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picoBrew: Automated Home Brew

A Major Qualifying Project Report:
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Abstract

The picoBrew project determined the marketable requirements of a small-scale automated beer brewing system. Techniques from industrial robotics were applied to the basic home brew cycle, resulting in a prototype design which could be easily controlled as well as manufactured. The prototype design focused on repeatability and ease of cleaning, two of the major requirements as determined from market studies. The prototype was capable of independently performing the heating, ingredient handling, and cooling cycles required to make beer.

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1 Introduction

The home brewing of beer has become an increasingly popular pastime in the United States since being federally legalized in 1978[1]. Currently, there are an estimated one and a quarter million home brewers in the US and Canada, brewing some 36 million bottles of beer a year[2]. These individuals support a thriving industry of home brew suppliers and associations.

The principle stages involved in the brewing of beer, as seen in Figure 1, are the malting of barley (or other grain), the boiling and cooling of wort, the addition of yeast, and the fermentation of the result. However, each of these stages includes a number of tasks which must be performed for the correct amount of time, in the correct sequence, and at the correct temperature, in order to result in a consumable product.

Due to the complexity of this process, home brewers address a number of challenges as they go about their hobby. They must control the quality of their ingredients, cleanliness of equipment, consistent temperature controls, and careful timing of their recipes. Minor changes in any of these variables can result in drastic changes in the final product which will not be clear to the home brewer until the first tasting, after weeks or months of fermentation.

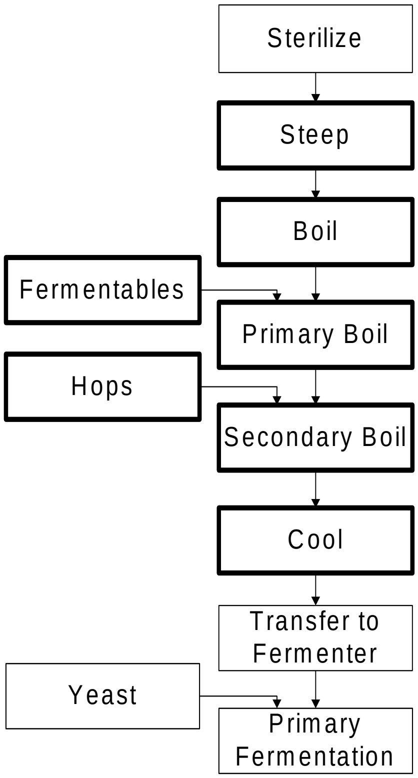

Figure 1: The Home Brew Process

In order to reduce the work required to get consistent brewing results, the picoBrew project was proposed to give control of the process to a computer-controlled system, eliminating errors in timing and temperature control. The aim was to give the computer control over heat levels, the steeping time of early flavoring ingredients, the addition of primary fermentables and hops, and the cooling cycle. The fermentation sequence was not addressed during the 2008-2009 project year.

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[1] http://www.beertown.org/homebrewing/legal.html

[2] http://answers.google.com/answers/threadview/id/745642.html

The final goal of the picoBrew project was to develop a prototype of a commercially viable automated homebrew system aimed at both novice and veteran home brewers who want a greater freedom to experiment with ingredients and recipes, leaving the procedural concerns to the computer.

2 Background

The brewing process is an exceptionally complex system. While wine is simply fermented grape juice, beer requires many more ingredients, processed in a very specific fashion. In order to understand the automation of brewing, a complete understanding of these ingredients and steps is required.

2.1 Brewing

Brewing is the name given to the process of creating beer from raw ingredients. The process of brewing consists of three major cycles; boiling, cooling, and fermentation. Each of these cycles alters the characteristics of the beer by the chemical processes that occur during the cycle.

2.1.1 Ingredients

There are four primary ingredients in the brewing of beer: water, malts, hops and yeast. Characteristics of malt and hops are particularly sensitive to small changes in the brewing process, and thus were the primary focus of the picoBrew system.

2.1.1.1 Water

The water used in the brewing process may change the taste of the beer, as varied mineral content exists from different water sources. Many brewers choose to use filtered water to eliminate these minerals; however, others choose not to, seeking to use the minerals to add distinctive additional flavor to their beer.

2.1.1.2 Malts

The sugars that drive fermentation come from the malt extract. In the malting process, barley is soaked in water then drained to initiate the germination process. Germination activates enzymes within the barley which convert starch and proteins into sugars that would subsequently be used by the plant. Once the seed starts to sprout, it is dried quickly to halt the germination process. At this point, it is shipped to commercial breweries, where it is crushed and soaked in hot water to restart and accelerate the enzyme activity to convert the remaining starches to sugars. The malt extract used by most home brewers is made by dehydrating the resulting sugar solution, which is then packaged for sale as either a powder or syrup with approximately 20% water content[3].

2.1.1.3 Hops

Hops are divided into one of two categories, bittering hops and aroma hops. They are characterized by their bitter flavor which is used to balance the sugars of malts in beer. They are classified by weight percent alpha acid resin within the hop cones. Bittering hops average around 10% by weight, while aroma hops only average 5% by weight[4]. The higher concentration of alpha acid resin in bittering hops allow for the release of flavor over a longer period of time.

2.1.1.4 Yeast

The yeast chosen to ferment the wort has a substantial influence on the finished beer. Different strains of yeast are able to survive in environments of varying temperatures and levels of alcohol. Therefore, yeast can be chosen based on the amount of sugar in the beer which the brewer wants converted to alcohol, as well as the fermentation environment. Different strains of yeast may also give the beer fruity or nutty flavors.

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[3] Palmer, J. (1999). *What is Malt*. Retrieved December 14, 2008, from How to Brew: http://www.howtobrew.com/section1/chapter3.html

[4] Palmer, J. (1999). *Hops: How Are They Used*. Retrieved December 14, 2008, from How to Brew: http://www.howtobrew.com/section1/chapter5-1.html

2.1.2 The Brewing Process

The brewing process starts with a vat of water. Flavoring grains are steeped in the water at a sub-boiling temperature then removed. Malt is added once the water reaches a boil, and hops are added at various points throughout the boiling cycle. As the mixture boils, flavors develop. However, some sulfur-based compounds form which must evaporate or they could adversely affect the flavor.

2.1.2.1 Steeping Cycle

The steep cycle adds sugars, flavors, and “mouth feel” to the beer, using a variety of cracked grains. These grains serve as the foundation for various flavors and are usually held at a given temperature, from 140-170 °F, for 30 to 90 minutes, and then removed. The water is then brought to a boil for the malt addition stage.

2.1.2.2 Malt Addition

The addition of malts to the boiling water results in wort, the unfermented precursor to beer. The malts add a sweet flavor and the sugars needed for fermentation to the beer. Most recipes call for the addition of malts at the start of the boil cycle, to allow the malts to fully dissolve in the water; however, others call for malts to be added at different intervals during the boiling cycle to impart a stronger sweet flavor to the wort before the boiling is complete.

Upon addition of malt extract, foaming occurs within the wort. This foam is the malt protein coagulating due to the heat and rolling motion of the boil. Boil over may occur when this foam expands over the edge of the pot and begins to spill out. This can be prevented by regularly mixing the wort in order to break up the coagulated proteins[5].

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[5] Palmer, J. (1999). The "Hot Break". Retrieved December 14, 2008, from How to Brew: http://www.howtobrew.com/section1/chapter7-2.html

2.1.2.3 Hop Addition

Hops are added at various intervals to impart specific flavors to the wort. These additions to the boil cycle fall into three categories: bittering, flavoring and finishing, each of which is a combination of specific hops with specific timing cycles.

Bittering hops are added at the beginning of the boil cycle in order to allow for full release of the alpha acid resin as it isomerizes. The bittering boil time is usually between 45 and 90 minutes. An increase in the boil time will improve the isomerization, by approximately 5% as time increases from 45 to 90 minutes. Further heating will result in boiling off aromatic oils, reducing aroma and flavor.

Flavoring hops are added partway through the boil cycle to reach a compromise between bittering and aroma characteristics. While less alpha acid resin will isomerize, creating less bitter flavor, less of the aromatic oils will evaporate, leaving the wort with a stronger aroma at the end of the boil cycle.

Finishing hops are added at the end of the boil cycle. These hops have a low alpha acid concentration but are higher in aromatic oils. By adding them at the end of the cycle, most of the aromatic oils remain in the wort adding a stronger aroma characteristic[6].

2.1.2.4 Cooling

Cooling the wort quickly is important for sanitation and flavor reasons. While the wort is still hot it is protected from bacterial formation by the elevated temperatures. As the wort cools, bacteria are able to colonize the liquid, negatively impacting the flavor throughout the fermentation process. By rapidly cooling the wort, it can be transferred into the sterilized fermentation container quickly, reducing the chance for bacterial contamination[7].

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[6] Palmer, J. (1999). *Hops: How Are They Used*. Retrieved December 14, 2008, from How to Brew: http://www.howtobrew.com/section1/chapter5-1.html

[7] Palmer, J. (1999). *Cooling the Wort*. Retrieved December 14, 2008, from How to Brew: http://www.howtobrew.com/section1/chapter7-4.html

Additionally, the sulfur compounds that form throughout the boil cycle are still produced as the wort cools. Without boiling there is no evaporation to carry off these compounds. By rapidly cooling the wort, the formation of these sulfur compounds is halted more readily.

2.1.2.5 Fermentation

In fermentation, yeast is used to turn wort into beer by the conversion of sugars to alcohol. Fermentation takes place over three distinct stages: adaptation (aerobic), primary (anaerobic), and secondary.

In the adaptation stage, yeast cells rapidly reproduce. They use oxygen and their own glucose reserve to synthesize sterols, which are essential for the yeast cell membrane to become permeable to sugars and nutrients within the wort. This allows fermentation to progress to the second stage, primary fermentation, where yeast cells begin to metabolize the sugars within the wort into alcohol. At the end of this stage, the majority of the yeast dies off. Finally, in secondary fermentation, remaining active yeast breaks down fusel alcohols, which are characterized by their aggressive chemical taste, into esters, producing a fruity, pleasant taste.

2.2 Challenges in Automation

In automating the complex processes of brewing, many challenges arise. The first challenge is that of developing a mechanical system; the second, developing a control system; finally, interfacing the two.

The mechanical system challenges start with designing a brew kettle which can handle the heat and chemical exposure of the brewing process, while not adversely affecting flavor. Once a kettle is designed, heating and cooling methods must be developed which can be readily controlled. The cooling cycle is the most crucial stage, as explained above, due to the importance of sterility in brewing.

A method of controlling large quantities of ingredients must then be laid out. The method chosen must be safe for food contact and easily cleaned. It also must control up to ten pounds of mixed ingredients over a relatively small brew pot, including high density, high viscosity syrups and low density, finely ground powders. It is not uncommon for the volume of ingredients to be larger than the volume of water at the start of the brew cycle.

The control system must be able to track and direct positioning of all these mechanical components. It must also simultaneously track time and temperature changes. These control loops may be low voltage systems with milliamps of current measuring temperature, or line voltage systems pulling tens of amps controlling heat; the system must handle them all.

For practicality, the user needs full control over all portions of the brewing cycle, from initial steeping time to final cooling temperature. Therefore, the controller needs to be simple to use, yet still having sufficient processing capability to manage the system.

To manufacture the complete prototype, there are a number of secondary considerations. For the mechanical portion, various test jigs as well as machining and assembly fixtures must be developed. Electronics boards must be designed and assembled to fit in a compact package, but must allow sufficient cooling for the hot and humid brewing environment. Additionally, software must be written and thoroughly debugged.

2.3 Similar Products

There are only a few examples of products that accomplish a similar goal as the picoBrew project. These systems have regulated temperature control and movement between tanks; however, ingredient additions must still be made manually. There are two products commercially available.

First is the Brewmation[8]. It is designed in a horizontal configuration and capable of brewing fifteen gallon batches between three tanks. The entire system is electric, and the retail cost is $2,950.00. This system also allows for full mash brewing; however, ingredient addition is not automated, and some user work is still required during the process.

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[8] http://brewmation.com/Brewery.html

Next is the Brew-Zer System[9]. Unlike the Brewmation, it is designed in a vertical fashion and is capable of brewing five to eleven gallon batches. It is propane heated, with the rest of the systems being electrical and has a retail price of $2399.99.

The picoBrew projects aims to fill the gap in the current market by developing a small scale automated brewery in the five gallon range, at a price point under $750. There are currently no commercial products in this category. Such a product is expected to draw interest from more advanced hobby brewers looking for an affordable automated system.

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[9] http://www.homebrew.com/shopping/static/BREWZER.shtml

3 Methodology

The design process for the picoBrew system followed a standard design cycle, as shown in Figure 2. Having identified a potential need and completed background research, a single goal statement was put forward: Automate the home brew process. Due to limitation on the project, this goal was restricted to the portions shown in bold on Figure 1 of the Introduction. In order to outline performance specifications, a review of common home brewing recipe was done. From this review minimum system requirements were established. The system was divided into a series of individual problems to be solved. Possible solutions to each of these problems were found, and then rated against each other to determine the best outcome. These were initially assembled digitally into the final system, with portions built on experimental fixtures for initial testing. Once the viability of the design was proven, the complete prototype was machined and assembled.

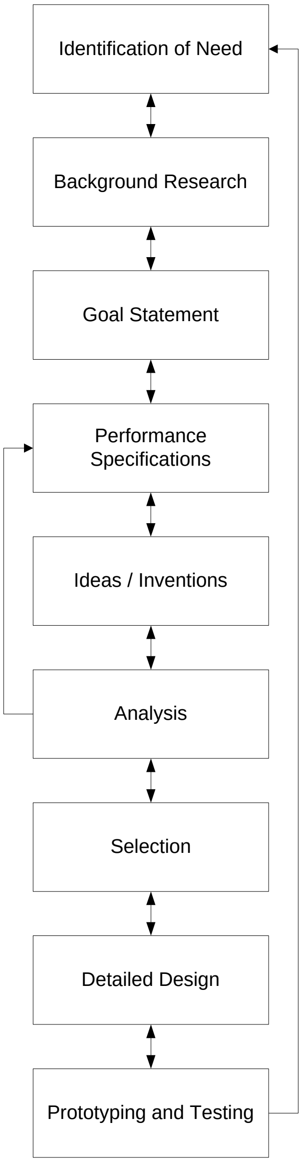

Figure 2 - Standard Design Cycle

3.1 Computer Aided Design (CAD) Modeling

To reduce surprises in final construction, the entire system was digitally created in Solidworks 3D modeling software. This allowed opportunity to investigate possible collisions and interference between moving parts. A sample of the CAD model may be found in Figure 3, below.

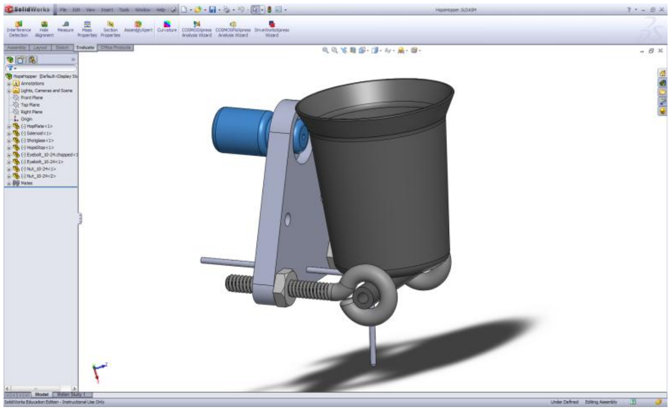

Figure 3 - CAD model of Hops Handling Cell

3.2 Computer Aided Manufacture (CAM)

The ESPRIT CAM package was used to develop tool paths and NC code for the Haas computer numeric control (CNC) machines used for machining many of the billet parts. This combination allowed high precision machining while requiring minimum programming ability. An example of the ESPRIT program is shown in Figure 4.

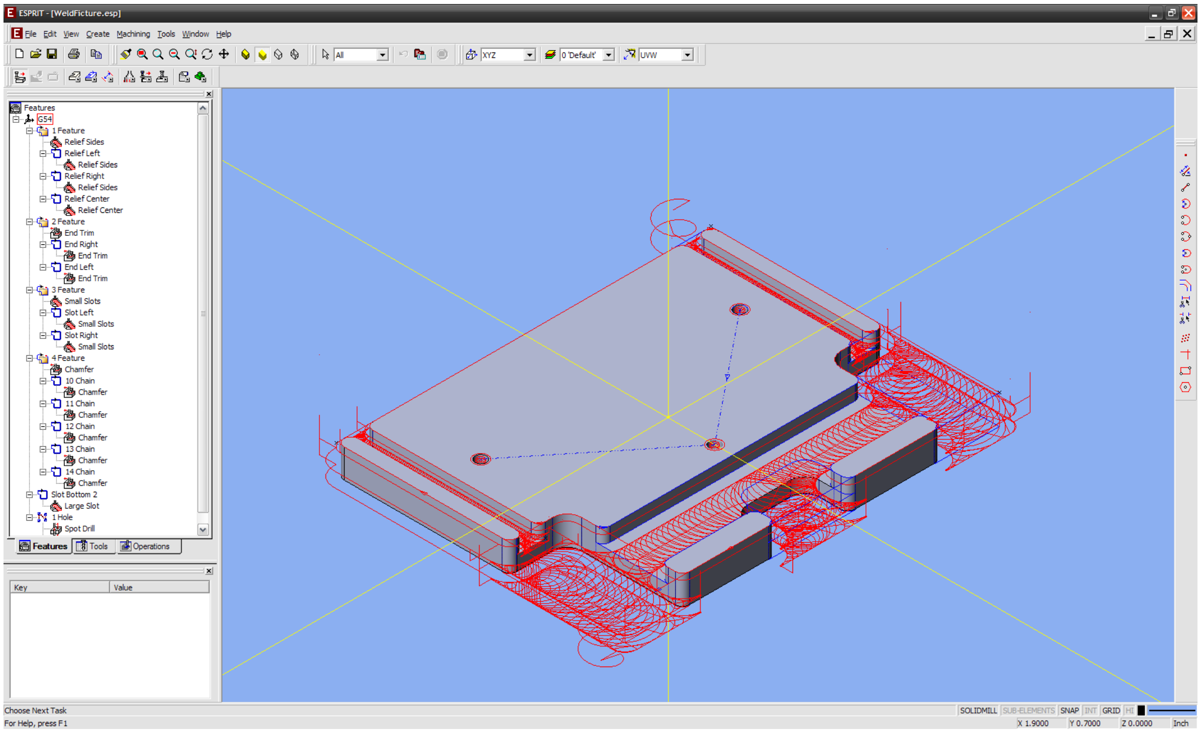

Figure 4 - Example of CAM for welding fixture

3.3 Physical Build

Before building the entire prototype, specific subsystems were assembled on trial fixtures to assure correct operation. Once the designs had been tested, they were machine and assembled. Since much of the system required welding, several fixture jigs were made to hold parts in alignment during the welding process. An example is shown in Figure 5.

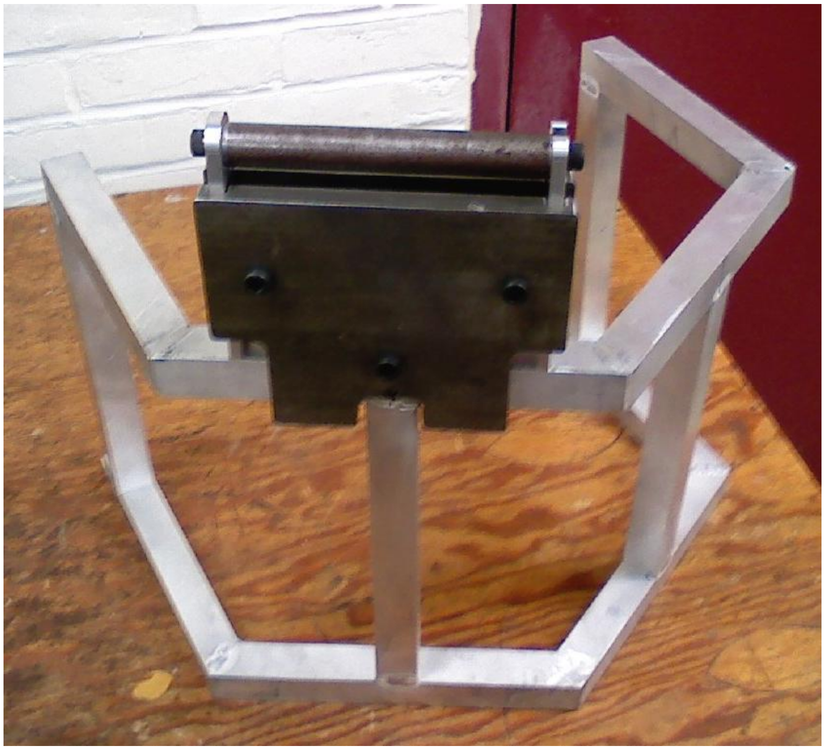

Figure 5 - Welding Fixture Mounted on Frame

3.4 Control Assembly

The control system was built in parallel to the mechanical system, to allow continual testing of both systems. The system was initially built on protoboard to allow easy reconfiguration and analysis. As the system was tested, various portions were permanently assembled on perforated board, and then installed in the final project box. Programming was continuously re-factored throughout the process. A software flow chart can be shown below in Figure 6.

Figure 6: Software Flow Chart

4 Results

As outlined in the Methodology, the various options for each of the subsystems was analyze. The final design was developed from the collated data then assembled and tested.

4.1 System Options

There are a number of subsystems within the prototype, each with its own set of challenges. To make design decisions, possible resolutions to each design challenge were organized, with a listing of the advantages and drawbacks of each option.

4.1.1 Boiling Vessel

The main requirement for the boiling vessel was to hold the three gallon volume required. The boiling vessel also needed to be easy to clean, and of sufficient thickness to prevent scorching. In addition, to simplify cooling, a straight sided boiling vessel was preferred.

Four main materials were considered for the boiling vessel: stainless steel, aluminum, cast iron, and enameled steel. The advantages and disadvantages of each are compiled below in Table 1.

	Advantages	**Disadvantages**
Stainless Steel	Easier to Clean	More Expensive
	Better heat distribution	
Aluminum	Less Expensive	Adds metallic flavor to brew
	Lighter	Anodized as expensive as stainless
	Easy to modify	Thinner bottoms prone to scorching
	Low thermal mass (for cooling)	
Cast Iron (raw)	Excellent heat distribution	Very hard to clean completely
	Inexpensive	Heavy
		Difficult to machine
Enameled Steel	Inexpensive	Difficult to modify
	Easy to clean	Corrosion if cracked
	Reasonable heat distribution	Only commonly available in large sizes

Table 1 - Boiling Vessel Advantages vs. Disadvantages

4.1.2 Heating Element

The main requirement for the heating element was to provide sufficient heat to boil the required amount of water. The heating element also needed to be safe for indoor use, be easily controlled, and use a readily available fuel or power source. The different options considered, with their advantages and disadvantages, are listed below in Table 2.

	Advantages	Disadvantages
Natural Gas	No refill system required	Harder to control
	High heat output	Safety issue with open flame
		Not all houses equipped
Propane	High heat output	Control issues
	Easy availability	Open flame safety concerns
		Constant refills required
Electric Element (resistive)	Simple	High thermal mass
	Inexpensive	Difficult to clean
	Can use relay for binary control	High current requirements
Electric Element (Inductive)	Easy control (relay)	Expensive
	Easy clean-up	May not function with all pots
	Higher efficiency (less heat lost to room)	
	Cool to touch (safety advantage)	
Submersion Heater (electric)	Higher efficiency (all heat into brew)	Hard to find appropriate size
	No exposed heating element	Difficult to clean
		Expensive
Heat Exchange Coil	Can use same coil for cooling	Complex pluming
	Minimal chance of overheat/scorching	Difficult to clean
		Still requires external heat source

Table 2 – Heating Element Advantages vs. Disadvantages

4.1.3 Cooling Methods

Choosing the appropriate cooling method was a vital aspect of this project. The main cooling requirement was to cool the wort from 100 °C (212°F) to 25 °C (75°F) in less than twenty minutes. Additionally, the cooling method needed to be easy to clean and have a sufficient level of controllability.

Three main options were considered for the cooling of the wort: internal coil, external coil, and external water jacket. An internal coil, commonly used in home brewing, consists of coiled metal tubing immersed in the hot wort with cold water running through. An external coil is similar to the internal coil, except it attaches to the outside of the boiling container to reduce contact with the wort. The water jacket is a closed channel on the outside of the boiling vessel, constructed of metal sheeting, through which water flows to cool the wort. The advantages and disadvantages of each cooling method are compiled below in Table 3**.** Each configuration allows the use of either open or closed coolant loops, and any closed coolant loop allows the use of either water or a specialized refrigerant.

	Advantages	**Disadvantages**
Internal Coil	Most common method	Difficult to clean
	High surface area for cooling	Can flavor brew
	Fairly simple plumbing	Potential interference with mixer
External Coil	No wort contact	Lower surface contact/heat transmission
	Simple to plumb	
External Water Jacket	No wort contact	Difficult to clean
	Larger surface area than coil.	Potentially slow cooling cycle
	Inexpensive	More custom assembly required

Table 3 - Cooling Option Advantages vs. Disadvantages

In the considerations of an open or closed system, each system was defined in terms of user impact; an open system allows a constant influx of cold water, but also leads to more water usage. A closed system requires a secondary reservoir or pump in order to cool.

To choose the cooling agent, a list of reasoning factors behind using each case was created, as shown in Table 4 below. Cooling wort directly by passing it through a chilled coil, similar to distilling, requires a sanitary pumping method, as well as cooling system. This results in a more complex, difficult to clean system. For this reason, this system was not considered.

	Advantages	**Disadvantages**
Water	Inexpensive	Lower heat transfer
	Readily available	Open loop requires nearby plumbing
	Ice pass-through chamber possible	
Refrigerant	Lower temperature, faster cooling	Larger power load
		Cool-down time required.

Table 4 – Water vs. Refrigerant Cooling Systems

4.1.4 Ingredient Handling

The main requirement for the ingredient handling aspect of the project was that all components with food contact needed to be easily controlled. These systems also needed to be easy to clean. As mentioned previously, a review of common homebrew recipes was done in order to determine the required size of various portions of the ingredient handling systems. This may be found in Appendix B. From this data, secondary requirements were created for each sub-assembly: steep cycle, initial fermentable, and the hops handler.

4.1.4.1 Steep Cycle Handler

The steep cycle handler had to be able to add and remove ingredients. The steep ingredients are often light but bulky. They are traditionally placed in a mesh bag, similar to a very large tea bag, for removal after steeping. This system was designed with such a method in mind, using a stainless steel chain as a lifting mechanism. Drive options are shown in Table 5 below.

	Advantages	Disadvantages
Stepper Motor	Open loop control	Higher control complexity
	Adjustable speed	Limited torque capability
		Requires external gearbox
DC Gear Motor	High torque capabilities	No speed control
	Simple control	Limit switches required due to variable speed under load

Table 5 – Steep System Drive Options

4.1.4.2 Malt Handler

This system had to be able to handle both solid and liquid ingredients, to allow additions of all varieties of malt extract. The system needed to have variable speed capabilities, in order pour at a controlled rate to limit boil over potential. Also, to allow for easy cleaning, the stainless steel hoppers had to be removable. Drive options for these hoppers are shown in Table 6 below.

	Advantages	Disadvantages
Stepper Motor (spur gear)	Open loop control	Higher control complexity
	Adjustable speed	Limited torque capability
	Simple gearing system	
Stepper Motor (worm gear)	Open loop control	Higher complexity in gearing
	Adjustable speed	Bulky gear train
	High torque output	
Servo	Adjustable speed and travel	PWM requirement
	Reduced external control circuitry	Minimal torque capability (not enough travel for reduction gears)

Table 6 – Malt Handling Drive Options

4.1.4.3 Hops Handler

The hops addition system was required to add hops at four different times during the boil cycle. Like the malt system, the hoppers had to be removable for easy cleaning. Unlike the malt system, the volume of hops addition is sufficiently small that boil over issues do not arise, so hopper speed control was not a concern. Control options are shown in Table 7 below.

	Advantages	Disadvantages
Stepper Motor	Open loop control	Higher control complexity
	Adjustable speed	Bulkier linkage
Solenoid	Simple Control	No speed control
	Low cost	

Table 7 – Steep System Drive Options

4.1.5 Control System

The main requirement for the controller was the need to be able to handle multiple user inputs: time of steep, temperature of steep, boil time, boil sequence (including ingredient addition times). The controller also needed to be able to interpret temperature sensor inputs, and process the necessary functions and information as needed.

4.1.5.1 Programmable Logic Controller (PLC)

The controller selected needed to meet a number of conditions. It was necessary for it to have at least 33 standard digital I/O ports: four for each of four stepper motors; one each for the four solenoids; one each for the mixer, heater, and cooling systems; one for each of the five buttons; four for LCD control; and one for the cycle indicator light. These port listings can be seen in Appendix C. The microcontroller also needed to have one analog to digital converter port for a thermistor, and one port with PWM (pulse-width modulation) available for speaker output. Ease of use was of great concern in the selection of the microcontroller. Table 8 displays the advantages/disadvantages between two controller options.

	Advantages	Disadvantages
CUBLOC CB-280	Expandability of Externals	High Cost
	Simple Basic Programming	Bulky Development Board
	Large Online Support Base	
TI MSP-430	Low Cost	Assembly Programming Needed
	Higher ADC Resolution	Multiple External Components Needed
		Limited Support Available

Table 8 – Controller Options

Two microcontrollers were primarily considered, the MSP-430 by Texas Instruments, and the CB-280 by Comfile Technologies. Both of these controllers had the required number of I/O ports. The MSP-430 was considered due to its use by the Electrical and Computer Engineering department at WPI. The MSP-430 was a barebones chipset, with no peripherals. The CB-280, a commercial product with development board, was provided with a full manual with description and usage of each of its possible functions, as well as schematic and code examples for specific uses.

4.1.5.2 Display

With all the functionality to be built into the prototype, the system had to be able to display all options and outcomes in an easy, understandable fashion. There were three primary interface options that were considered: LCD screen, LED displays, and a touch screen. The advantages/disadvantages can be seen in Table 9 below.

	Advantages	Disadvantages
LCD	Easier for user to understand	More expensive
	Higher data output to user	Harder to implement (both hardware and software)
LED	Less complex programming	Harder for user to input commands
	Inexpensive hardware	No ability to show error messages
	Simple interface	
Touch screen	Easier for user to understand	Most expensive
	Capable of most aesthetic interface	Hardest to implement

Table 9 - Display Advantages vs. Disadvantages

4.1.5.3 Temperature Sensor

The system needed to be able to accurately measure the temperature of the wort during the brewing cycle. The temperature sensor needed to be capable of measuring temperatures in the range from 15 °C (60 °F) to 100 °C (212 °F). A few options were considered: thermistor, RTD (resistive temperature device), and a digital thermometer. The advantages and disadvantages of each can be seen below in Table 10.

	Advantages	**Disadvantages**
Thermistor	High precision within Range	Calibration requirement
	Low Cost	
	Easy to Implement	
RTD	Accurate over large range	High Cost
	Resistive to Noise	Calibration requirement
	Easy to Implement	
Digital Thermometer	Low Cost	Harder Implementation
		Hard to waterproof

Table 10 – Temperature Sensor Advantages vs. Disadvantages

4.2 Final System Design

The final system design was guided by the decision tables shown in the Methodology. The design was divided into three different segments: mechanical, electronics, and software.

4.2.1 Mechanical System

A twelve quart stainless steel stock pot was selected as the boiling vessel. An inexpensive one was found which could contain the necessary volume of wort, be cleaned easily, and not impart any unpleasant tastes to the final brew.

A resistive electric heating element was chosen as the heating method. Using propane was deemed too unsafe for indoor use, while the submersion heater and inductive electric element options were too expensive given the available resources.

The water jacket was determined to be the option best suited to the projects cooling needs. The cooling method chosen was an open loop, water cooled jacket with flow fully circling the pot. Water cooling was chosen for simplicity and to reduce potential exposure to possibly hazardous refrigerants. A solenoid valve, commonly used on dishwashers to control input flow, was chosen to control the cold water flow. The cooling jacket was chosen over the internal coil to reduce cleaning and contamination concerns.

4.2.1.1 Cooling Thermodynamic Study

To prove feasibility as part of the decision process, a thermodynamic study was completed on the external water jacket. In order to simplify such an analysis, several assumptions were made. The water jacket system was calculated as a series of steady-state systems with constant temperature differences between the wort and the cooling water. The inner wall of the boiling vessel would be treated as a vertical plate heat exchanger, with natural convection on the wort side and forced convection on the coolant side. Research had shown that incoming ground water temperature would be an average of about 13 °C (55 °F) in New England[10] (up to 20 °C (68°F) in the extreme southern United States) and therefore 13 °C was used. Water flow was presumed to be available at 1.5 gallons per minute, about 70% of the EPA mandated maximum of 2.2 gallons per minute[11]. An arbitrary size was chosen for the water jacket, one within the expected range of size options, and a standard twelve quart, 304 stainless steel stock pot was used for evaluation. A schematic diagram of the system is shown below in Figure 7.

Based on these assumptions, heat transfer rates were calculated at temperature extremes, as well as at an average value. From the total heat removal required and the heat transfer rate, a time value for each temperature case was then calculated. These values fell within the acceptable range of cooling times. These calculations can be found in Appendix A.

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[10] http://public.dep.state.ma.us/wsc_viewer/Default.aspx?formdataid=0&documentid=9113

[11] http://www.epa.gov/WaterSense/pubs/bathroom_faucets.htm

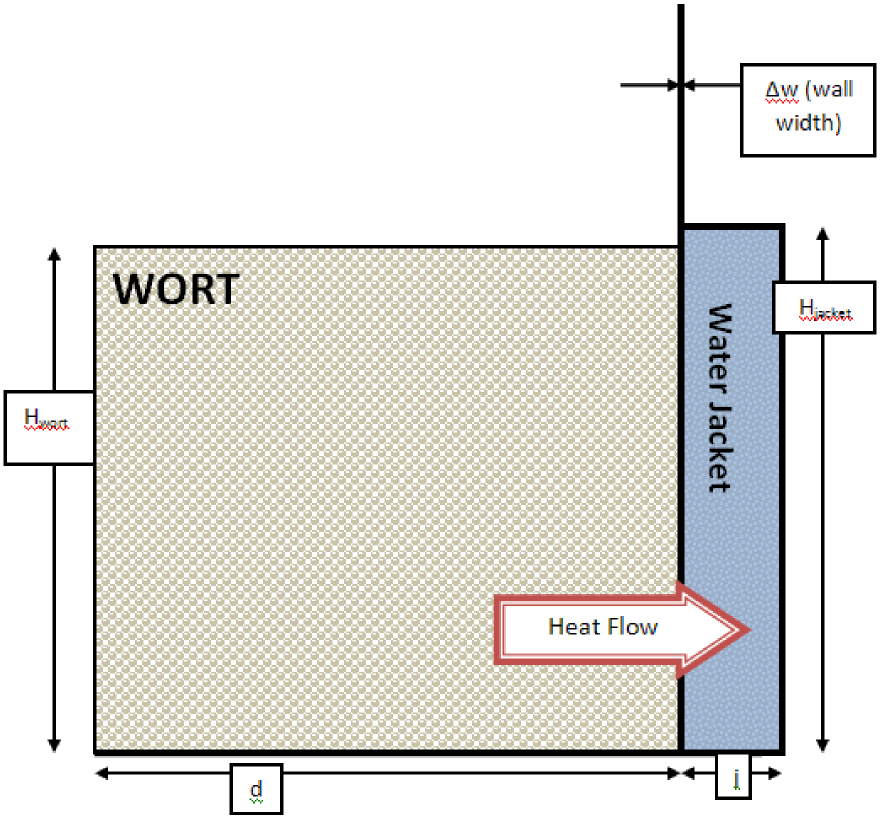

Figure 7 - Thermoydynamic Representation of System

The steeping handler consists of stainless steel flat chain attached to a worm-gear winching systems driven by a stepper motor with a 50:1 gear ratio. This will allow the grain bag to be slowly dropped into the wort then removed when appropriate. It also allowed use of identical stepper motors for both the steep and malt systems.

The main fermentable hoppers are composed of three stainless steel containers, able to hold about 3.3lb of liquid malt extract or 2lb of dried malt extract. These hoppers are driven by stepper motors, through a 12:80 gear drive.

The hops hoppers consist of four solenoid released stainless steel shot glasses with stainless steel axles soldered to the bottoms. This allows them to pivot easily when suspended between eye bolts, leading to quick and simple release of the hops when the solenoids are triggered.

The mixer head is a surplus take-off from a Hamilton Beach blender. It attaches to a clamping block, which holds it and the thermistor onto the upper edge of the brew kettle.

The frame is constructed of aluminum one inch square tubing, arranged in a hexagonal formation around the pot and water jacket for the base. An upright column rises off the base to support the steeping chain and bag. Two aluminum bars branch off from the trunk to support the hops hoppers.

A picture of the final prototype is shown below in Figure 8.

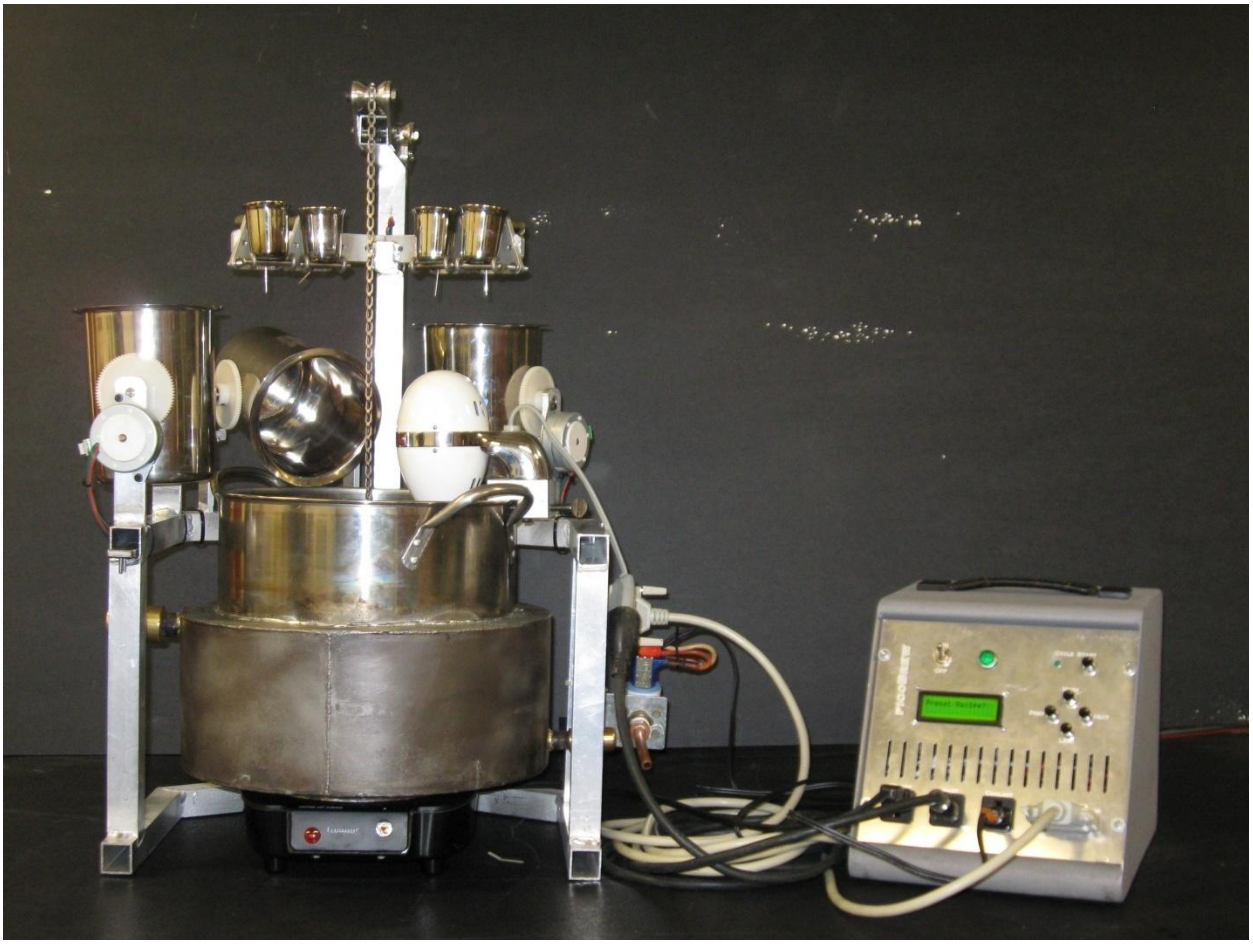

Figure 8 – Prototype

4.2.2 Control System

4.2.2.1 Control Hardware

For materials handling, stepper motors were chosen for both steep and hops handlers, with solenoids being used to control the hops hoppers. The Minebea-Matsushita Motor Corporation PM55L stepper motor was chosen for its high torque capabilities and reasonable price. The Ledex, Inc. 191172-001 was chosen as the best solenoid for the intended purpose, due to its easy availability and low cost.

The power supply needed to be able to provide power to all DC components that could possibly be running at one time. The maximum load situation involved the CB-280 running at full capacity, a fan running, and one stepper motor running. The stepper motor required about 800 mA at 24V running at full capacity. The CB-280 comes standard with a 12V 500 mA power supply, so this was assumed to be its maximum load. The case fan required about 200 mA at 12V. A 24V power supply was necessary in order to be able to run the stepper motors, and could be stepped down to 12V using a voltage regulator to run the CB-280 board, fan, and solenoids. Assuming 80% efficiency in the conversion from 24V to 12V, the fan and CB-280 board would need 420 mA total at 24V to make the required 700 mA at 12V. The power supply had to be able to provide at least 1220 mA at 24V with conversion from a 120VAC line. The Power-One # MAP42-1024 was selected. This power supply provides 1700 milliamps at 24VDC from an input source of 85-264 VAC. The additional power capacity provides for unexpected inefficiencies or overlooked loads, as well as future expansion.

A thermistor was eventually chosen for temperature sensing. These devices were readily available in the temperature range required, with high precision and accuracy. Although calibration was needed, it ensured that the reading at the controller would match the temperature across the appropriate range.

The RTD was too expensive and lacked the required precision needed over the wide temperature range. The digital thermometer, being an integrated circuit (IC), would have been difficult to waterproof as well as implement with our current control system.

In order to interface the CB-280 with the various powered components, a series of control boards was created. Schematics for these can be found in Appendix D.

Solid-state relays were needed in order to control 120V power to the heater, mixer, and the cooling valve with the CB-280. For the heater, which runs at 1100 watts, a relay of at least 10 amps was needed, and the D-240A10Z was used. Both the mixer and the cooling valve required less than 1 Amp of power and the Crouzet M-OAC5-315 was used to control these two components.

Both the stepper motors and the solenoids required a voltage and current larger than what could be supplied by the CB-280 so MOSFET-based control boards were built to control these components. The control board for each stepper motor required four MOSFETS, eight Schottky diodes, and four 10kOhm resistors. The MOSFETS, when activated, provided the grounding for each of the four signal lines on the stepper motor which were connected to the source pins on the MOSFET. The source pins were wired with Schottky diodes to provide protection against potential power surges. The CB-280 was connected to the gate lines on the MOSFET, so that when a 5V signal was sent from the microcontroller, the MOSFET would allow electron flow. The gate also contained a 10kOhm pull down resistor which allowed for faster voltage drop and therefore quicker switching of the MOSFET. The drain on the MOSFET was wired directly to ground.

The solenoid control board required fewer components. Each solenoid only required a single MOSFET and 10kOhm resistor. The I/O pin from the CB-280 was wired to the MOSFET gate, and a 10kOhm resistor was wired from the gate to ground, once again to provide for faster switching. One side of the solenoid was wired to the source on the MOSFET, and the drain was wired to ground.

From the available display options, the LCD screen was chosen. Comfile Technologies, our chosen controller manufacturer, had available prewritten code and attachment points for an LCD which allowed for easy output to the LCD screen.

While the touchscreen would have simplified input and output, the cost was beyond the scope of this project. The LED display would have been more difficult to understand, less adaptable, and more challenging in the long run. A single LED was used as a signal indicator light, but not to display any values.

Due to potential heat buildup in the stepper motor, a protection resistor was wired into the stepper power input. The stepper required a maximum of 800 mA at 24V and had an internal resistance of 5.5Ohms. Using the Ohm's Law, the value of the protection resistor was calculated at 24.5 Ohms. A 25 Ohm resistor was chosen as the protection resistor.

To increase modularity, many of the electronics were fitted with connectors in order to make the changing of parts as easy as possible. PCB connectors were used on many of the boards so that in the case of a failure, or a bad design, new components could be quickly and easily switched into their places. A chart of the final system design can be seen in Figure 9**.**

Overall System Schematic
Parts Listing

1x 275-636 20A 125VAC DPST Toggle Switch
1 x 120V Neon Indicator Light
1 x 1.7A 24V Power Supply
1 x DB0BH-12 120VDC Fan
1 x 10A Solid State Relay
2 x 1A Solid State Relay
3 x 120VAC 15A Grounded Outlet
1 x DE23309 1100W Electric Heater
1 x No.51 Hamilton Beach Mixer
1 x 303650 Dishwasher Fill Valve
1 x Cubloc CB280
1 x CLCD216-G LCD
1 x NTCAPIPE3 Thermistor
1 x 0.47 μF Capacitor
1 x 5.1V Zener Diode
1 x 10kΩ 1% Resistor
1 x DB25 Cable

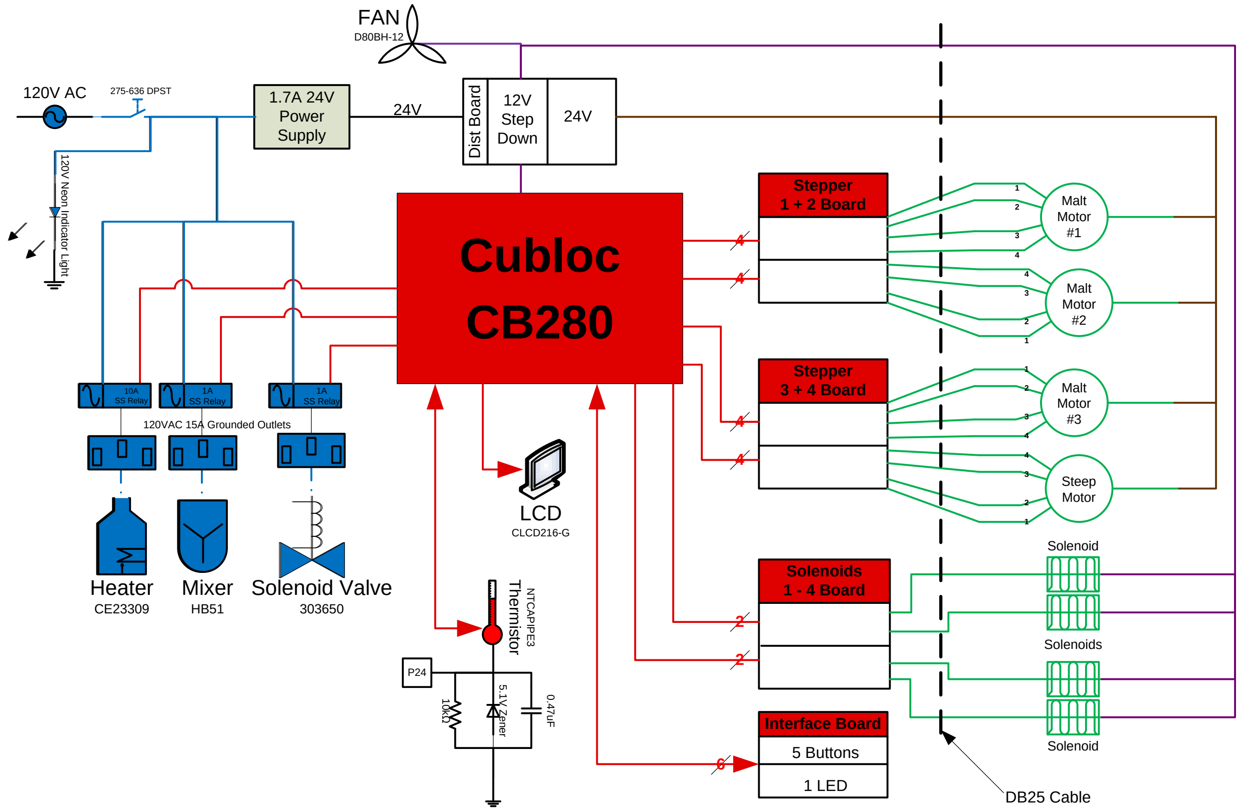

Figure 9: Final System Schematic

4.2.2.2 Control Software

The control system had to incorporate both programming and electrical components together into a functional, user-friendly product. The block diagram for the control system is shown below, in Figure 10.

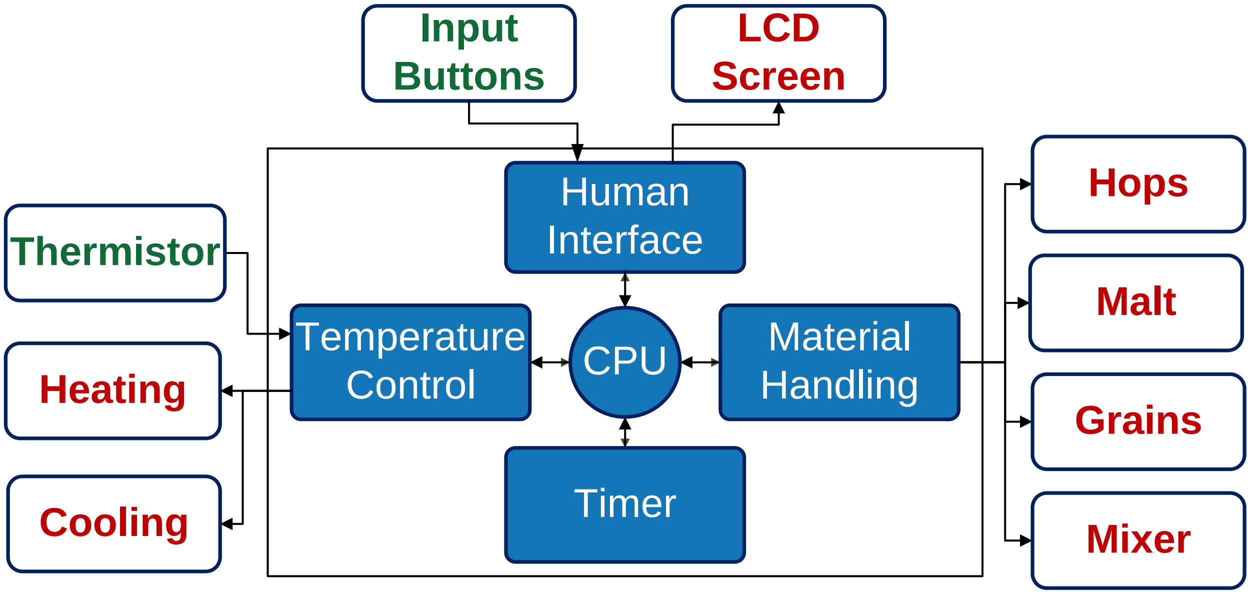

Figure 10: Control System Block Diagram

The programming segments were broken up into four main categories: material handling, timing, temperature control, and human interface. These categories were then coupled to the respective electrical components to achieve the desired task.

For material handling, the software had to be able to efficiently control the multiple stepper motors and solenoids. As the stepper motors were being controlled by the PLC, through MOSFETs, it was vital that efficient code be written to maximize available stepper speed.

For timing, the software had to be able to track multiple timed actions, as well as accurately record total time elapsed. The timing of each sub-cycle was recorded for display after the program finished, for user reference.

For temperature control, the PLC first had to configure its port to an analog input, and then read in a voltage. Using one of the CB-280's 10bit analog-to-digital converters (ADC), the voltage was converted to a value between 0 and 1023. During testing, this data was recorded and compared with temperature data, allowing accurate calibration of the complete system. Due to accuracy requirements in the cooling, steeping, and boiling ranges, three independent calibration curves were implemented to achieve highest precision in the required ranges. Calibration data can be seen in Appendix E.

On the human interface side, the code had to both retrieve and output the required information in the most user-friendly way possible, while limiting possibilities for input errors. The general menu flow was designed to cater to both novice and advanced brewers. Novice users can choose a preset recipe, load ingredients, and press "Cycle Start." Advanced users can choose a custom cycle, with the ability to control all timing and temperature decisions. The user also has the option of saving up to three custom recipes and cycles for future use. An annotated flow chart of the menu options may be found in Appendix F.

4.3 System Performance

The picoBrew prototype proved quite capable during both dry runs and final testing. The system was able to read and control temperature to within 1.1 °C (2 °F) throughout the entire cycle, with the ability to read within 0.28 °C (0.5 °F) within the important portions of the steep, heat, and cool stages. Timing control was consistent within one second over the course of the average three hour brewing cycle. Cooling was rapid despite minor plumbing leaks.

However, final testing showed a few easily correctable flaws in the prototype. The heating element chosen was barely sufficient to boil the wort, and suffered from a drop in temperature during ingredient additions. The current prototype is unable to support a larger heating element due to the current limit on the solid state relay controlling the heater. However, replacing this relay with a similar but higher-rated unit would allow the use of a larger heating system.

The second issue which arose was with the mixer head. As the wort boils away, the fluid level may drop, reducing the amount of fluid covering the mixing head. This can result in the propulsion of hot sticky wort above the edges of the brew kettle, coating any object within a one meter radius. This can be corrected by extending the mixer shaft several inches, insuring that the mixer head is submerged at all times.

The final issue was with the steep system. When tested with the largest steep requirements, the winch proved unable to lift the waterlogged grain bag from the brew kettle. A more powerful stepper motor would overcome this problem easily.

5 Conclusion and Recommendations

The picoBrew prototype works well as a proof of concept. It handles the heating and cooling stages of the brewing cycle with excellent temperature and timing control. Reception amongst home brewers and other interested individuals was uniformly positive, with many expressing an interest in commercialization.

It is hoped that this project will be continued at WPI, as there are many upgrades and additions that could be made. For example, a system intended to control and track the fermentation cycle would be a clear continuation. Temperature control is vital to consistent fermentation, and the ability to record alcohol level as measured by hydrometer would allow brewers greater control over the timing of secondary fermentation and bottling.

A full mash cycle could also be added to the system. This addition would require a second stainless steel vessel capable of holding about three gallons of water, a second heating element, a second thermistor, a pump, a plastic five gallon mash tank, and water level sensor. This full grain system would not require the current steep or primary fermentable handlers. This system could be easily added onto the current setup and would allow the system to be sold with various setups for different level brewers.

Even within the scope of the current prototype, there are many areas where systems could be updated. The control system could be streamlined by a team with greater experience in electronics. A superior cooling jacket could be fabricated, possibly of an annular aluminum design to be pressed onto the stainless brewing pot. This would reduce leakage and allow direct contact between the brew kettle and heating element.

6 Business Plan

Assessment of Market Viability

The beer market within the country is expanding both in production and value, with an increase of 1.7% in production volume in the overall market and an increase of 12% in sales for craft brews alone. The beer market has since been increasing each year, and the expansion in the market shows that markets within are sustainable.

According to the most recent data presented in the The Annual Beer Handbook on consumer characteristics there appears to be a reasonable market for the picoBrew. Currently there are 202.9 million people[12] within the legal beer drinking community of the United States.

However, the population of homebrewers within the beer drinking population is unknown. Because of this, data pertaining to the craft brew community was analyzed to account for the specialty of homebrewing within the general market. Craft brews consist of the section of the market pertaining to brewpubs, microbreweries and regional craft brewers. The United States largest homebrewing organization, the American Homebrewers Association (AHA) has released approximations of its membership size. The AHA currently has around 17,000 active members[13], which represents only a portion of the homebrew population because only registered, due paying members are counted.

Of the 202.9 million people in the beer drinking population 9.6 percent fall into the market of craft beer drinkers. This amounts to approximately 19.5 million people. In this subset of the community 70.8% make over $60,000 a year in pretax income, amounting to 13.8 million people[14].

While a viable market appears to exist in the homebrewing community, interactions between competitors in a market can create challenges for small companies depending on cost structure and demand within the market. This may be lead to a minimum share of the market being required to remain competitive[15].

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[12] 2007. Consumer characteristics. The Beer Handbook. p172(10)

[13] http://www.beertown.org/homebrewing/membership.html

[14] 2007. Consumer characteristics. The Beer Handbook. p172(10)

[15] Karnani, Aneel. Minimum Market Share. Marketing Science, Vol. 2, No. 1 (Winter, 1983), pp. 75-93

However, specialization within a market lessens the minimum market share required. In a case where a company is able to carve a niche in the market the minimum market share decreases.

In the case of the picoBrew project there would be no minimum market share because of a lack of competition and the specialization of the market. With no comparable products in the market in either scale or cost, the picoBrew project would be able to hold a competitive niche in the market allowing sales to be independent of larger competition in the market.

Using the membership of the AHA as a population base and an estimated market share of between 1% and 5% the customer base for the picoBrew project can be estimated between 1,700 and 8,500 people.

Consumer Needs

The consumer needs for the product determined the systems added to the product in development. To this end, a survey was taken to gain a basic understanding of the desires of homebrewers in an automated system.

The set of survey questions in Appendix G were distributed over two internet forum sites targeted towards the homebrew community. Ratebeer.com and Beeradvocate.com are both websites that focus on craft brewing a commercial and home scale. These sites are frequented by practitioners of the hobby and enthusiasts who are more focused on the works of the commercial brewers.

Overall, the design of the picoBrew project matched the desired system capabilities of respondents to the survey, with the system having at least the minimal capabilities users would look for in a home brew system. The results of the survey questions can be seen in Appendix G.

Manufacturing Cost Considerations

Three major costs are associated with the manufacturing process: materials, direct labor, and overhead costs. In the analysis of the manufacturing cost of the picoBrew prototype, only cost of materials and manufacturing labor are evaluated.

Material cost for the prototype of the system can be seen within the bill of materials (BOM). The BOM was developed with the principles of the manufacturing process in mind, reducing the number of levels in the BOM to a minimum. Garwood[16]states that “an over structured bill of materials generally implies long lead times, unnecessary tasks, and, thus, higher costs.”

The levels within the BOM presented in appendix H were chosen to divide the various processes in manufacturing to allow for each level of a subsystem to only require one type of labor. This was done to assist in the process of the cost analysis, so that each section of the BOM has an associated material, and labor cost.

The costs of materials in the BOM are representative of the prototyping costs of the project. Material costs can be reduced in the transition from prototyping to production due to bulk discounts from suppliers on materials. The cost of ideal materials should average around 50% of the total manufacturing cost[17].

Direct labor costs in the production of a product average between 12% and 15% of the total manufacturing cost. The cost of direct labor is a product of the man hours and the wage rates specific to the type of labor being performed.

While this cost estimate follows a simple base function, the factors of variability in labor productivity can alter the estimate associated with manufacturing labor. A base productivity can be defined in order to account for the regional variables associated with manufacturing[18].

The manufacturing of the picoBrew prototype would require several types of employees based upon their specialized skills; specifically machinists, welders and assemblers.

Machinist’s wages depend largely on the training and experience they have completed, and on the level of detail in the job, with precision jobs paying higher wages. In the United States the mean hourly wage of a general machinist is $17.36 where as the mean hourly wage increases to $19.72 when only Massachusetts is considered.[19]

Welders are defined by the Bureau of Labor Statistics as a group of workers whose specialty centers on welding, soldering and brazing operations. Welder’s job in a manufacturing process varies between skill levels and the level of automation in a process.

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[16] Garwood, Dave. 1995. Bill of Materials. Dogwood Publishing Company, Inc. Marietta, GA

[17] Black, J.T. 1991. The Design of the Factory with a Future. McGraw Hill Inc. New York. P. 14.

[18] Clark, F.D., and Lorenzoni, A.B. 1985, Applied Cost Engineering. Marcel Dekker, INC. New York. Chpt 5

[19] http://www.bls.gov/oco/ocos223.htm

The mean hourly wage of a welder in the US is $15.43 for general or all purchase machinery welding operations. However, in Massachusetts this is increased to $19.68 since Massachusetts is ranked one of the highest paying states in this profession.

Assemblers fall into one of two categories needed for an automated project. The physical body of the product must be assembled in line with the electronic components being assembled. In the end these two subassemblies are brought together to create the finished product. Since assembly is a less specialize vocation in comparison to welding and machining it can be expected that the mean hourly wages are less, with electronics assemblers making $13.75[20] and team assemblers making $12.72[21]

System Prototype Cost

This data was used along with the production time estimates made based upon our build of the prototype system to determine what the prototyping cost of the picoBrew project was. The detailed breakdown of material cost can be seen in the BOM in appendix H while the wage cost can be seen in appendix I.

Overall the prototyping of the picobrew project cost $994.12 in material cost. This includes the cost of materials that were freely available to us in Washburn shops stock.

Labor cost or the product was determined using the mean hourly wage of the various types of work needed to carry out the production of the prototype. Labor cost came to a total of $339.69 including an estimated 18.8 labor hours. In addition to this, a productivity factor of 90% was used to offset the relation of worker conditions to efficiency of employees. The total cost of the picoBrew prototype and labor came out to be $1,333.81.

Future of Commercialization

Future considerations for the commercialization of the picoBrew project include reducing production cost and including a focus on the design for manufacturability. Cost can be reduced by both streamlining the existing processes and making the system as a whole more efficient. While the picoBrew prototype acts as a valid proof of concept for the idea of a small scale,

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[20] http://www.bls.gov/oes/current/oes512022.htm#ind

[21] http://www.bls.gov/oes/current/oes512092.htm

affordable, automated homebrewing system it would have to be redesigned to be both more mechanically effective, and aesthetically appealing to the consumer before it could be taken into the market.

8 Appendices

8.1 Appendix A - Overall thermodynamic equations:

Overall thermodynamic equations:

$$\dot{Q} = U_{oa} * A * \Delta T, \text{ where } U_{oa} = \frac{1}{A * \sum_j R_{th,j}}$$

$$R_{th,wort} = \frac{1}{h_{wort} * A_{wall}}, \quad R_{th,water} = \frac{1}{h_{water} * A_{wall}}, \quad R_{th,wall} = \frac{\Delta w}{k_{wall} * A_{wall}}$$

$$A_{wall} = \pi * d * H_{wort}$$

For the wall:

k_{wall} is a material property, and Δw is a measured value for the stock pot. Therefore, $R_{th,wall}$ may be calculated directly.

For the cooling flow:

$$h_{conv,forced} = \frac{Nu * k_{water}}{D_{hydraulic}}, where\ D_{hydraulic} = \frac{2LW}{L + W}$$

The hydraulic diameter can easily be determined from H_j and j, while the k_{water} is available in standard tables. However, the Nusselt number depends on the Reynolds number

$$Re_D = \frac{\rho * V_{avg} * D}{\mu} = \frac{V_{avg} * D}{\upsilon}, V_{avg} = \frac{\dot{V}}{A_{cross}}$$

In this instance, the calculations show that the Reynolds number indicates a laminar flow pattern within the cooling jacket, indicating that the Nessult number is either 4.36 or 3.66 for constant heat flux or constant wall temperature, respectively. We used the lower number, to assume a worst case situation.

For the wort:

$$Nu_{local} = \left(.707Gr^{\frac{1}{4}}\right)\left(\frac{0.75Pr^{\frac{1}{2}}}{\left(0.609 + 1.221\mathrm{Pr}^{\frac{1}{2}} * 1.238\mathrm{Pr}\right)^{\frac{1}{4}}}\right)$$

$$\overline{Nu} = 1.333Nu_{local}$$

$$Gr = \frac{g * \beta * \Delta T * L^3}{\upsilon^2}$$

By looking up the Prandl number, kinematic viscosity, thermal conductivity and beta, the Nusselt value for the wort is easily calculated.

Time Calculations	Best Case:	Worst Case:	Median Case:	Units
T(wort)	373	298	333	K
T(cool)	286	293	289	K
ΔT	87	5	44	K
β (hot)	7.51E-04	2.75E-04	5.35E-04	1/K
ν(hot)	2.94E-07	8.96E-03	4.78E-07	m^2/s
Pr(hot)	1.75E+00	6.15E+00	2.99E+00	
L (vert. plate length)	9.22E-02	9.22E-02	9.22E-02	m
k(hot)	6.79E-01	6.07E+02	6.54E-01	W/m*K
Conduction Area	8.11E-02	8.11E-02	8.11E-02	m^2
Grashof (wort)	5.80E+09	1.32E-01	7.94E+08	
Nu	1.34E+02	4.33E-01	9.67E+01	
Nu (avg)	1.78E+02	5.77E-01	1.29E+02	
h(conv)	1.80E+03	5.20E+03	1.25E+03	W/m^2*K
R(th,hot)	6.86E-03	2.37E-03	9.85E-03	K/W
R(th,wall)	4.14E-04	4.14E-04	4.14E-04	K/W
R(th, cold)	3.26E-05	3.19E-05	3.23E-05	K/W
U(oa)	1.69E+03	4.37E+03	1.20E+03	W/m^2*K
Q(dot)	1.19E+04	1.77E+03	4.27E+03	W
Time	1.50E+02	1.00E+03	4.17E+02	s
Total Cooling Time	**2.49**	**16.73**	**6.94**	**min**

8.2 Appendix B – Recipe Research

		LME #1 (lb)	LME #2 (lb)	DME (lb)	Steep Grains (lb)	Hops #1 (oz)	Hops #2 (oz)	Hops #3 (oz)	Hops #4 (oz)
Ale	Scottish 60	3.15		1	0.5	0.5			
	British Bitter	3.15		1	0.5	1	1		
	Irish Red Ale	6			1	1	0.5		
	Extra Special Bitter *	3.15	3.15		1	2	1	1	1
	Nut Brown Ale	6			1	1			
	German Ale	6		1	1	1	1	1	1
	Nukey Brown Ale	6		1	0.75	1			
	Extra Pale Ale	6			1	2	1		
	Mild Ale	3.15		1	0.625	1			
	American Amber Ale	6.3			1	2	1		
	Kolsch	6		1		1	1		
	St Paul Porter	6		1	1	1	1		
	Dry Irish Stout	6			1	1			
	Sweet Stout	6		1	1	1			
	Scottish 80 *	3.15	3.15		1	1			
	Cream Ale	6			1	1			
	English Pale Ale	6		1	0.5	1	1		
	Tongue Splitter	6			1	1	1	1	1
	Irish Draught Ale	3.15	1	1	1	1			
	Oud Bruin de Table	6			1.625	1			
	Notre Dame d'Golden Valley	6.3			1	1	1	2	
	St. James'	6		2	1.5	1			0.5

	Gate Foreign Extra Stout								
	XX Ale	6	3		1.5	1	3.5		
	Peace Coffe Stout	6			1.5	1			
	Cumbrian Double Brown Ale	6	1		2.24	1			
	The Inn Keeper	3.15	1	1	0.5	1	1	1	
	Biere de Chute	6	1	1	0.5	1			
	Saison de Table			4		1	1		2
	La Saison Noire	6		1	1.5	2			
	Hefe Weizen	6		1		1			
	American Wheat Beer	6				1	1		
	Dunkelweizen	3.15	3.15			1			
	Honey Weizen	6				1	1		
	Raspberry Wheat	6.3				1			
	Honey Brown Ale	6			1	1	1		
	Peat-Smoked Porter	6		2	1.5	1	1	1	
	California Common	3.15	3.15		1	1	1		
	Dark Cherry Stout	3.15	3		1.5	1			
	Spiced Winter Ale	6.3			1	1	0.25	0.5	
	Bourbon Barrel Porter	6.3		2	2	1	0.5	0.5	
	Honey Kolsch	6	1			2			
	Breakfast Stout	3.15		1	2	1			
High Gravity Ale	India Pale Ale *	3.15	6		1	1	1	0.5	
	Imperial Stout	6	6		1.5	2			
	Scottish Wee Heavy *	6	6		1	1			

	Winter Warmer *	3.15	6.3		1	2	1		
	Barley Wine	9	3		0.5	2	1		
	Baltic Porter	3	6		2	2	0.5	0.5	
	Double IPA	9	3		1	1	1	1	
	Three Hearted Ale	9.15			1	1	1	2	
	New Old Ale	6	1	2	1	1			
	Lord FatBottom			12	1	2	2	2	
	Big Honkin' Stout	3.15	6		1.5	2	1	1	
	Super Alt	3.15	3.15	2	0.625	2	0.5	0.5	
Belgian Ale	Phat Tyre Amber Ale	6		1	1	1	1		
	Patersbier	6			0.5	1	0.5		
	Belgian Dubbel	6.3	1	1	0.5	1	1		
	Belgian Tripel	6	3.15		0.5	1	0.5		
	Witbier	6.3				2	1	1	
	Belgian Strong Golden Ale	7	2		0.5	2	1		
	Saison	6.3	1		0.5	2.5	0.5		
	Biere de Garde *			7	1	1			
	Imperial Wit	9.15				1	1	1.5	
	Dawson's Kriek			6		1			
	Lefse Blond *	6.3	1			1.5	0.5		
Lager	American Lager	3.15	2			1			
	World Wide Lager	6		1		1	0.5	0.5	
	Czech Pilsner	3.15	3.15		1	1	1		
	Bavarian Helles	6		1		1	0.5	0.5	
	Oktoberfest	6		2	1	1			
	Bock	6	3.15		1	1	1		
	Maibock	6	3.15		1	2	1		
	Bavarian Dunkel	6	1		1	1	1		

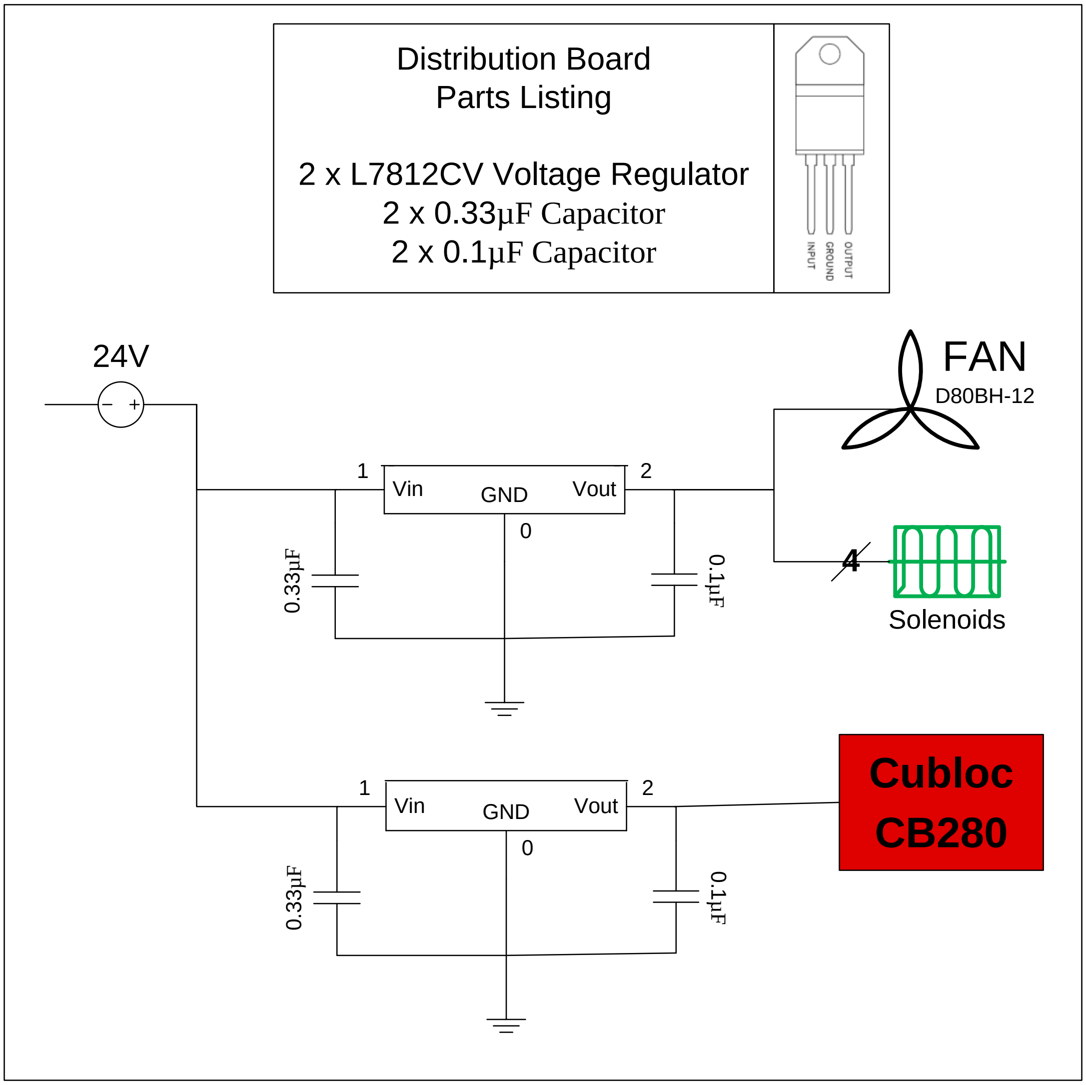
	Rauchbier	6		1	2	0.5	0.5	0.5	
	Schwarzbier	6		1	1	1	1		
Porters	Mild Brown Porter	6			2	1.5	1		
	Playa Porter	6			0.83	1.2	0.4		
	Holiday Porter			3	3	1	1	1	1

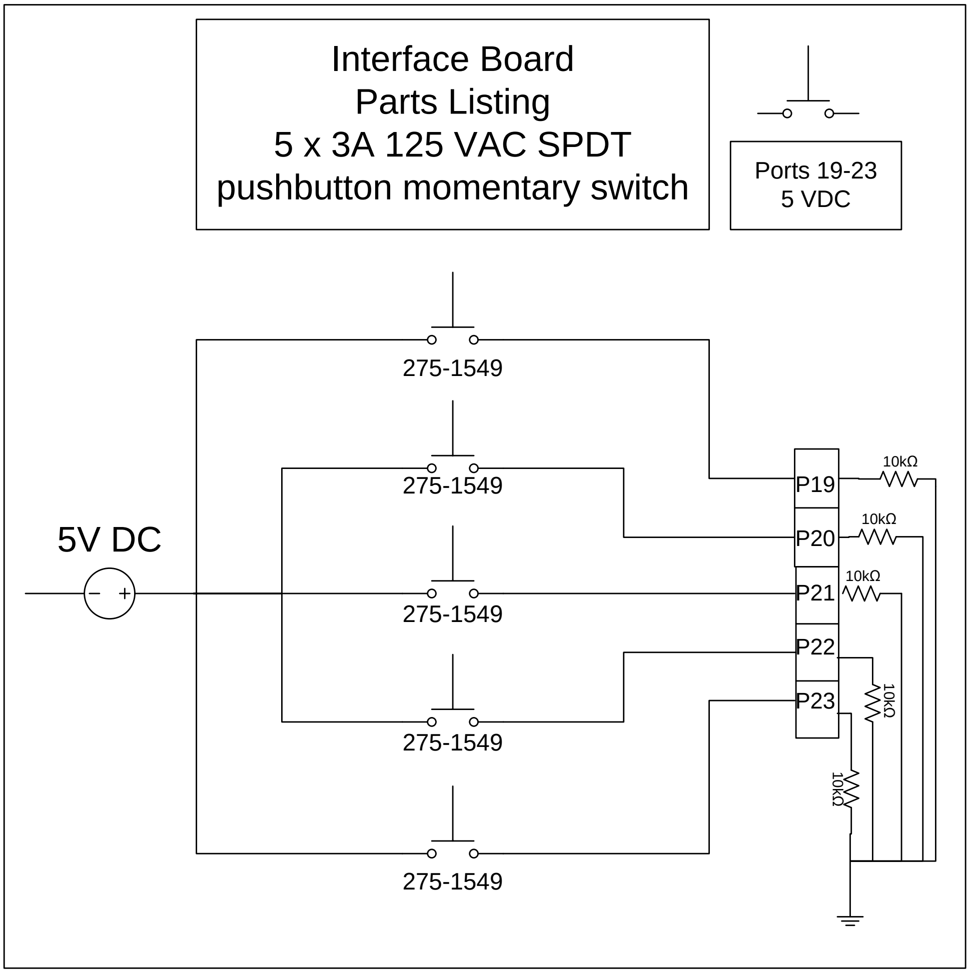
Total Recipes	78
Recipes Not Meeting Malt Addition Requirements	4
Recipes Not Meeting Steep Addition Requirements	0
Recipes Not Meeting Hops Addition Requirements	2
Total Recipes Not Meeting System Requirements	6
Percentage of Satisfactory Recipes	**92.31%**

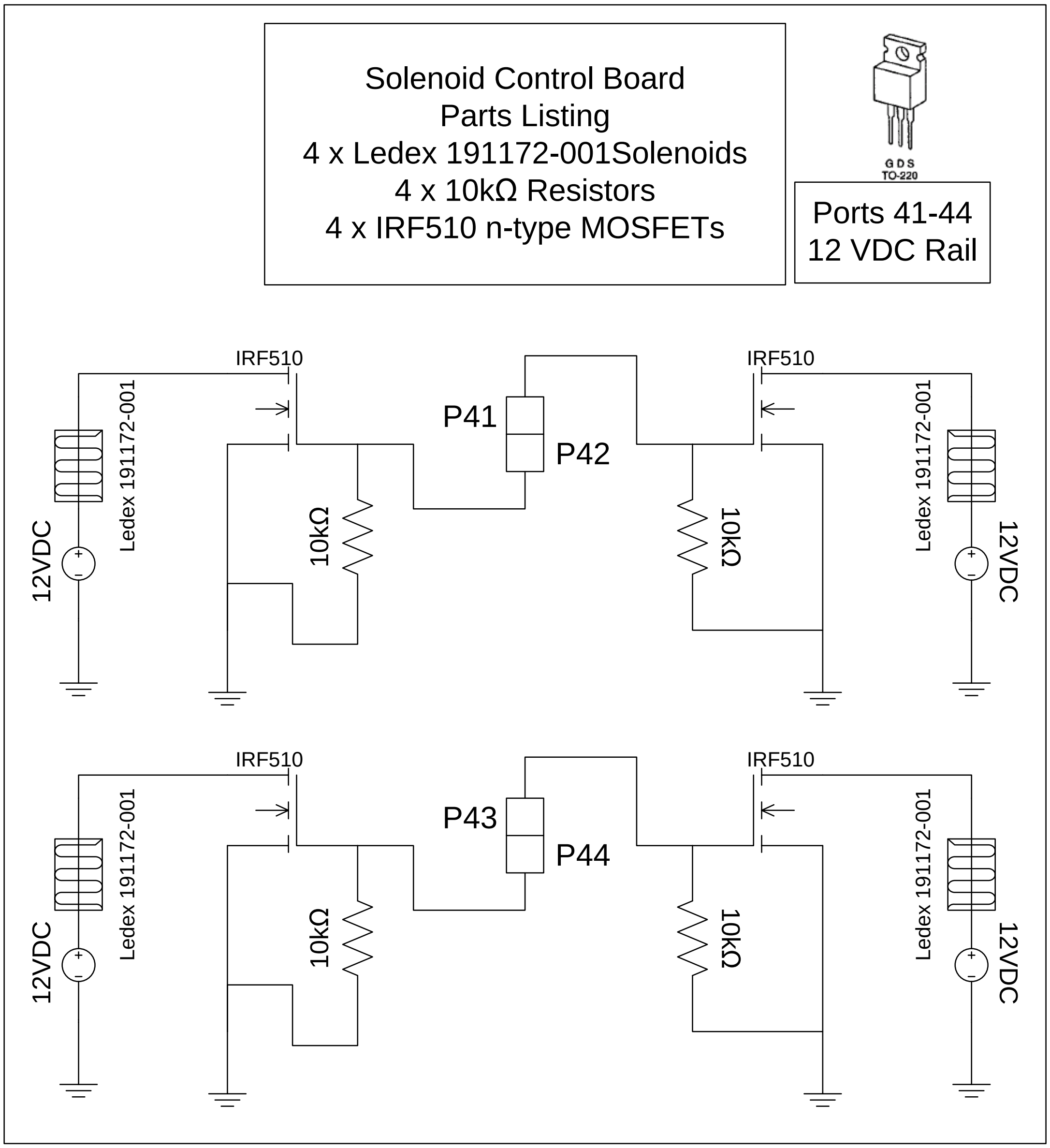
8.3 Appendix C – CuBloc Port Listing

Port Listings	
0	Mixer
1	Dishwasher Fill Valve (Coolant Valve)
2	Cycle start LED
5	Buzzer
18	Heater
19	“Start Cycle” Button
20	“Less” Button
21	“More” Button
22	“Prev” Button
23	“Next” Button
24	Thermistor
25-28	Stepper #4
29-32	Stepper #2
33-36	Stepper #3
37-40	Stepper #1
41	Solenoid #1
42	Solenoid #2
43	Solenoid #3
44	Solenoid #4
Unused	{3,4,6,7,8,9,10,11,12,13,14,15,16,17,45,46,47,48}

8.4 Appendix D – Schematic Diagrams

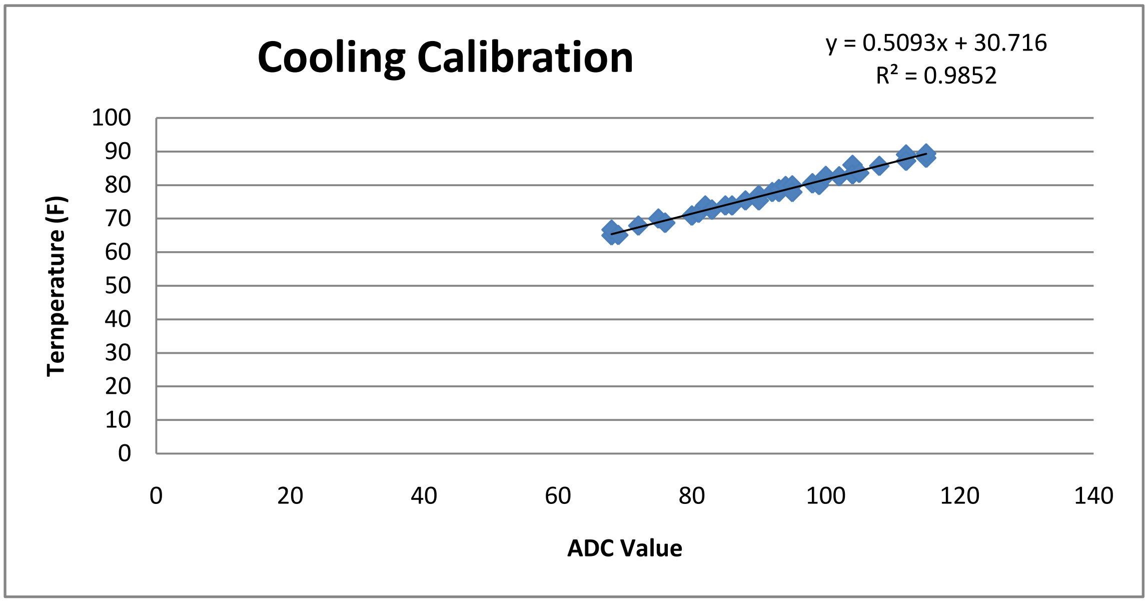


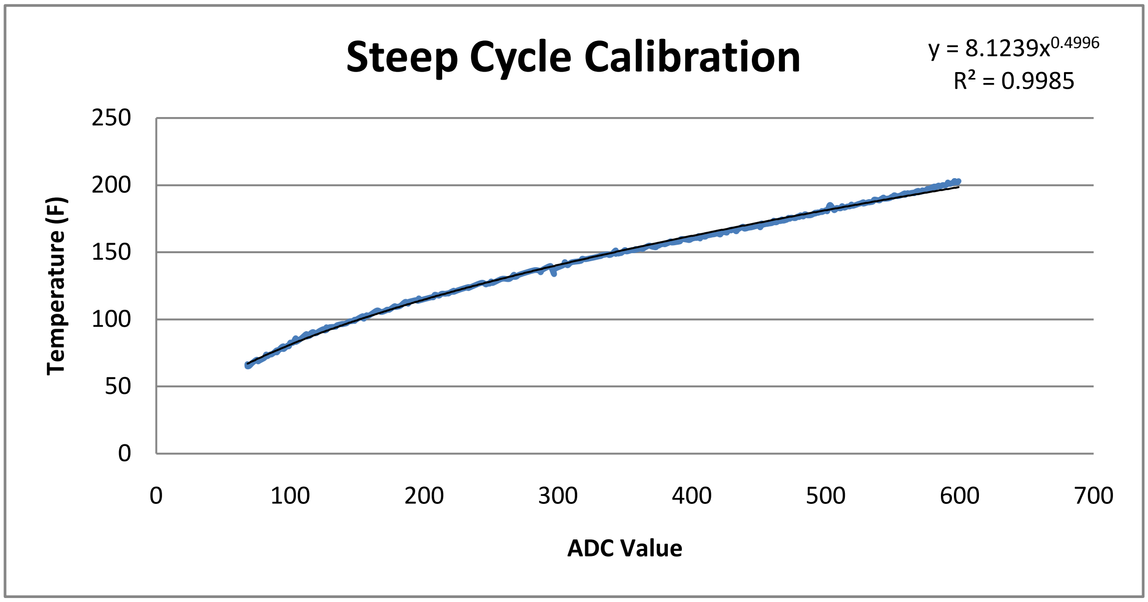

Interface Board
Parts Listing
5 x 3A 125 VAC SPDT
pushbutton momentary switch
Ports 19-23
5 VDC
5V DC
275-1549
275-1549
275-1549
275-1549
275-1549
P19
P20
P21
P22
P23
10kΩ
10kΩ
10kΩ
10kΩ
10kΩ

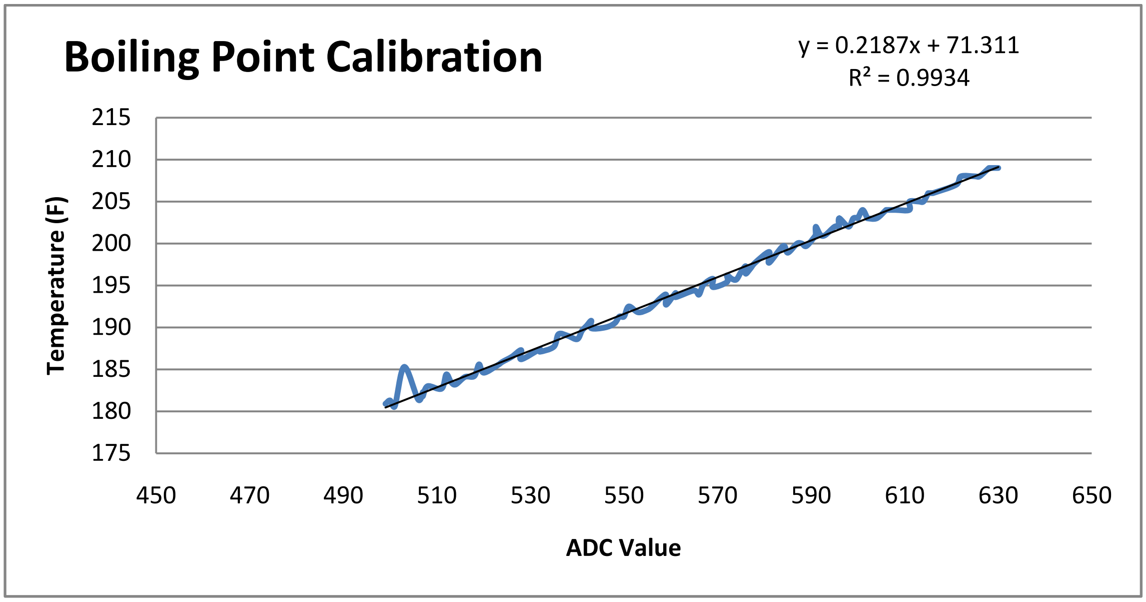


Solenoid Control Board
Parts Listing
4 x Ledex 191172-001Solenoids
4 x 10kΩ Resistors
4 x IRF510 n-type MOSFETs

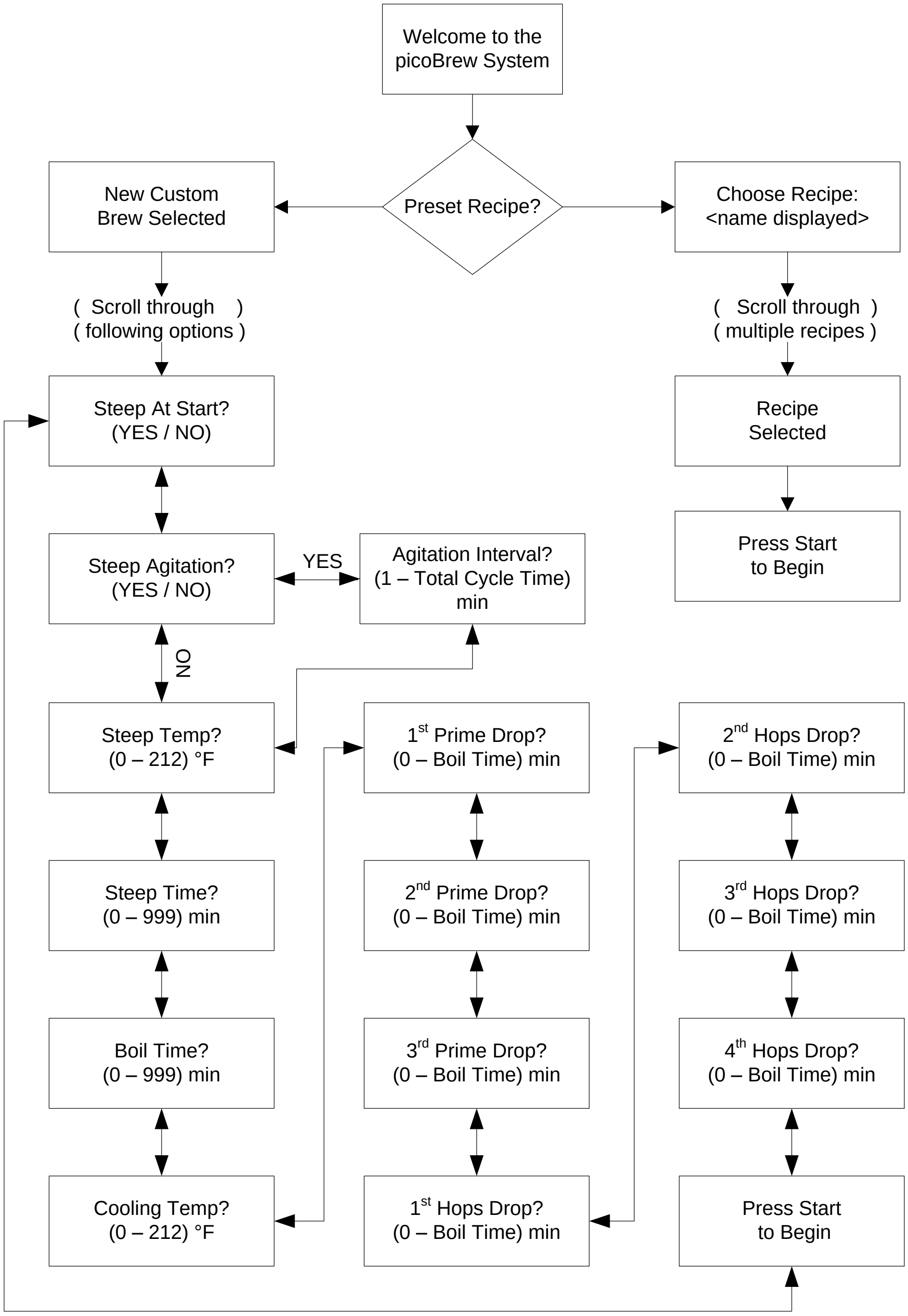
8.5 Appendix E – Calibration Data






Boiling Point Calibration
y = 0.2187x + 71.311
R² = 0.9934
Temperature (F)
215
210
205
200
195
190
185
180
175
450
470
490
510
530
550
570
590
610
630
650
ADC Value

8.6 Appendix F – Menu Flow Chart



Prompt	Description
“Steep At Start?”	Yes: Steeping bag will be lowered before heater is turned on.
	No: Steeping bag will only be lowered after steeping temperature reached.
“Steep Agitations?”	Yes: Steeping bag will be lifted and lowered slightly during steeping times
	No: Steeping bag will remain in the lowered position until steep removal time.
“Agitation Interval?”	**Only possible if Steep Agitation is set to Yes** This sets how often steep agitation will take place. Range can be from 1 minute to the addition of steep time and boil time if “Steep At Start” is set to Yes, or 1 minute to boil time if “Steep At Start” is set to No.
“Steep Temp?”	This sets what temperature the user would like steeping to occur at.
“Steep Time?”	This sets how long you would like steeping to occur for
“Boil Time?”	This sets how long the boiling cycle should last for. Note that time begins after the water has first achieved a boil.
“Cooling Temp?”	This sets what temperature the user would like to have the wort cooled to.
“1st Prime Drop?”	This sets what time the user would like each primary hopper to be dumped. Note that if the same time is selected for multiple primary hoppers, they will be only lowered sequentially.
"2nd Prime Drop?"	
"3rd Prime Drop?"	
“1st Hops Drop?”	This sets what time the user would like each hops addition to be fired at. Note that if the same time is selected for multiple hops firing, they will be only fired sequentially.
"2nd Hops Drop?"	
"3rd Hops Drop?"	
"4th Hops Drop?"	

8.7 Appendix G – Survey Information

1. Approximately how many gallons of beer do you brew annually?

	Answer	Result	Percent
A	0-10	1	5.88%
B	11-25	5	29.41%
C	26-50	5	29.41%
D	51-100	2	11.76%
E	100+	4	23.53%
	total	17	

2. What is the typical size of a batch of beer, in gallons, you brew?

	Answer	Result	Percent
A	0-4	1	6.25%
B	5-9	11	68.75%
C	10+	4	25.00%
	total	16	

3. On average, how many malt additions do you add to a typical batch?

	Answer	Result	Percent
A	0	1	7.69%
B	1	7	53.85%
C	2	0	0.00%
D	3	4	30.77%
E	4	1	7.69%
F	5+	0	0.00%
	total	13	

4. By weight (pounds) what is the average size of each malt addition used in a typical batch of beer.

	Answer	Result	Percent
A	0	1	6.67%
B	1	0	0.00%
C	2	1	6.67%
D	3	1	6.67%
E	4	1	6.67%
F	5+	11	73.33%
	total	15	

5. On average, how many hop additions do you add to a typical batch.

	Answer	Result	Percent
A	0	0	0.00%
B	1	0	0.00%
C	2	2	14.29%
D	3	6	42.86%
E	4	5	35.71%
F	5+	1	7.14%
	total	14	

6. by weight (ounces) what is the average size of each hop addition used in a typical batch of beer?

	Answer	Result	Percent
A	0	0	0.00%
B	1	7	50.00%
C	2	2	14.29%
D	3	3	21.43%
E	4	1	7.14%
F	5+	1	7.14%
	total	14	

7. What is the preferred time (in minutes) you would allow for the wort to cool from boiling temperature to approximately 75 degrees Fahrenheit?

	Answer	Result	Percent
A	0-14	7	53.85%
B	15-24	4	30.77%
C	25-34	1	7.69%
D	35+	1	7.69%
	Total	13	

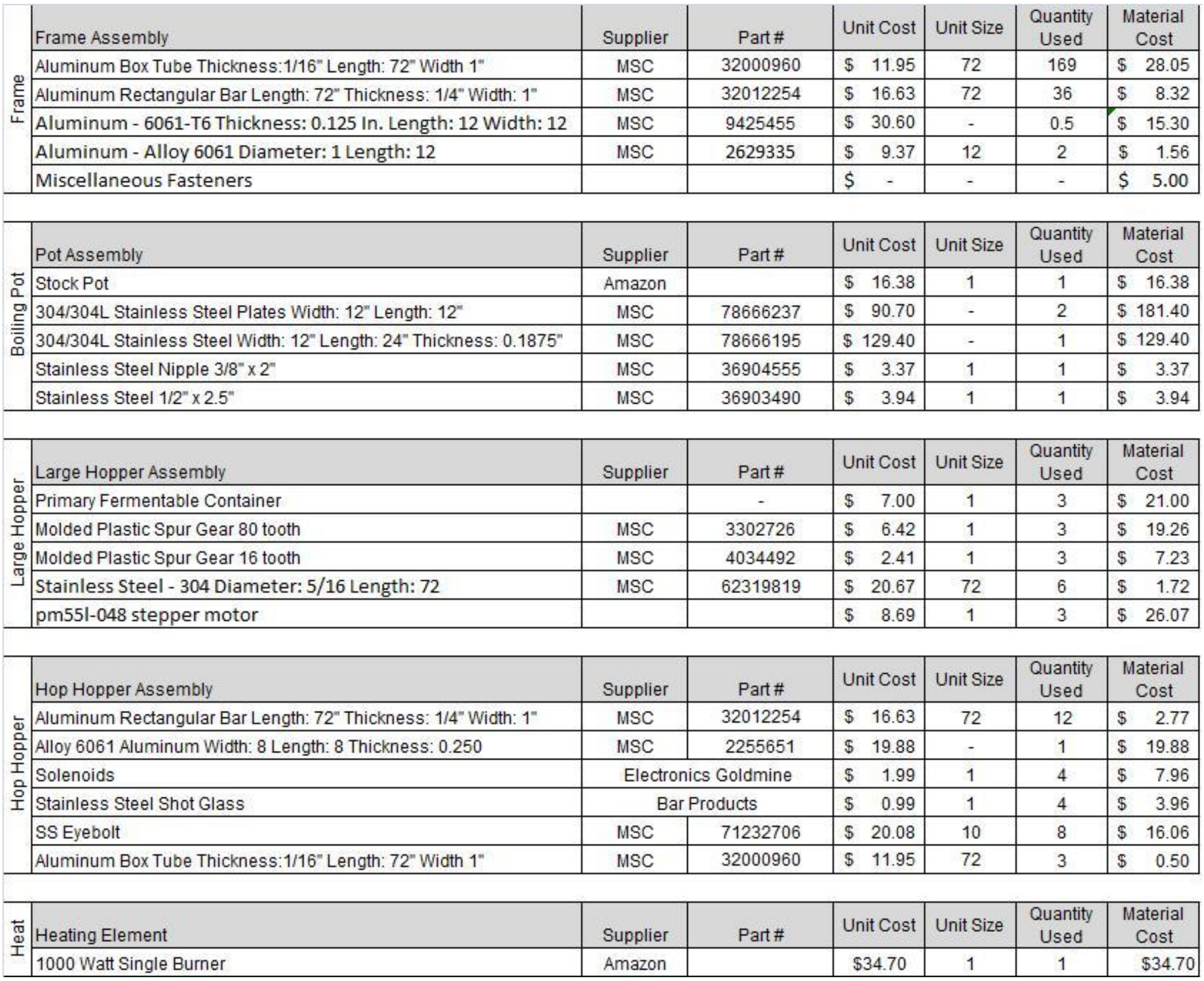
8. What is the preferred time range you use to boil your wort in minutes?

	Answer	Result	Percent
A	0-59	2	15.38%
B	60-119	10	76.92%
C	120+	1	7.69%
	Total	13	

9. Please indicate which three of the following features would add the most value to an automated home brewing system.

	Answer	Result	Percent
A	Temperature Regulation	11	26.19%
B	Automated Ingredient Addition	1	2.38%
C	Cooling System	10	23.81%
D	Customizable Cycle Times	4	9.52%
E	Number of Ingredient Additions	0	0.00%
F	Sanitation	9	21.43%
G	Ease of Use	7	16.67%
	Total	42	

8.9 Appendix H – Bill of Materials



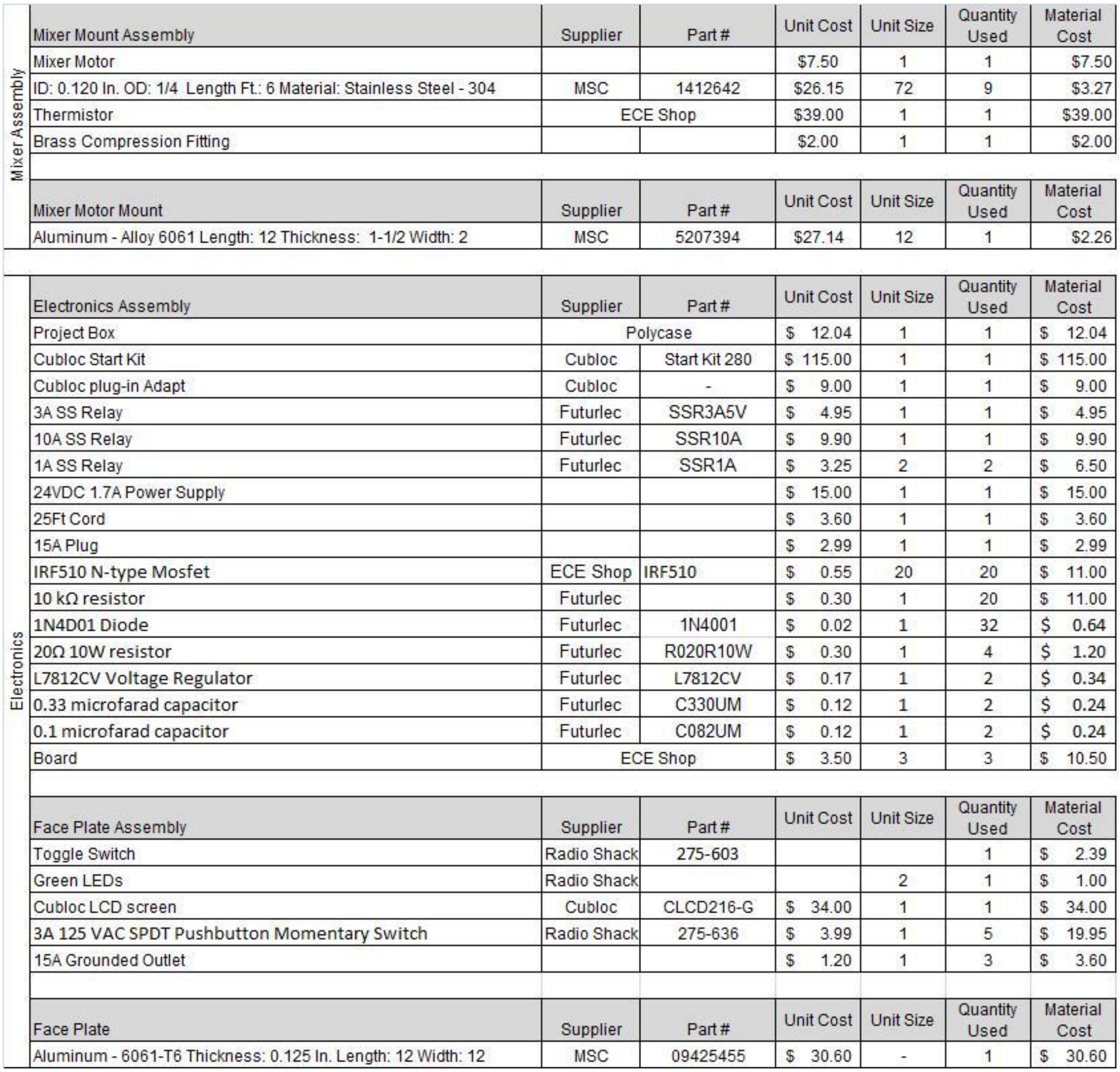
Frame	Frame Assembly	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
	Aluminum Box Tube Thickness:1/16" Length: 72" Width 1"	MSC	32000960	$ 11.95	72	169	$ 28.05
	Aluminum Rectangular Bar Length: 72" Thickness: 1/4" Width: 1"	MSC	32012254	$ 16.63	72	36	$ 8.32
	Aluminum - 6061-T6 Thickness: 0.125 In. Length: 12 Width: 12	MSC	9425455	$ 30.60	-	0.5	$ 15.30
	Aluminum - Alloy 6061 Diameter: 1 Length: 12	MSC	2629335	$ 9.37	12	2	$ 1.56
	Miscellaneous Fasteners			$ -	-	-	$ 5.00

Boiling Pot	Pot Assembly	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
	Stock Pot	Amazon		$ 16.38	1	1	$ 16.38
	304/304L Stainless Steel Plates Width: 12" Length: 12"	MSC	78666237	$ 90.70	-	2	$ 181.40
	304/304L Stainless Steel Width: 12" Length: 24" Thickness: 0.1875"	MSC	78666195	$ 129.40	-	1	$ 129.40
	Stainless Steel Nipple 3/8" x 2"	MSC	36904555	$ 3.37	1	1	$ 3.37
	Stainless Steel 1/2" x 2.5"	MSC	36903490	$ 3.94	1	1	$ 3.94

Large Hopper	Large Hopper Assembly	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
	Primary Fermentable Container		-	$ 7.00	1	3	$ 21.00
	Molded Plastic Spur Gear 80 tooth	MSC	3302726	$ 6.42	1	3	$ 19.26
	Molded Plastic Spur Gear 16 tooth	MSC	4034492	$ 2.41	1	3	$ 7.23
	Stainless Steel - 304 Diameter: 5/16 Length: 72	MSC	62319819	$ 20.67	72	6	$ 1.72
	pm55l-048 stepper motor			$ 8.69	1	3	$ 26.07

Hop Hopper	Hop Hopper Assembly	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
	Aluminum Rectangular Bar Length: 72" Thickness: 1/4" Width: 1"	MSC	32012254	$ 16.63	72	12	$ 2.77
	Alloy 6061 Aluminum Width: 8 Length: 8 Thickness: 0.250	MSC	2255651	$ 19.88	-	1	$ 19.88
	Solenoids	Electronics Goldmine		$ 1.99	1	4	$ 7.96
	Stainless Steel Shot Glass	Bar Products		$ 0.99	1	4	$ 3.96
	SS Eyebolt	MSC	71232706	$ 20.08	10	8	$ 16.06
	Aluminum Box Tube Thickness:1/16" Length: 72" Width 1"	MSC	32000960	$ 11.95	72	3	$ 0.50

Heat	Heating Element	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
	1000 Watt Single Burner	Amazon		$34.70	1	1	$34.70



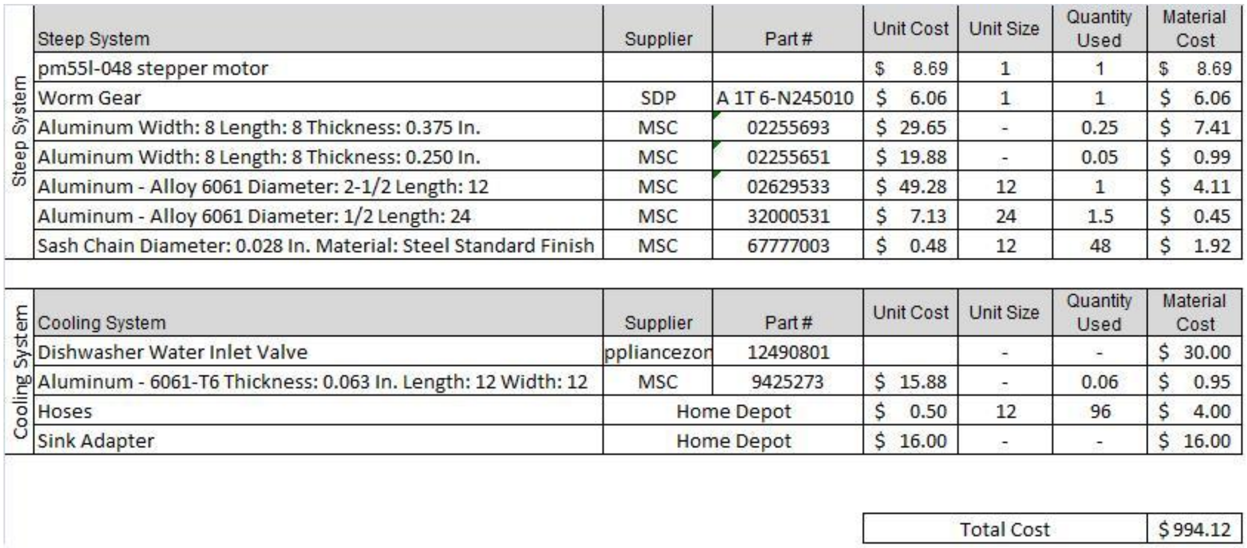
	Mixer Mount Assembly	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
Mixer Assembly	Mixer Motor			$7.50	1	1	$7.50
	ID: 0.120 In. OD: 1/4 Length Ft.: 6 Material: Stainless Steel - 304	MSC	1412642	$26.15	72	9	$3.27
	Thermistor	ECE Shop		$39.00	1	1	$39.00
	Brass Compression Fitting			$2.00	1	1	$2.00

	Mixer Motor Mount	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
Mixer Assembly	Aluminum - Alloy 6061 Length: 12 Thickness: 1-1/2 Width: 2	MSC	5207394	$27.14	12	1	$2.26

	Electronics Assembly	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
Electronics	Project Box	Polycase		$ 12.04	1	1	$ 12.04
	Cubloc Start Kit	Cubloc	Start Kit 280	$ 115.00	1	1	$ 115.00
	Cubloc plug-in Adapt	Cubloc	-	$ 9.00	1	1	$ 9.00
	3A SS Relay	Futurlec	SSR3A5V	$ 4.95	1	1	$ 4.95
	10A SS Relay	Futurlec	SSR10A	$ 9.90	1	1	$ 9.90
	1A SS Relay	Futurlec	SSR1A	$ 3.25	2	2	$ 6.50
	24VDC 1.7A Power Supply			$ 15.00	1	1	$ 15.00
	25Ft Cord			$ 3.60	1	1	$ 3.60
	15A Plug			$ 2.99	1	1	$ 2.99
	IRF510 N-type Mosfet	ECE Shop	IRF510	$ 0.55	20	20	$ 11.00
	10 kΩ resistor	Futurlec		$ 0.30	1	20	$ 11.00
	1N4D01 Diode	Futurlec	1N4001	$ 0.02	1	32	$ 0.64
	20Ω 10W resistor	Futurlec	R020R10W	$ 0.30	1	4	$ 1.20
	L7812CV Voltage Regulator	Futurlec	L7812CV	$ 0.17	1	2	$ 0.34
	0.33 microfarad capacitor	Futurlec	C330UM	$ 0.12	1	2	$ 0.24
	0.1 microfarad capacitor	Futurlec	C082UM	$ 0.12	1	2	$ 0.24
	Board	ECE Shop		$ 3.50	3	3	$ 10.50

	Face Plate Assembly	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
Electronics	Toggle Switch	Radio Shack	275-603			1	$ 2.39
	Green LEDs	Radio Shack			2	1	$ 1.00
	Cubloc LCD screen	Cubloc	CLCD216-G	$ 34.00	1	1	$ 34.00
	3A 125 VAC SPDT Pushbutton Momentary Switch	Radio Shack	275-636	$ 3.99	1	5	$ 19.95
	15A Grounded Outlet			$ 1.20	1	3	$ 3.60

	Face Plate	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
Electronics	Aluminum - 6061-T6 Thickness: 0.125 In. Length: 12 Width: 12	MSC	09425455	$ 30.60	-	1	$ 30.60

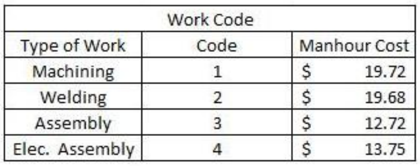


	Steep System	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
Steep System	pm55l-048 stepper motor			$ 8.69	1	1	$ 8.69
	Worm Gear	SDP	A 1T 6-N245010	$ 6.06	1	1	$ 6.06
	Aluminum Width: 8 Length: 8 Thickness: 0.375 In.	MSC	02255693	$ 29.65	-	0.25	$ 7.41
	Aluminum Width: 8 Length: 8 Thickness: 0.250 In.	MSC	02255651	$ 19.88	-	0.05	$ 0.99
	Aluminum - Alloy 6061 Diameter: 2-1/2 Length: 12	MSC	02629533	$ 49.28	12	1	$ 4.11
	Aluminum - Alloy 6061 Diameter: 1/2 Length: 24	MSC	32000531	$ 7.13	24	1.5	$ 0.45
	Sash Chain Diameter: 0.028 In. Material: Steel Standard Finish	MSC	67777003	$ 0.48	12	48	$ 1.92

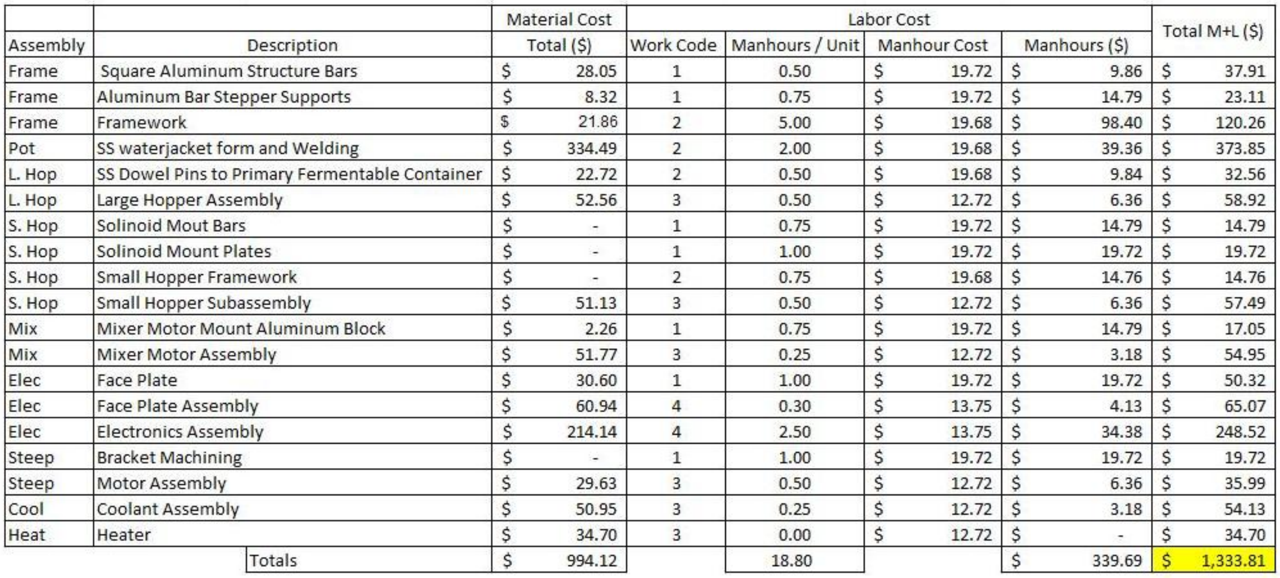
	Cooling System	Supplier	Part #	Unit Cost	Unit Size	Quantity Used	Material Cost
Cooling System	Dishwasher Water Inlet Valve	ppliancezon	12490801		-	-	$ 30.00
	Aluminum - 6061-T6 Thickness: 0.063 In. Length: 12 Width: 12	MSC	9425273	$ 15.88	-	0.06	$ 0.95
	Hoses	Home Depot		$ 0.50	12	96	$ 4.00
	Sink Adapter	Home Depot		$ 16.00	-	-	$ 16.00

Total Cost	$ 994.12

8.10 Appendix I – Labor Costs



Work Code		
Type of Work	Code	Manhour Cost
Machining	1	$ 19.72
Welding	2	$ 19.68
Assembly	3	$ 12.72
Elec. Assembly	4	$ 13.75



		Material Cost	Labor Cost				Total M+L ($)
Assembly	Description	Total ($)	Work Code	Manhours / Unit	Manhour Cost	Manhours ($)	
Frame	Square Aluminum Structure Bars	$ 28.05	1	0.50	$ 19.72	$ 9.86	$ 37.91
Frame	Aluminum Bar Stepper Supports	$ 8.32	1	0.75	$ 19.72	$ 14.79	$ 23.11
Frame	Framework	$ 21.86	2	5.00	$ 19.68	$ 98.40	$ 120.26
Pot	SS waterjacket form and Welding	$ 334.49	2	2.00	$ 19.68	$ 39.36	$ 373.85
L. Hop	SS Dowel Pins to Primary Fermentable Container	$ 22.72	2	0.50	$ 19.68	$ 9.84	$ 32.56
L. Hop	Large Hopper Assembly	$ 52.56	3	0.50	$ 12.72	$ 6.36	$ 58.92
S. Hop	Solinoid Mout Bars	$ -	1	0.75	$ 19.72	$ 14.79	$ 14.79
S. Hop	Solinoid Mount Plates	$ -	1	1.00	$ 19.72	$ 19.72	$ 19.72
S. Hop	Small Hopper Framework	$ -	2	0.75	$ 19.68	$ 14.76	$ 14.76
S. Hop	Small Hopper Subassembly	$ 51.13	3	0.50	$ 12.72	$ 6.36	$ 57.49
Mix	Mixer Motor Mount Aluminum Block	$ 2.26	1	0.75	$ 19.72	$ 14.79	$ 17.05
Mix	Mixer Motor Assembly	$ 51.77	3	0.25	$ 12.72	$ 3.18	$ 54.95
Elec	Face Plate	$ 30.60	1	1.00	$ 19.72	$ 19.72	$ 50.32
Elec	Face Plate Assembly	$ 60.94	4	0.30	$ 13.75	$ 4.13	$ 65.07
Elec	Electronics Assembly	$ 214.14	4	2.50	$ 13.75	$ 34.38	$ 248.52
Steep	Bracket Machining	$ -	1	1.00	$ 19.72	$ 19.72	$ 19.72
Steep	Motor Assembly	$ 29.63	3	0.50	$ 12.72	$ 6.36	$ 35.99
Cool	Coolant Assembly	$ 50.95	3	0.25	$ 12.72	$ 3.18	$ 54.13
Heat	Heater	$ 34.70	3	0.00	$ 12.72	$ -	$ 34.70
	Totals	$ 994.12		18.80		$ 339.69	$ 1,333.81

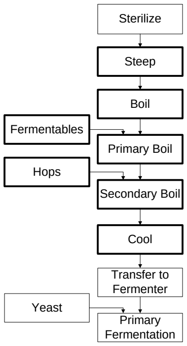
8.11 Appendix J – Poster

picoBrew: Automated Home Brew

Peter Bertoli (ME), Daniel Flavin (ME),
Christopher Moniz (ME), Sean Seymour (MFE)
Advisor: Professor Yiming(Kevin) Rong

Abstract

The picoBrew project determined the marketable requirements of a small-scale automated beer brewing system. Design techniques from industrial robotics were applied to the basic home brew cycle, resulting in a prototype design which could be easily controlled as well as manufactured. The prototype design focused on repeatability and ease of cleaning, two of the major requirements as determined from market studies. The prototype was capable of independently performing the heating, ingredient handling, and cooling cycles required to make wort, the unfermented precursor to beer.



Steps in Home Brewing

The picoBrew system controls the portion shown in bold.

Background

Due to the complexity of the brewing process, home brewers must address a number of challenges including:

- Ingredient quality
- Equipment sanitation
- Process temperature controls
- Precise recipe timing

Minor changes in any of these variables will result in changes of flavor in the final product.

Objectives

Primary:

- Automate the pre-fermentation stages of the brewing process.

Secondary:

- Simplify sanitation
- Design with commercialization considerations

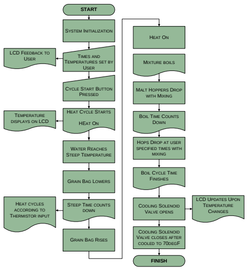
Process

The system was designed from the core outward. Once the correct size and material for the brew kettle had been determined, a thermodynamic analysis of cooling options was done. Requirements for material handling were determined, and various alternatives were considered for control of material flow. Three separate subsystems were designed for the main ingredient types: grains, malts, and hops. A mixer was also designed, to insure proper agitation of the ingredients during the boiling cycle. After the primary systems had been designed, a frame was laid out that would allow them all to interact.

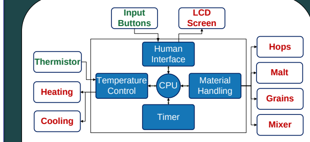
The control system was then designed to direct the automation cycle, using a temperature sensor and timer to trigger changes.

The system had to be:

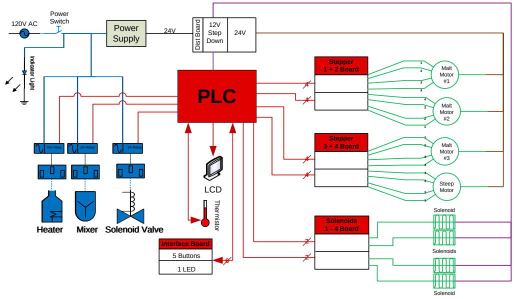
- Robust to power the subsystems
- Flexible to handle many recipes
- Simple to attract novice users.



Software Flow Diagram



Control System Block Diagram



Hardware Block Diagram

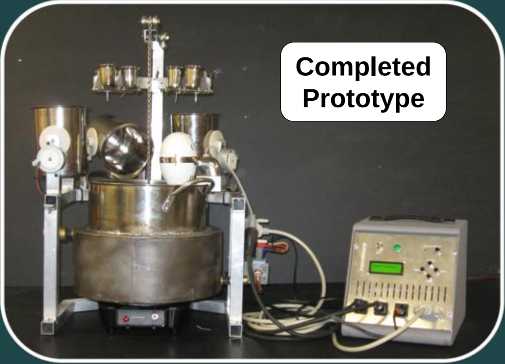
Outcome

The mechanical portion features:

- Hot plate for heating
- Wrap-around water jacket with solenoid valve for cooling
- Stepper controlled winching system for flavoring grains
- Stepper driven hoppers for adding fermentable malts
- Solenoid fired dump hoppers for adding hops
- Kettle-mounted mixer with temperature probe

The control box features:

- 24V, 1.7A DC power supply
- CuBlock 280 programmable logic controller
- LCD output
- MOSFET driven stepper and solenoid control boards
- Solid state relay control for line voltage systems



Completed Prototype

Conclusions and Recommendations

Despite a few setbacks, the system is a valid proof of concept. While the heating system is inadequate for the purpose, the remaining physical systems and all controls function properly. Potential future work would include a stronger heating system and a more efficient steep system. Expanding on this project, a similar system intended to control the fermentation cycle would likely be readily received by the craft brew community.