Self Temperature and Taste Regulating Tea Cup

ECE 445 Design Document - Spring 2025

Project #44

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Introduction

Problem

Tea is one of the most popular drinks in the world. In the U.S. alone, the estimated market size for the beverage is USD 25.1 billion as of 2024, with 80% of households having it at their homes. [1]. Furthermore, there are stated to be numerous health benefits to the consumption of tea. For instance, green tea can lower blood pressure and total cholesterol, while white tea can strengthen teeth and fight plaque [2].

Current methods to brew tea lack ways to handle different tea leaves and maintain temperature. Tea is usually brewed by adding boiling water to a cup of tea leaves. This is effective for tea leaves like black tea, however, for more delicate teas like green tea, this would bring out more bitterness as it burns the green leaves. This is because adding boiling 100°C water matches the preferred temperature range for black tea, but it is way over green tea's preferred temperature range of 70-80°C. In addition to inadvertently burning the tea leaves, temperature is important in brewing tea because different tea leaves require different temperatures to effectively bring out its aromatic compounds. The ability to heat different tea leaves to their optimal temperatures and maintain their warmness would provide the best possible tea drinking experience. However, it can be difficult to know the different times and temperatures needed for each type of tea leaf, considering there are hundreds of them.

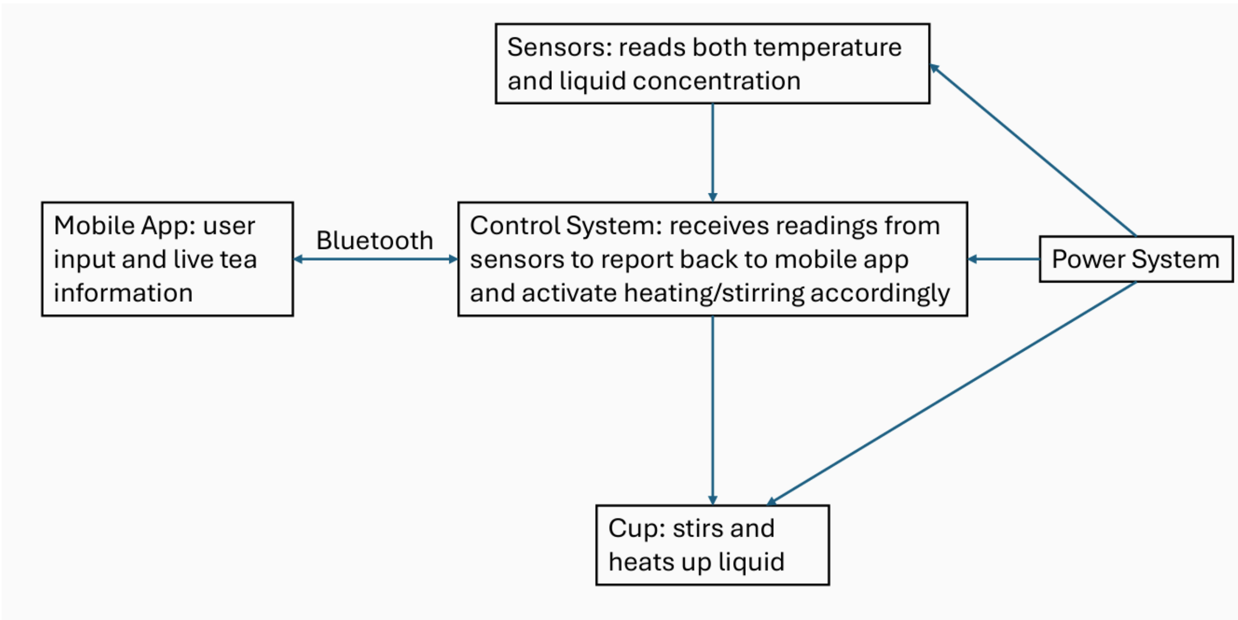
Solution

We propose a cup that can heat water optimal to the type of tea leaf chosen and maintain it to the best temperature. Our system provides a precise temperature control to combat inconsistencies in conventional tea brewing methods. Our cup integrates multiple subsystems to ensure optimal flavor extraction, temperature retention, and ease of use.

These include sensors to measure temperature as well as a TDS sensor to measure tea strength / bitterness. Of course, we will also have a power subsystem, which will be provided via a battery. Two of the functionalities we want to provide are temperature heating and control, as well as stirring, both of which are important for the tea making process. The user can interact with the cup through a mobile application through Bluetooth - the cup will communicate information from the sensors, while the application can be used to change settings and the like. Here is a visual aid to demonstrate the general overview of our project:

Visual Aid

The following visual aid demonstrates how the different components of our proposed solutions will connect to and interact with each other.



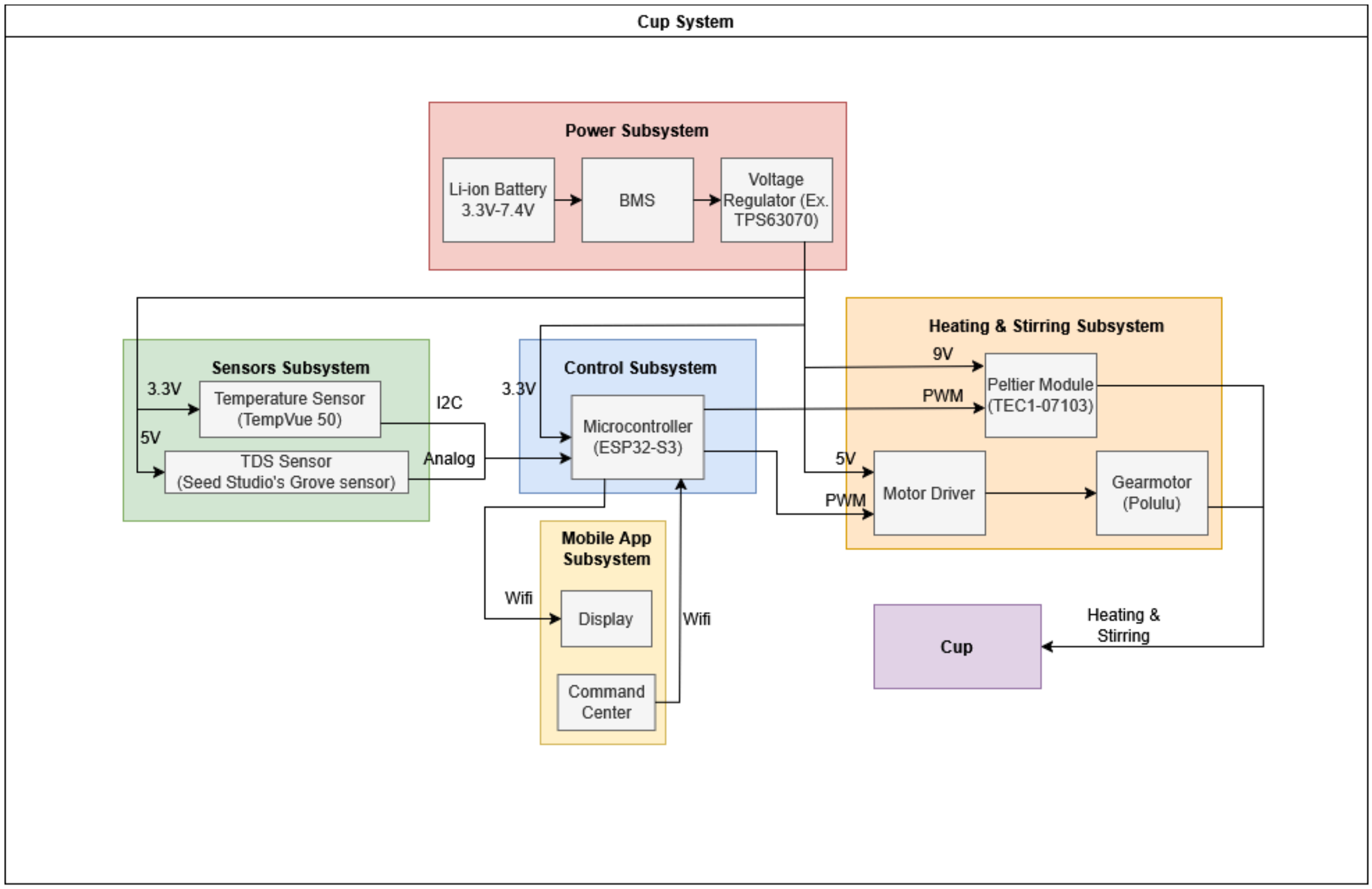
High Level Requirements

We believe our project must display these four high-level characteristics to solve the problem:

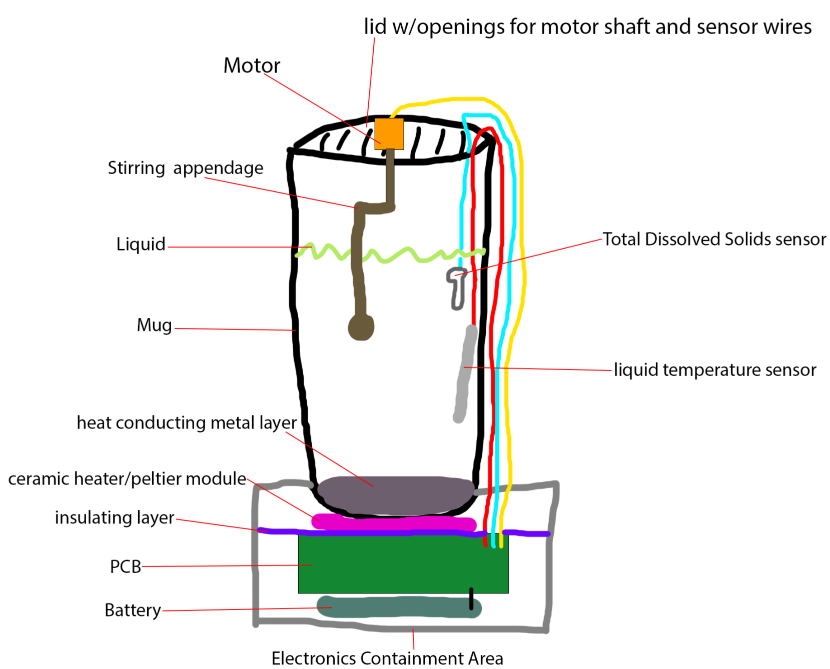
1. The cup should be able to maintain the desired temperature for at least six hours. Given that this is designed to be portable, it would be important for the tea to be kept warm as long as the user is outside, which of course varies, but could be at least the length of a working day. This also means that we would want other subsystems to be as efficient as possible, to minimize the energy loss.
2. The cup should be able to maintain the temperature within 1-2°C of the desired user temperature. This requires precise sensors that can communicate effectively with the user application which in turn needs to communicate with the heating element to control its behavior.
3. Ideally, the cup should not be too heavy. Some of the heavier water bottles that people carry around are about 0.5kg [3], and ours should also fall within a similar weight range. One can consider that people might use this in situations when they are outside in a cold area, perhaps doing tourism, and it is important to travel a little light.

Design

Block Diagram



Physical Design



The device’s superficial design will consist of the mug, an area below it for containing electronics, and the three devices wired from the main electronics area in through the lid: the motor (and its shaft), the TDS sensor, and the temperature sensor. Inside the mug, there will be an appendage attached to the motor shaft such that the liquid can be stirred. Additionally, the bottom of the mug will be replaced with a metal layer (such as steel) so that heat may be conducted more efficiently from the ceramic heater/peltier module. The heater will be located at the top of the electronics area with an insulating layer to protect the PCB and battery from the heat. The electronics area will be accessible from the bottom and also have openings for the sensor and motor wires.

Subsystem 1: Sensors

The sensor's subsystem is responsible for reading the necessary data from the liquid to be used to maintain its tea qualities and temperature. Specifically, it will consist of a Total Dissolved Solids (TDS) sensor for tea strength and a temperature sensor. This data will be relayed to the control system to be analyzed and acted upon. These sensors will also be connected to the power system.

The sensors allow for the tea temperature and strength to be constantly measured to a significant degree of accuracy (within 1-2°C for temperature), which is essential for maintaining the temperature of the liquid at the user’s desired point. These sensors are generally lightweight (<50g) and require lower amounts of power compared to the motor and heating element (~5 mW for temperature, ~15 mW for TDS). These sensors will be directly connected to the control subsystem (ESP32-S3) such that the temperature data can be processed and then converted into the necessary output for the heating element to modify the temperature as needed; likewise the TDS sensor will relay information to the ESP32-S3-WROOM, which then notifies the user of the tea readiness/quality via the user interface. The sensors will also receive power from the battery system, however a buck converter or other method of stepping down voltage will likely be needed.

Requirement	**Verification**
Using the temperature sensor, we should be able to detect once the water temperature is within 1-2°C of the desired temperature.	1. Put water from a tap into the cup and set the desired temperature as 100 °C. Verify that the boolean value for the temperature sensor (as read from the microcontroller) is 0. 2. Continuing from the previous test, measure the water temperature in the cup using a thermometer. Change the desired temperature to the exact temperature of that water and then test for desired temperatures within 1-2 °C of

	that water temperature. Verify that the boolean value for the temperature sensor is 1, as these temperatures would be within our acceptable threshold of error. 3. Continuing from test 2, set the desired temperature to be just outside our acceptable threshold of error (i.e. 3 °C away from the temperature of the water in the cup). Verify that the boolean value for the temperature sensor is 0. 4. We should perform a similar test for boiling water. This will of course be a bit risky due to the high temperature which can cause serious burns so we will need to be careful. However, it is necessary to do this test because firstly, most of the tea brewing temperatures are in the higher range, and secondly, for many water based temperature sensors, their tolerance values are less well known for those high temperatures.
Using the TDS sensor, we should be able to detect once the tea concentration / strength is within a certain range. This tea concentration via TDS will be in parts per million (ppm).	This will be a bit more difficult to test than temperature. In our research, we were unable to find some relation between tea strength and actual values for tea concentration. In addition, tea strength is of course subjective and based on user taste. We will likely have to brew some cups ourselves to ‘determine’ a ppm value for a few tea strengths (weak, medium and strong). Once we do that, we will have similar tests as to those for the temperature sensors. 1. Brew tea for a long time, till we reach our ‘weak’ tea strength. Check the TDS value and see if it is within the previously determined ppm value for ‘weak’ tea. If so, verify that the sensor reads 1. 2. Continue brewing the tea, till we reach our ‘medium’ tea strength. Check the TDS value and see if it is within the previously determined ppm value for ‘medium’ tea. If so, verify that the sensor reads 1.

	3. Continue brewing the tea, till we reach our 'strong' tea strength. Check the TDS value and see if it is within the previously determined ppm value for 'strong' tea. If so, verify that the sensor reads 1.

Subsystem 2: Heating and Stirring

The Heating and Stirring subsystem will maintain the liquid/tea at the user's desired temperature and tea strength. The heating element will be under the liquid, conducting through a thin metal layer. The stirring system will consist of an appendage attached to a Pololu DC Micrometal Gear Motor, the shaft of which will be sent through a small hole in the lid of the cup. This system will require power from the power subsystem and it will also receive input from the control subsystem such that temperature and motor speed can be maintained. Given that the motor is just intended to stir liquid, we will not need anything incredibly strong. The low power version of the Pololu Motor uses 6V at 0.36A, which will be sufficient for our purposes. Further, we only need the motor to act for perhaps ten seconds at any time, operating at ~60 RPM.

Requirement	**Verification**
The heating element should start and stop within a few seconds upon request by the control system.	1. Fill the cup with room temperature water. Send the message to the heating device to begin its operation. Continuously measure the temperature of the water in the cup and ensure that it is rising. 2. In continuation of the first test, after the water is sufficiently above room temperature (perhaps around 40 °C), send the message to the heating device to cease its operation. Continuously measure the temperature of the water and verify that it starts to go down.
The stirring element is also operated through the control system. By default, we would want it to turn on every minute and last for ten seconds. However, there can also be the option for the user to turn off the stirring element, which should be tested as well.	1. It is likely that the temperature differences are very minute anyway, but measure the temperature at the surface and the bottom of the water before and after stirring. If there is a discrepancy, after stirring it should be reduced.

Subsystem 3: Power

The power subsystem is responsible for supplying power to the sensors, motors, and heating element, as well as monitoring battery level. It will also be connected to the control system such that warnings of low battery level can be sent to the user interface and/or indicated via LED. The battery should supply at least 6V and support current draw of a max of 160 mA. Buck converters/regulators are also needed, with functioning output voltages of 3-6V.

Requirement	**Verification**
The battery should supply 6 - 9V with current draw of up to 160 mA.	1. Measure voltage using a multimeter and ensure that it is in the desired range. 2. Measure current using the current setting of the multimeter to ensure that the current draw is not too high and the motor does not stall.
The voltage regulators should output voltages within 5% of the desired value	1. Connect an oscilloscope to voltage output and measure average voltage ripple of the signal. We can also measure the input voltage ripple to check that the device rated ripple rejection ratio is within values as stated by the datasheet.

Subsystem 4: Control and Communication

We can use a microcontroller such as ESP32-S3-WROOM to collect the data from the sensors and communicate it to the mobile app / user interface (Subsystem 5). It will also be able to receive information (user settings) from the mobile application and then control the other subsystems as and when needed. It should monitor temperature and TDS regularly, perhaps every thirty seconds or even more frequently. Stirring will also be controlled by this subsystem and done at a regular interval as well.

Requirement	**Verification**
When the control system learns that the temperature of the water in the cup has reached the desired temperature, it should signal to the heating device to power off.	1. Put room temperature water into the cup, and set the desired temperature as 40 °C. Firstly, verify that the control system tells the heating device to stop its operation. Monitoring the water temperature manually (e.g. via a thermometer), verify that once the desired temperature is reached, the control system tells the heating device to stop its operation.

The control system should periodically start and stop the motor for the stirring aspect of our cup.	1. Start the brewing process via the control system. Verify that the stirring occurs every minute and lasts ten seconds each time. 2. Send a message from the control system to turn off stirring. Repeat the brewing process, and just ensure that no stirring occurs.

Subsystem 5: Mobile App / User Interface

We will be using a mobile app rather than something web - based. Given that we want the user to be able to use our device outdoors as well, this will be more convenient and easy to manage. It will display temperature and TDS readings to the user, as well as allow them to control both those values. This data from the sensors will be adjusted before being displayed to the user - the temperature does not need to go into decimal points, and we will map the TDS values to qualitative descriptions (i.e. strong, weak, etc). The app should also alert the user when their tea has reached the desired strength or temperature and allow them to provide settings for stirring. This app will communicate with the microcontroller from Subsystem 4 via Bluetooth. Again, since we want this to be usable outdoors, we chose Bluetooth over Wi-Fi.

Requirement	**Verification**
Ensure that the user is able to connect to the cup via Bluetooth.	1. Verify that when Bluetooth is activated on both devices, they can connect. Once this is done, verify that there is confirmation of this connection.
Ensure that the water temperature is reflected in real time to the user.	1. Put room temperature water in the cup and ensure that the temperature is immediately updated in the application. 2. Put in much hotter water on top of the existing water and verify again that the temperature is updated immediately (within 1-2 seconds).
Allow the user to set custom conditions for temperature, stirring and tea strength.	1. Put room temperature water in the cup. Set some specified higher temperature (perhaps 40 °C again) through the application. Verify that the heating device is activated and that it is turned off when that temperature is reached.

	2. Repeat test 1, but this time, add an option for no stirring. Ensure that this time, the brewing process does not activate the motor at any time. 3. Repeat test 1, but this time, instead of testing for temperature, allow the user to select ‘Strong’ for the tea strength level. Once the brewing process is completed, check the TDS value and drink the tea to verify its strength.
Notify the user when the tea is finished brewing.	1. When the brewing process is completed, verify that the user gets a notification of some sort that their tea is ready.

Subsystem 6: Cup

The cup/mug will consist of a generic stainless steel mug. The bottom of this mug will be cut off and replaced with a thin sheet of metal to conduct heat through (via welding at the machine shop). Below that, there will be a sizable compartment to hold all electronic components. Additionally, a hole will be cut out of the lid such that the motor shaft from the stirring subsystem can be slotted through. The cup will need to have a large enough radius to have enough space on the lid to place the motor and an orifice for the user to drink from, likely at least 3-4 cm.

Requirement	**Verification**
The cup should not be too heavy. This is not a requirement, but rather one for user convenience.	1. Once it is ready, weigh it, and verify that the cup’s weight is around 500 grams when it is empty.
Given that this is a handheld solution, the temperature of the outside should not be significantly	1. The pain threshold temperature for the human hand was found to be 43.8 °C [4]. To be safely away from this limit, verify that the temperature of the outside of the cup does not exceed 35 °C.
The electronics in our product should not be damaged when coming into contact with water.	1. Use some cheaper / unimportant electronics and put them as temporary placeholders into the base of the cup. Pour water into the cup and vigorously shake it around. Remove the water and the temporary placeholder electronics from the base, and verify that they

	still function.

Cost and Schedule

Cost is broken down into two parts. Labor costs and hardware costs. The average UIUC ECE undergraduate's hourly salary is $42.31. We can expect the labor cost for each partner to be 42.31 x 2.5 x 60 = $6346.5. Total labor cost is 6346.5 x 3 = **$19039.5**.

Parts Cost

Part	Manufacturer/Vendor	Quantity	Cost	Subtotal
6V 150RPM Micro DC Gear Motor	Lagogia/Amazon LLC	1	$7.99	$7.99
DS18B20 Liquid Temperature Sensor	Amazon LLC	1	$8.49	$8.49
TEC1-12706 12V 6A Peltier Module	HiLetgo/Amazon LLC	1	$9.79	$9.79
Total Dissolved Solids Sensor	CQRobot / Amazon LLC	1	$11.99	$11.99
Insulated Travel Mug	YINBAOGE/ Amazon LLC	1	$7.96	$7.96
Voltage Regulators	Texas Instruments	3	$2.12	$6.36
ESP32 WROOM-1	Espressif/Amazon LLC	1	$10.89	$10.89
19W Meal Ceramic Ring Heater with 10 kic Thermistor	Thorlabs	1	$69.17	$69.17
Parts Subtotal				**$132.64**

Category	Cost
Total Labor	$19039.5
Parts Subtotal	$132.64
Machine Shop Service	$50
Grand Total	**$19222.14**

Schedule

Week	Dates	Tasks	Member Responsibilities
Week 1	02/24-02/28	- Confirm hardware and software MVP - Start on PCB design	Lahiru: Order hardware components Anirudh: Validate hardware components with Lahiru James: Confirm mobile app platform All: Start on PCB design
Week 2	03/03-03/07	- Design document - Setup github - Setup breadboard for demo	Lahiru: Order hardware components Anirudh: Organize and submit design document James: setup github and prepare software environment
Week 3	03/10-03/14	- Second round PCB orders - Revisions to machine shop if needed - Revise bread board via demo feedback	Lahiru: submit PCB design Anirudh: Research improvements/alternatives to our current hardware components

			James: confirm any revisions needed to machine shop All: revise breadboard based off demo feedback
Week 4	03/17-03/21	SPRING BREAK	SPRING BREAK
Week 5	03/24-03/28	- Assemble PCB - Software MVP - Revise/test breadboard	Lahiru: Assemble PCB design and mark any important notes Anirudh: Work on connecting ESP32 with mobile app James: Work with Anirudh and
Week 6	03/31-04/04	- Assemble PCB - Software MVP - PCB order if needed - Revise/test breadboard	Lahiru: Order another PCB if needed and notify team if any problems come up Anirudh: Collect data transfer latency to account in liquid heating James: Confirm data transfer between ESP32 All: Work on connecting hardware component to software
Week 7	04/07-04/11	- Assemble PCB - Finalize Software UI - PCB order if needed - Revise/test breadboard	Lahiru: Finalize breadboard Anirudh: Finalize software and hardware connection

			James: Finalize user-friendly software UI All: make any necessary adjustments according to material uncertainty
Week 8	04/14-04/18	- Finalize Software - Finalize integration testing with software and hardware - Prepare other component for demo	All: Finalize project Prepare for demo and go through practices
Week 9	04/21-04/25	- Revise based off mock from feedback to prepare for final demo - Prepare for mock presentation	Lahiru: Make any necessary hardware adjustments Anirudh: Make any necessary changes to software James: Organize and setup mock presentation powerpoint All: fill in powerpoint and prepare for the final demo. Divide presentation into parts for each person
Week 10	04/28-05/02	- Revise presentation based off mock presentation feedback	All: make changes to presentation based off demo feedback Edit individual parts in the presentation

Week 11	05/05-05/09	- Final presentation - Submit final papers, lab notebook, lab checkout	Lahiru: Submit Final presentation Anirudh: Lab checkout James: Submit final papers

Ethics and Safety

There are of course a few safety concerns, specifically in relation to 1.1 from the IEEE Code of Ethics [5]. For instance, since this is meant to be for tea, we will be dealing with very hot water that can seriously scald or burn a person. The lid of the cup should only come off intentionally; in other words, it can not accidentally come off. In essence, we want to make it spill proof. Another potential safety concern is washing the cup. The user will need to do this for hygienic purposes. We want to make sure this is possible to do without the water coming into contact with the electronics, which could be dangerous.

1.2 from the IEEE Code of Ethics is also important to our project [5]. This discusses the importance of improving individuals and society's understanding of smart devices. Our cup would likely fall under this category, as it will communicate with the user's smartphone via Bluetooth. Such connections can be intercepted or interfered with, and it is important for the user to be aware of this. Also, we can envision the application storing data such as user preferences. We need to store user data, no matter how inconsequential it may seem, securely. One last more ethical aspect is more about avoiding waste and proper design. Our cup should be made of a series of parts that can be replaced rather than one singular device. This can avoid waste of materials, and make it cheaper to get one's cup functioning again if something goes wrong.

Tolerance Analysis

Temperature control system is the most crucial part of our design. A successful implementation would allow users to heat up and maintain their tea at a high temperature. This means that our heating system must be powerful enough to do so as well as being able to conduct heat well through the cup. To meet this requirement, we can use Fourier's Law to calculate heat loss and the heat energy equation to find the estimated energy needed to heat up different liquid temperatures.

$Fourier's\ Law:\ Q = k * A * \Delta T$

We're using a cup made out of 304 stainless steel which has a thermal conductivity of 16 W/mk. We estimate A, area in which heat is lost, to be 0.03 meters squared

Changes in T = target temperature - standard room temperature (20 celsius)

We'll also use $70°C$, $75°C$, $80°C$ as targeted temperatures in our calculation as it's standard optimal temperatures for many tea leaves.

$70\,°C\ heat\ loss\ Q = 16 * 0.03 * (70 - 20) = 24W$
$75\,°C\ heat\ loss\ Q = 16 * 0.03 * (75 - 20) = 26.4W$
$80\,°C\ heat\ loss\ Q = 16 * 0.03 * (80 - 20) = 28.8W$

$Specific\ Heat$: $Q = m * c * \Delta T$
We assume mass of water to be 250g
Specific heat capacity of water c = 4186 J/(kg * K)
Changes in T = target temperature - standard room temperature (20 celsius)

$70\,°C\ energy\ requirement\ Q = 0.25 * 4186 * (70 - 20) = 52325J$
$75\,°C\ energy\ requirement\ Q = 0.25 * 4186 * (75 - 20) = 57557.5J$
$80\,°C\ energy\ requirement\ Q = 0.25 * 4186 * (80 - 20) = 62790J$

Concluding our calculation, to reach $70\,°C$ - $80\,°C$, the mug needs about 52-63kJ of energy. Once we reach our desired temperature for brewing the team, the system needs to continuously supply 24-29W for some time to offset heat loss.

For other considerations relating to our heating system, the time in which we heat up the cup is also essential to estimating the required energy needed. We may estimate this require power through $P = Q\ required/time$

Suppose we want to heat liquid to $70\,°C$ in 3 minutes.
$P = 52325\ (from\ previous\ calculation)\ /\ 3 * 60 = 290.9644W$

Furthermore, there will be uncertainties within our sensors, cup material, etc which we will need to account for in our calculations to accurately heat/maintain liquid temperature.

References

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[5] IEEE, “IEEE Code of Ethics,” *ieee.org*, Jun. 2020. https://www.ieee.org/about/corporate/governance/p7-8.html