The University Of Sheffield.

Department Of Mechanical Engineering

MEng Mechanical Engineering

Open Source Espresso Machine for Makers

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SUMMARY

In the last decade there has been a growing number of open source designs aimed at makers, which are available for anyone to access, modify, and improve, and can often be manufactured in a maker space. This project followed a practical-based design approach to produce the first open source espresso machine. This involved reverse engineering a consumer-level machine and producing two functional prototypes, whilst sharing progress and the final documentation with the open source community. This documentation contains enough information so that anyone can build the design themselves. The design matched the consumer level machine in both temperature stability and taste of espresso but lacked the same level of functionality. The final design produced can be considered the first iteration of a wider open source project, which can be developed by the maker community.

CONTENTS

Summary....ii
Contents iii
Acknowledgements v
1 Literature Review 1
1.1 Introduction to Coffee 1
1.1.1 Overview....1
1.1.2 Coffee Processing.... 2
1.1.3 Roasting 3
1.1.4 Grinding 4
1.2 Introduction to Brewing Technology.... 4
1.2.1 Brewing Methods.... 4
1.2.2 Espresso Machine Components 7
1.3 Introduction to the Maker Community 16
1.3.1 History 17
1.3.2 Current State....17
1.3.3 Open Source 18
1.4 Previous work 19
1.5 Conclusion 19
2 Design Process....20
2.1 Aims & Objectives 20
2.1.1 Aims 20
2.1.2 Objectives....20
2.2 Methodology....21
2.3 Design Selection 21
2.4 Reverse Engineering....24
2.4.1 User Experience 25
2.4.2 Experimentation....26
2.4.3 Dismantling....28
2.5 Design Specification....29
2.5.1 Manufacturing Facilities 30
2.6 First Prototype 31
2.6.1 Design 31
2.6.2 Testing....34
2.7 Second Prototype 41
2.8 Documentation for Open Source Design....44
3 Conclusion & Discussion 44
3.1 The Design Process 45

3.2 Evaluation of the Open Source Approach 45
3.3 Evaluation of the Espresso Machine 46
3.4 Further Work 47
References 49
Appendix 1. Prototype photos 53
Appendix 2. Open source documentation 54

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1 LITERATURE REVIEW

1.1 Introduction to Coffee

1.1.1 Overview

Over 2.25 billion cups of coffee are consumed in the world every day (1). That is 800 billion cups per year, with 95 million cups of coffee drunk per day in the UK alone (2). The coffee industry is worth over $100 billion, the only commodity more sought for is crude oil (3).

Coffee is drunk all over the world, it is also grown all over the world, in over 50 countries. It is usually grown in countries near to the equator, due to the conditions that favour growth of the plant. Coffee beans (Figure 1.1 (4)) are dried and roasted seeds from the cherry of the Coffea tree (Figure 1.2 (5)).

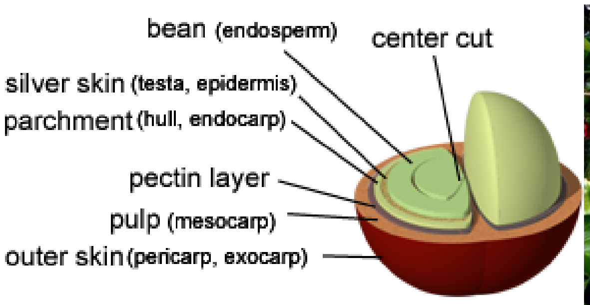

Figure 1.1 Inside a coffee cherry

Figure 1.2 Coffea Arabica tree

There are two main species of coffee tree that are used for commercial coffee: Coffea Arabica – which has multiple varieties, and Coffea Canephora – with the main variety being Robusta.

Coffee produced from Arabica accounts for most of the world's coffee, approximately 70% (4). They produce a fine, mild, aromatic coffee and typically are more expensive. Their ideal terrain tends to be steep which makes access difficult, coupled with the fact that they are more disease prone than Robusta, this makes the plant difficult to grow. The largest producers of Arabica are Brazil, closely followed by Colombia.

Robusta is more resistant to diseases, and it can withstand warmer climates such as in Vietnam, the world's leading producer. This means it can grow at far lower altitudes and is therefore cheaper to produce (approximately half the price). Also, they contain 50-60% more caffeine (6), which results in a more bitter taste.

Therefore, Arabica are considered to be of higher quality and have a larger flavour diversity.

Coffea plants grow for 4-5 years before they can be harvested. Once matured, they are annually harvested, with the exception of a few countries such as Colombia, which have two harvest seasons. Often the coffee cherries are harvested by hand, due to cheap labour costs or difficult terrain for machinery. The cherries are stripped from the plant once bright red.

1.1.2 Coffee Processing

Next, they need processing so that the bean can be obtained from the several layers of skin surrounding them. There are three predominant methods: natural, washed and honey.

Natural

Natural processing involves leaving the beans out to dry in the open air (Figure 1.3 (7)). The fruit is left on the bean, which gives the potential for very flavoursome coffee. However, unripe fruit drying alongside ripe fruits can lead to inconsistencies in flavour. Therefore, this method is sometimes considered lower quality, but it is also the eco-friendliest.

Figure 1.3 Naturally drying coffee beans

Figure 1.4 Wash processing coffee beans

Wash

Wash processed coffee has its fruit removed using substantial amounts of water (Figure 1.4 (8)) and machinery before being dried, this uses a lot of energy and thus has a large carbon footprint. Unripe or damaged fruits will sometimes float to the surface and are removed, increasing consistency in flavour. As only the bean is used, the flavour of the coffee is dependent only on the bean, which makes each variety more distinguishable based on its origin.

Honey

Honey processing is the most difficult of the three. The coffee is pulped, then spread out to dry without washing, which leaves some of the pulp on the beans (Figure 1.5 (9)). This results in the fine attributes of a washed coffee and the fruit sweetness of the natural method.

Figure 1.5 Honey processing beans

Figure 1.6 Weasels waiting to process the cherries

Animals

There are some less common methods of processing, such as for weasel coffee. In this process, weasels naturally pick out the ripest, highest quality coffee cherries to eat (Figure 1.6 (10)). When they digest the cherries, they only digest the flesh, with the enzymes in their stomach aromatizing the beans, adding flavour, and removing bitterness. After the digestion process, beans are washed, dried, and roasted as normal. This process produces the most expensive coffee in the world.

1.1.3 Roasting

Once processed, the beans are stored and shipped; then they are roasted (Figure 1.7 (11)) before they are used. Roasting the beans dries them out, so that they can be ground. It also brings out the flavour and aroma of the bean due to chemical changes that occur when exposed to high temperatures

Figure 1.7 Different shades of coffee - from light to dark

Generally, lighter roasts tend to keep more of the original flavour of the bean, and so high-quality coffees are often roasted in this way. Medium roasted beans exhibit slightly more of a roasted flavour than light. Medium-dark roasts start to bring out some of the oils of the bean, resulting in slight bittersweet aftertaste. Dark roasted beans are very oily and result in bitter and smoky flavours.

1.1.4 Grinding

Once roasted, the beans are then ground so that they are ready to be used. Beans can be ground to different coarseness, which affects flavour extraction in brewing. If the coffee is under-extracted, not enough flavour will have been extracted (ground too course). If the ground is too fine then over-extraction can occur, resulting in a very bitter, unpleasant taste. The perfect coarseness of the grind depends on the roast of the coffee and the brewing method used.

1.2 Introduction to Brewing Technology

1.2.1 Brewing Methods

With 65% of coffee being drunk at home (2), there is clearly a huge market for the multiple home brewing technologies that exist.

Instant

One of the most common, and the simplest method of home brewing, is instant coffee (Figure 1.8 (12)). Water is simply poured on top of the instant coffee granules and is then ready for consumption. The processing stage of instant coffee creates soluble granules, allowing the coffee to be drunk without any filtration. However, creating these granules involves brewing the coffee, followed by a dehydration step, which detracts flavour from the coffee. Also, cheap beans are used and process steps are not closely monitored (due to cost), which is why instant coffee is often considered the worst tasting method of brewing.

Figure 1.8 Instant coffee granules ready for brewing

Filter

Another very popular brewing method is drip coffee (Figure 1.9 (13)). This brewing technique is automated using a machine which heats the water and pours it into a cone shaped filter which contains the coffee granules. The coffee brews in the cone and slowly drips through into a cup or carafe. This method requires little skill and can produce many cups of coffee at once.

Pour-over coffee (Figure 1.10 (14)) is effectively a manual take on drip coffee. By manually pouring the water into the filter, the variables of coffee brewing can be easily controlled, such as water temperature, water distribution and stirring the mixture. Correctly controlling these variables can result in a higher quality brew than using a drip machine.

Figure 1.9 Drip coffee maker

Figure 1.10 Pour over coffee device

Aeropress

The Aeropress (Figure 1.11 (15)) has a chamber, at the bottom is a paper filter to stop coffee grinds getting through, and a filter cap to prevent premature dripping. Water and coffee are immersed in the chamber with a small amount of stirring, before being pushed through the filter by the pressure of the plunger. The pressure from the plunger allows more flavour to be extracted from the grinds. The quality of the method is generally considered to be high, and the technology used is very simple and portable. However, it can only brew one cup at a time and can be difficult to push the plunger through the chamber.

Figure 1.11 Aeropress device

Figure 1.12 French press cafetière

French press

French press (Figure 1.12 (16)) is another form of immersion brewing, coffee is immersed in water inside a cafetière for several minutes. Then, a metal filter is pushed down through the mixture, filtering the coffee grounds so that the coffee can be poured out. As pressure isn't used in extraction, brewing takes longer than with an Aeropress. This method also has many variables to control, so with practice a high-quality cup of coffee can be made, and multiple cups at once.

Espresso machine

Espresso machines produce very different coffee to the methods mentioned previously. These other methods always produce a whole cup of coffee, whereas espresso machines produce a very small concentrated shot of coffee called an espresso. The espressos produced can be used to make longer drinks, either by topping up with water or milk. Espresso machines often have steam wands, which can heat and froth or foam the milk, used to produce drinks such as lattes, flat whites or cappuccinos. These machines are generally considered the best way to produce coffee, for both the quality and the variety of drinks that can be made.

Espresso machines work by forcing pressurised, nearly-boiling water through finely ground and tightly packed coffee held in a filter, called a portafilter. By extracting the coffee at such a high pressure, a lot of the flavour of the beans can be extracted quickly, allowing espresso shots to be made very quickly compared to other brewing methods. There is a huge variety in ways an espresso machine can work, which vastly affects the price. They can be automatic, semi-automatic or manual, with a variety of heating and pressurising mechanisms.

Automatic

Automatic machines are the easiest to use, all they require is for a coffee pod to be inserted and a button to be pressed, then within a minute a coffee has been made. However, the ease of use influences both the taste and the environment. The pods used are made of plastic and a lot of waste is produced this way. Also, due to their simplicity, the user cannot alter the brewing variables, so they cannot change the taste of the brew.

Semi-automatic

These machines require coffee grounds to be compressed into the portafilter by a process called tamping (Figure 1.13 (17)). Using a semi-automatic machine produces a lot less environmentally damaging waste and can produce better tasting coffee than automatics, but only if tamped properly for the grind sized used. Therefore, semi-automatic machines have a smaller margin for error, especially with new users. However, with practice the user can produce exactly the type of coffee they want, as they have complete control over what beans they buy and how fine they grind the beans.

Figure 1.13 Coffee grinds being tamped in the

Manual

Manual machines work in a similar way to semi-automatics. However, to pressurise the water a lever must be pulled by the user, which is where the term "pulling an espresso" comes from. This method is extremely difficult to be consistent with and requires a lot of training.

1.2.2 Espresso Machine Components

Although some machines are very complex and have additional features, all machines require the same basic mechanisms: heating, driving and filtering. The complexity of the mechanisms used determines the price of a machine and often its use, either home or commercial. The range of technology available was evaluated so that suitable components could be used in the chosen design. The basic schematic of how a general machine works is shown in Figure 1.14.

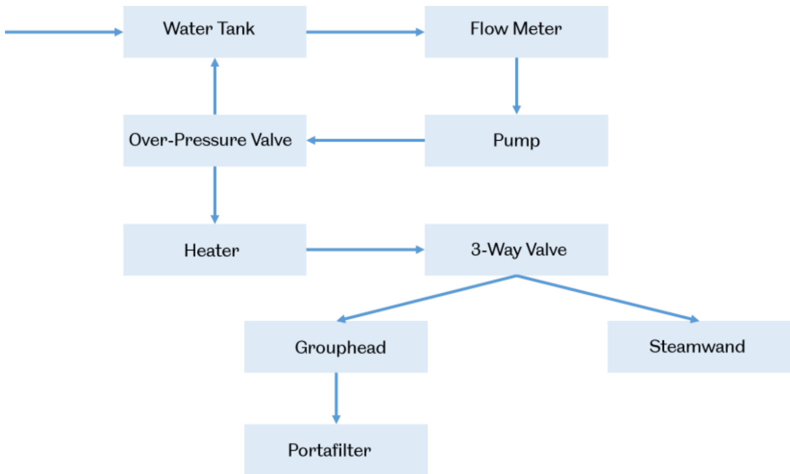

Figure 1.14 Espresso machine schematic

Heating Mechanisms

Boiler

This is a vessel filled with water which is heated using an electrically driven coil inside the boiler. An electrode is hung from the boiler ceiling to ensure the coil is submerged, to prevent it burning out. Once the water level descends below the electrode, more water is pumped in to raise the water level. If no more water can be pumped in, the coil will switch off (18).

The boiler can reach different temperatures depending on whether brew water or steam is desired, as only one can be produced at a time (87-93 degrees for brew water and 125 degrees for steam (19)). As the boiler will be pressurised when heating, the inlet water needs to be pressured above this pressure.

Heat Exchanger

Alternatively, a heat exchanger is used. Similarly, there is a reservoir of water which is heated by a heater coil to steam temperatures, but it also contains a heat exchanger inside of it. Steam generated in the boiler can be used to froth milk at the same time as pulling a shot. However, as the boiler is used to heat water for both steam and brew water, changing the boiler temperature will affect both streams, which usually leads to an unideal temperature in one of them (20).

Mineral deposits can build up in a boiler, this can affect the purity of the water and therefore taste of the brew. So, the water used for brewing comes from a clean supply which passes through the heat exchanger and is heated up to temperature, ensuring the taste of the brew is not affected.

Despite this advantage over a single or double boiler system, adjustments to temperature in a heat exchanger are less precise, making it harder to fine-tune flavour. These systems have more components than a single boiler system, making it more expensive, however they are still cheaper than a double boiler machine.

Double Boiler

The most expensive machines tend to use a two-boiler system; one boiler at brewing temperature and another at steam temperature (20). This allows both steam and brewing water to be heated simultaneously and at their ideal temperatures, leading to higher quality product. Water temperature is more precise than in heat exchangers, so it is better for commercial scenarios in which accurate temperature is vital.

Two-part Thermoblock

Unlike traditional boilers which store water, a thermoblock heats the water upon demand. It is made up of metal blocks that are mounted together, with a seal between them (Figure 1.15 (21)). Inside there is a long pathway for the water to travel through. The block is heated using an embedded heating element, which heats the water as it travels through, reaching the desired temperature as it exits the thermal block. This method is a lot cheaper and more compact than using a boiler and has a lower start-up time to brew. However, as it made from two separate pieces it is prone to leakage due to seal failure. Also, due to its narrow passages it is prone to blockages from scale build up, which can result in a lot of maintenance.

Figure 1.15 Inside a two-part thermoblock

Single-part Thermoblock

This thermoblock is essentially stainless-steel piping encased in a block of aluminium (Figure 1.16 (22)). This has several advantages: being made of a single piece minimises any risk of leakage, stainless steel is also less susceptible to scale than aluminium (23) so the chance of blockage is reduced, and the block of aluminium used is larger so it retains heat better, resulting in more consistent shots.

Figure 1.16 Cut view of a single-part thermoblock

Drive Mechanisms

Steam-driven

Water is heated in a boiler to produce steam and build up pressure that is used to push the water through the coffee grinds. This method requires no additional components to the heating mechanism, so is less expensive. However, it cannot achieve the pressure needed for a high-quality espresso (24). This method is often used in lower-cost consumer machines.

Piston-driven

In piston-driven systems a lever is used to pressurise hot water, by the use of a piston, and push it through the coffee grinds. There are two types of lever used; manual and spring. Spring lever systems work the same as in manual systems, but the operator works to tension a spring which then delivers the pressure to the water, usually producing more consistent results and with less practice needed (25).

Vibratory Pump

Both vibratory and rotary pumps can achieve the 9-15 bar range required for good espresso and produce it very consistently (26). Vibratory pumps are electromagnetically driven. They are composed of a piston attached to a magnet, inside a metal coil.

As electrical current runs through the coil, the electromagnetic effect causes the piston to move rapidly back and forth, at sixty pushes per second. As the piston moves back, water fills the pressure chamber. Then, as it moves forward the one-way ball pushes against the end of the piston, preventing any water flowing back from where it came. As the piston compresses, water is pressurised and then forced out the one-way valve and towards the heating mechanism.

Rotary Pump

A rotor is positioned eccentrically in the pump housing. Vanes are slotted into the rotor, and loaded with springs or hydraulics, to ensure they are always contacting the housing walls, creating separate chambers. As water enters the pump, the chambers expand in size, reducing pressure and creating a pressure suction on the inlet, causing water to flow into the pump. As the rotor continues to rotate, the chambers get smaller, creating the pressure in the water leaving the pump.

Rotary pumps are significantly quieter in use, more durable and limit the pressure oscillations in the outlet. However, they are much larger than vibratory pumps, more expensive, and are considered to have no effect on the taste of the espresso (26).

Water Delivery Mechanisms

Group head

The group head is the point in the machine at which the water is delivered to the coffee. It ensures an even spread of water across the coffee grinds using a dispersion block. This acts like a showerhead, to ensure all the coffee comes into contact with the water, for full extraction. There are three main types of group head: E61, saturated and semi-saturated.

The E61 is a classic espresso machine component, being widely used since 1961 (Figure 1.17 (27)). It is a heavy component, made of a large mass of brass. Therefore, it takes around 15 minutes to heat up to the desired temperature, but then retains the heat easily, which makes it ideal for producing large amounts of espresso. It is also entirely mechanical, making it very reliable but also requires more participation from the user when pulling a shot. It is effectively a mechanically operated three-way valve: one valve to let the water into the group head, one from the group head to the portafilter, and one to relieve back pressure from the portafilter.

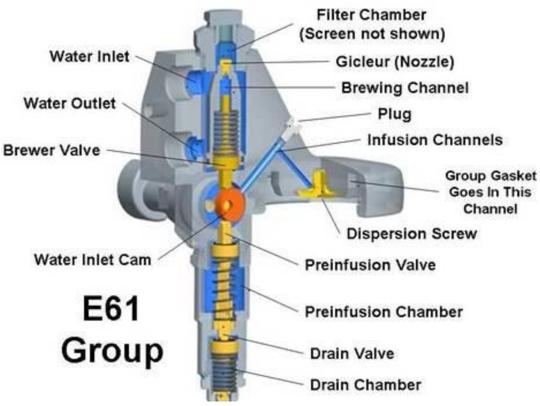

Figure 1.17 E61 Group head

In saturated group heads (Figure 1.18 (27)), the group head is open to the boiler, acting as an extension of its so that its saturated with hot water, which allows to it come to temperature quickly. It also acts as a 3-way valve working in a similar way; however, it is electronically controlled. Despite heating much quicker, they are often more expensive and require an expert to perform maintenance work.

Figure 1.18 La Marzocco GS3 group head

As they are cheaper and easier to maintain, semi-saturated group heads are often recommended for home espresso machines. They work the same way as saturated groups, except they have an area directly above the dispersion block which is separated from the boiler, which does result in marginally less temperature stability.

Portafilter

This is the component which holds the ground coffee, it is comprised of a handle, for easy handling of the portafilter unit, and a filter basket, where the coffee grounds are inserted. The filter basket is a removable metal component that fits into the portafilter exterior. It has lots of small holes in the bottom, which act as a screen for the coffee grounds, but allow the water with the extracted coffee flavour to pass through and out into the cup.

Once the ground coffee is inserted into the filter basket, it is then tamped to compress the grounds. If it is too loosely or too tightly tamped, the result will by sub-par espresso. Portafilters typically come in either 53mm or 58mm size, either can make good espresso but the same size tamp needs to be bought to ensure even compression of coffee grounds. After tamping, the portafilter is locked into the group head and espresso is ready to be made.

Control Mechanisms

Most modern espresso machines will use some form of control system to regulate the use of the driving and heating mechanisms, complexity of these systems depends on the price of the machine. Lower-end machines use a very simple system for controlling the heating. They have a thermostat at some point in the machine, often the boiler. Once the temperature of the water reaches above a certain point, the heating element turns off. When the water then drops below a certain temperature, the heating element turns back on (28). Although this is very simple and cheap to implement, it results in a highly fluctuating temperature of water for brewing. At best this leads to inconsistent taste in espresso but can cause poor taste at certain temperatures.

More expensive units use more complex control, achieved by the use of microcontroller (MCU) or microprocessor (MPU) based development boards. A development board is essentially a very small and simple computer, they are programmable and come in varying complexities. In an espresso machine they are usually used for Proportional Integral Derivative (PID) control. PID controllers attempt to predict what is going to happen and act accordingly to keep the system under control. In this case, the development board keeps the water temperature under control before it goes askew. This is done by programming an algorithm into the board. There are a huge number of development boards available, and different boards are suited to different uses.

Development Boards

Computer Chip

The biggest differentiation between boards is whether they are run using an MCU or MPU, both of which are just types of computer chip. An MCU is slower, more integrated, easier to program, easier to design, requires no operating system, consumes less power, and is generally cheaper than an MPU. On the other hand, an MPU is faster, has more memory, but usually more complex to program. However, this does mean MPUs can carry out more complex tasks than MCUs (29).

Voltage

The voltage is also a huge consideration when selecting a development board, their specifications will state both the input voltage and operating voltage. Input voltage is that provided to the board via an external power source (varying from 7-20V depending on the board). Operating voltage is the voltage the board supplies for externally connected devices (generally either 3.3 or 5V). Any externally connected devices that operate with a different voltage to the operational voltage will require a voltage divider or bidirectional level shifter. This is needed to ensure the devices can operate without any damage to them.

Current

Boards also have a DC current per I/O pin on their specification, this refers to how much current is available to externally connected electrical components. If the component connected requires a different current to operate then the supplied current may need to be regulated before connecting the pins.

Clock-speed

This is the processing speed of the board. High clock-speeds are used for highly complex and time-critical functions. However, high clock-speeds use comparatively more power.

GPIO

General Purpose Input/Output pins (GPIO) allow for the board to communicate with external components. GPIO pins can be categorised into analog and digital.

Digital pins are seen as either HIGH, above 66% of the operating voltage, or LOW, anything below 66%. However, sometimes more than just HIGH or LOW signalling is needed. For example, varying the amount of heat exerted by a heating element. These applications use Pulse-Width Modulation (PWM) digital pins. They allow toggling between HIGH and LOW at programmable ratios. This allows the average voltage to be controlled, similar to an analog output.

Analog pins are capable of reading analog voltage signals (using an Analog-to-Digital Converter) and output true analog voltage (using a Digital-to-Analog Converter). This is useful in scenarios where you need to measure a voltage, rather than just a HIGH or LOW logic state.

Size

Boards can come in all different sizes. If the project has size constraints, then only certain boards can be used.

Software

Each board will support certain coding languages, from low-level to high-level. Low-level languages, such as C, are closer to how computers “talk” and run directly on the processor, they are more difficult to learn but use less storage and can be highly powerful. High-level languages, such as Python, are closer to how humans “talk”, and take less time to program, but perform poorer (30). Some boards will support a variety of coding languages.

Available Technologies

As there are too many development boards to list, only the most popular boards were evaluated. The advantage of using a popular board is that there is a larger online community to support any issues that arise. Also, there is a greater chance of finding a base code for any activities, which can then be edited to tailor to the situation, saving a lot of time in comparison to writing code from scratch.

Arduino Uno

The Arduino family of boards are microcontroller-based and are an open source design, therefore do not have an operating system and run purely off written code. However, they communicate very easily with a wide range of electronic components, such as sensors and motors and are very power conservative. Also, there is many add-ons – shields - that can be installed to increases the uses of the Arduino, such as a Wi-Fi connectivity, touchscreen, cameras and microphone capabilities.

Arduino Micro & Mega

Although the Uno is the most popular Arduino, there are others available for slightly different uses. If size of board is a restriction, the Micro is an alternative to the Uno. as it is 3x smaller, with the same processing power, memory and even more GPIO pins. However, it does not have the capability to use shields, restricting its uses.

If the project requires a large amount of code, lots of GPIO pins, and size is not a restriction, then the Mega is an excellent choice. It has 8x more memory space than the others and 4x more SRAM, allowing it to create and manipulate more variables when it runs. It is also compatible with shields, but it the most expensive of the three Arduino boards.

Raspberry Pi 3

The Raspberry PI is in fact an entire computer with its own operating system, giving it a huge range of functionality and can handle more complex tasks. It can do everything that an Arduino can, however interacting with hardware components is more complicated on the Pi. When dealing with software, the Pi excels and already has Wi-Fi, HDMI and Bluetooth capabilities built-in.

BeagleBone

This board is very similar to the Raspberry Pi, offering all the same benefits but with a more powerful processor, more GPIO pins and onboard storage (no SD card required), making it perfect for very complex tasks, such as face detection. However, these improvements come with a cost, and thus the BeagleBone is more expensive than the Raspberry Pi. Similarly to the Arduino, the BeagleBone is open source.

The attributes of the listed technologies were compared in Table 1.1.

Development Board	Arduino Uno	Arduino Micro	Arduino Mega	Raspberry Pi 3	BeagleBone
Price	£20	£18	£35	£35	£50
Dimensions	69mm x 53mm	48mm x 18mm	102mm x 53mm	85mm x 56mm	86mm x 53mm
Processor	Atmega328P	Atmega2560	Atmega32U4	Quad Core ARM Cortex-A53	ARM Cortex-A8
Clock Speed	16MHz	16MHz	16MHz	1.2GHz	1GHz
Flash Memory	32kB	32kB	256kB	microSD	2GB
SRAM	2kB	2.5kB	8kB	1GB	512MB
Voltage (V)	5	5	5		
Digital I/O Pins	14	54	20	40	46
Digital I/O Pins with PWM	6	15	7	2	5
Analog Pins	6	16	12	0	7
Ethernet/Wi-Fi/Bluetooth	No (A shield can enable it)	No	No (A shield can enable it)	Yes	Yes

Table 1.1 Control board attributes

1.3 Introduction to the Maker Community

By definition, a *maker* is simply someone who creates, or forms, something. More commonly it is linked to someone involved in the *maker movement*. It is changing the way people think about education, technology and more (31). It is harbouring the collaboration of people, helping them to realise that more can be achieved together than alone.

The maker community is made up of people that share their successes and failures, allowing others to learn, develop their skills and build upon others work. A maker in the community is someone who builds their own, or improves an existing, product. Makers often use makerspaces (also known as hackspaces), which are shared workshops which contain various tools and manufacturing equipment to be used.

1.3.1 History

The maker movement has developed from the wider *do it yourself (DIY)* movement. This is a movement that can be traced back to centuries ago, where a collection of Greek buildings were found to have been built almost identically using instructions inscribed on parts of the building (32).

More recently, there was a surge in population of DIY in the 60s and 70s in the UK. One of the reasons for this surge was economic difficulties for many at this time. Making your own, or repairing, items such as clothing, furniture and electronics became a way to help deal with the struggle for economic stability for many people.

However, as the global economy improved during the 90s and 2000s, popularity of DIY took a dip, as those who were doing it purely for economic reasons no longer needed to (33). During this time, the internet advanced dramatically and became much more widespread, making the sharing of information accessible to almost anyone. Websites such as Wikipedia have enabled people to educate themselves on a vast range of topics, encouraging them to have a more proactive mindset. Also, sites such as Instructibles and Youtube, which provide millions of user-submitted tutorials, have made it so easy for people to get involved with DIY.

In 2008 there was another economic crash, leaving people looking for ways to save money, and once again finding DIY. This, along with the development of maker-friendly manufacturing methods (3D printing), and the ease and accessibility to DIY information from the internet, has led to huge growth in the DIY movement, particularly in the subculture of the maker movement.

1.3.2 Current State

With the increased popularity of the maker movement in the last 10 years, there has been several websites and magazines supporting this culture. For example, Maker Media publish magazines and books every year, have a large presence on youtube, sell products online and even host Maker Fairs. These faires celebrate the "DIY mindset" through people's projects and creations, bringing in over a million visitors a year. Their Youtube channel now has over 1.5 million subscribers, and they even created their own site, MakerSpace, created to allow people to share their projects with others.

There are many websites similar to MakerSpace, allowing people to interact with the maker community. Thingiverse, owned by MakerBot (a 3D printer company), is primarily 3D printed projects only. Hackaday is one of the largest collaborative hardware development communities, which isn't restricted to just 3D printed projects. Most projects here involve the use of development boards, often to "hack" existing products to improve them, but also to create products from scratch. The website also runs contests with prizes, increasing the activity within the community. Another website, Instructibles, was bought by AutoDesk in 2011 for $32 million, highlighting the value of this growing community. Instructables allows users to share any type of DIY projects, it also has a list of classes available to help makers learn new techniques, such as 3D printing, electronics, crafts and even food courses. In addition to just sharing their projects, all these sites allow users to upload their files and build instructions in an open source format, so anyone else can re-create the project they have developed.

1.3.3 Open Source

The term "open source" refers to something people can use, modify and share because it is publicly accessible. This originated in reference to software development, where users could access freely available source code. For example, this is the basis on which Linux is built. By freely sharing the source code, it allows users to modify for their own personal gain but often these modifications are shared with the community. This results in quicker and better development of software than would not be achievable with a small, closed group of people, leading to shorter time-to-market.

Today, however, "open source" has branched out to involve hardware projects too, such as Arduino, who sell their products but also share their blueprints online. Whilst sharing an open source software design only requires source code, hardware designs require a lot more information to be considered truly "open source" and can change from design-to-design. Generally, it will include: instructions for manufacture, bill of materials, digital files for manufacture (CNC routers, 3D printing, Laser cutting), technical drawings, electronic schematics, along with any source code if programming is required.

Open source is often used to democratise designs, taking existing products and creating open source variations on them, making them customisable to different needs and therefore accessible to a larger group of people. Along with accessibility, the community-based approach of open source ensures greater reliability and security, as there are more people thoroughly reviewing and vetting designs.

To prevent others stealing, privatising and monetizing open source designs, licenses are used to outline the terms of use. There are a variety of software licenses available, as per *The Open Source Initiative* (34), which slightly differ from each other, but generally cover the same points:

- The source code is available to, and may be distributed freely to anyone
- If any changes are made to the source code it must be released as a new version with a unique version number
- The above two points hold true as long as the copyrights and disclaimers of warranty of the licence are maintained

Hardware projects are also covered by licences such as the CERN Open Hardware Licence (CERN OHL), which protects design documentation in the same way software licences protect source code. Design documentation is defined in this licence as "schematic diagrams, designs, circuit or circuit board layouts, mechanical drawings, flow charts and descriptive text, and other explanatory material that is explicitly stated as being made available under the conditions of this Licence." (CERN Open Hardware License V1.2) It also states that any code, software or firmware used in programmable devices in the design must be explicitly expressed to be subject to the licence, otherwise it will be subject to the applicable licence terms and conditions.

1.4 Previous work

Research was conducted to find existing DIY coffee machine and open source projects. The most common form of project found was "hacking" existing espresso machines by installing PID controllers (35). There is many of these projects which share enough detail to be considered open source. However, these projects are model specific and have only been carried out on boiler systems, which limits their use and means there is many espresso machine models without an open source PID controller available.

There are more "hacking" projects which implement an additional control board (sometimes multiple) to an existing machine (36) for a variety of functions such as: Wi-Fi connectivity, mobile/laptop application control, voice control, along with many more. Although there is a lot of "hacking" projects, they all require modifying an existing machine. There are much fewer entire coffee machine open source projects and are all for either drip or pour-over machines (37).

1.5 Conclusion

Coffee is grown, harvested, and processed in such a number of ways that using constant brewing parameters will not produce "good" tasting coffee for every variety of coffee grounds. Therefore, a successful coffee machine design will have scope for altering brewing parameters.

There is a wide range of brewing technologies, each have their own advantages, disadvantages and intricacies. However, none of the other technologies have the same complexity or variety of components as the espresso machine, which makes it the appropriate technology to pursue for a final year project. One of the main differences between low-end and high-end machines is their temperature accuracy and stability. Thus, a primary focus of the design was to use low-end components and improve these attributes, effectively increasing the value of the machine.

Another focus was to create a novel design. The coffee industry is huge, worth billions of dollars and has been around for a long time, meaning a vast quantity of designs have been explored already and it would have been difficult to compete without the financial backing that other companies have. Conversely, the open source community is relatively new and as research has shown, there was no "fully" open source espresso machines available, which provided a lot of freedom for a novel design. An open source approach meant becoming part of the "open source community", which provided support for obtaining information or accessing help, and offered an opportunity for the project to continue beyond given timescale.

2 DESIGN PROCESS

2.1 Aims & Objectives

2.1.1 Aims

The main aim of this project was to design and build an open source espresso machine, whilst providing enough documentation so that anyone could build it in a typical makerspace using publicly available components. Another aim was to replace components for more standardised and widely available components.

2.1.2 Objectives

- Use research to influence the selection of an existing machine to purchase
- Carry out primary research of the advantages and disadvantages of existing products
- Test the performance of the machine, providing a benchmark for comparison with prototypes created
- Reverse engineer the existing machine to obtain further understanding of how the technology works
- Utilise existing components to a simple Arduino controlled first prototype

- Make a second prototype which is comprised of the same components, but in a casing which resembles that of a coffee machine
- Identify components which are not widely available and replace them with standardised, readily available components
- Outline direction for further work to aid the continuation of the project by the wider open source community.

2.2 Methodology

Once research had been completed, it was decided to take the approach of reverse engineering an existing consumer machine. This helps to develop a deeper understanding of what is desirable in an espresso machine design and how they work, which influenced the design specification. It also provided the opportunity to measure the performance of a consumer product, allowing for comparison with any designs produced.

The design was chosen to be developed by using a series of prototypes, rather than producing the final design at first attempt. This helped to incorporate a "learning by doing approach", which is often carried out in the maker community (38), and helped to debug any issues that arose.

Following the values of many open source projects, the progress of the project was shared on Hackaday to interact with the open source community. It was expected that this interaction would provide assistance and support to the project.

2.3 Design Selection

The main components that required design selection were the pump, heater and control board. As these components are drastically different, their selection criteria also differed. The weighted objectives method (39) was used to aid selection.

The relevant objectives for the heater, pump and control board all differ from each other. Thus, a criterion-weighting matrix was created for each of the component types.

Heater

The technologies evaluated for the heating mechanism were those identified in Section 1.2.2.

	Price	Start-up time	Temperature stability	Maintenance	Steaming ability	Total	**Weighting**
Price	X	1	1	1	1	4	**5**
Start-up time	0	X	0	1	1	2	**3**
Temperature stability	0	1	X	1	1	3	**4**
Maintenance	0	0	0	X	1	1	**2**
Steaming ability	0	0	0	0	X	0	**1**

Table 2.1 Heater weighting matrix

	Price	Start-up time	Temperature stability	Maintenance	Steaming ability	**Weighted total**
Boiler	3	1	4	2	3	**41**
Double Boiler	1	1	4	2	5	**33**
Heat Exchanger	2	1	2	3	5	**32**
Thermoblock (two-part)	4	5	3	2	2	**53**
Thermoblock (single-part)	3	5	3	4	2	**52**

Table 2.2 Heater decision matrix

Clearly, it would be ideal to use either type of thermoblock due to their low price, quick start up time (approximately half a minute compared to several minutes in boiler systems) and reasonable temperature stability, which could be improved by implementing temperature control methods.

Drive mechanism

The same method was used to select the technology used for the drive mechanism, which were outlined in Section 1.2.2.

	Achievable pressure	Consistency	Noise	Price	Total	**Weighting**
Achievable pressure	X	1	1	1	3	**4**
Consistency	0	X	1	0	1	**2**
Noise	0	0	X	0	0	**1**
Price	0	1	1	X	2	**3**

Table 2.3 Pump weighting matrix

	Achievable pressure	Consistency	Noise	Price	**Weighted Total**
Steam driven	1	4	4	5	**31**
Piston driven	5	1	5	3	**36**
Vibratory pump	5	4	1	4	**41**
Rotary pump	5	5	3	2	**39**

Table 2.4 Pump decision matrix

Even though the rotary pump scored so closely to the vibratory pump, there is no evidence of improved taste of espresso with a rotary pump. Therefore, the vibratory pump was chosen due to its significantly lower cost.

Control board

The most important criteria were selected from the more extensive list of attributes seen in Section 1.2.2.

	Price	Size	No. of suitable pins	Shield capability	Processing power	Total	**Weighting**
Price	X	1	0	0	1	2	**3**
Size	0	X	0	0	1	1	**2**
No. of suitable pins	1	1	X	1	1	4	**5**
Shield capability	1	1	0	X	1	3	**4**
Processing power	0	0	0	0	X	0	**1**

Table 2.5 Control board weighting matrix

	Price	Size	No. of suitable pins	Shield capability	Processing power	**Weighted total**
Arduino Uno	5	3	2	5	1	**52**
Arduino Micro	5	5	4	1	1	**50**
Arduino Mega	3	2	2	5	1	**44**
Raspberry Pi	3	3	1	5	5	**45**
BeagleBone	1	3	3	5	5	**49**

Table 2.6 Control board decision matrix

As the processes the control board will be carrying out will be very simple tasks (at least so in the first few iterations of the project), not much processing power will be required. Due to their lower cost, power consumption and large online community, the Arduino Uno and Micro are the more favourable options. Both have a good range of digital, PWM and analogue pins which will be required for the design. Despite the Micro costing less and being smaller, the ability of the Uno to support shields makes it the chosen model for the project, as this allows features such as interaction with sensors or Wi-Fi capabilities much easier, and size is not of huge concern to begin with. The Arduino Uno is also an open source design, which fits very well into the ethos of the project.

2.4 Reverse Engineering

It was decided to purchase an espresso machine and reverse engineer it. This involved using the machine to gain first-hand experience of the pros and cons of a consumer machine, which helped to influence the open source machine design. The machine's temperature stability was then measured, before dismantling it to obtain a greater understanding of its workings. The components were then re-used, provided they could either be manufactured otherwise or were openly available to buy.

Machine selection was influenced by several factors, mainly components desired from the design selection (Section 2.3), reviews, and budget (£150). The De'longhi Dedica Style EC865.M satisfied all the criteria, and thus was chosen (Figure 2.1).

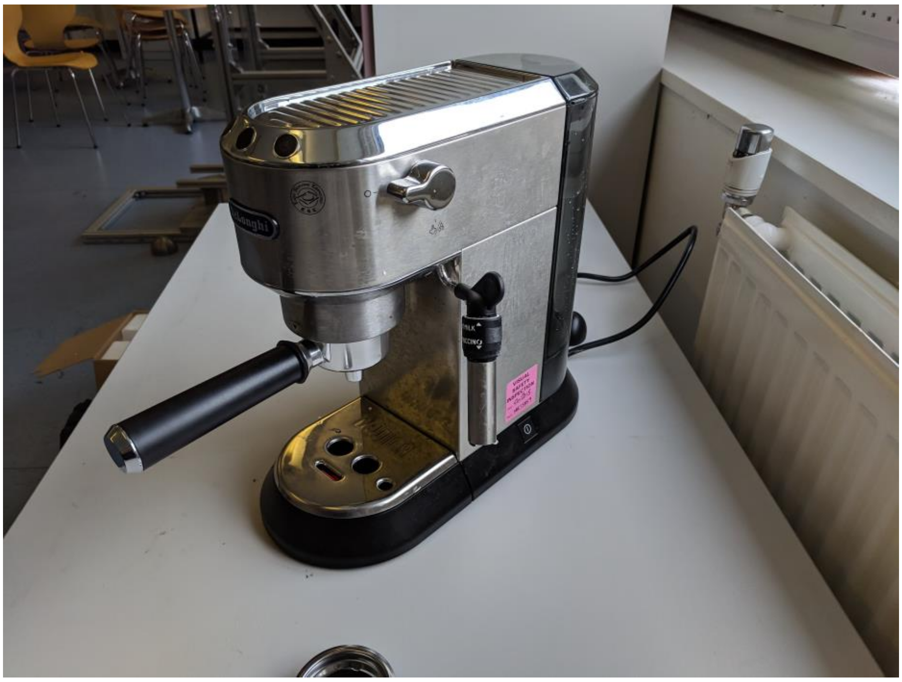

Figure 2.1 De'Longhi Dedica Style EC685.M

2.4.1 User Experience

From use of the machine, the following pros and cons were identified:

Pros

- Removable water tank
- Quick start-up time was very convenient
- Option for single or double espresso
- Does not run if there is no water in the tank

Cons

- No indication of low water level
- Temperature intervals are not quantitative – low, medium and high
- User interface is complicated due to a lack of a screen
- Very difficult to disassemble
- Requires running hot water through the machine to achieve good tasting espresso, but lacks a pre-heat function

From personal use of this machine, it was found that running several cycles of hot water through the machine before pulling a shot drastically improved the taste of the espresso. Therefore, an investigation was designed to measure the variation of water temperature from cycle-to-cycle. Also, it was suspected, from the price of the machine, that it had a cheap and simple control system for regulating water temperature throughout the cycle. Thus, water temperature variation throughout a single cycle was also a variable of interest to be measured.

2.4.2 Experimentation

A temperature probe was inserted to a tee fitting and placed between the heater and group head (Figure 2.2), testing under various scenarios. In all cases the machine was run without any coffee or the portafilter in. As there were a lot of tests to be ran, this would have made experimentation slow and expensive if coffee was used.

Firstly, the machine was run from cold, allowing approximately 30s between cycles (roughly the time to change the portafilter), running double shots each time. Next, the machine was run with each cycle back-to-back, from cold, running the next cycle as soon as possible. Then, once again cycles were ran with 30s between each, but after preheating the machine with two back-to-back cycles.

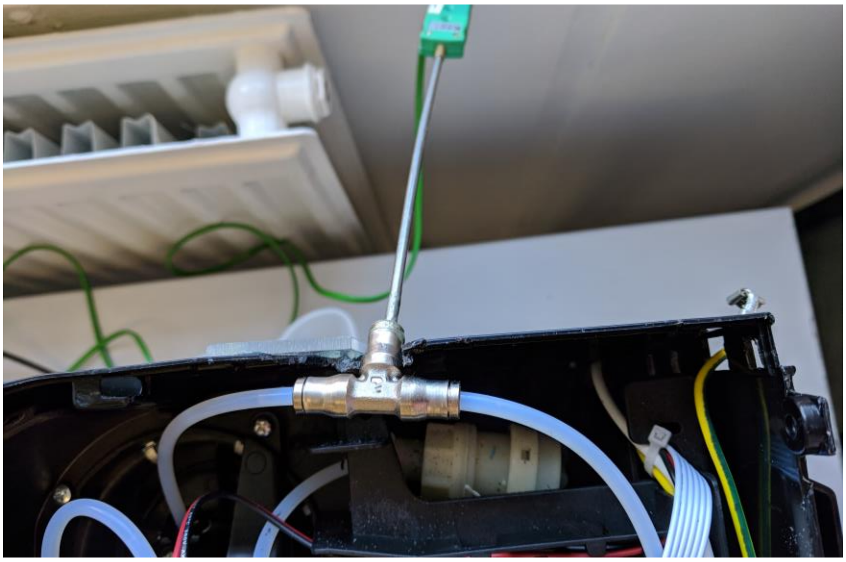

Figure 2.2 Thermocouple inserted into a tee fitting

Experiment one

The first experiment (Figure 2.3) shows that temperature varies from cycle-to-cycle - ±2°C. But, it also shows that when heated from cold the temperature peaks at approximately 75°C, which is lower than desired. It is clear that temperature during the cycle changes drastically, with a large portion of the cycle at low temperature, which will result in poor tasting coffee. Red lines indicate the pre-infusion pumping stage, green indicate the main pumping cycle.

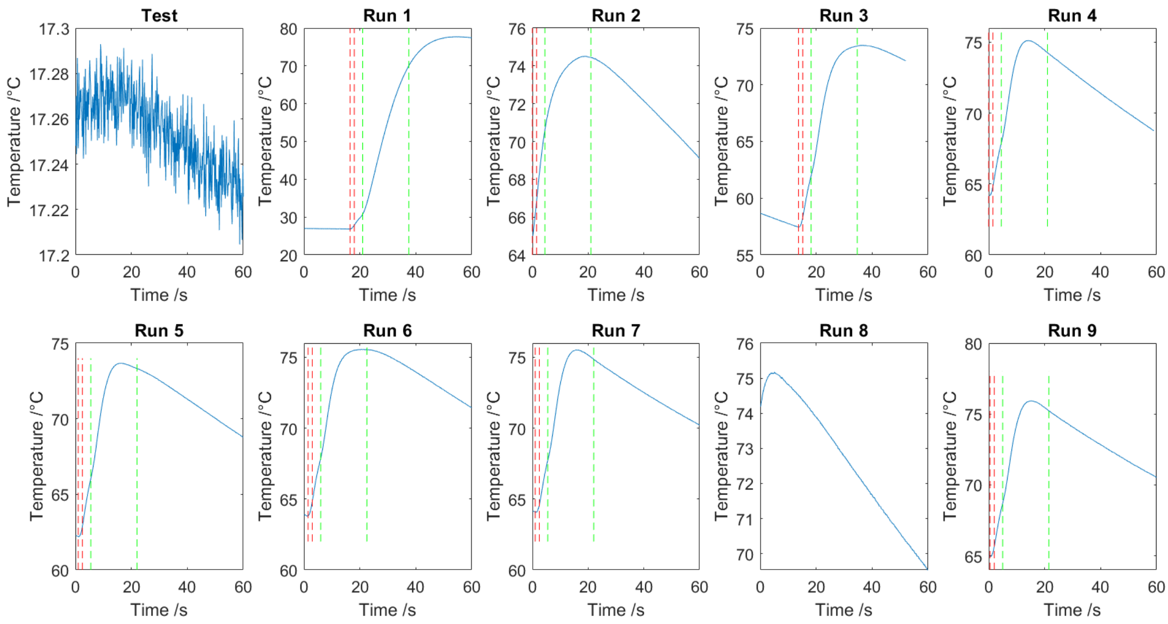

Figure 2.3 Experiment one

Experiment two

This experiment (Figure 2.4) demonstrates that when running multiple cycles through the machine to effectively "Pre-heat", higher peak temperatures can be achieved, a lot closer to the desired range of 87-93°C, with a larger portion of the cycle occurring at desirable temperatures

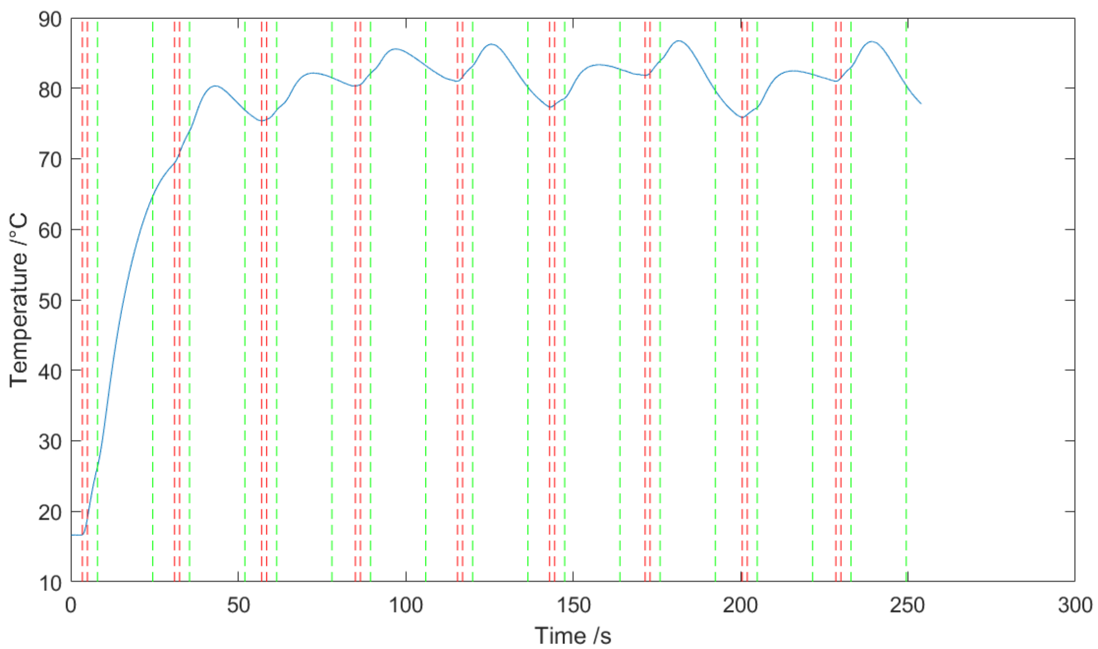

Figure 2.4 Experiment two

Experiment three

The final experiment further investigated the effect of using “pre-heat” cycles, but emulates actual machine use more realistically, by allowing a 30 second break (similar to the time taken to tamp and insert a portafilter) between the brew cycle and “pre-heat” cycles. As shown in Figure 2.5, this proves the “pre-heat” cycles are an effective method to ensure the majority of the cycle occurs in an acceptable temperature range.

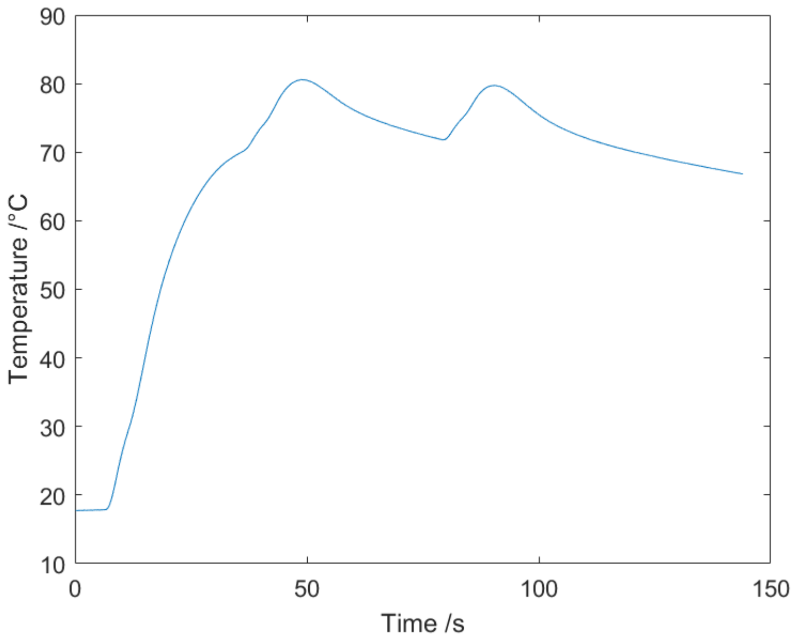

Figure 2.5 Experiment three

In all the cycles, the temperature curves are composed of one rise and one fall, suggesting that the heater simply turns on once and then turns off, making it difficult to achieve a flat temperature curve. From this, it was concluded that not only should the open source design include a pre-heat function to reduce cycle variation at start-up, but it should also attempt to achieve greater temperature stability during each cycle.

2.4.3 Dismantling

Once the existing machine had been tested, it was dismantled (Figure 2.6). This helped to reaffirm the understanding how the technology works by providing visual aid. It also helped to learn how the components were connected electronically, which influenced the electronics used in the first prototype.

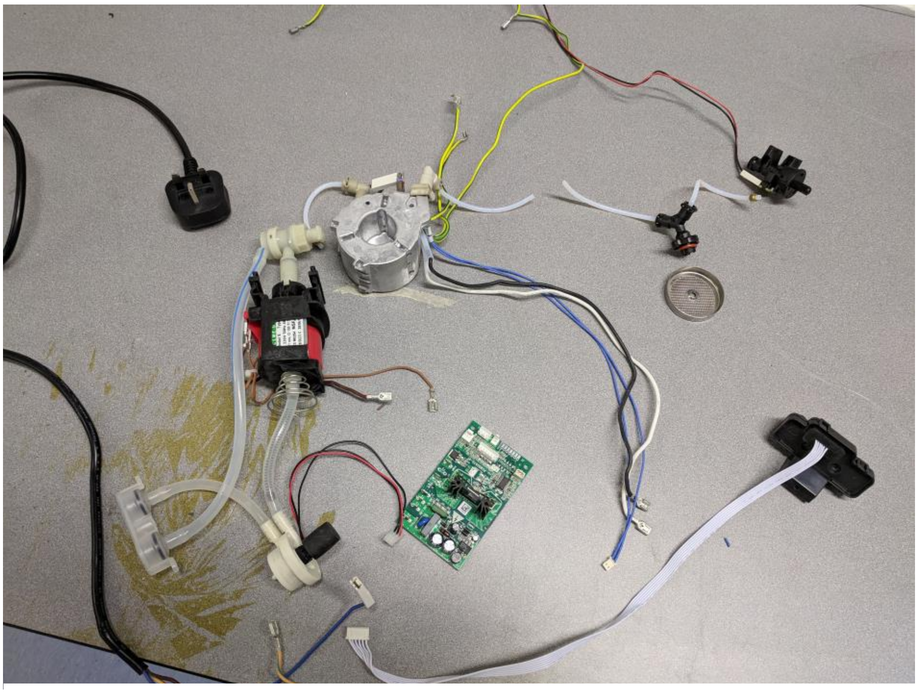
Figure 2.6 Components from the dismantled machine

Research was then carried out on all the components, evaluating their public availability for purchase. Generally, widely available components were not used in the existing machine. However, all components were publicly available, apart from some of the group head design, which was integrated into the casing.

2.5 Design Specification

A design specification was written to identify the boundaries which the design must comply with to be considered successful. The specification took into account both the performance of the machine and the ability for it to be manufactured in a maker space.

Performance

- The machine should be able to produce both single (25-30ml using 7g dried coffee) and double (50-60ml using 14g dried coffee) shots
- The machine should produce a water pressure of at least 9 bar when the water contacts the coffee
- The machine should heat the water to 87-95 °C when it contacts the coffee
- The machine should pump water briefly in a pre-infusion stage before the main pumping stage
- Water tank should be able to hold at least 1 litre

Environment

- Internal piping components must be rated to withstand up to 125°C
- Internal piping components must be rated to withstand up to 15 bar

Maintenance

- The design should allow for ease of dismantling and replacement of parts

Target cost

- Total cost of materials and components should not exceed £300

Manufacturing

- The machine must be able to be manufactured in a typical maker space, using machines such as those mentioned in Section 2.5.1

Size

- The total size of the machine should be reasonable for a home espresso machine, not exceeding 0.4m x 0.4m x 0.4m

Materials and Components

- All materials and components should be readily available to be purchased
- As many components as possible should be able to be manufactured by the user

Safety

- The machine must pass PAT testing
- The machine must be safe to operate under standard usage
- Build instructions must include relevant safety warnings

Documentation

- All information required to build the machine should be made readily available to the open source community

Disposal

- The machine should be designed for safe dismantling to allow individual components to be reused, recycled or disposed of

2.5.1 Manufacturing Facilities

For the machine to be manufactured in a maker space, first the tools available in a maker space must be defined. The tools in each space will vary slightly from location to location, however they will typically share a lot of the same resources. Therefore, the iForge, a maker space located at The University of Sheffield, was used as an example for typically available tools, which are listed below.

- Metal & wood working unpowered hand tools
- Handheld power tools (rotary tool, power drill)
- Machining tools (pillar/bench drill, band saw, scroll saw, disc sander)
- Water jet cutter
- Laser cutter
- CNC machine
- 3D printers (FDM/SLS)
- Electronics tools

2.6 First Prototype

2.6.1 Design

The main focus of the first prototype was to replace the existing control board with Arduinos, so the user can change the programming, providing scope for accurate temperature control strategies. For simplicity in writing code and making it easier it debug any problems, two Arduinos were used, one to control the pump and one to control the heater. The rest of the components from the existing design were re-used due to their public availability, with a few additions.

Steamer

For simplicity of design, it was decided to focus on the espresso-producing aspect of the machine. Therefore, the steam wand was not included in the first prototype and the tubing that leads to the steam wand from the 3-way valve was blockaded using high temperature epoxy resin.

Electronic components

To aid temperature control strategies, sensors were installed. The same waterproof thermocouple used in the reverse engineering stage was installed between the heater and group head, in a tee fitting. It was submerged in the water to accurately measure water temperature during cycles. To assist the heater control strategy, an additional thermocouple was placed on the exterior of the heater, near the point where water exits, in an attempt to measure water exit temperature and relay this information back to the Arduino. To communicate with the Arduino, a MAX31855 thermocouple shield was used.

To allow the Arduino to control power to the heater and pump, a solid-state relay (SSR) and a relay were used, respectively. As these components required 24V, a separate power supply was installed. MOSFETs were used to amplify the signal between the relays and the Arduino. More detail of the electrical circuit is provided in Appendix 2.

Casing

A new case was required to fit the additional components. As aesthetics were not a concern for a first prototype, the components were fit into two boxes – one with the majority of the electronics parts, the other with the parts which water flows through (Figure 2.7). This was done to reduce the chance of an electrical fault in the case of leakage. To reduce the change of leakage, sealant was applied to applicable joints.

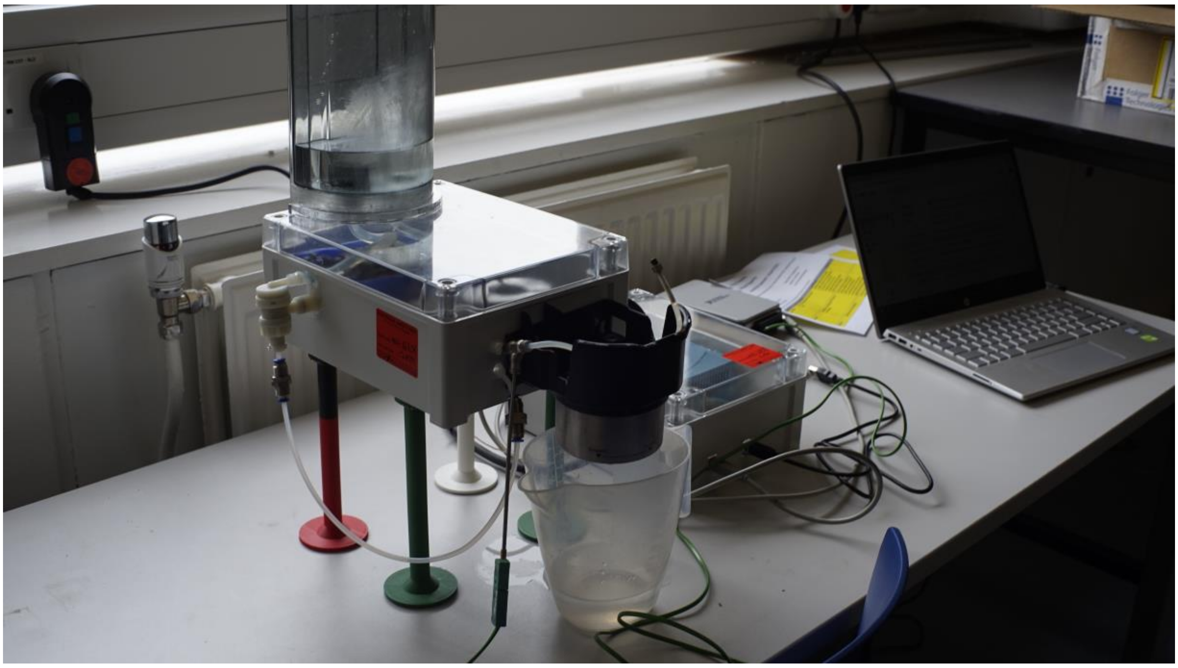

Figure 2.7 First prototype

Inside the boxes, the SSRs and heater were fit onto metal plates, heat sinks, to prevent them damaging the plastic of the box. The pump was fit into a 3D printed housing. The first iteration of this housing was very simple, and the pump was placed inside with no fixings (Figure 2.8), however this resulted in unacceptable levels of vibration. The second iteration replicated the fitting in the existing machine, allowing the silicone casing to slot into the housing (Figure 2.9), this new housing also held the spring to allow damping, which reduced vibration significantly.

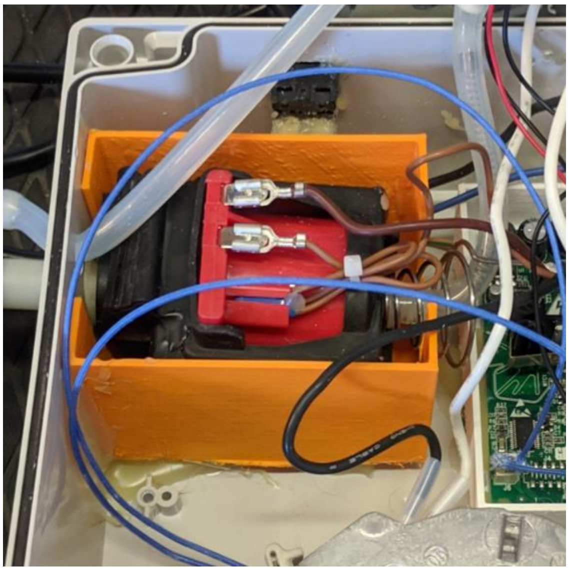

Figure 2.8 First iteration pump housing

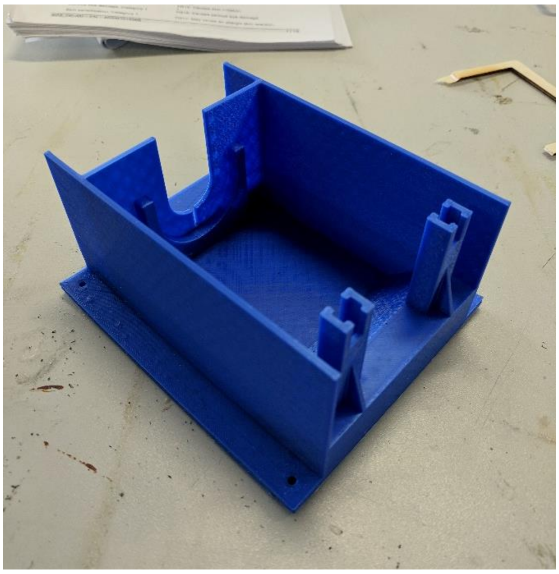

Figure 2.9 Final pump housing

As the group head was part of the casing in the De'Longhi EC685.M, this part was cut out of the casing and retrofit onto one of the boxes. Ideally, a publicly available group head would have been used. However, group heads are both quite rare (to buy individually) and typically very expensive. Thus, an attempt was made to create an open source group head within the second prototype.

Legs

The box which held the group head needed to be fixed on to legs so that there was room for a cup underneath. The legs were designed in Solidworks and 3D printed using PLA on an FDM printer. The first iteration of legs were printed at 30% density, as this was the machine default, which resulted in mechanical failure during installation (Figure 2.10). Once the legs were re-printed at 90% density they were much stronger, so were tapped (Figure 2.11) and installed, and gave the group head enough clearance for a standard sized mug to fit underneath. Non-slip adhesive pads were placed on the bottoms of the legs, which significantly reduced vibration and noise of the machine.

Figure 2.10 Failure of legs during installation

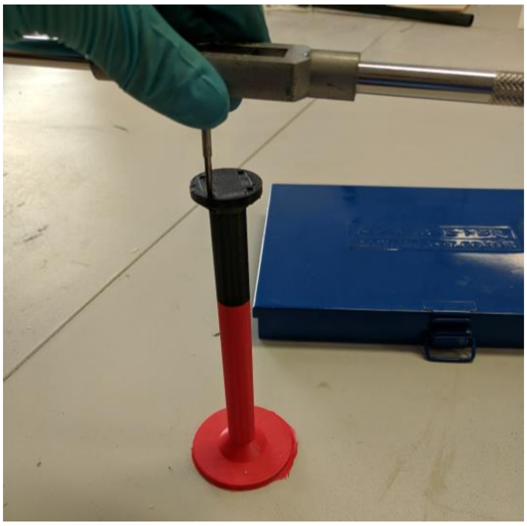

Figure 2.11. Tapping the successful legs

2.6.2 Testing

There were two main aims during the testing of the first prototype. Firstly, to find a heater control method for a stable temperature profile throughout a cycle. Secondly, finding the difference between the internal & external thermocouple readings (heater & water after heater) – allowing for the correct heater temperature to be reached for the desired water temperature.

Once these aims were achieved, the findings were implemented into replicating the espresso cycle from the De'Longhi EC685.M and the performance of the two machines were compared.

Procedure

As the espresso cycle comprises heater activity during pumping and non-pumping phases, temperature stability in both phases was investigated. In theory, once a heating control method was found for each, combining the two should result in temperature stability across the whole cycle.

Initially, a simple heater control method was used, with a plan to implement a more complex method, such as PID control, if deemed necessary. As the heater was connected to an SSR, which was controlled by an Arduino, heater temperature could be controlled by turning the heater on and off at decided time intervals.

Preliminary testing was carried out to gauge the difference in temperature stability during pumping and non-pumping, so appropriate heating times could be applied. During constant heating and constant pumping, temperature rose gradually (5°C over 10s), indicating a high level of heating should be applied during this phase. When the heater was constantly on but with no pumping occurring, temperature increased rapidly (10°C over 10s), therefore a more careful approach to heating had to be applied in this phase, to prevent overheating.

To make results comparable to the De'Longhi EC685.M experiment results, the same test conditions were used. This involved using the same sensor to measure water temperature and running cycles without using coffee or a portafilter.

Constant pumping phase

The majority of an espresso cycle is the main pumping phase, therefore achieving temperature stability in this phase is important for improving performance compared to the De'Longhi EC685.M.

The required heating ratio for different target temperatures was tested, starting at 60°C, increasing in 10°C increments. Due to the preliminary testing showing that heating was gradual with constant heating, the heater control strategy implemented was to constantly heat below the target temperature and turn the heater off above it. This resulted in reaching the target temperature without overshooting (Figure 2.12), with slight fluctuation. It also shows that when the heater is in a steady-state, the external thermocouple reads a temperature 8-9°C lower than the internal thermocouple.

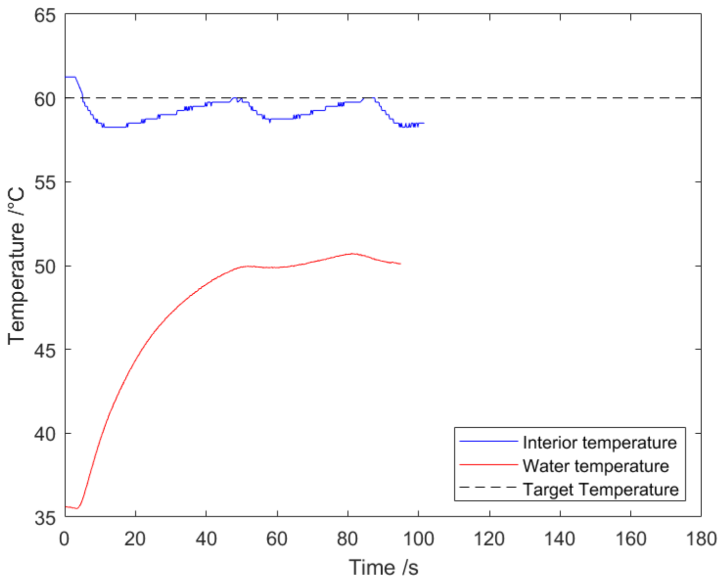

Figure 2.12 Constant pump heater control

The fact that there was no overshooting when using constant heating suggested that the heater may not be able to reach much higher than 60°C. This was proven correct when the target temperature was changed to 70°C and the temperature did not reach higher than 61°C, as shown in Figure 2.13. This iteration also backs up the difference between the external and internal thermocouples as 8-9°C.

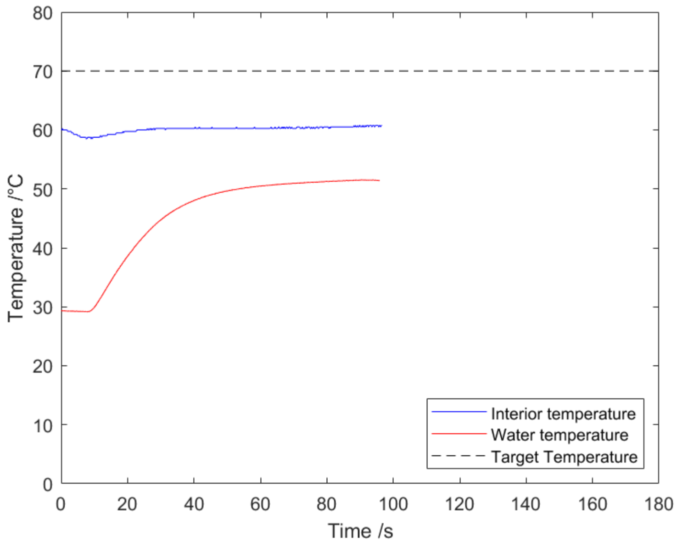

Figure 2.13 Constant pump heater control

Heating limitations of the thermoblock explain the lack of temperature stability of the De'Longhi EC685.M, as the heater used cannot maintain a temperature above 60°C during constant pumping. Implementing a more complex heating control method, such as PID control, would only work if a more powerful heater were used that would maintain the desired temperature during constant pumping. As temperature drop-off was inevitable with the current heater, replicating the performance of the De'Longhi EC685.M was the best that could be done.

Non-pumping phase

Further investigation was carried out to find a method which provided temperature stability in this phase, which was vital for both machine start-up and during espresso cycles. Initially, the target temperature was set lower than required for the espresso cycle to prevent any potentially overheating when developing a heater control method. Once a method had been chosen, it was then verified for the espresso cycle conditions.

Firstly, a single stage partial heating method was used, with the heater being turned on and off at different ratios over half second intervals, until a target temperature was reached. Once reached, the heater would turn off completely until the temperature dropped below the target again. Each iteration is referred to by the amount of time the heater was turned on during each half second interval (e.g a 100ms cycle refers to the heater being on for 100ms and then off for 400ms). As shown in Figure 2.14, both the 375ms and 250ms iterations resulted in overshooting the target temperature. The 125ms iteration overshot the target by a smaller margin, however it took significantly longer to reach the target temperature, which is undesirable.

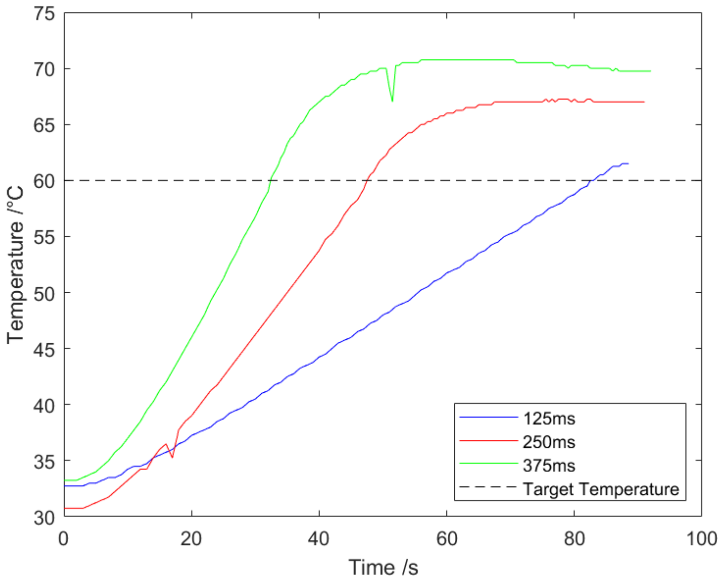

Figure 2.14 Single stage heater control

In an attempt to improve performance, a two-stage method was used. A higher heating ratio was used at lower temperatures to keep heat-up times desirable. Then, once heater temperature reached 10°C below target, a lower heating ratio was used to reduce overshooting, which was particularly important due to the slow cooldown time of the heater. Figure 2.15 shows that a two-stage method reduced overshooting but did increase heat-up times.

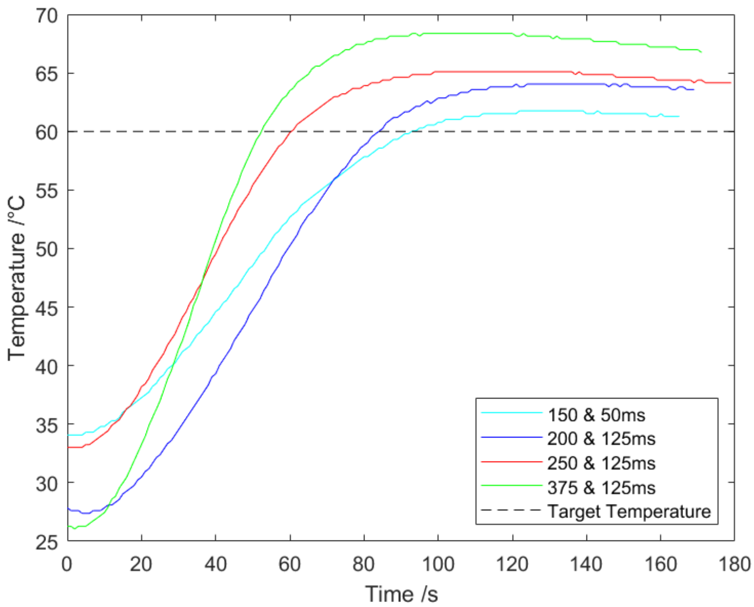

Figure 2.15 Two stage heater control

As overshooting was still an issue, a three-stage method was used. Although heat-up times with this method were longer, Figure 2.16 shows that temperature increase is more gradual than previous method, resulting in overshooting falling to within a single degree (in the 200, 125 & 50ms cycle).

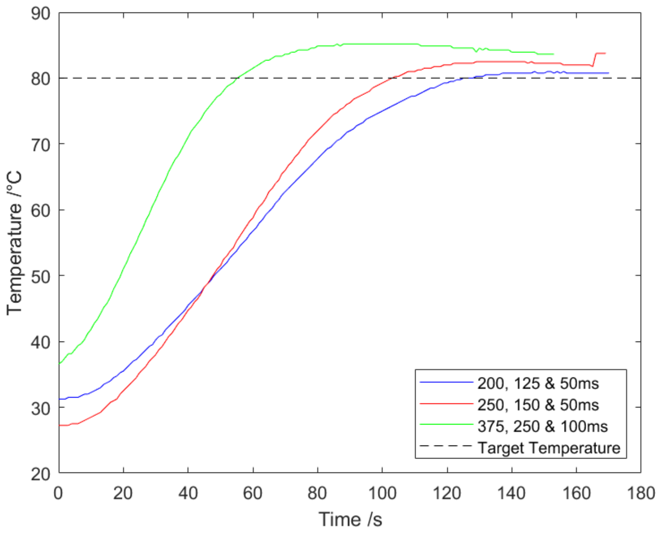

Figure 2.16 Three stage heating method

To reduce heat-up time, an alternative approach was tried. This involved using constant heating, to promote quick heat up time, until a temperature threshold was reached. After which, heating was drastically reduced (to 50ms) to try and prevent overshooting, but not stopped completely, to prevent underheating.

Testing proved that the full heating method reduced heat up in comparison to the previously tested partial heating methods. However, as there is minimal heating between the threshold and target temperature, it was suspected any drop in temperature within this range would result in a long recovery time back to the target temperature.

Both methods were tested for a target temperature of 95°C (which should yield a water temperature of 87°C), comparing their heat-up times, overshooting and recovery. Figure 2.17 shows that neither methods have much issue with overshooting (1°C). The full heating method heats up much quicker (41s vs 74s). On the other hand, the partial heating method had a quicker recovery time (72.5s vs 93s). Thus, the full heating method is more appropriate for machine start-up from cold, whereas the partial heating method will result in quicker heat-up times when the machine is not starting from cold, such as between espresso cycles.

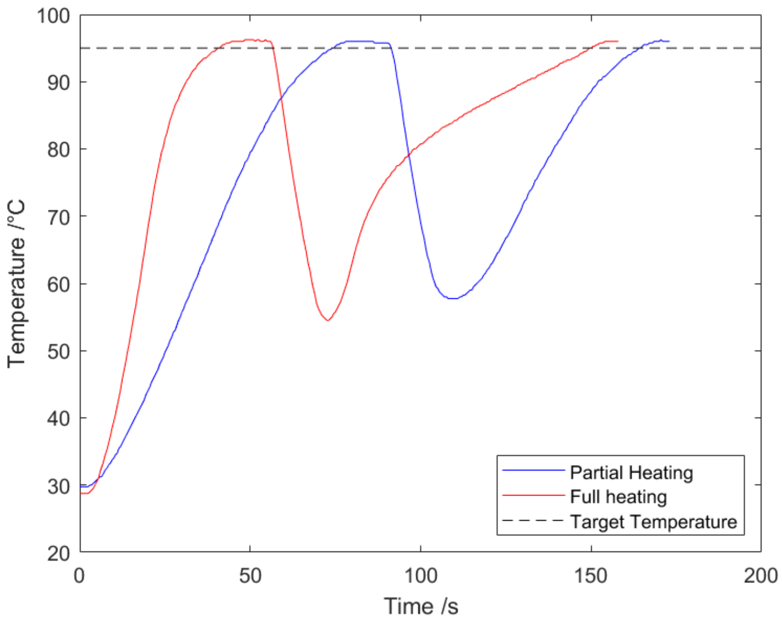

Figure 2.17 Method comparison

Combining the developed methods

To replicate the espresso cycle, a combination of the methods developed for both the pumping and non-pumping phases was used. Initially, the full heating method from the non-pumping phase was used, with the heating reduced once 60°C was reached. This managed to reach 95°C with little overshoot, at which point a signal was sent to the second Arduino to begin the pumping phase.

During both the pre-infusion and main cycles constant heating was applied, which as demonstrated in previous testing is the best way to try and maintain the target temperature. In between the two cycles, heating was applied for a quarter of each second. This enabled the heater to reach the target temperature again after dropping due to the pre-infusion cycle, without overshooting before the main cycle.

Cycles were ran back-to-back as quickly as possible, the results are shown in Figure 2.18. The temperature stability of the prototype is comparable with the performance of the De'Longhi EC685.M, but the recovery time between cycles is slower.

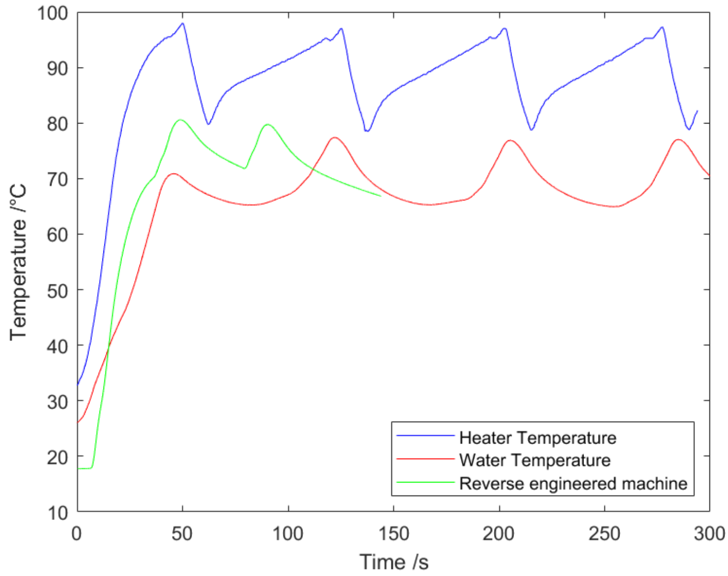

Figure 2.18 Comparison with the Delonghi EC685.M

Finally, the combined method was tested with coffee and the portafilter inserted to check the taste of the espresso. However, when running this cycle the temperature increased, and overshot, during the pumping cycles. It was suspected that the introduction of the portafilter was causing an increase in back pressure, due to the small orifice that water is forced through when passing through. This increase in back pressure caused the flow rate to decrease, which resulted in the water temperature to increase due to the increased time for heat transfer in the thermoblock .This newly found information disproved the previous hypothesis that the thermoblock does not have the capacity to maintain a stable temperature during a pumping phase.

Final heating strategy

To prevent overshooting, the full heating method used during the pumping phases was replaced with a partial heating method. Figure 2.19 represents the final heating strategy.

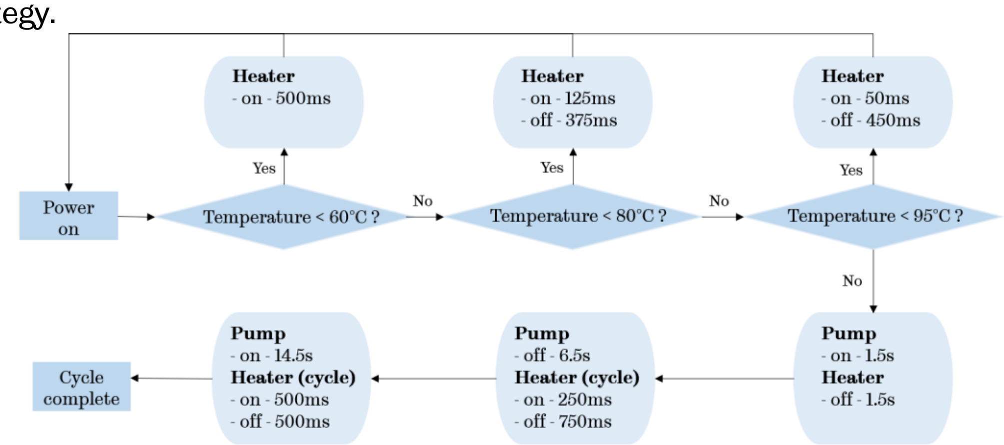

Figure 2.19 Final code strategy

Once this method was implemented, temperature stability in the heater was achieved within 8°C degrees, as shown in Figure 2.20, with the water temperature varying by only 2°C. Similarly to the De'Longhi EC685.M, temperature stability was improved after pre-heating. The espresso produced from this cycle tasted as good as from the De'Longhi EC685.M. When a higher heating ratio was applied to reduce the temperature drop to 5°C, the espresso began to taste burnt, thus a temperature drop of 8°C was deemed acceptable.

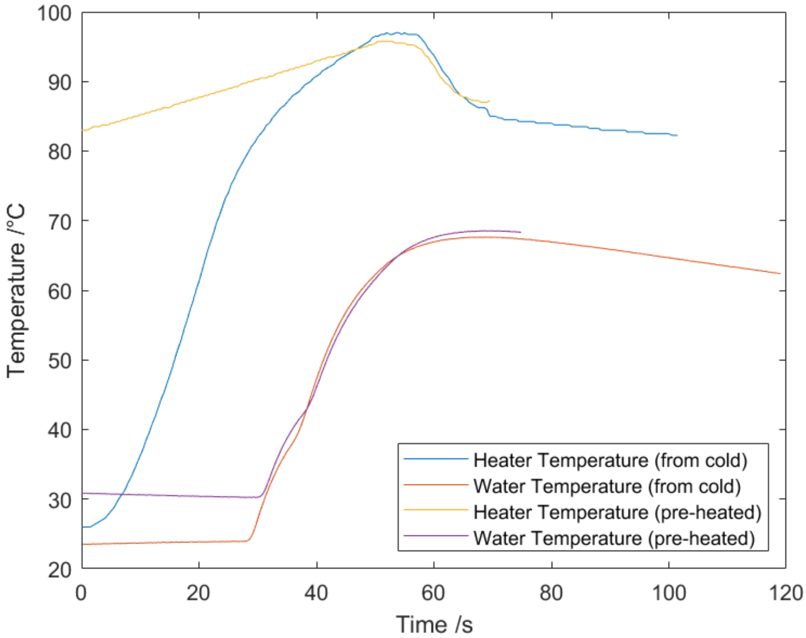

Figure 2.20 Final heater control method temperature stability

2.7 Second Prototype

One of the main issues with the first prototype was the fact that it was not fully open source – the group head design used is not publicly available. However, some parts of the group head are in fact publicly available, it is only the housing which is not, as it is integrated into the machine casing. Hence, one of the aims of the second prototype was to create a housing for these components.

Another aim was to create a new casing for all the components, as the first prototype was made up of two separate boxes, which made it difficult to transport and was not aesthetically pleasing.

Group head

The group head housing design was based off the section of the De'Longhi EC685.M which housed the group head components (Figure 2.21). The dimensions of this section of casing were measured as accurately as possible and a CAD model of the design was created in Solidworks, which was then 3D printed in ABS using an FDM printer. ABS was chosen over PLA due to its superior mechanical properties at higher temperatures (40). Despite the components successfully fitting in the 3D printed housing, the portafilter could not. Measurements were taken on how the design could be changed to fit the portafilter, the CAD model was altered, then a second housing was printed (Figure 2.22). The alterations were successful, allowing both the portafilter and group head components to fit.

Figure 2.21 Group head attached to the casing

Figure 2.22 Successful group head

Casing

The casing was designed so that it had enough room to fit all the machine's components into a single box, plus more room for possible future developments of the design. It was decided to use acrylic for the design, as it was easy to cut using a laser cutter, provided an aesthetically pleasing glossy finish, and comes in a range of colours which allows the user to select their own colour scheme. The parts of the case were designed in Solidworks and arranged in an assembly before cutting to ensure the parts would fit together (Figure 2.23).

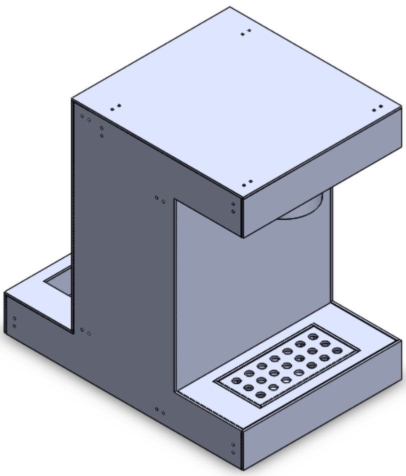

Figure 2.23 Second prototype casing

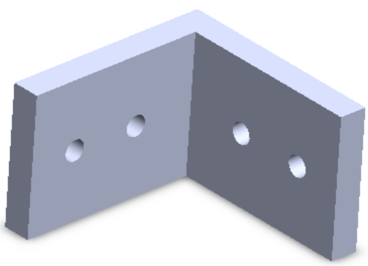

Figure 2.24 Second prototype brackets

Another consideration of the design was to ensure ease of both assembly and disassembly – making it easy to open up the machine and make modifications. This was implemented by using brackets (Figure 2.24) to join parts of the case together, which meant that the top and back of the case could be unscrewed to provide access to the interior. The brackets were 3D printed using an FDM printer with screw holes included in the design, which were then tapped. Screw holes were included in design of the laser cut parts to reduce manufacturing time.The casing was fixed together using a combination of brackets and epoxy glue, as shown in Figure 2.25.

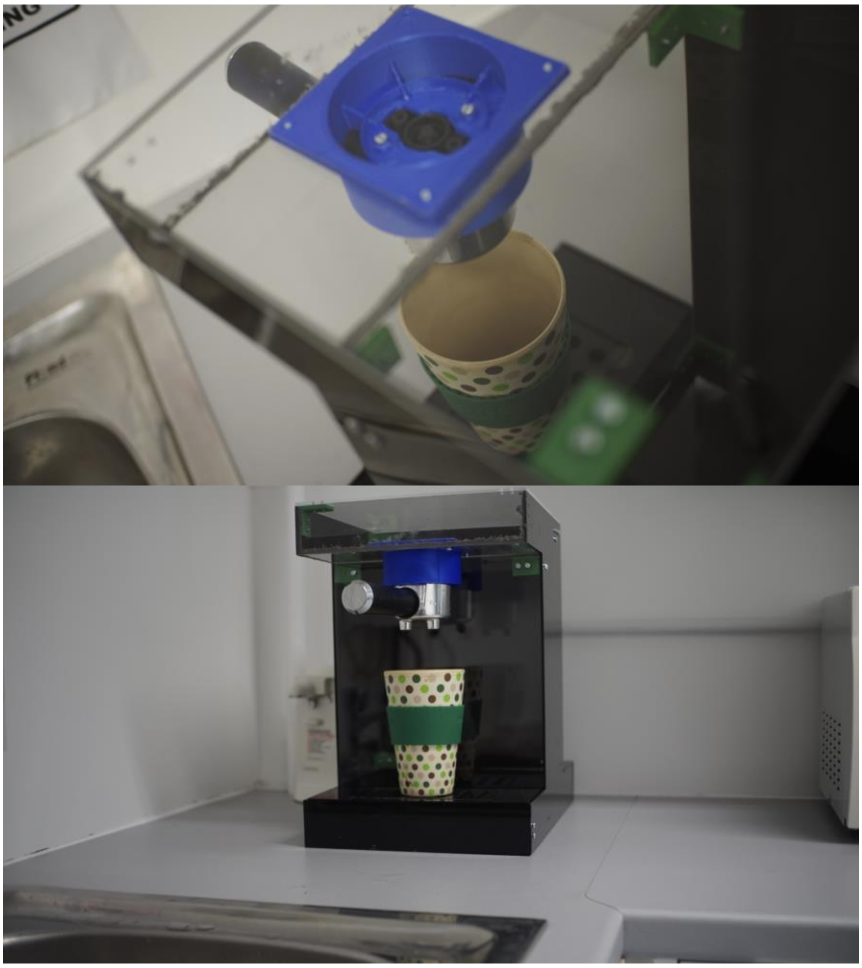

Figure 2.25 Second prototype casing constructed with black and clear acrylic

Unfortunately, due to time constraints a component to house the water tank was not developed, and only the group head housing was installed into the case. However, guidance on the proposed orientation of parts within the casing was provided, as shown in Figure 2.26.

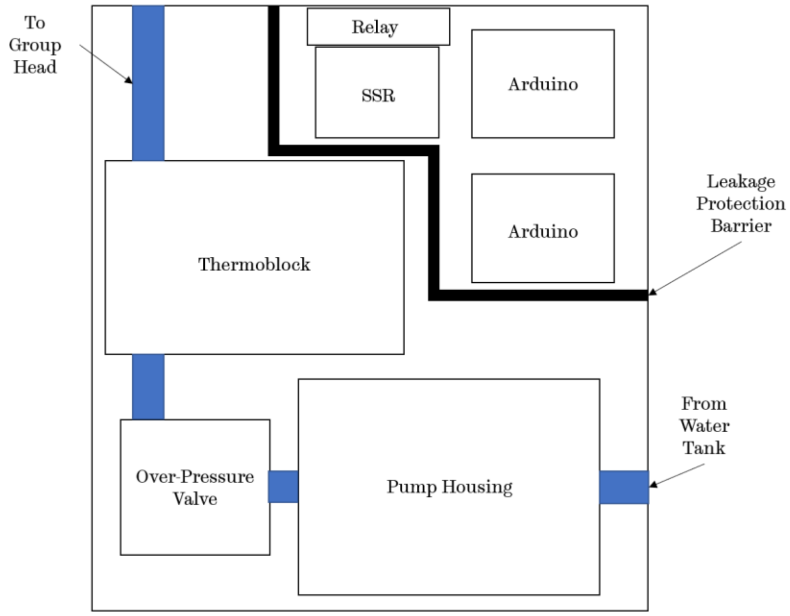

Figure 2.26 Suggested component orientation upon backboard of second prototype casing

2.8 Documentation for Open Source Design

Using the guidelines of typical documentation provided in an open source project, found in Section 1.3.3, the following documentation was provided:

- A part list allowing users to easily purchase components
- Solidworks and STL files for the pump housing, group head housing, legs and brackets
- Solidworks and DXF files for laser cutting the second prototype casing
- A wiring diagram
- Arduino code for the heater and pump

Makers would be expected to have enough technical knowledge to be able to construct the design using this documentation, but it was also supplemented with build instructions to improve ease of building.

3 CONCLUSION & DISCUSSION

This project involved designing and building the first open source espresso machine. The design process was influenced by the maker movement and aligned with values of most open source projects. The following chapter will evaluate the success of the project and outline future work.

3.1 The Design Process

A reverse engineering approach was advantageous in this project for a variety of reasons. Firstly, it allowed a level of primary research on a consumer product to be carried out that could not have been matched by any other method, providing invaluable information. Secondly, it provided a way to compare performance between the proposed design and existing market technology, highlighting where the design succeeded and failed and thus aided to outline future work for later iterations of the project. "Learning by doing" helped to develop a range of practical skills and understanding that could not have been achieved otherwise. Lastly, this approach provided a good starting point by providing working and compatible components for prototyping, which considering the limited timescale of the project, ensured it could be completed on-time with two iterations of prototyping completed.

3.2 Evaluation of the Open Source Approach

The growth of the maker movement over the last decade made the decision to undertake an open source project particularly appealing. It provided the opportunity to become a part of the development of an exciting community, which upholds good values, and added a novel aspect to the project.

Uploading updates on to Hackaday as the project progressed facilitated interaction with the open source community that would not have occurred otherwise. This interaction assisted in realisation of the huge extent of projects being developed and their range of applications, which inspired motivation to contribute to the community. Despite the project receiving over 1000 views and gaining 14 followers, the feedback upon project process was minimal, receiving only 2 comments. However, when reaching out to people there was generally a positive response, and during this process an open source espresso machine PID controller project was found. When contacting the user who developed the project, they were interested in helping to integrate the projects together, so this was detailed in further work (Section 3.4). As the majority of the prototype work was completed towards the end of project timescale, this did not leave much time for makers to give feedback on the project, so this may be the cause for low volume of feedback.

This project can be seen as a great starting point for, and first iteration of, the wider open source project. It is expected that makers will improve upon the design and update the documentation, sharing their findings, so that the community can work together to develop the project further.

3.3 Evaluation of the Espresso Machine

The first prototype met most, but not all, of the specification criteria outlined in Section 2.5. Not all components were open source, it did not comply with the maximum size requirements, and it didn't produce both single and double espresso shots. The first two of these issues were solved within the development of the second prototype, however only double shots can be produced.

The first prototype did have some shortcomings in comparison to the De'Longhi EC685.M. In terms of performance, it had longer recovery times, lacked the capability for varying the target temperature and pumping was regulated by timings rather than flow. It had some limitations in functionality, as the espresso cycle automatically began once the target temperature had been reached, whereas the De'Longhi EC685.M uses buttons to trigger the cycle. However, the temperature stability was comparable between the machines, and most importantly, so was the taste of the espresso. By replacing the control board with two Arduinos, there is scope for modifying and improving the design to suit the needs of the user. Also, the shortcomings of the prototype were not difficult things to amend, but due to time constraints could not be carried out. Therefore, details of how these issues can be amended is outlined in Section 3.4.

The second prototype was not an attempt to change the performance of the machine, but it allowed the project to be truly considered open source. The design of the group head housing was a particular highlight of the project, as the starting price for individually bought group heads starts at approximately £95 (41) and are not widely available. Using the 3D printed housing with the publicly available group head components, the total cost comes to £12, which is a huge saving. Despite concerns of the housing warping due to high temperatures, if printed in ABS this should not be an issue as hot water never comes in to contact with this part. The casing design allowed the project to satisfy the size criteria, provided a more aesthetically pleasing design than the first prototype, and enables much easier access into the interior of the machine for modifications than in the De'Longhi EC685.M. Unfortunately, due to time constraints the components were not installed into this prototype. However, this should be a straightforward process and guidance is provided in the further work.

As shown from the part list provided in Appendix 2, the total cost of the prototype is currently approximately £295. However, as several of the components used are only available from the De'Longhi spares website, they are very overpriced. The total cost will be drastically reduced once components are swapped for more widely available alternatives. Also, this design would allow for PID control to be implemented without having to purchase any further components. This would add value to the design and make it very competitive in the espresso machine market, as consumer level PID controlled machine have a starting price of approximately £680 (42).

Overall, the two prototypes produced provide an excellent starting point for the wider project. The temperature stability achieved, and espresso taste produced, managed to match that of a consumer-level machine. Using the aid of details outlined in further work, future versions of the project will allow the machine to outperform other machines within the same price bracket.

3.4 Further Work

Open source projects are often comprised of several iterations by different makers. Thus, outlining future work was important to try and encourage other makers to progress the design. There are several small additions that could be made which would have a huge impact on the success of the design.

Firstly, the flow meter could be re-installed between the water tank and pump. This would change the way the pump runs, from set timings to be being controlled by the amount of flow passing through the flow meter, making the espresso servings more consistent. It should be connected to the Arduino which controls the pump and can be communicated with by using the data sheet provided by the manufacturer (43). Secondly, push buttons could be installed to initiate the pump, alongside LEDs to indicate when the thermoblock has heated up to temperature and when the espresso cycle can begin. Alternatively, rather than LEDs, a small LCD screen could be implemented. This could be used to display the target temperature of the heater and indicate when the machine is ready for an espresso cycle. If a couple of extra buttons were installed, they could be used to alter the target temperature of the heater. The addition of these extra features may require changing one of the Arduino Unos to an Arduino Mega, for the use of extra digital pins.

To improve the designs performance above that of the De'Longhi EC685.M, PID control could be implemented, which would result in greater temperature stability and quicker recovery times. The Therm PID controller (44) would be a great choice as it is an open source design, which aligns with the values of this project. The hardware controller could be used, or alternatively, the PID code could be implemented into the existing code (45).

Finally, there are some changes that could be made which will not drastically affect performance or functionality. Fitting all the components into the case developed in the second prototype would make the design more aesthetically pleasing, making it a more appealing project to makers to build and put in their homes. Guidance on orientation of parts within the case was provided in Section 2.7. Another way to appeal to makers would be to replace some of the components for more widely available components, such as swapping the current connectors out for standardised replacements. This would make it easier to build and reduce the cost.

REFERENCES

1. *The 'Latte Revolution'? Regulation, Markets and Consumption in the Global Coffee Chain".* Ponte, Stefano. 7, 2002, World Development, Vol. XXX, pp. 1099-1122.

2. Research, Centre for Economics and Business. *Coffee and Its Impact on the UK Economy.* 2018.

3. Global Coffee Industry Facts & Statistics of 2014-2015. [Online] Weivo, 29 May 2015. [Cited: 1 October 2018.] http://www.wevio.com/wevio-blog/global-coffee-industry-facts-statistics-of-2014-2015/.

4. What is Coffee? [Online] National Coffee Association. [Cited: 30 September 2018.] http://www.ncausa.org/about-coffee/what-is-coffee.

5. Incahoots. [Online] 19 February 2018. [Cited: 29 September 2018.] https://incahoots.biz/2018/02/coffea-arabica-coffee-tree/.

6. Oden, Garrett. The Differences Between Arabica and Robusta Coffee. [Online] JavaPresse. [Cited: 28 September 2018.] https://www.javapresse.com/blogs/buying-coffee/arabica-vs-robusta-coffee.

7. Processes. [Online] Cafe Imports. [Cited: 3 October 2018.] https://www.cafeimports.com/north-america/blog/processes/.

8. Drying Process. [Online] Kawi Sari Coffee. [Cited: 3 October 2018.] http://www.kawisaricoffee.com/methods/processing/.

9. Honey Coffee Processing. [Online] Los Lajones Estate. [Cited: 4 October 2018.] http://www.loslajonesestate.com/eng/processing/honey-coffee/.

10. Tuan, Pham. Vietnam Weasel Coffee - The True Story Behind The World Most Expensive Coffee. [Online] Huong Mai Cafe. [Cited: 4 October 2018.] http://www.huongmaicafe.com/blogs/vietnam-weasel-coffee/.

11. Different Shades of Coffee! [Online] Union Place Coffee Roasters, 14 April 2014. [Cited: 4 October 2018.] https://unionplacecoffeeroasters.com/different-shades-of-coffee/.

12. Goldie, Wayne. How Instant Coffee is Made. [Online] Better Coffee Makers, 9 June 2018. [Cited: 5 October 2018.] https://bettercoffeemakers.com/how-instant-coffee-is-made.

13. 13 Best Drip Coffee Makers. [Online] Roasty Coffee. [Cited: 7 October 2018.] https://www.roastycoffee.com/drip-coffee-makers/.

14. Large Gold Pour-Over Coffee Dripper. [Online] Osaka Coffee. [Cited: 7 October 2018.] https://www.osakacoffee.com/shop/large-gold-pour-coffee-dripper/.

15. AeroPress coffee maker Aerobie. [Online] Euronics. [Cited: 7 October 2018.] https://www.euronics.ee/t-en/51772/kitchen-appliances/aeropress-coffee-maker-aerobie/80r08.

16. Bodum Chambord 34 Ounce French Press. [Online] Crate&Barrel. [Cited: 7 October 2018.] https://www.crateandbarrel.com/bodum-chambord-copper-34-ounce-french-press/s268853.

17. Lee-Schneider, David. The Importance of Tamping Correctly. [Online] Barista Guide. [Cited: 9 October 2018.] http://www.baristaguide.com/knowledge/the-importance-of-tamping-correctly/.

18. HOW AN ESPRESSO MACHINE WORKS: WHAT'S REALLY INSIDE? *The Coffee Brewers.* [Online] [Cited: 30 October 2018.] https://www.thecoffeebrewers.com/howesmawo.html.

19. The Perfect Espresso. *No marketing No hunger.* [Online] [Cited: 1 November 2018.] http://www.no-marketing.de/index.php?seite=kw4&lang=en.

20. Single Boiler vs Heat Exchanger / HX vs Double Boiler Espresso Machine Comparison. *Espresso Outlet.* [Online] [Cited: 1 November 2018.] https://www.espressooutlet.net/espresso-outlet-blog/single-boiler-vs-heat-exchanger-hx-vs-double-boiler-espresso-machine-comparison/.

21. Types of Espresso Machine Boilers. *Love Latte Reviews.* [Online] [Cited: 2 November 2018.] http://www.lovelattereviews.com/types-of-espresso-machine-boilers/.

22. What is a Thermoblock? *Seattle Coffee Gear.* [Online] [Cited: 2 November 2018.] https://www.seattlecoffeegear.com/blog/2012/05/07/what-is-a-thermoblock/.

23. Sergeant, D. R. *Scale formation and adhesion to mild steels during.* s.l. : Sheffield Hallam University, 1974.

24. Espresso Machine. *Wikipedia.* [Online] [Cited: 3 November 2018.] https://en.wikipedia.org/wiki/Espresso_machine.

25. How Does A Manual / Lever Espresso Machine Work? *Better espresoo machines reviews.* [Online] [Cited: 3 November 2018.] https://betterespressomachinesreviews.com/how-does-a-manual-lever-espresso-machine-work/.

26. Overview: Rotary vs. Vibratory Pumps. *Youtube.* [Online] Seattle Coffee Gear. [Cited: 3 November 2018.] https://www.youtube.com/watch?v=HjdaqUso6wI .

27. How do Espresso Machines Work. *Clive Coffee.* [Online] [Cited: 4 November 2018.] https://clivecoffee.com/blogs/learn/how-do-espresso-machines-work#the-grouphead.

28. How to buy a machine. *Whole Latte Love.* [Online] [Cited: 4 November 2018.] https://wiki.wholelattelove.com/How_to_buy_a_machine.

29. How to choose the best development kit - the ultimate guide for beginners. *Predicable Designs.* [Online] [Cited: 4 November 2018.] https://predictabledesigns.com/how-to-choose-the-best-development-kit-the-ultimate-guide-for-beginners/.

30. Python - the next programming language for microcontrollers. *LinkedIn.* [Online] [Cited: 4 November 2018.] https://www.linkedin.com/pulse/python-next-programming-language-microcontrollers-swain.

31. Go make something! The growth of the Maker Movement. *British Council.* [Online] [Cited: 5 November 2018.] https://creativeconomy.britishcouncil.org/guide/go-make-something-growth-maker-movement/.

32. Ancient building came with DIY instructions. *NBC News.* [Online] [Cited: 5 November 2018.] http://www.nbcnews.com/id/36805531/ns/technology_and_science/t/ancient-building-came-diy-instructions/#.XJu3mCj7Q2w).

33. The rise of DIY culture. *The Horizon Sun.* [Online] [Cited: 6 November 2018.] https://thehorizonsun.com/student-opinion/2012/11/29/the-rise-of-d-i-y-culture/.

34. Open source licences. *Open Source.* [Online] [Cited: 5 November 2018.] https://opensource.org/licenses.

35. LIFE HACK: ADD A PID TEMPERATURE CONTROLLER TO YOUR ESPRESSO MACHINE. *SISAND'.* [Online] [Cited: 6 November 2018.] http://www.sisand.dk/?p=205.

36. Your personal home barista comes to life with this voice-enabled coffee machine. *Medium.* [Online] [Cited: 6 November 2018.] https://medium.com/snips-ai/your-personal-home-barista-comes-to-life-with-this-voice-enabled-coffee-machine-5fc333326f31.

37. Mugsy - The open source robotic coffee maker. *Kickstarter.* [Online] [Cited: 6 November 2018.] https://www.kickstarter.com/projects/413243358/mugsy-the-open-source-robotic-coffee-maker.

38. LEARNING BY DOING: THE IMPACT OF MAKER MOVEMENT ON EDUCATION. *3D Printing Industry.* [Online] [Cited: 14 December 2019.] https://3dprintingindustry.com/news/learning-impact-maker-movement-education-79054.

39. Cross, N. *Engineering Design Methods.* s.l. : Wiley, 2000.

40. PLA vs ABS Filament: Plastic Strength, Flexibility Compared! Which Is Better For 3D Printing? *All that 3D.* [Online] [Cited: 5 March 2019.] https://www.allthat3d.com/pla-vs-abs/.

41. Gaggia Classic Grouphead OEM. *The Espresso Shop.* [Online] [Cited: 5 March 2019.] https://www.theespressoshop.co.uk/en/GB/Gaggia-Classic-Grouphead-OEM---B0171/m-3109.aspx?PartnerID=22&utm_source=google&utm_medium=shopping&utm_campaign=UnitedKingdom&gclid=EAIaIQobChMIh7qzmMjP4AIVibTtCh3eHQypEAQYASABEgIl_fD_BwE) .

42. https://www.espressooutlet.net/ascaso-steel-uno-professional-espresso-machine-version-3/. *Espresso Outlet.* [Online] [Cited: 5 April 2019.] https://www.espressooutlet.net/ascaso-steel-uno-professional-espresso-machine-version-3/.

43. FHKSC Flow Meter Datasheet. *Farnell.* [Online] [Cited: 5 March 2019.] http://www.farnell.com/datasheets/59068.pdf.

44. therm - Tiny PID controller to control the temperature of anything. *Hackaday.* [Online] [Cited: 2 April 2019.] https://hackaday.io/project/2638-therm.

45. therm firmware. *Protofusion.* [Online] [Cited: 2 April 2019.] http://hg.protofusion.org/therm-ng.

APPENDIX 1. PROTOTYPE PHOTOS

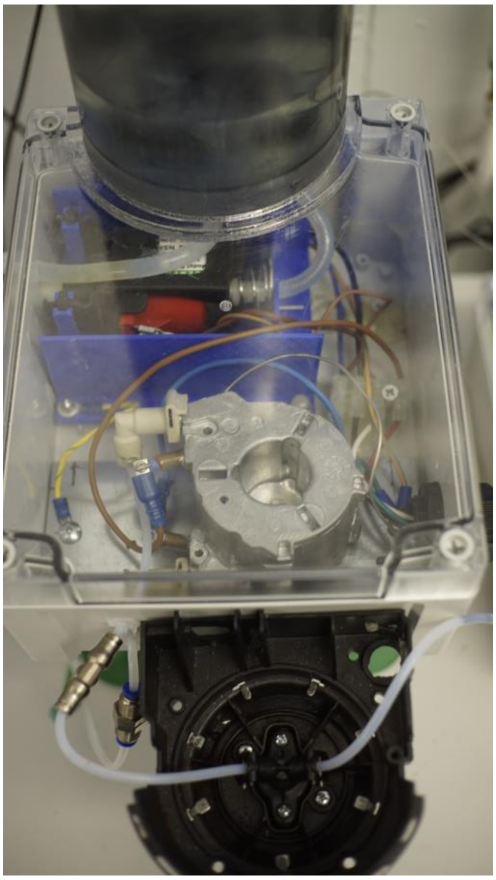

Figure A1.1 Detailed view of the first prototype

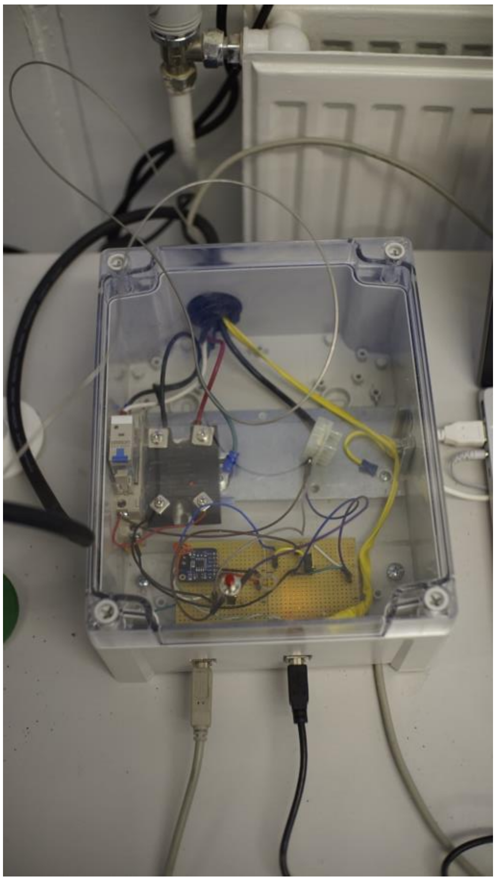

Figure A1.2 Detailed view of the first prototype

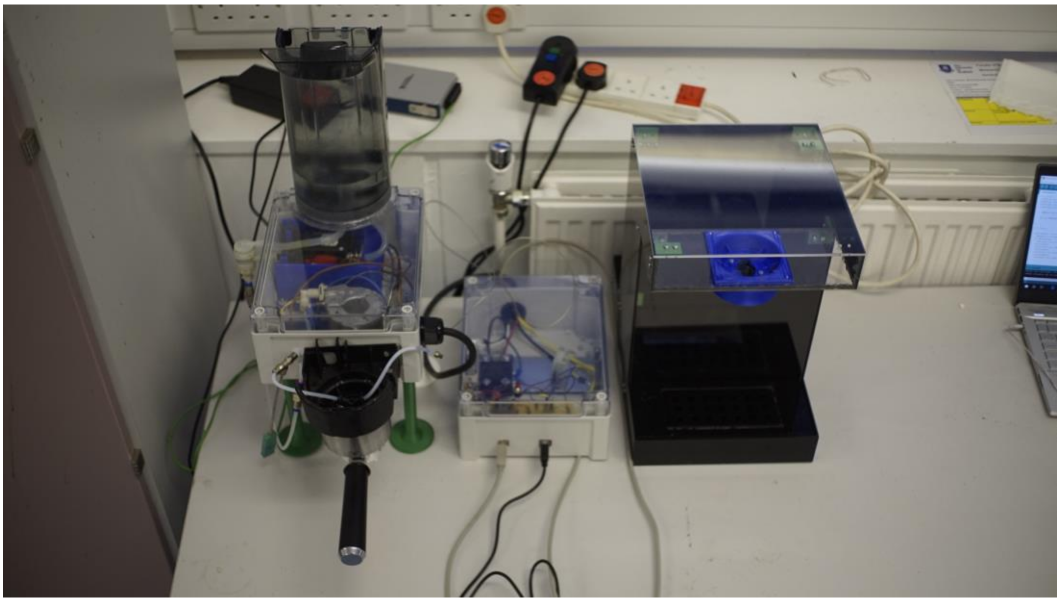

Figure A1.3 First and second prototypes

APPENDIX 2. OPEN SOURCE DOCUMENTATION

Schematic & Parts List

Bracketed numbers refer to the De'Longhi Schematics (Figure A2.1 and A2.2)

Casing (Approximately £25)

- 300mm x 600mm clear acrylic – 3mm thickness
- 600mm x 900mm black acrylic – 3mm thickness
- M3 8mm machine screws
- 16 3D printed brackets (PLA or ABS)
- Epoxy Glue (Ideally clear setting)

Group head (Approximately £12)

- 3D printed housing
- Brewing gasket (47) (£2.50)- https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/brewing-gasket/product.pl?pid=2793040&path=606454,640993&model_ref=10807013
- Brewing gasket support (48) (£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/brewing-gasket-support/product.pl?pid=2793148&path=606454,640993&model_ref=10807013
- Diffuser gasket (49) (£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/diffuser-gasket/product.pl?pid=2793037&path=606454,640993&model_ref=10807013
- Diffuser (52)(£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/diffuser/product.pl?pid=2793079&path=606454,640993&model_ref=10807013

Connections

- Heater connectors (£5)(67&70) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/right-angle-generator-

connection/product.pl?pid=2050051&path=606454,640993&model_ref=10807013
https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/connector/product.pl?pid=2235094&path=606454,640993&model_ref=10807013

- Spacer x2 (61) (£5) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/spacer/product.pl?pid=2050036&path=606454,640993&model_ref=10807013
- O-ring x4 (62)(£10) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/o-ring/product.pl?pid=2050057&path=606454,640993&model_ref=10807013
- Connector spring x4(35) (£10)- https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/spring/product.pl?pid=956760&path=606454,640993&model_ref=10807013
- Gasket x4 (36) (£10) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/gasket/product.pl?pid=957649&path=606454,640993&model_ref=10807013
- Tubing x2 (71) (£5) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/tube/product.pl?pid=1586494&path=606454,640993&model_ref=10807013
- 3-way connector (75)(£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/3-way-valve-connector/product.pl?pid=2793166&path=606454,640993&model_ref=10807013
- 3-way connector spring (74)(£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/3-way-valve-connector/product.pl?pid=2793166&path=606454,640993&model_ref=10807013
- 3-way connector valve(43)(£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/valve-barm30e/product.pl?pid=827035&path=606454,640993&model_ref=10807013
- 3-way connector ring (44)(£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/ring-for-valve-bar16e/product.pl?pid=486903&path=606454,640993&model_ref=10807013

- 3-way connector gasket (46)(£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/gasket/product.pl?pid=1587016&path=606454,640993&model_ref=10807013
- Water tank tubing (31)(£10) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/tube-elastosil-di4-l270-ec680m-ec680r-ec680b/product.pl?pid=4796201&path=606454,640993&model_ref=10807013
- Water tank gasket(30)(£5) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/gasket-ec680m-ec680r-ec680b/product.pl?pid=4796228&path=606454,640993&model_ref=10807013
- Water tank tray(32)(£2.50) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/gasket-ec680m-ec680r-ec680b/product.pl?pid=4796228&path=606454,640993&model_ref=10807013

Water tank(18)(£8)- https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/water-tank-ec680m-ec680r-ec680b/product.pl?pid=4795247&path=606454,640993&model_ref=10807013

Thermoblock (60)(£17) -https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/generator/product.pl?pid=4061006&path=606454,640993&model_ref=10807013

Pump

- 3D printed pump housing
- Pump (40)(£27) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/pump/product.pl?pid=1224713&path=606454,640993&model_ref=10807013
- Pump alternative (£16) - https://www.amazon.co.uk/Ulka-EP5-Vibration-Pump-Espresso/dp/B00JPH5YKA
- Spring (42)(£5) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/spring/product.pl?pid=2793181&path=606454,640993&model_ref=10807013
- Over-pressure valve (39)(£5) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/valve/product.pl?pid=5148379&path=606454,640993&model_ref=10807013

- Flow meter (45)(£13) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/switch/product.pl?pid=961309&path=606454,640993&model_ref=10807013

Portafilter (3&6)(£20) - https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/small-one-cup/product.pl?pid=2793076&path=606454,640993&model_ref=10807013

https://www.4De'Longhi.co.uk/espresso/ec-680m-0132106104/sump-assembly/product.pl?pid=4794515&path=606454,640993&model_ref=10807013

Other

- Arduinos x2 (£33) - https://uk.rs-online.com/web/p/processor-microcontroller-development-kits/7154081/
- SSR (£14) - https://uk.rs-online.com/web/p/solid-state-relays/9032970/
- MOSFETs x2 (£5)
- Relay (£12) - https://www.tme.eu/gb/details/g2rvsl70024dc/electromagnetic-relays-sets/omron/g2rv-sl700-24vdc/?brutto=1&gclid=EAIaIQobChMI_5iS5_jz4QIVq7ftCh1lcQuJEAQYASABEgKm7PD_BwE
- Thermocouple shield (£14) - https://shop.pimoroni.com/products/adafruit-thermocouple-amplifier-max31855-breakout-board?gclid=EAIaIQobChMI9Z3Wyfnz4QIVarHtCh1fDQ6AEAQYAyABEgJKpvD_BwE&utm_campaign=google+shopping&utm_medium=cpc&utm_source=google&variant=288858286
- Thermocouple (£10) - https://shop.pimoroni.com/products/thermocouple-type-k-glass-braid-insulated-k

Total cost: £295

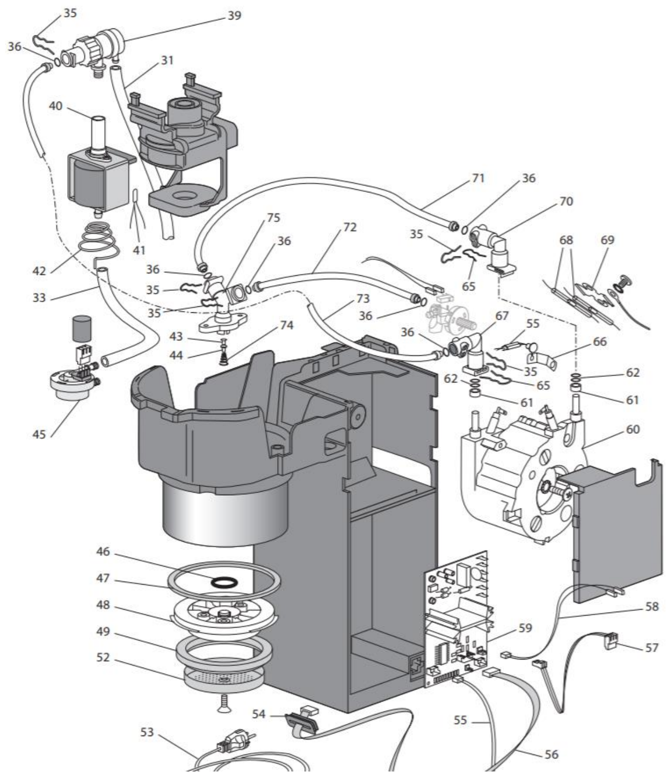

Figure A2.1 Interior Schematic

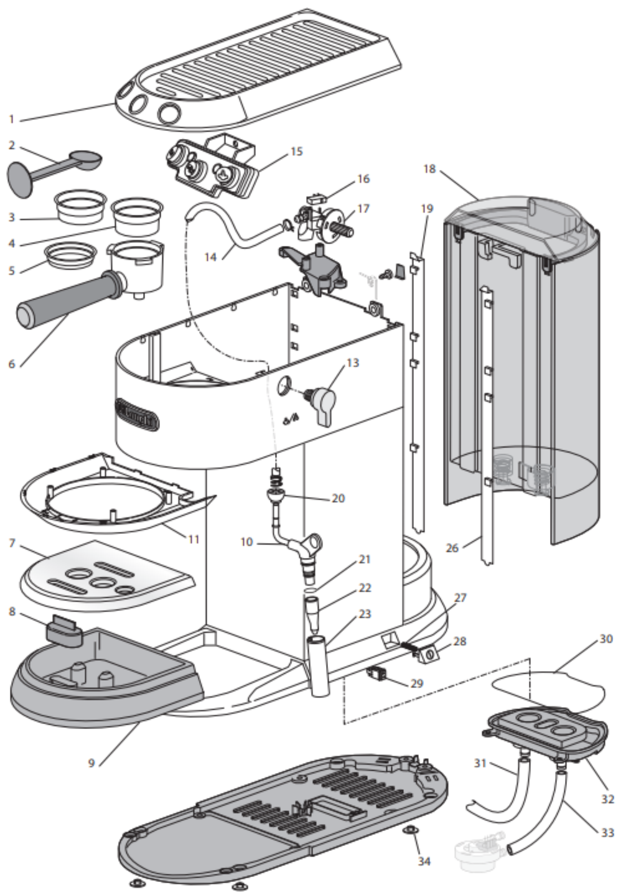

Figure A2.2 Exterior Schematic

Manufacturing Notes

Casing

- Attach brackets to provide structure for gluing
- Be careful not to glue anything to the back or top surfaces as they need to be removeable
- Tap the brackets to an M3 size
- Use latex gloves when gluing

Group head housing

- Remove supports with pliers
- Thread holes using an M3 tap

Heater

- Use a hacksaw to cut a heat sink from a steel sheet
- Make sure to "Earth" the heat sink
- Install the thermocouple near the water exit
- Use thermal paste to prevent the thermocouple shorting on the metal heater

General

- Use a safety mains plug, so power is cut in the case of a leak
- When building the machine, test without applying power to the heater to check for leaks
- Any 3D printing should be completed as close to 100% density as possible

Usage

- Always place a container underneath the group head before turning on the power
- If no water is passing through the portafilter, check the orifice for blockages (coffee grounds can get stuck in it)

Figure A2.3 An extract of manufacturing notes to assist the maker

Wiring Diagram

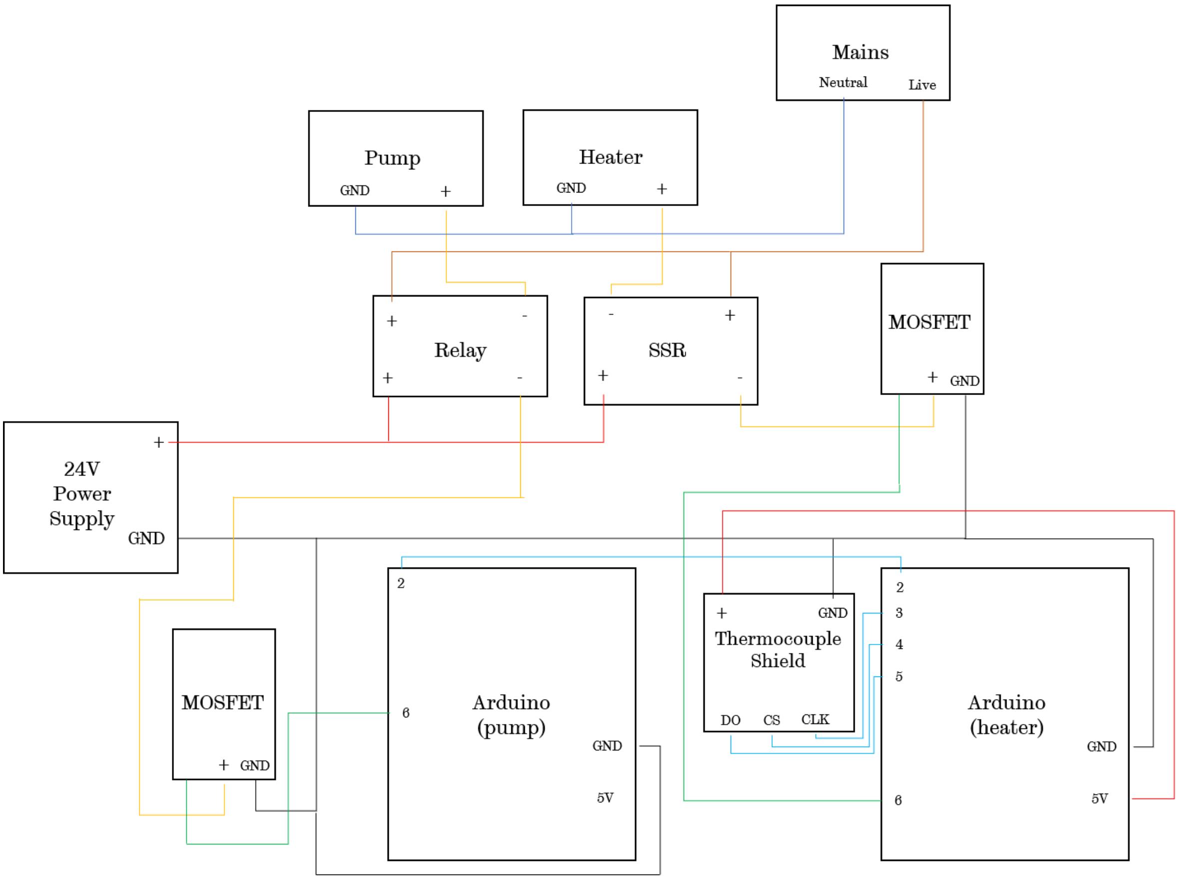

Figure A2.4 Wiring schematic of the design