Arduino-Based Small Scale Electric Brewing System

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Abstract

The goal of this project is to create a small-scale, low cost, electric home brewing system that allows a user to more easily brew large (5 gallon) batches of beer in an enclosed space. This is accomplished by using an Arduino microcontroller in conjunction with a Yun WiFi shield to host a local website which allows a user to enter a temperature into the system via their phone, tablet, or computer. This data is then passed from a website running on the Yun shield to the Arduino sketch which runs a check against the current temperature reported by a thermometer installed in the brewing kettle and switches a heating element on or off depending on the goal temperature set by the user.

This process is meant to be a more precise method of temperature control that allows the user to brew higher ABV beer than other common homebrew setups and will require less of the user's time in terms of monitoring temperature.

Data taken from brewing several batches using the completed brew kettle does suggest that more precise control of temperature increases the efficiency of saccharification during a mash phase, and thus increases alcohol by volume in the final product.

Acknowledgements

I would like to first and foremost thank my mother and step father; Jim and Joanne Geneva. My path to this point in my life has been winding, and throughout every curve you have been there to love and guide me. Truly, I would not be where I am today without your support.

I would be remiss if I did not also thank my good friend Brian Aida, whom I have had the pleasure of knowing since we were assigned to be roommates in college. My love of the art of brewing can be attributed directly to you. Your instruction and advice have made me a better brewer, and have also made this project possible.

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The inspiration for this project came from a class I took at Harvard Extension School which I have described to friends and family as the most difficult, interesting, and exciting class I have ever taken. Thank you to my professors Bakhtiar Mikhak and Eric Blankinship for introducing me to microcontrollers and all the possibilities they offer.

Finally, to my beautiful and brilliant fiancée Dr. Pamela Gaddi; thank you for putting up with me, supporting me, and sharing my life with me. I love you.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

OG: Original Gravity is a measurement of the relative density of wort before it is fermented.

FG: Final Gravity is a measurement of the relative density of beer after it has been fermented.

ABV: Alcohol by Volume is a calculation of the amount of alcohol in a fermented solution.

SRM: Standard Reference Method is system used by brewers to define beer color.

BIAB: Abbreviation for Brew in a bag.

WiFi: Wireless fidelity, or wireless internet.

Introduction

This project seeks to bring some of the precise controls enjoyed by large-scale, industrial breweries into the reach of homebrewers by focusing on the automation of what is arguably the most important variable when brewing beer: temperature. Considering the equipment typically available to the homebrewer, temperature is one of the most difficult elements to control. While some options for precise temperature control do exist for this small but growing market, they are relatively expensive. By utilizing an open source microcontroller, specifically an Arduino, and components readily available in most hardware stores, this project aims to find a balance between precise temperature control, cost, and convenience.

History

Brewing beer is at the same time an ancient, simple, and incredibly complex process. At the most basic level, it can be described as making a tea from grains and herbs, and then allowing the solution to ferment either spontaneously or by adding yeast. At the most complex level, it is a precise biochemical process carried out on an industrial scale with no measurable variation between batches of the same recipe. In one form or another, humans have practiced beer brewing for millennia. In fact, during the middle ages in much of Europe beer was considered so important to daily life that if was an acceptable form of currency with which people could pay taxes, settle debts, and make donations to the church (Oliver, 2012).

Throughout history, beer has been brewed at what today would be considered very small scales; often in the home or in a common gathering place such as a tavern. By the time prohibition ended in the United States in 1933, beer brewing in the country had become almost exclusively the domain of large, national and multinational corporations. As such, the variety of beer once enjoyed by the public had dwindled to very few options that were cost effective to produce on a large scale. Consequently, many beers available post-prohibition until the 1960's in the U.S. shared similar flavor profiles. Today, there is a renaissance of beer taking place in the U.S. that can, in part, be attributed to a renewed interest in brewing beer in the home. While wine has often been the sophisticated choice for food pairings and classy socialite consumption, society has begun to acknowledge and accept beer as an equally refined option due to the higher quality of beer now available.

Brewing Process

The technical goal of brewing beer is to render soluble the insoluble components of grains so that it can ultimately be converted into alcohol through fermentation. This is done through a multi-step process beginning with the treatment of grains.

Grains

Any cereal grains used for their sugar content must first be crushed in order to expose the endosperm, which is the tissue inside a grain that acts as a food storage mechanism meant to provide the seed embryo with energy. Steps must be taken during this process to avoid damage to the grain husk as it contains components that can be detrimental to beer quality in certain quantities, such as excess tannins that can yield an astringent taste (Colby, Tannins in the Mash, 2014). Grain husks also act as a filter medium during the separation of wort. Crushed grain in this context is referred to as grist.

Mash

Once the grist is prepared, it is blended with water heated to a specific temperature that varies depending on the types of grains used and what flavors the recipe seeks to produce. This step is referred to as mashing and is responsible for extracting fermentable sugars from grains. The chemical process involved in sugar extraction is called saccharification. Sugar extraction is accomplished through a process wherein enzymes, either naturally occurring or artificially added, act upon substrates exposed by crushing grains, and produce maltose as the product of this reaction. It is the job of the brewer to optimize enzymatic activity in a way that produces desirable products. Optimization is accomplished by using an appropriate amount of grains relative to the volume of the brewing equipment and by maintaining precise temperature control to gelatinize starches to make them digestible. Once the starches are gelatinized, they can then be broken down into maltose by beta amylase and alpha amylase enzymes. This breakdown occurs when an enzyme-substrate complex forms by the binding of an enzyme to the substrate at an active site (Figure 1). The shape of the protein molecules, along with available amino acids in the enzyme, are what create an available active site for substrate binding (Colby, Enzymes for Brewers (II: Function), 2014).

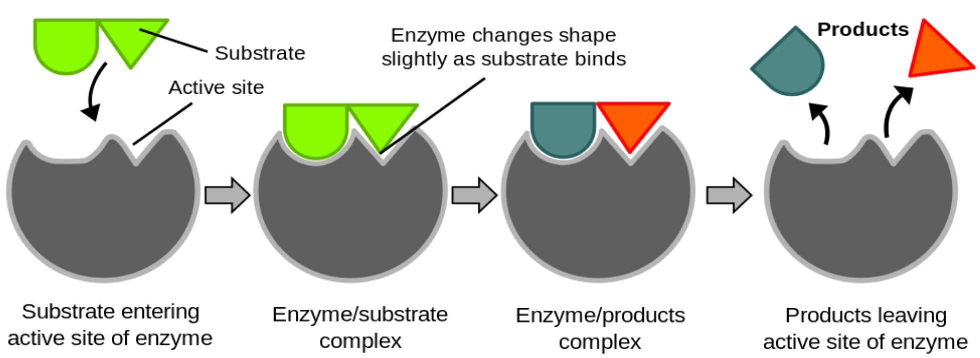

Figure 1 - Substrate entering an Active site.

Image from http://beerandwinejournal.com/enzymes-ii/, originally from Wikipedia

Heat disrupts the structure of proteins, and in so doing changes the shape of an active site. According to Arrhenius's Law (Levine, 2005), heat also directly affects the rate of chemical reactions. Furthermore, stresses caused by several factors, notably pH and temperature, affect the interactions in the enzymes and can also interfere with substrate binding, thus slowing or halting enzymatic activity. It is for these reasons that temperature control while mashing plays such a vital role in the production of beer. In fact, many modern, industrial brewhouses use a multi-step temperature mash program that can heat and hold the mash at several step temperatures in order to maximize the enzymatic activity at different stages of saccharification. Such temperature-controlled programs can not only boost the efficiency of saccharification, but also foster the development of additional compounds which yeast can later break down into desirable flavor components and aromatics. This type of complex step-heating process is generally only available to large-scale commercial breweries due to the difficulty in maintaining precise temperature points over a period of time.

Sparg

Sparging or lautering, is the process where extracted sugars are separated from grains and can be thought of as essentially washing sugars out of the grain bed. This is accomplished by adding water to the top of the grains and collecting the runoff after it filters through the grain bed. The sugary runoff, referred to as wort, is then transferred to a vessel where it will be boiled.

Boil

After sparging, wort is boiled for a set amount of time depending on several factors. During the boil, some of the remaining glucose that was not converted into maltose reacts with amino acids, forming color compounds that both darken beer and also impart flavor compounds that are often reminiscent of toffee and caramel. This process is known as a Maillard reaction and should be familiar to chefs as it is the same process by which food browns when it is cooked. Boiling in an open kettle also concentrates wort through evaporation and increases viscosity. Finally, it has the added benefit of sanitizing the kettle and all ingredients added up to this point in the process. As explained later on, sanitization in brewing is a vital process and is equally, if not more important than temperature control.

Cool

Once the wort has been boiled for the appropriate amount of time, it needs to be cooled. The primary reason for this is simply that the yeast, which will consume the sugars and produce alcohol, cannot survive at high temperatures and generally are most efficient between 68° and 72° Fahrenheit for ale yeast, and between 45° – 57° Fahrenheit for lager yeast. However, once the wort drops below 160° Fahrenheit, it becomes susceptible to infection from other undesirable organisms that can produce off-flavors and potentially render beer unfit for human consumption. For this reason, brewers take steps to make the temperature transition from boiling to yeast friendly as quickly and efficiently as possible.

Pitch

Once the wort has cooled to a suitable temperature for the strain of yeast being used, it can be moved to a fermentation chamber where yeast is added and the solution is sealed with an airlock.

As mentioned in the Boiling section, the danger of infection is ever-present once wort cools below 160° Fahrenheit. For this reason, absolutely everything that touches the wort after boiling must be sterilized. Ideally, everything that comes into contact with the wort even prior to boiling will be sterilized, but it is especially important if it will come into contact with wort after boiling. Poor sterilization techniques when brewing can result in anything from a few off-flavors including vinegar-like souring, to creating a toxic solution which, if consumed, could cause serious health problems.

Fermentation

The final step to beer brewing is fermentation. Much can be said on this topic and techniques and equipment vary wildly depending on a number of factors including, but not limited to, climate, cost, and volume. Essentially, fermentation is the process where sugars are converted into alcohol and carbon dioxide.

Homebrew Setups

Home brewing setups can be classified into two main families or styles: extract brewing, and all-grain brewing. Most homebrewers take their first steps into the hobby via extract brewing, then gradually build their skill and equipment to a point where they can try their hand at the more technical, expensive, and time-consuming all-grain.

Extract

Extract brewing follows all the same basic steps as all-grain brewing with one notable exception: there is no mashing step. In lieu of steeping crushed grains to extract sugar, a commercially available concentration of wort is used. This allows the brewer to focus their attention on the other steps in the process while ensuring their original gravity is consistent and predictable.

All-grain

All-grain brewing means sugar extraction is accomplished through mashing. Commercial breweries are generally large-scale all-grain operations. The most popular homebrew all-grain configuration is a three-step gravity fed setup (Figure 2).

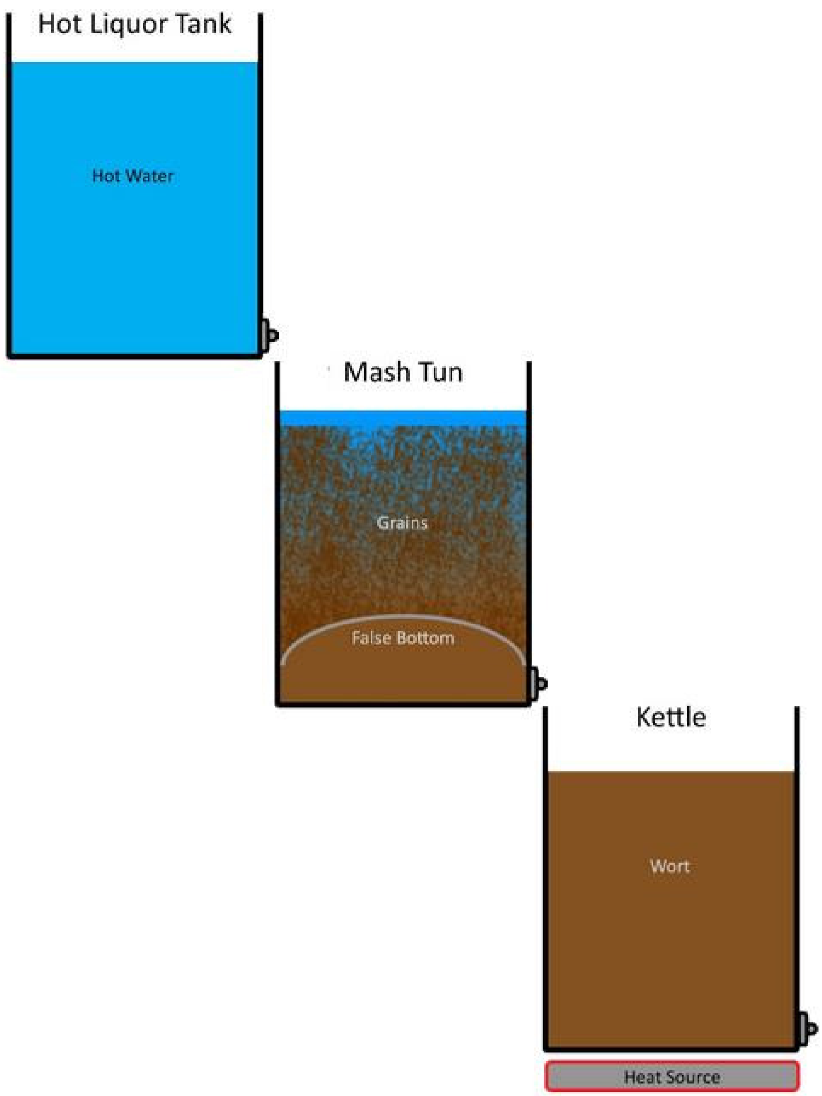

Figure 2 - Diagram of three-step gravity-fed all-grain brewing system

In this setup, the brewer uses two well-insulated holding vessels and one vessel reserved for boiling. Grist is held in the middle vessel and is mashed with hot water. During the sparging step, hot water from the top vessel is allowed to run into the middle vessel containing grains, which filters through the grain bed into the lower vessel to be boiled. The timing and temperature of each step vary depending on the recipe.

While this may be the most common setup for the all-grain homebrewer, it is somewhat labor intensive and requires a lot of space. Furthermore, since the heating element is most commonly propane it needs to be well ventilated, meaning it must be used either outside or in space with a good airflow such as a garage with an open door. For this reason, many apartment dwelling homebrewers have had few choices but to stay with extract as their sugar source.

Brew in a bag (BIAB)

A relatively new technique for all-grain brewers is "Brew in a bag", or BIAB. This method originated in Australia sometime around 2005 or 2006 by most accounts. When first introduced to the brewing world via the Aussie Homebrewer forum (Squire, 2006), there was a fair amount of controversy surrounding the process and many detractors claimed the setup would not work for one reason or another. A decade later, this technique has gained enough popularity to be more widely accepted as a viable middle ground between extract brewing and all-grain brewing. While technically it is a form of all-grain brewing, it is often categorized separately.

The primary innovation in a BIAB setup is the combination of the three vessels from the three-step method (Figure 2) into a single vessel.

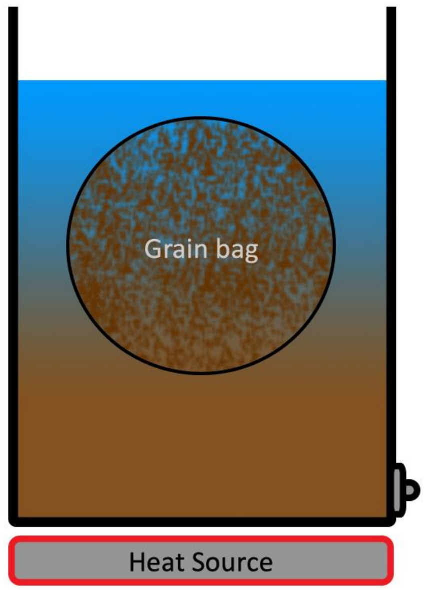

Figure 3 - Diagram of a Brew in a Bag (BIAB) system

There are some additional difficulties present in BIAB that are not issues in three-step all-grain brewing; most notably the fact that the brewer is limited in the amount of grain they can use by their method of extraction as bags containing grains must be manually removed prior to boiling. This is compounded by the fact that there is an expected loss in saccharification efficiency versus three-step all-grain brewing due to the fact that there generally is no sparging step in BIAB. For this reason, BIAB beers are often lower in alcohol than either three-step all-grain beers, or extract beers. If, however, the brewer is able to come up with a clever method of extracting grains that enables them to increase the amount of grain they use for a recipe, the expected loss in efficiency can be offset by simply increasing the volume of grain. Many BIAB brewers utilize some kind of pulley extraction system that allows them to lift very heavy bags of hot grain with little effort.

Project

For this project, the microcontroller-based system is built around the BIAB technique that is ideal for brewing in a smaller space and requires a smaller investment in equipment. It is a stated goal of this project to make the end result economical compared to other options on the market which offer similar automated temperature controls (see Prior Work section). The BIAB system offers many of the same benefits in terms of the control and variety of all-grain brewing, but in a smaller footprint. The single vessel also lends itself to easier electric heating integration as there needs only be one heat source compared to the multiple heat sources required in three-step all-grain setup.

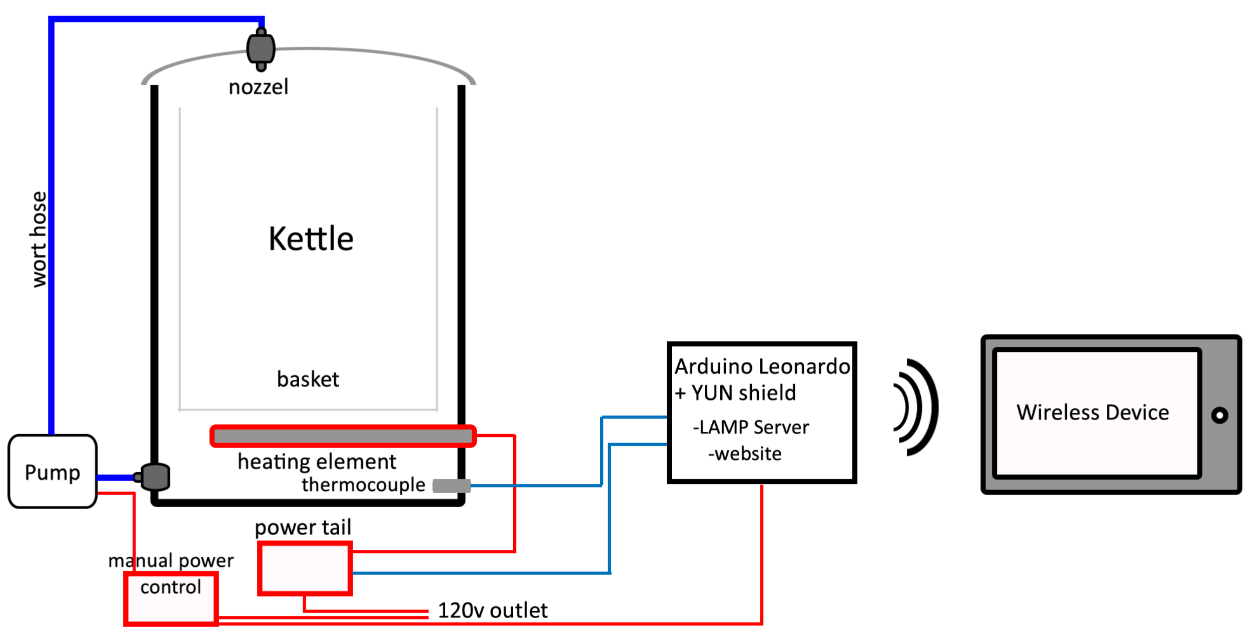

Figure 4 - Diagram of Arduino-Based Small-Scale Electric Brewing System

Figure 4 shows a cross-section diagram of the system designed for this project. Each component was selected from several options based on price, functionality, and compatibility with the other components of the project.

The goal of this project is to take advantage of the one-vessel convenience offered in BIAB systems, while also improving heat control. To achieve this, an electric submersible heating element is used to improve heat efficiency since all of the heat from the element is transferred directly to the wort, as opposed to an external heat source where some heat is reflected off the kettle. Using an electric heating element also makes integration with a microcontroller much simpler (and safer) than setting up a control valve for a gas-fed heat source.

Temperature control is achieved by integrating a thermometer into the kettle and feeding data directly into an Arduino microcontroller. The Arduino then runs a simple conditional loop to compare the temperature from the thermometer against a goal temperature set by the brewer. If the temperature reported by the thermometer is less than or equal to the goal temperature, then the heating element is turned on. See code section for greater detail.

During the mash, there is a need to ensure the grains are mixed well. When this project was designed several options, including a motorize auger, were investigated to achieve a complete mixing of grains. In the end, the most economical and consistent way to achieve a thorough mix during the mash was a combination of a high-heat pump which pulls wort from the bottom of the kettle and sprays it onto the top of the grains in a process similar to sparging, and to manually stir the grains with a large spoon. Pump control was left to a manual switch rather than automation due to the danger of accidental pump activation while the cover is off the kettle.

In that situation, the pump would spray ~155º wort at a high rate and in a wide dispersal, which would result in the scalding of anyone in the vicinity. An auger was also investigated for the purpose of grain mix automation, however the idea was deemed unacceptable due to the complexity of modifying the kettle cover to allow the auger to contact the grains and anchor the base of the auger motor in combination with the added cost to the project.

Equipment

Figure 5 - Bayou Classic 44-Quart All Purpose Stainless Steel Stockpot with Steam and Boil Basket. Image from Amazon.com

The kettle used is a Bayou Classic 44-Quart All Purpose Stainless Steel Stockpot with Steam and Boil Basket purchased from Amazon.com for around $100 (see Table 1 for complete parts list). This particular kettle is a favorite among homebrewers due to its size and optional basket, which allows for simple grain extraction. The stainless steel composition makes it resistant to scratching and allows the pot itself to have a thinner wall and still remain strong. In brewing, the major disadvantage of a stainless steel pot over an aluminum pot (a popular alternative) is that stainless steel is a less efficient conductor of heat. This is a disadvantage if the heat source is external to the pot, however this project makes use of an internal submersible electric heating element so the poor thermal conductivity is, in fact, an advantage.

Heating Element

The heat-source for this project is a 120 V 1650 watt heating element originally designed for use in hot water tanks. Since it is 120 V, it can run off a normal wall outlet and bring 6 gallons of liquid to a boil from a starting point of 150º in about 35 minutes.

Pump

In order to achieve a complete mix of grains, a high heat pump was used to pull wort through the grain-bed from the bottom of the kettle and spray it back on top. The pump itself is the single most expensive item in the entire project, however it is designed specifically for use in brewing and is one of the few pumps in its category (size and price) that can circulate liquids up to 250°F. Silicone tubes were used to connect the nozzle on the ball valve at the bottom of the kettle to the intake on the pump, and also the output of the pump to the nozzle installed in the kettle cover.

Thermometer

Precise temperature control relies on accurate readings, and for this reason a high temperature waterproof thermometer was used. Specifically, a modified DS18B20 was inserted into the kettle through a stainless steel weldless bulkhead and sealed into place with silicone.

Parts list

Component	Price	Item description and purchase location
Kettle	$96.69	Bayou Classic 1144 44-Quart All Purpose Stainless Steel Stockpot with Steam and Boil Basket https://www.amazon.com/gp/product/B000FTLY1K/ref=oh_aui_detailpage_o04_s00?ie=UTF8&psc=1
Step-bit	$13.08	Neiko 10194A Titanium Step Drill Bit 1/4' to 1-3/8' in 1/8' Increments, 10 Steps https://www.amazon.com/gp/product/B000FZ2UOY/ref=oh_aui_detailpage_o02_s00?ie=UTF8&psc=1
Ball-valve	$37.95	Weldless 316 Stainless Steel Ball Valve with Bulkhead and 1/2 Inch Nipple https://www.amazon.com/gp/product/B00JHMRH2Q/ref=oh_aui_detailpage_o01_s00?ie=UTF8&psc=1
Heating Element	$56.95	120v Electric Brew Pot / Still Pot Kit with 1650 Watt Element https://www.amazon.com/gp/product/B00K7V8SUQ/ref=oh_aui_detailpage_o00_s00?ie=UTF8&psc=1
Thermometer	$14.95	High Temp Waterproof DS18B20 Digital temperature sensor https://www.adafruit.com/products/642
Powerswitch tail	$25.95	Powerswitch tail 2 https://www.adafruit.com/products/268
Pump	$147.79	Chugger Stainless Steel Brewing Pump Center Inlet http://www.amazon.com/dp/B009Z17DJQ/ref=pe_385040_128020140_TE_3p_dp_i1
Wort Chiller	$53.47	Homebrew Immersion Wort Chiller - 25' Copper Tubing http://www.amazon.com/dp/B003UCCLG6/ref=pe_385040_128020140_TE_3p_dp_i1
Tubing	$15.85	White SiliconeTubing, 3/8"ID, 1/2"OD, 1/16" Wall, 10' Length http://www.amazon.com/gp/product/B000FOWGGW/ref=od_aui_detailpages00?ie=UTF8&psc=1
Connectors	$19.84	Home Depot - purchased in store
Power center	$16.47	ADJ Products PC-4 4-Channel A/C Power Center http://www.amazon.com/gp/product/B007EYG04A/ref=od_aui_detailpages00?ie=UTF8&psc=1
Arduino Yun shield	$33.95	Dragino Linux, Wifi, Ethernet, USB, All-in-one Yun Shield for Arduino Leonardo http://www.amazon.com/gp/product/B00PHCWACW/ref=od_aui_detailpages00?ie=UTF8&psc=1
Total	**$532.94**	

Table 1 - Parts list for Arduino-Based Small-Scale Electric Brewing System

Assembly

Mounting the thermometer, heating element, and ball valve into the kettle required that holes be drilled using a standard electric drill with a step-bit and mineral oil at several mounting points.

Figure 6 - Kettle during the drilling process

Figure 7 - Kettle with thermometer, ball valve, and heating element installed alongside cover with pump connector installed

The cover of the kettle was also drilled to install a connector that allows integration with the pump.

Microcontroller

Several different microcontrollers were evaluated for this project:

The Raspberri Pi line of microcontrollers was an attractive option initially due to their low cost, integrated WiFi antenna, and easy setup of Linux that would allow for simple installation of a webserver without the need for any additional equipment. After trials using both the Raspberri Pi B+ as well as the Raspberry Pi 2, it was determined that while there were attractive elements to this microcontroller, it was overly complex for the scope of this project and more vulnerable to crashing than simpler microcontrollers.

An older model Arduino Uno was also evaluated and passed several viability tests including theoretically having the option to integrate with an Arduino YUN shield to provide web server and WiFi functionality. However in practice, it was discovered that older Arduino Unos have fewer pins than the newer ones which makes them incompatible with YUN shields.

In the end, an Arduino Leonardo was used in conjunction with an Arduino YUN shield. This combination of simple microcontroller and shield provides easy integration with hardware components as well as a Linux build (Linino) along with a WiFi antenna for inexpensive wireless control of hardware components.

Figure 8 - Arduino Leonardo with YUN shield and USB drive installed

The YUN shield also adds a USB port to the Arduino to optionally expand the storage capacity. In this case, the USB drive is used to host the HTML, Javascript, CSS, and image files used on the local website.

Circuit

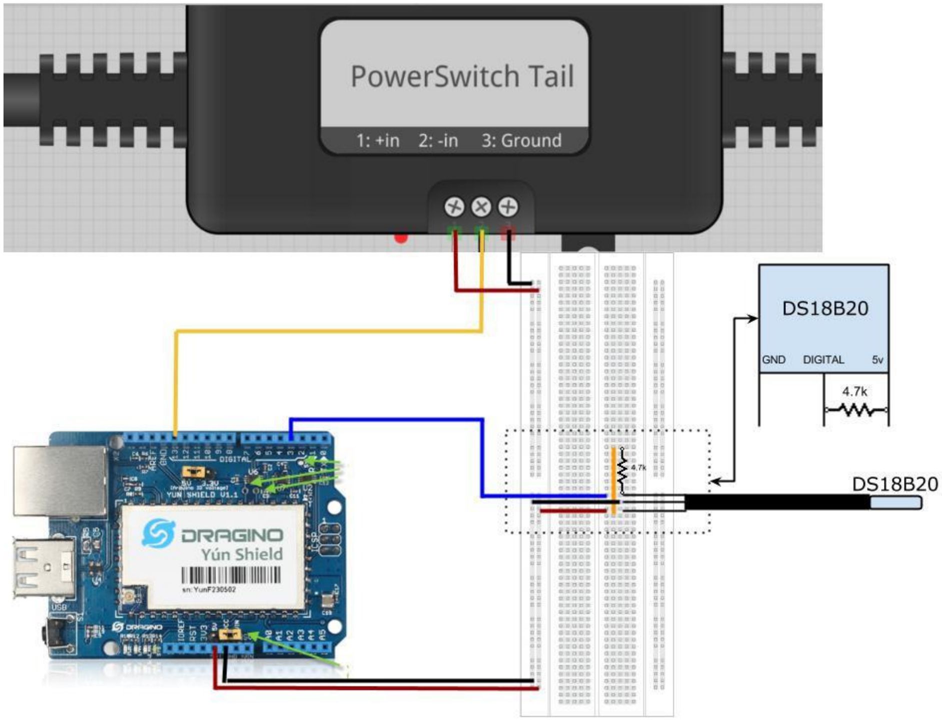

Figure 9 - Wiring schematic.

Images from: http://wiki.dragino.com/ and https://learn.adafruit.com

Figure 9 illustrates the circuit used for this project. In this circuit, a DS18B20 temperature sensor reads and reports voltage to the Arduino, which references the Dallas one-wire temperature control library to convert this reading into a human-readable temperature. The Arduino takes the reported temperature and compares it to a goal temperature that has been set by the brewer via a simple conditional statement (Figure 10).

```
if (dac <= correctedTemp)
{
  digitalWrite(13, HIGH);
}
else
{
  digitalWrite(13, LOW);
}
```

Figure 10 - control loop

If the reported temperature from the DS18B20, stored in the variable `dac` (Figure 10), is less than or equal to the goal temperature, stored in `correctedTemp`, then pin 13 is set to *`HIGH`*. Pin 13 is connected directly to the PowerSwitch Tail which, itself, is directly connected to the heating element. When pin 13 is set to *`HIGH`*, the PowerSwitch Tail allows a connection between the wall outlet and the heating element. When pin 13 is set to *`LOW`*, the PowerSwitch Tail blocks the flow of electricity to the heating element, effectively switching it off. In this way, the temperature in the kettle is regulated by the brewer through the web interface which allows him or her to set a goal temperature by using the range bar and dragging it to the left or right or by using the arrow keys on a keyboard. This web interface also prominently displays the current temperature of the liquid in the kettle (Figure 11).

Figure 11 - local webpage for kettle

Figure 11 is a picture of the local responsive website running on a laptop, but it can also be loaded from a phone or tablet as long as the device is on the same WiFi network. The current temperature of the liquid in the kettle is displayed prominently in red and the goal temperature is displayed in green. To adjust the goal temperature, they brewer can use the mouse (or finger if on a touchscreen) to drag the slider left or right. If the brewer is using a laptop, they are also able to use the arrow keys on a keyboard to make finer adjustments.

This setup leverages open source software as well as pre-existing libraries to bootstrap the overall project, as enumerated below.

Libraries and other Software

- Dallas Temperature Control
  https://milesburton.com/Dallas_Temperature_Control_Library
- One-wire
  http://www.pjrc.com/teensy/td_libs_OneWire.HTML
- Yun Server
- Yun Client
- Bridge
  The bridge library allows communication between the Arduino Leonardo and the Yun shield. Essentially, it provides a shared storage space for sensor data and allows the Leonardo to execute commands and run programs on Linux.

Figure 12 - Completed brewing system

Prior Work

1 - Brew Bot

http://www.brewbot.io/

Brew Bot is a self-contained, semi-autonomous brewing system of a slightly larger scale than the Pico Brew. The Brew Bot currently retails for $2800.

2 - Control Input and Output or Arduino YUN with Ajax

The tutorials and examples provided by Samir Sogay of http://babaawesam.com (Sogay, 2014) as well as Boris Landoni of http://open-electronics.org (Landoni, 2014) were instrumental in helping me understand the interaction of the Arduino with the local website.

3 - Pico Brew

http://www.picobrew.com/

Pico Brew is a self-contained, automated desktop brewing appliance that retails for $1699 for the base model.

4 - RasPiBrew

http://raspibrew.com/

The RasPiBrew is a microcontroller based temperature control unit with a very refined set of hardware and software. The Arduino based project outlined in this paper certainly has similarities when compared against the RasPiBrew, however it is much simpler in terms of code and equipment and also cheaper in terms of total cost. It is worth noting that the RasPiBrew also cites The Electric Brewery as a source of inspiration and information on electric brewing setup and techniques.

5 - The Electric Brewery©

theelectricbrewery.com

All electric do-it-yourself brewery. The Electric Brewery (Figure 13) costs around $4,500 and involves quite a lot more components than the project outlined in this paper aims to utilize. The Electric Brewery also does not allow control via wireless device and is based on the more common three vessel brewing setup (Figure 2).

Figure 13 - Photo of The Electric Brewery (assembled)

Image from theelectricbrewery.com

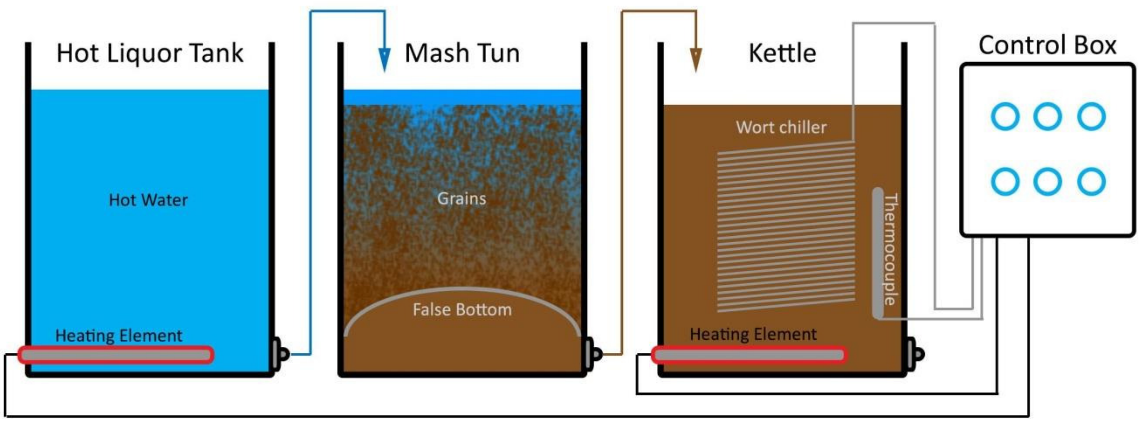

Figure 14 - Simplified diagram of The Electric Brewery

Data & Analysis

In order to measure the effect of more precise temperature control, the same recipe was used to brew four batches of beer. Original gravity (OG), final gravity (FG), alcohol by volume (ABV), and the standard reference method (SRM) were all calculated for each batch and compared to the goal numbers for the recipe which were calculated by the professional brewer who created the recipe.

Brewing Data

Batch	OG	FG	ABV	SRM	Notes
Goal Numbers	1.062	1.01	6.70%	11	
1 (control)	1.052	1.01	5.51%	7	medium mixing
2	1.040	1.01	3.94%	5	no mixing
3	1.056	1.01	6.04%	7	medium mixing
4	1.065	1.01	7.22%	10	frequent mixing

Table 2 - Brewing data

The first batch was done using manual temperature control. This was accomplished by using an analog thermometer, similar to a meat thermometer used for grilling, and manually connecting and disconnecting the heating element from the electrical outlet. This technique was used so that the only change in subsequent batches would be the automation of temperature while all other equipment remained the same. One additional element that changed throughout the process, though somewhat unintentionally, was the frequency of turning the grains over during the mash. This had a greater than expected effect on the original gravity. The intent was to replace the need to turn grains over with a high volume pump which would recirculate wort throughout the mash, however the results from batch number 2 where all mixing was completely replaced by recirculating indicate the turning over of grains during the mash is vital to efficient saccharification.

Batch 3 is comparable to the control batch and in terms of mixing frequency. This batch also came much closer to the goal OG and thus had a much higher efficiency. Since all other elements were the same in batch 3, the higher efficiency can be attributed to more precise temperature control. In fact during the brewing process, once the temperature came up to the goal temperature, the variance was only a maximum of 2 degrees Fahrenheit on either end of the goal temperature. Conversely, manual temperature control often varied by 10 or more degrees Fahrenheit on either side of the goal temperature. Considering the fact that the mash temperature for this recipe was 152º Fahrenheit which needed to be held as precisely as possible for 45 minutes, it is easy to see how a more precise temperature control could affect the batch.

Batch number 4 used all the same techniques as batch 3 with the exception of slightly more frequent stirring (once every 6 minutes for batch 4 versus once every 10 minutes for batch 3). This change in stirring frequency was able to raise the OG above the goal OG. This essentially means that the efficiency of this setup with more frequent stirring is higher than the efficiency of the setup used to calculate the goals.

Tools & Methods

Calculate ABV

To calculate ABV, an online calculator was used which was hosted on the Brewer's Friend website:

http://www.brewersfriend.com/abv-calculator/

Convert BRIX to Gravity

Refractometers measure in brix, however hydrometers measure in gravity. To convert brix to gravity, an online calculator was used which was hosted on the Brewer's Friend website:

http://www.brewersfriend.com/brix-converter/

Final Gravity (FG) measurement

FG was measured using a hydrometer as refractometers are often not accurate after fermentation has occurred. This measurement was taken after fermentation had completed and just prior to transferring the beer from a carboy (fermentation chamber) into a keg.

Original Gravity (OG) measurement

OG was measured using a refractometer once the wort was cooled to room temperature, just prior to pitching yeast.

Standard Reference Method (SRM) measurement

SRM was measured at the same time FG was measured; just prior to kegging the beer. Beer was decanted into a cylinder (the same cylinder used for the hydrometer) and it was positioned in front of a white sheet of paper with different SRM values printed on it, as shown in Figure 15 below.

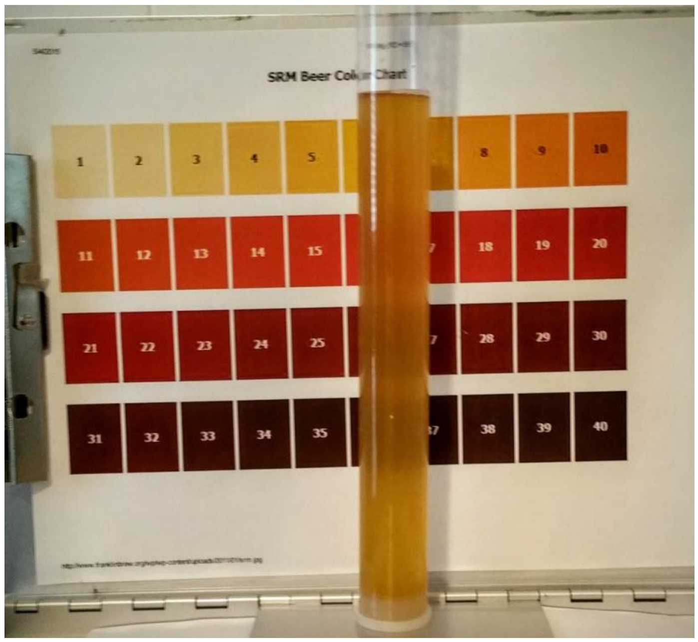

Figure 15 - Measuring SRM

Recipe

INDIA PALE ALE – 2.5 GALLON BREW IN A BAG

5/3/15 - RIMS Test

OG 1.062 FG 1.011 6.7% ABV
72BU 11°SRM
Ready in 4-5 weeks

KIT INVENTORY:

GRAIN
- 8.25 lbs. 2 Row 16.5
- 0.5 lbs. Crystal 30 1

HOPS
- 1.5 oz. Citra 3
- 1.75 oz. Simcoe 3.5

YEAST
- Safale US-05 GY054 Vermont IPA

PROCEDURE:

BREW DAY

1. Collect 6 gallons of cold water in a 14 gallon kettle and heat to 158°.
2. Turn off heat, put nylon bag into the kettle, wrap the extra top part of the bag over the side of the kettle and tie up the bag.
3. Pour crushed grain into the water inside of the bag, mix the grain and water slowly and thoroughly. This is your mash.
4. Check the temperature of the mash in several places. You want it to be 152°. If the temperature is high, add an ice cube or two and stir slowly. If the temperature is too low, turn on the burner and stir so that it doesn't burn. Once you get the temperature to 152°, put the lid on the kettle and leave the burner off.
5. Maintain the mash temperature of 152° for 45 minutes. Check the temperature every 15 minutes or so. It usually needs to be raised a little so if you need to bring the temperature up then turn on the burner and stir. Once you get back to 152°, turn off the heat and put the lid back on.
6. After the 45 minutes is up, pull the bag out and let the wort drip out of the bottom of the bag into the kettle. When it stops dripping or your arm gets tired put the bag in another pot or bucket to let it continue to drip. You can add the wort that collects in your other pot or bucket to the kettle in a few minutes. Discard the spent grain.
7. You probably have around 0.75-1 gallon less in your kettle than what you started with. This water got absorbed by the grain. 1 – Add 1.5-2 gallon of water to the kettle. The more water the better but it will make it harder to chill down after the boil.
8. Bring the liquid to a boil, watch for the kettle to boil over. If it wants to boil over just turn down the heat and stir.
9. Boil for 60 minutes and add hops for the specified times:

.5 - 0.25 oz. Simcoe (13.2%) 60 min
.5 - 0.25 oz. Simcoe (13.2%) 15 min
.5 - 0.25 oz. Citra (14.1%) 15 min
.5 - 0.25 oz. Simcoe (13.2%) 5 min
.5 - 0.25 oz. Citra (14.1%) 5 min
1.5 - 0.5 oz. Simcoe (13.2%) 0 min
1 - 0.5 oz. Citra (14.1%) 0 min

Time shown is how long the hops are boiled for.
60 min = add at the beginning of boil
0 min = turn off heat at end of boil and add

10. Turn off heat, add last hops, cover pot and let stand for 10 minutes. Then cool the wort as quickly as you can. Use a wort chiller or place the kettle in an ice bath in your sink.
11. Mix up your sanitizing solution (1 oz. Star San in 5 gallons of water). Sanitize your fermenter, lid or stopper, airlock, pair of scissors and anything else that will touch the wort.
12. Once the wort cools to around 65°, pour the cooled wort into the fermenter. Leave any sludge in the bottom of the kettle.
13. Add more cold water as needed to bring the volume to 2.5 gallons. The 2.5 gallons of wort should ideally be between 60° and 70°.
14. Aerate the wort. Seal the fermenter and rock back and forth to splash for a few minutes, or use an aeration system with an oxygen stone.
15. Use your sanitized scissors to open the package. Carefully pour the yeast into the fermenter.
16. Seal the fermenter and put sanitized airlock in place. Fill the airlock half way with sanitizing solution.
17. Move fermenter to a cool, dark and quiet spot.

AFTER BREW DAY

18. Active fermentation should begin within 48 hours. There will be foam (known as the "Kreusen") on the surface and bubbles will be coming through the airlock.
19. Active fermentation ends after 1-2 weeks. Add the dry hops (0.5 oz. Citra and 0.5 oz. Simcoe) to the beer 10-14 days after brewing. Leave the beer to condition for another 1-2 weeks (2-3 weeks total after brew day).

BOTTLING DAY

20. 2-3 weeks after brew day, your beer is ready to be bottled.
21. Make priming solution. Boil 1 cups (8 oz.) of water with 2.5 oz. of priming sugar in a small pot for 5 minutes. This will sanitize and mix the solution. Let this mixture cool.
22. Sanitize bottling equipment, siphon, bottles and caps.
23. Pour the priming solution into the sanitized bottling bucket. Siphon the beer into the bottling bucket. Be careful to not splash the beer while siphoning and leave the sludge behind in the fermenter. Gently mix the beer and priming solution with a sanitized spoon, do not splash the beer.
24. Fill and cap bottles. You should get around 25 bottles. Leave ¾" to 1" of headspace (about halfway up the neck of the bottle) in the bottles.
25. Store the bottles upright at room temperature for 2 weeks to carbonate and condition.

DRINK YOUR HOMEBREW

26. After 2 weeks of bottle conditioning, your homebrew is ready to drink. Store the bottles upright in a fridge or a cool dark place.
27. Slowly pour the beer into a clean glass, being careful to leave the layer of sediment at the bottle of the bottle.
28. Enjoy your delicious homebrew!
29. Buy another kit from Boston Homebrew Supply.

Figure 16 - Recipe - originally from Boston Homebrew Supply, modified for this project

Note the recipe was scaled up from 2.5 gallons to 5.

The handwritten notes are the changes followed for this project.

Lessons Learned

Throughout the course of this project there were several situations encountered that, given more experience, could have been avoided.

The first such situation came about when drilling into the kettle. Some articles and homebrewing forums cautioned against using a high speed when drilling through stainless steel as this, so they claimed, could heat the metal and harden it making it nearly impossible to pierce. As a result of this advice, the first two holes were drilled very slowly and took approximately 45 minutes each. The last hole, however, was drilled using a much higher speed (though still not as fast as one might use when drilling a hole in wood). This last hole took only 5 minutes from start to finish and did not appear any worse for having used a faster drill speed.

Another problem that was encountered very early on in this project was the need to distribute the load put onto a single home circuit. Though a circuit breaker has not yet been tripped during any brew days, precautions are taken to ensure the heating element is not plugged into the same circuit as the pump (especially in older homes). This is accomplished by using an extension cord to run the heating element off an electric outlet in a different room from the pump.

A very recent problem that arose late in testing was the Arduino's ability to maintain a stable WiFi connection. When the Arduino loses its connection to the WiFi network, it also stops reading from the local website. The result of this issue is that if the Arduino loses the WiFi connection while it is in the process of heating, it can continue heating past the goal temperature set by the brewer. In this situation, the Arduino must be reset. A possible resolution to this problem would be to rewrite the heating loop so that logic to turn the heating pin on or off is built into the webpage rather than in the Arduino sketch. Another failsafe would be to force a handshake between the Arduino and the webpage every time the temperature is called. If the handshake fails, set the pin controlling the heating element to LOW and perhaps sound an alarm to alert the brewer that something is wrong. More tests would need to be conducted to ensure these are stable solutions.

Conclusion

The data from the four batches brewed on the completed system does suggest that automating temperature control during brewing will, in fact, yield a higher gravity beer. In addition to the higher gravity, there is also a large convenience factor in being able to essentially set-and-forget a temperature. Most home brewing systems require the brewer to constantly monitor an analog thermometer and make many small adjustments to their heating system that are both stressful and tedious. By automating temperature control, the brewer can confidently leave the room knowing their temperature will not vary and focus on other aspects of the brewing process such as sanitization and preparing the next ingredients or steps.

An unexpected result shown in the data in Table 2 is that the turning over of grains during the mash process has a much greater effect on gravity than anticipated. As mentioned earlier in this paper, an auger was evaluated to automate this process, however the idea was discarded in favor of a pump for recirculation due largely to the cost of materials required to implement and automate an auger versus utilizing a recirculating pump. In fact, the first schematic for this project outlined both a pump as well as a “corkscrew” or auger (Figure 17).

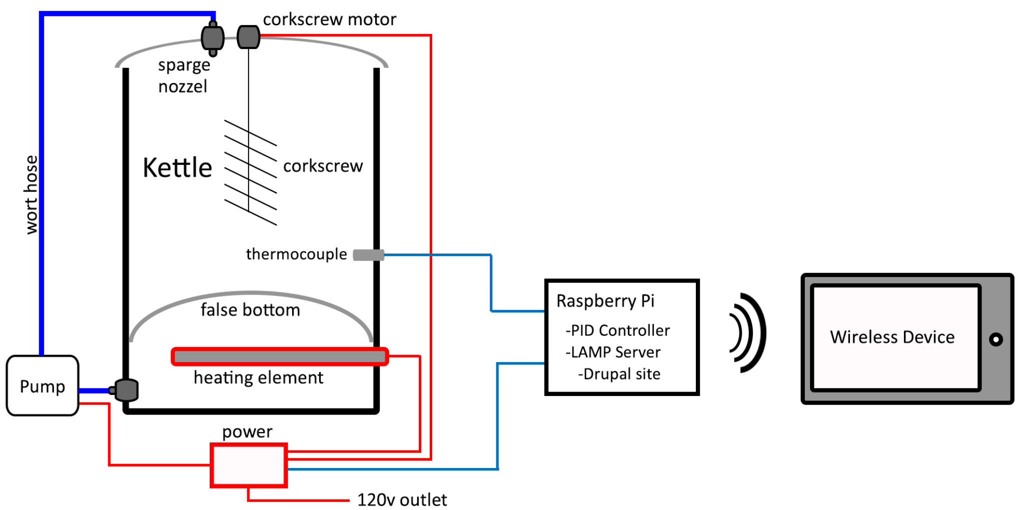

Figure 17 - First schematic for project

(outdated - included to show method for stirring grains)

Given more time, I believe this project would greatly benefit from utilizing a system to automate turning over grains. In fact, both the HTML as well as the Arduino sketch have built in variables tied to digital pins that are currently unused. These are left in place to allow simple integration of additional hardware at a later time. For example, these variables could be used to start and stop an auger based user input, temperature, or even time spent at goal temperature.

Another useful addition would be the inclusion of an automated cooling system. This project utilized a simple copper coil connected to a sink for the purpose of running cold water through the coils while submerged in hot wort. This is a very common method for cooling wort as it is both simple to setup and clean, as well as being relatively inexpensive. In order to automate cooling with a copper coil as is done with the Electric Brewery (see Prior Work section), a wort chiller would have to be submerged in the kettle throughout the entire process - from mash to boil. The basket used in this kettle for the purpose of grain extraction made the inclusion of a semi-permanent chilling coil very challenging. Copper coil wort chillers are also very wasteful as cold water must be run through the coil, which then becomes hot and cannot be reused in the system. Many brewers simply run this heated water down the drain. Thermoelectric coolers were evaluated for the purpose of efficiently automating cooling, but in the end they were not used due to cost and complexity. Given more time, I believe that a ring of external thermoelectric coolers attached directly to the outside of the kettle in conjunction with running the circulating pump may effectively cool the the wort without having to submerge anything, which would make this method more sanitary than most alternatives. This method would also save a substantial amount of water. Some unknowns here are the number of thermoelectric coolers necessary to effectively cool a large volume of liquid starting at a high temperature. Given that many thermoelectric coolers are roughly the size of a quarter and cost around $12 (not including the necessary heatsink and fan), this method could quickly become cost prohibitive.

In conclusion, this project is a cost effective method for using a microcontroller to automate temperature control of a large volume (5 gallons) of liquid. It is hoped that it will be simple to reproduce this project and that doing so will aid a homebrewer in making better, and more consistent beer.

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