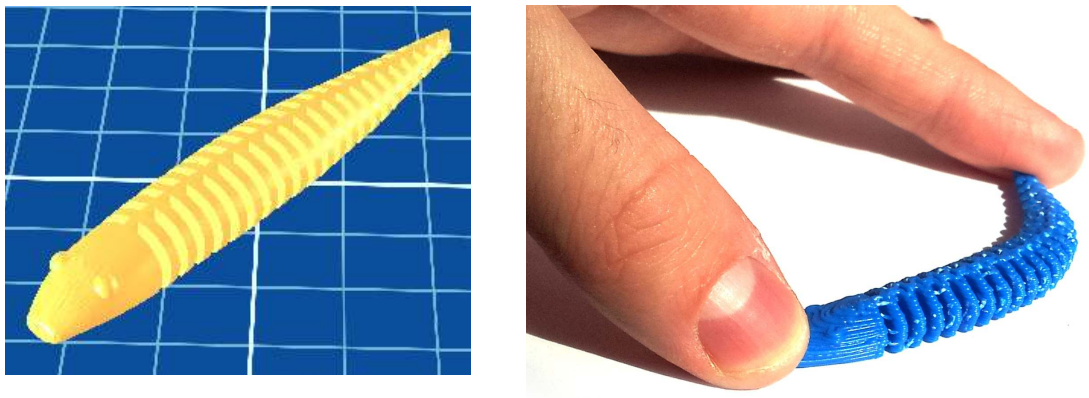

Figure B.1: Flexible snake to test printing many thin fins

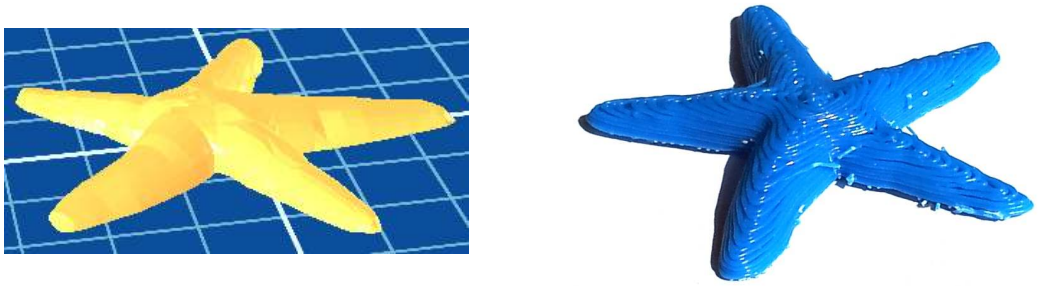

Figure B.2: Starfish to test layering appearance

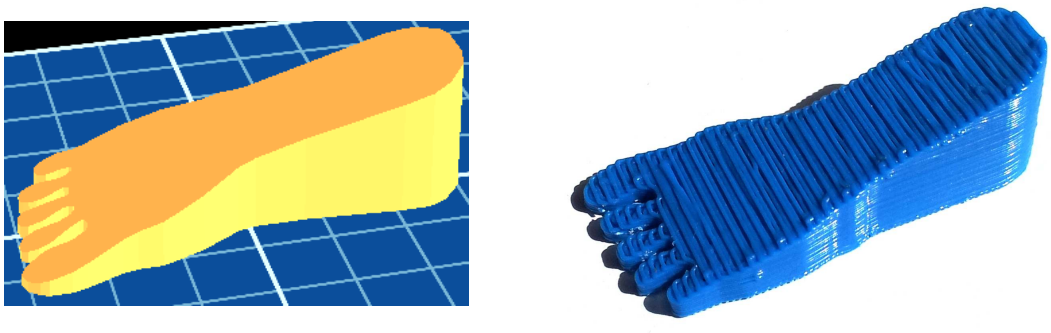

Figure B.3: Doorstop to test large, smooth gradients

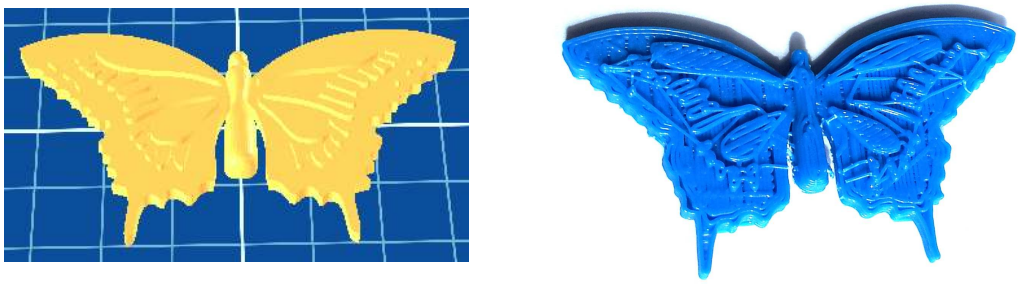

Figure B.4: Butterfly to test intricate islands of print

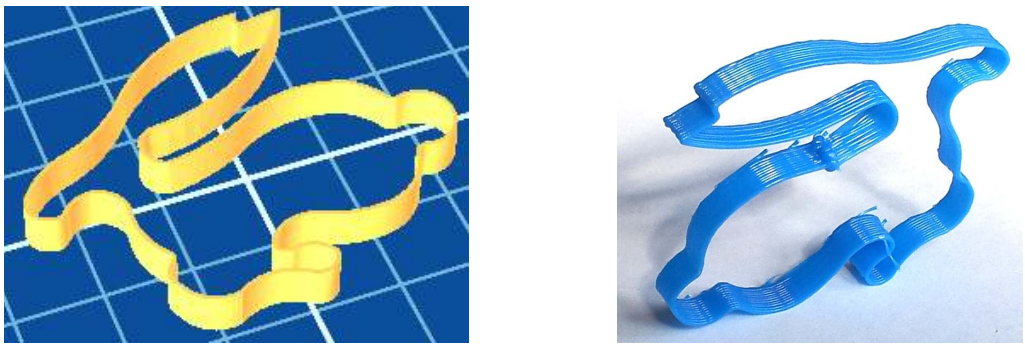

Figure B.5: Rabbit outline to test very thin structures

B.2 Large Prints

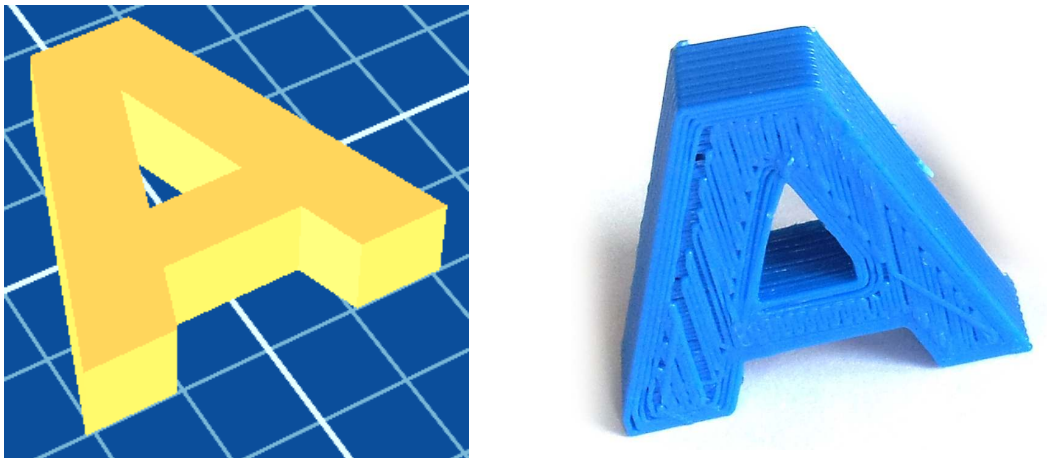

Figure B.6: Letter ‘A’ to test simple large shapes

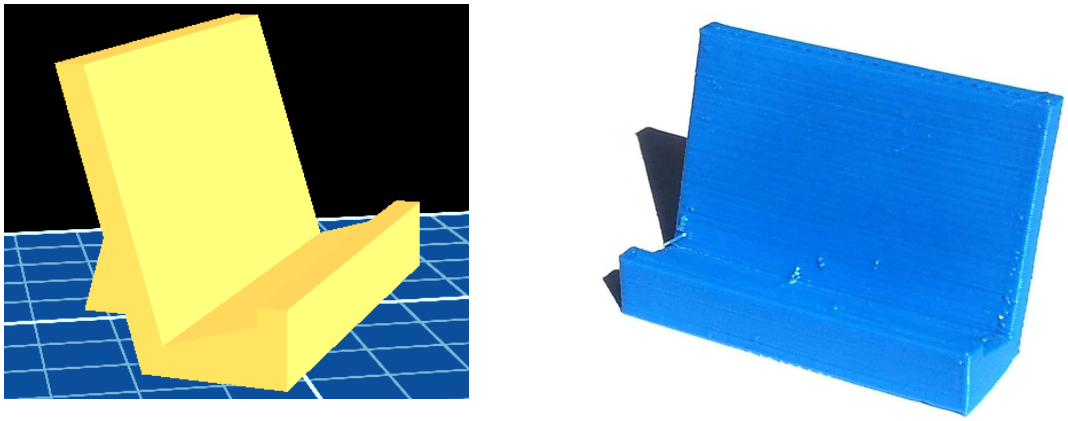

Figure B.7: Phone stand to test steep gradients

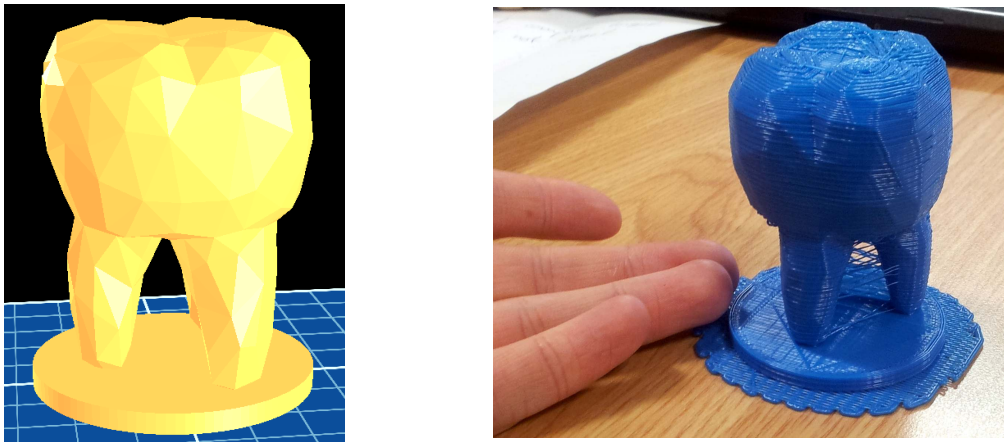

Figure B.8: Tooth to test large models with large overhanging areas

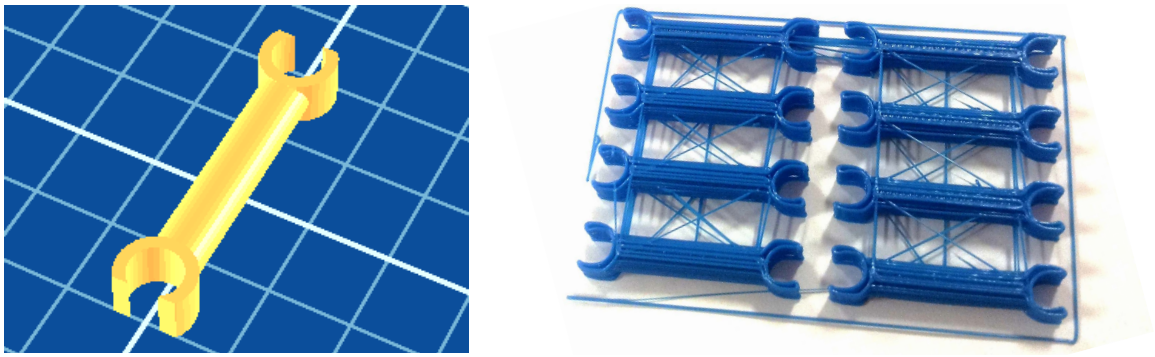

Figure B.9: Multiple ‘metabricks’ to test building batches of objects

B.3 Functional Prints

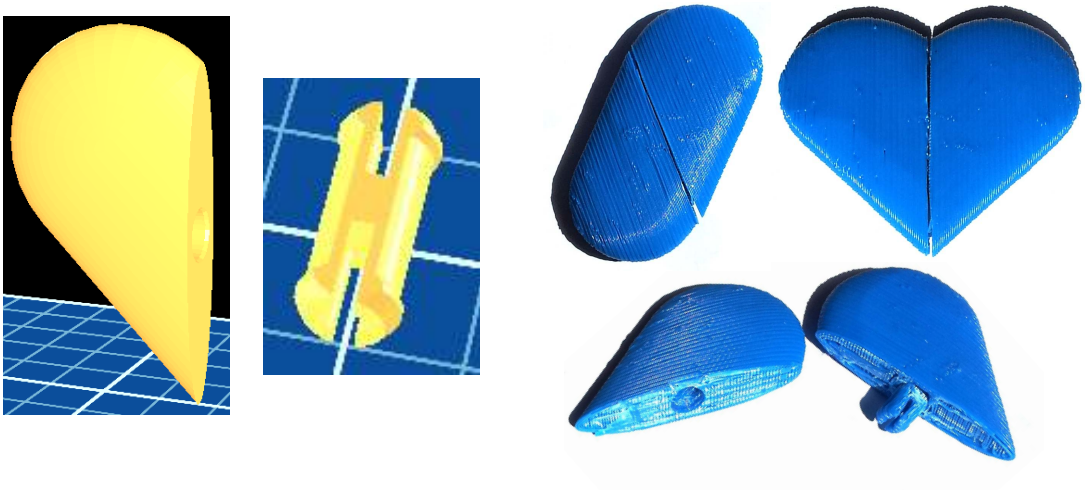

Figure B.10: Twistable heart to test simple mechanisms and multi-part objects

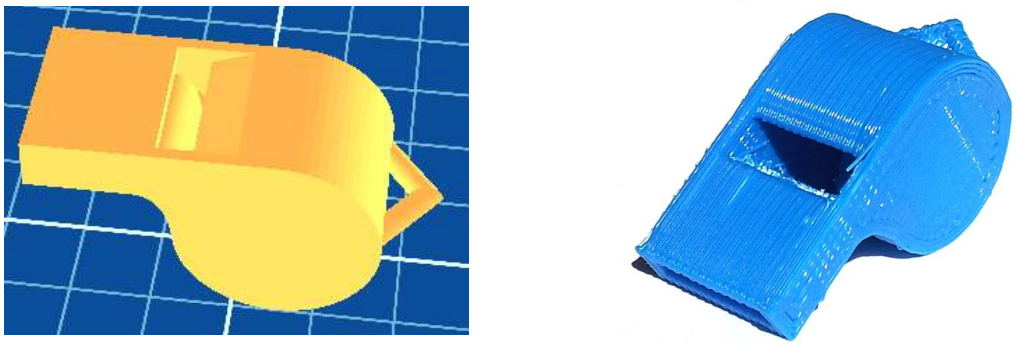

Figure B.11: Whistle (with pea printed inside) to test precise, air-tight objects with simultaneously printed sub-components

Figure B.12: Tweezers to test flexible designs (frequently used to remove excess extrusion produced during self-cleaning)

Appendix C

Circuit Diagrams

This appendix contains the documentation required for the circuits produced within the project.

C.1 Control Electronics

The pinout for the Mbed (table C.1) and schematic (C.1) for the main board produced in the project are given below. The connections to stepper motors have been omitted for clarity (but the associated Mbed pins labelled).

Pin	Name	Definition	Connection
1	GND		PSU Ground
2	VIN		PSU +5V Standby
3	VB		Real-time Clock Battery (Unused)
4	nR		Reset switch
5	5	PIN_POWER_OK	PSU Power OK
6	6	PIN_ENDSTOP_0_MIN	X-axis Min End-stop
7	7	PIN_ENDSTOP_0_MAX	X-axis Max End-stop
8	8	PIN_STEPPER_0_STEP	X-axis Stepper Step
9	9	PIN_STEPPER_0_DIR	X-axis Stepper Direction
10	10	PIN_STEPPER_0_NEN	X-axis Stepper nEnable
11	11	PIN_ENDSTOP_1_MIN	Y-axis Min End-stop
12	12	PIN_ENDSTOP_1_MAX	Y-axis Max End-stop
13	13	PIN_STEPPER_1_STEP	Y-axis Stepper Step
14	14	PIN_STEPPER_1_DIR	Y-axis Stepper Direction
15	15	PIN_STEPPER_1_NEN	Y-axis Stepper nEnable
16	16	PIN_ENDSTOP_2_MIN	Z-axis Min End-stop
17	17	PIN_ENDSTOP_2_MAX	Z-axis Max End-stop
18	18		Unused
19	19	PIN_THERMISTOR_PLATFORM	Platform Thermistor
20	20	PIN_THERMISTOR_EXTRUDER	Extruder Thermistor
21	21	PIN_STEPPER_2_STEP	Z-axis Stepper Step
22	22	PIN_STEPPER_2_DIR	Z-axis Stepper Direction
23	23	PIN_STEPPER_2_NEN	Z-axis Stepper nEnable
24	24	PIN_POWER_EN	PSU Power On
25	25		Unused
26	26		Unused
27	27	PIN_HEATER_EXTRUDER	Extruder Heater
28	28	PIN_HEATER_PLATFORM	Platform Heater
29	29	PIN_EXTRUDER	Extruder Motor
30	30	PIN_PLATFORM	Platform Motor
31	D+		USB (Unused)
32	D−		USB (Unused)
33	TD+		MagJack (Ethernet)
34	TD−		MagJack (Ethernet)
35	RD+		MagJack (Ethernet)
36	RD−		MagJack (Ethernet)
37	IF+		Reserved (Unused)
38	IF−		Reserved (Unused)
39	VU		USB +5V (Unused)
40	VOUT		+3.3V Out

Table C.1: Mbed pin connections

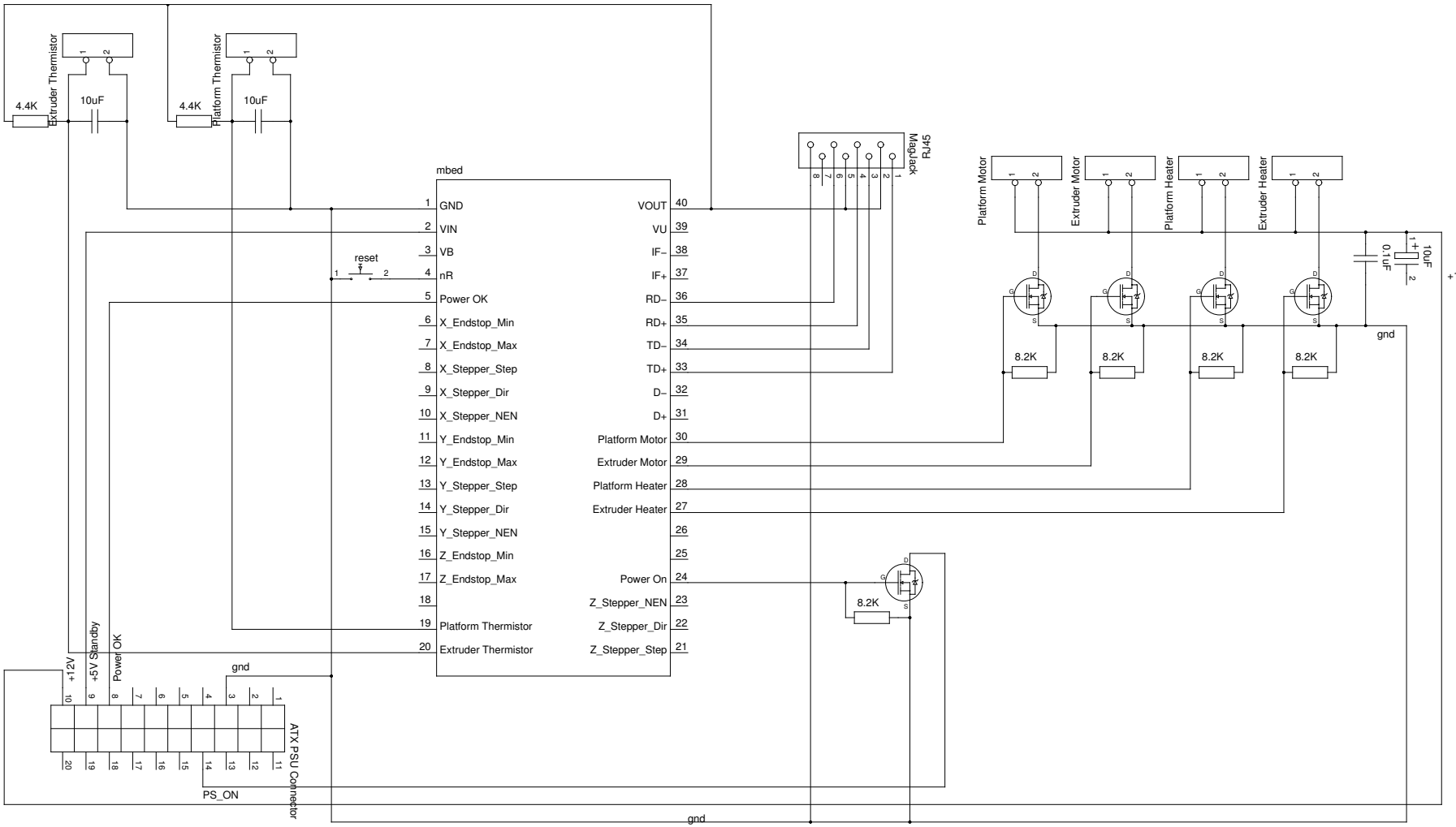

Figure C.1: Main board circuit diagram (direct connections to stepper controllers omitted for clarity)

C.2 End-stop Electronics

The schematics and wiring colour codes for the end-stop electronics are given in this section.

C.2.1 Wiring Colour Codes

The colour codes for the connections from the end-stop board are given in table C.2 and the connections to the opto-interrupters are given in table C.3.

C.2.2 Schematic

The endstops are interfaced via the circuit in figure C.2. This circuit is duplicated once for each end-stop on the end-stop board.

Colour	Connection
Green Solid	Signal
Green Striped	Unused
Blue Solid	+5V
Blue Striped	+5V
Orange Solid	Unused
Orange Striped	Unused
Brown Solid	Ground
Brown Striped	Ground

Table C.2: End-stop interface cat-5 wire allocations [Rep12d]

End-stop	LED +	LED −	Photo-transistor Collector	Photo-transistor Emitter
X-axis	Red	Brown	Orange	Yellow
Y-axis min	Red	Brown	White	Black
Y-axis max	Green	Blue	Orange	Yellow
Z-axis	Green	Blue	Purple	Gray

Table C.3: Opto-interrupter connection colour codes

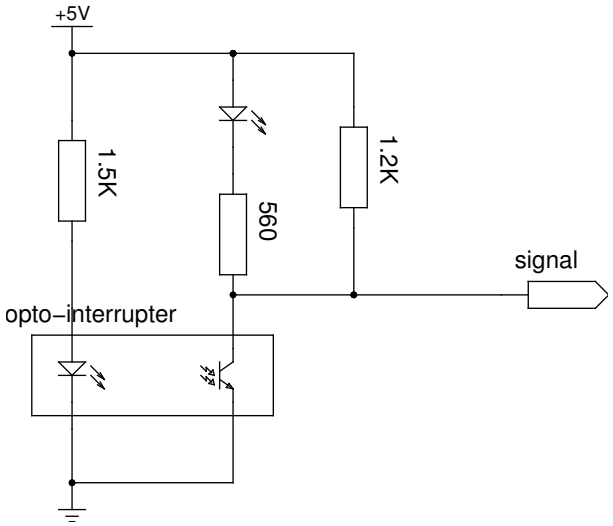

Figure C.2: End-stop circuit schematic

Appendix D

G-Code Reference

The subset of G-code interpreted by the system is described in the following sections.

D.1 Language

The G-code machine is implemented as in §2.1.5. The following subsections specify the syntax and registers of the language.

D.1.1 BNF

```
<instruction> ::= <reg-write> <new-line>

<reg-write> ::= <reg-name> <number> <white-space>* <reg-write> | <comment> | ""
<reg-name>  ::= [A-Z]

<comment>            ::= <line-comment> | <block-comment>
<line-comment>       ::= <line-comment-start> <non-newline>* <new-line>
<line-comment-start> ::= ";" | "/"
<block-comment>      ::= "(" <non-close-bracket>* ")"
```

D.1.2 Register Types & Behaviour

Table D.1 shows the type and reset behaviour of each of the G-code registers.

D.2 Actions

Each instruction should write a value to the 'G' or 'M' register. Depending on the value written, the printer will carry out a different action. These actions are specified below.

Register	Type	Reset at instruction start
A	Integer	No
B	Float	No
C	Float	No
D	Float	No
E	Float	No
F	Float	No
G	Integer	Yes
H	Float	No
I	Float	No
J	Float	No
K	Float	No
L	Float	No
M	Integer	Yes
N	Float	No
O	Float	No
P	Integer	No
Q	Float	No
R	Float	No
S	Float	No
T	Integer	No
U	Float	No
V	Float	No
W	Float	No
X	Float	No
Y	Float	No
Z	Float	No

Table D.1: G-code register types and behaviours

D.2.1 'G' Actions

G0 & G1 : Move extruder to coordinate

G1 moves the extruder through a straight line in 3D space from the current position to the position given in the arguments.

G0 is included for compatibility reasons and does the same thing as G1.

Argument	Description	Unit
X	X-coordinate	Current unit
Y	Y-coordinate	Current unit
Z	Z-coordinate	Current unit
F	Feed rate (speed) of movement	Current unit per minute

G4 : Sleep

Pause the printer for a specified period.

Argument	Description	Unit
P	Period	Milliseconds

G20 & G21 : Set unit

Set the unit used to specify movements to inches or millimetres respectively.

Argument	Description	Unit
No arguments		

G90 & G91 : Set absolute/relative positioning

Sets whether positions are specified absolutely or relative to the current position. Relative positioning is not supported by the system.

Argument	Description	Unit
No arguments		

G92 : Set origin

Set the current position without moving the extruder. Used to set the initial position of the extruder to the origin or some known homing location. If this instruction is not used, the current position is undefined and moving the extruder may have unexpected effects.

Argument	Description	Unit
X	X-coordinate	Current unit
Y	Y-coordinate	Current unit
Z	Z-coordinate	Current unit

D.2.2 'M' Actions

M-2 : Home axes

Custom extension to the standard G-code actions.

Slowly move the specified axes until hitting the endstop. The current position in the X, Y and Z registers is then set to the locations of the end-stops (essentially calibrating the printer's position).

Argument	Description	Unit
A	Axis Selection	Bit mask. Bit 1: X, Bit 2: Y, Bit 3: Z.

M-1 & M0 : Turn the PSU on/off

Turns the PSU on and off respectively. Note that if the PSU is not powered on, many actions may block indefinitely.

This action blocks until mains power is available if the microcontroller is being powered via USB.

M-1 is a custom extension to the standard G-code actions.

Argument	Description	Unit
No arguments		

M6 : Wait for heaters

Block until both heaters have reached their target temperature. Contrary to the standard, this command will not block waiting for the heaters to cool down to a new target temperature.

Argument	Description	Unit
No arguments		

M17 & M18 : Power stepper motors on/off

Enable or disable power to all stepper motor drivers. The steppers are automatically powered on when moved.

Argument	Description	Unit
	No arguments	

M101, M102 & M103 : Extruder motor forward/backward/off

Set the extruder motor moving forward, backward or not at all respectively. M102 is not supported by the system and will raise an error and stop the motor.

The extruder should not be turned on unless it has heated up enough to melt the incoming filament.

Argument	Description	Unit
	No arguments	

M104 : Set extruder temperature

Set the target temperature of the extruder. This action does not block. To wait for heating to complete use M6.

Argument	Description	Unit
S	Target temperature	°C

M106 & M107 : Platform conveyor on/off

Turn the platform conveyor belt on or off respectively.

Argument	Description	Unit
	No arguments	

M108 : Set extruder speed

Set the speed at which the extruder motor turns. Not supported by the system.

Argument	Description	Unit
	No arguments	

M109 : Set platform temperature

Set the target temperature of the platform. This action does not block. To wait for heating to complete use M6.

Argument	Description	Unit
S	Target temperature	°C

D.3 Examples

The following examples of G-code files show how it can be used for various useful tasks.

D.3.1 Power On, Heat Up

Heats the system up to a temperature suitable for printing. Can be used to prepare the printer before starting a print.

```
(Turn on the PSU)
M-1

(Set the target temperature for the extruder to 225*c)
M104 S225

(Set the target temperature for the platform to 120*c)
M109 S120
```

D.3.2 Power-down

Powers down all components and then the PSU. When the PSU is turned back on, the heaters and motors will still remain off.

```
(Turn off extruder)
M104 S0 (Heater: set target to 0*c)
M103    (Motor)

(Turn off platform)
M109 S0 (Heater: set target to 0*c)
M107    (Conveyor)

(Turn off stepper motors)
M18

(Power off PSU)
M0
```

D.3.3 Skeinforge Print Prefix

Prefix added to all print jobs to heat up and prepare the printer before a print job.

```
(power on)
M-1

G21 (set units to mm)
G90 (set positioning to absolute)
```

```
(Start in parking position)
G92 X-60 Y-45 Z10

(Raise up to avoid the loop)
G1 Z12 F100

(Move to squirt position)
G1 X-55 Y-10 F1000
G1 Z7 F100

(Heat up)
M104 S225
M109 S120
M6

(Extrude a bit and stop)
M101
G4 P5000
M103
G4 P6000

(Wipe)
G1 Y10 F2000

(Go to origin)
(M101)
(G1 X0 Y0 Z0 F2400.0)
```

D.3.4 Skeinforge Print Postfix

Postfix added to all print jobs to cool down and eject the object after printing.

```
G1 X0 Y40 F3300.0 (move platform to ejection position)
(cool down platform)
M104 S225
M109 S80
M103 (Extruder off)
G04 P100000 (wait t/1000 seconds)
M106 (conveyor on)
G04 P10000 (wait t/1000 seconds)
M107 (conveyor off)

(start wipe)
(Move to squirt position)
G1 X-55 Y-10 F1000
G1 Z7 F100
```

```
(Heat up extruder)
M104 S225
M6

(Extrude a bit and stop)
M101
G4 P5000
M103
G4 P6000

(Wipe)
G1 Y10 F2000

(Go to starting position)
G1 Z12 F100
G1 X-60 Y-45 F3300
G1 Z10 F100


(Turn off heaters)
M104 S0 (set extruder temperature)
M109 S0 (set heated-build-platform temperature)

(power off)
M0
```

D.3.5 Home X & Y Axes

Home the X & Y axes using the end stops. Assumes that the Z-axis is initially placed at the correct height to fit in the homing bracket.

```
(Power on)
M-1

(Use mm)
G21

(Set the Z axis as we're not homing that)
G92 X0 Y0 Z10

(Lift the head out of its hole)
G1 Z15 F100

(Home x[1] and y[2] at the same time[1+2 = 3])
M-2 A3
```

```
(Move to the calibration ring)
G1 X-56 Y-44 Z15 F3300
G1 Z10 F100

(Power off)
M0
```

D.3.6 Circle

Plots a circle segmented into lines using the X and Y axes. Assumes the extruder is hovering safely above the centre of the platform before moving.

```
(Power on)
M-1

(Use mm)
G21

(Assume we're starting in the middle)
G92 X0 Y0 Z0

(Move to the edge of the circle)
G1 X40.000000 Y0.000000 F330.000000

(Plot the circle)
G1 X32.360680 Y23.511410 F330.000000
G1 X12.360680 Y38.042261 F330.000000
G1 X-12.360680 Y38.042261 F330.000000
G1 X-32.360680 Y23.511410 F330.000000
G1 X-40.000000 Y0.000000 F330.000000
G1 X-32.360680 Y-23.511410 F330.000000
G1 X-12.360680 Y-38.042261 F330.000000
G1 X12.360680 Y-38.042261 F330.000000
G1 X32.360680 Y-23.511410 F330.000000

(Move to the center of the circle
G1 X0 Y0 F330.000000

(Power off)
M0
```

Appendix E

Code Documentation

This appendix contains the documentation required to configure and build the microcontroller firmware. It also contains the required documentation for using the communication utilities.

E.1 File Listing

Table E.1 describes the purpose of each of the key project files.

E.2 Firmware

This section describes the compilation and configuration process for the Mbed firmware.

E.2.1 Dependencies

The tools/libraries required to build the firmware are listed in table E.2.

E.2.2 Compilation

The following steps can be used to build the Mbed firmware:

1. Make sure the dependencies mentioned above are installed
2. Ensure that `arm-none-eabi-gcc` is in your path
3. In the Makefile, set `RTOS_SOURCE_DIR` to the `Source` directory of your FreeRTOS distribution.
4. In the Makefile, set the path of the Mbed mount point on your computer in the `install: all` make rule.
5. Run `make` to build the firmware
6. `make install` will build as above and also copy the firmware to the Mbed. Reset the Mbed to start the newly installed firmware.

Filename	Description
core_cm3.h	ARM CMSIS header for Cortex-M3
cr_startup_lpc17.c	Defines interrupt-handler functions
FreeRTOSConfig.h	System & networking parameters
freertos_hooks.{c,h}	FreeRTOS callback handlers
LPC17xx.h	NXP CMSIS header for LPC17xx series
main.c	Initialises system starts all tasks
MakebedConfig.h	Configuration for 3D printing firmware
makedefs	Definitions used by the Makefile
Makefile	Makefile which builds the project
mbed_boot.{c,h}	Functions to boot up chip peripherals
rtosdemo_rdb1768_Debug.ld	Linker script
system_LPC17xx.h	ARM CMSIS header for Cortex-M3
analog/analog_in.{c,h}	Analog input driver
float_parsing/strtod.{c,h}	Implementation of strtod
GPIO/gpio.{c,h}	General purpose input/output driver
makerbot/makerbot.{c,h}	Print manager/scheduler
network/emac.h	FreeRTOS EMAC driver
network/EthDev*.h	Ethernet driver
network/network.{c,h}	Network interface μIP 'application'
network/network_uip_state.h	State struct for μIP 'application'
network/network_debug.{c,h}	Debugging/Status interface
network/network_gcode.{c,h}	G-code transmission interface
pid/pid.{c,h}	PID controller
stepper/stepper.{c,h}	Stepper motor driver
thermistor/thermistor.{c,h}	Thermistor library
util/makebed.py	Communication utility
util/makebed_live.sh	Live printer status monitor
util/gsend.py	G-code UDP library
util/debug.py	Status interface library
util/gcode/*.gcode	Example G-code files
watchdog/watchdog.{c,h}	Watchdog timer driver

Table E.1: Key source file listing

Package	Version
CodeSourcery G++ Lite	2011.03-42
FreeRTOS	7.0.2
GNU Make	3.81

Table E.2: Firmware software dependencies

Package	Version
Python	2.6
Bash	4.1
GNUPlot	4.4 patchlevel 0

Table E.3: Utility dependencies

E.2.3 Configuration

All printer-related parameters can be found fully documented in `MakebedConfig.h`.

To set the system's IP, net-mask and MAC addresses, the definitions `configIP_ADDR0-3`, `configIP_ADDR0-3` and `configMAC_ADDR0-5` can be set as the contents of the dot-file `FreeRTOSConfig.h`. DHCP is not supported.

E.3 Utilities

Utilities are provided for interacting with the printer over the network. Their dependencies and use are described below. They should be executed from the `util` directory.

The utilities require that the printer's IP address is specified in `~/.makebedrc`.

E.3.1 Dependencies

The utilities depend on the programs mentioned in table E.3.

E.3.2 Send

Files can be sent to the printer using the command

```
makebed.py send
```

which accepts G-code on its standard input or from a file specified as an argument. The program will block until the entire file has been received by the printer.

If the printer is suffering buffer underruns, the rate at which the utility polls the printer can be increased with the `-p` option which takes a number of seconds (defaulting to 0.1) to wait between poll requests. This should not need changing for most prints and can result in a large amount of network traffic being generated if set very low.

Safety

If the program is terminated while sending a G-code file, the printer will keep running after executing the last intact G-code instruction received. During a typical print, this could leave the printer stationary and extruding plastic. It can also potentially result in damage or unsafe behaviour. As a precaution, it is recommended that the printer is reset using the reset button if the utility is stopped prematurely.

E.3.3 Get

The command

```
makebed.py get
```

allows printer status information to be fetched. The command expects a list of categories for which status should be fetched and returns a tab-delimited data file containing those values and exits.

The `-p` option causes the printer to be repeatedly polled for status information until the utility is terminated.

The output of this utility is compatible with GNU Plot.

E.3.4 makebed_live.sh

To provide a live view of the printer's status during a print, a shell script has been provided which plots live data from the printer's status interface. It is a simple wrapper for the `makebed.sh get` command. A screen shot is shown in figure 4.19 on page 40.

Appendix F

Protocol Specifications

The printer provides two network interfaces for which the protocols are described in the following sections.

The port numbers used by these services are shown in table F.1.

F.1 UDP G-code Transmission Protocol

This interface is required to reliably send data to the printer and provide flow control such that the printer doesn't receive data it can't handle. A discussion of the protocol's general design and requirements can be found in §4.2.6

F.1.1 Sender Packets

Packets sent to the printer consist of an unsigned 32-bit integer sequence number followed by bytes of payload data up to the window size advertised by the receiver.

Initially the sequence number is 0 and the window size is assumed to be zero. This means that the first datagram consists of the sequence number alone.

F.1.2 Acknowledges

The receiver is required to acknowledge each datagram received and accepted and advertise its current window size. Packets consist of a copy of the 32-bit sequence number followed by an unsigned 32-bit integer window size. Datagrams are only accepted when

- Their sequence numbers are sequential
- An empty first packet with sequence number zero has been received
- The data contained fits into the system buffer (i.e. obeys the window size)

Port	Service
1818	G-code interface (UDP & TCP)
2777	Status interface (TCP)

Table F.1: Network interface ports

F.1.3 Retransmission

If the sender does not receive an acknowledgement with a matching sequence number within a certain period it will repeatedly resend the request.

If a zero-window size is reported, the sender must poll the printer until the window re-opens by issuing new empty packets with increasing sequence numbers.

Exponential back-off is not used in an effort to reduce the latency between the window opening and sending the next piece of data. Shorter timeouts result in more traffic and less delay in restarting transmission after a zero window. Longer timeouts result in less wasted traffic but, if too long, can result in buffer underruns before more data is sent after a zero window.

F.1.4 Errors

If the printer receives some unexpected data (for example if the printer is reset and receives a datagram from the middle of a transmission before it was reset), an acknowledgement with sequence number 0 and a zero-window is returned indicating a terminal error.

F.2 Status Monitoring Protocol

To monitor the printer's status, newline-terminated commands are sent to the printer over a TCP connection. Responses consist of a series of integers separated by spaces and terminated with a newline. Table F.2 lists the commands and their responses.

The 'Integer $\times 100$' format is used for decimal values as printing floating point values are not supported by the standard libraries used. The floating point value is multiplied by 100 and truncated to an integer.

Command	Response	Unit	Format
`tmp`	Extruder temperature	°C	Integer ×100
	Extruder set point	°C	Integer ×100
	Extruder heater on		Boolean
	Platform temperature	°C	Integer ×100
	Platform set point	°C	Integer ×100
	Platform heater on		Boolean
`gcd`	G-code instructions interpreted		Integer
	Last interpreter error number		Integer
`buf`	G-code buffer utilisation	Bytes	Integer
	G-code buffer size	Bytes	Integer
	Command buffer utilisation	Commands	Integer
	Command buffer size	Commands	Integer
	Command buffer overrun count this print		Integer
`pow`	PSU Power On		Boolean
`pos`	X-axis Position	Millimetres	Integer ×100
	Y-axis Position	Millimetres	Integer ×100
	Z-axis Position	Millimetres	Integer ×100
`dbg`	Debug Register	Undefined	Undefined

Table F.2: Status interface commands and responses