

Chai Station (IoT-Enabled Automated Tea Vending Machine)

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Certificate

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Dedication

This project is dedicated to our parents, without whom prayers, sacrifices, and constant support, this journey would have been much more difficult. We also owe much to our teachers and mentors at Bahria University who were patient and guided us along the way. Lastly, this book is in honor of all the people who think that little, seemingly ordinary amenities are worthy of careful engineering, since a good cup of chai every time, all the time, to everyone, is a goal to chase.

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Abstract

Automation is now a way of life in most areas of life, yet in the preparation of tea in offices and universities in Pakistan, manual labour remains virtually undone. The outcome is poor quality, hygiene issues and a repetitive consumption of staff time. This thesis proposes the Chai Station, a smart tea vending machine with IoT capability that prepares traditional milk tea in Pakistan and dispenses customised cups to authenticated users using a mobile web-based interface, brewed out of raw liquid and solid tea ingredients.

The entire system operates on a single ESP32 microcontroller which controls hardware actuation, reads digital temperature sensors, hosts a local web application and communicates with Google Firebase Realtime Database to authenticate users and manage balances.. The physical layout of the machine is as follows: an upper zone, containing the main boiler, which brews tea with a three-cycle boiling program under infrared induction heating, a middle zone, which contains the intermediate boiler, which holds the serving temperature with conventional induction heating, and a lower zone, which houses the sugar dispenser, limit switch, and dispensing solenoid, serving single cups.

Students scan in on their phones with enrollment data, choose one of three levels of sugar, grab their cup, and pick up their chai. An admin panel with a password provides the operators with complete access to brewing, student accounts, pricing and live monitoring. The sequential operational logic with power recovery, which is non-volatile and stored, safeguards student balances during unforeseen power failure. Ten full brewing cycles of testing ensured the consistency of the quality of brews, the integrity of the Firebase integration, and the responsiveness of web interfaces on Android and iOS platforms.

Contents

1	Introduction	1
1.1	Background of Project	2
1.1.1	Understanding Tea and Its Cultural Importance . .	3
1.1.2	Automation of Beverage Preparation.	3
1.1.3	IoT and Cloud Services integration in Vending Sys- tems.	4
1.2	Problem Description	5
1.3	Project Objectives	6
1.4	Significance of the Study	7
1.5	Relevance to Sustainable Development Goals (SDGs)	8
1.6	Scope of the Project	8
1.7	Structure of the Thesis Report	9
2	Literature Review	11
2.1	Automated Cooking and Beverage Systems	12
2.2	IoT-Based Smart Tea and Beverage Machines	13
2.3	Selection of Milk-to-Water Ratio for Doodh Pati	15
2.4	Cloud-Integrated IoT Vending Systems	16
2.5	Automated Cooking- Induction Heating.	17
2.6	Food System Sensor-Based Process Control.	18
2.7	Vending and dispensing: Embedded Microcontrollers	19
2.8	IoT Data Systems in real time.	20
3	Requirement Specifications	22
3.1	Current System: Manual Preparation of Tea	23

3.2	Suggested System: Chai Station	24
3.3	Requirement Specifications	25
3.3.1	Functional Requirements	25
3.3.2	Non-Functional Requirements	26
3.4	System Interaction and User Role	27
3.5	Design Methodology	28
3.5.1	Requirement Analysis	29
3.5.2	System Architecture Design	29
3.5.3	Component Selection	29
3.5.4	Microcontroller Selection: ESP32	29
3.5.5	Prototype Development and Testing	31
3.5.6	Final Integration and Evaluation	31
4	System Design	32
4.1	System Architecture	33
4.1.1	Architectural Overview	33
4.1.2	System Components and Interactions	35
4.2	High Level Design	36
4.3	Low Level Design	36
4.4	Hardware Component Design	37
4.4.1	Enclosure and Physical Layout	37
4.4.2	Upper Section: Main Boiler and Brewing Assembly .	37
4.4.3	Middle Section: Intermediate Boiler and Holding As- sembly	37
4.4.4	Lower Section: Serving Assembly	38
4.4.5	3D-Printed Pocket-Wheel Dispensers	38
4.4.6	Dallas Temperature Sensors	38
4.5	Software Architecture	39
4.5.1	Sequential Operational Logic	39
4.5.2	Firestore Database Design	40
4.5.3	Web Application Design	41
4.5.4	Safety and Power Cutoff Recovery	42

4.5.5	Hardware Constraints	42
4.6	System Flow Diagram	42
4.7	Design Constraints	42
4.7.1	Safety Constraints	43
4.7.2	Food Safety Constraints	43
4.7.3	Firebase Connectivity Constraint	43
5	System Implementation	45
5.1	Physical Construction	46
5.1.1	Frame and Enclosure	46
5.1.2	Upper Section Assembly	46
5.1.3	Middle Section Assembly	47
5.1.4	Lower Section Assembly	47
5.1.5	3D-Printed Dispenser Assembly	48
5.2	Electronics and Wiring	48
5.2.1	Power Supply Architecture	48
5.2.2	Relay Module and Component Wiring	49
5.3	Tools and Technology Used	49
5.4	Development and Libraries Used	52
5.5	Firmware Implementation	53
5.5.1	Temperature Reading	53
5.5.2	Brewing Sequence Logic	53
5.5.3	Session Management and Transaction Recovery . . .	53
5.6	Calibration Procedures	54
6	System Testing and Evaluation	55
6.1	Control Circuit Simulation Testing	56
6.2	Hardware Component Testing	56
6.2.1	Pump and Liquid Delivery Testing	56
6.2.2	Temperature Sensor Testing	58
6.2.3	Three-Cycle Boiling Verification	58
6.2.4	Temperature Holding Verification	58
6.2.5	Servo Dispenser Testing	59

6.2.6	Solenoid Valve and Sensor Testing	59
6.3	Software and Firebase Testing	60
6.3.1	Authentication and Balance Testing	60
6.3.2	Power Recovery Testing	61
6.3.3	Web Interface Cross-Device Testing	61
6.4	Hardware-Software Integration Testing	62
6.4.1	End-to-End Cycle Validation	62
6.4.2	Concurrent Web and Hardware Operation Testing .	63
6.4.3	Live Operation Testing of the Admin Panel	64
6.5	Limitations Identified During Testing	64
7	Conclusion	67
	References	70

List of Figures

1.1	Traditional Pakistani Milk Tea	4
2.1	Chai Station System Block Diagram	14
3.1	Traditional Manual Tea Preparation	24
3.2	Humans Interacting with Mobile Web	28
4.1	System Architecture	34
4.2	3D-Printed Rotating Pocket-Wheel	39
4.3	Temperature Sensor	40
4.4	Chai Station Complete System Flowchart	44
5.1	Upper Section	47
5.2	Middle Section	48
5.3	Lower Section	49
5.4	3D-Printed Pocket-Wheel	50
5.5	Relay's & Power Supply Architecture	51
5.6	ESP32 Microcontroller	52
5.7	Servo Motor	52
6.1	Caption	57
6.2	3 Cycle Testing Of Temperatue Sensor	59
6.3	Firestore Realtime Database Console Showing Student Records and Machine State	60
6.4	Power Recovery	61
6.5	Bewring	62
6.6	Student Web Application Tested Simultaneously	63

6.7	Admin Interface	64
6.8	Admin Panel Displaying Live Machine	66

Chapter 1

Introduction

This chapter presents the Chai Station, and discusses the reason behind the creation of it. The cultural background of tea in the Pakistani institutional life is discussed, followed by the practical inadequacy of the existing preparation strategies and finally the project objectives, the relevance of this project to the larger framework of smart automation and connection with the United Nations Sustainable Development Goals. These sections, combined, form the engineering requirement which the project is responding to and introduce the reader to the technical discourses which will be presented in the following chapters.

1.1 Background of Project

The need to have everyday life managed efficiently and expeditiously is something nearly universal. One of the most steady of these ritual is the preparation and serving of chai in Pakistani offices, university departments, and commercial buildings. Traditional milk tea, doodh pati, whether served early in the morning, between meetings, as the anticipated courtesy when a guest is introduced to it, is part of the rhythm of institutional life like few other things. But the manner in which it is made has remained the same. It still involves the need of somebody standing in a stove, over a pot, three boils, and serving the outcome. This is a real waste of time in an environment where such moment can be used to do something more constructive.

The general shift to automation of food and beverage systems has been very successful in industrial and commercial environments [1]. Connected appliances, smart kitchen systems, and automated dispensing machines are being created and rolled out at an accelerated pace, boosted by the progress in embedded microcontrollers, wireless communication, and cloud services [2]. What has not yet seen much progress is the use of these technologies to culturally specific beverages - namely those whose preparation process has particular steps and timing constraints that cannot be easily overlaid onto available commercial vending solutions.

1.1.1 Understanding Tea and Its Cultural Importance

The making and serving of chai is one of the most significant rituals of work in Pakistan, among the numerous everyday practices that characterize the working life in this country. It is not only a drink, but also a social sign, a gesture of hospitality, and indicator of the working day rhythm. People who regularly drink doodh pati are aware of the taste and the nature of the rightly brewed doodh pati, attained by means of repeated boiling of milk and water with loose tea leaves. Any automated system which attempts to substitute the manual preparation process must then be based on the premise that it is not an option to recreate this taste in a faithful manner, but rather the whole point.

The design of this project was based on this knowledge. All the choices regarding the brewing equipment, the amount of boiling steps, the ratios of the ingredients, and the dispensing system were taken with the aim of developing a cup that could be considered as similar to the one that would be prepared by a skilled operator as much as possible. Technical labor to be described by this thesis is eventually subservient to that cultural goal [3]

1.1.2 Automation of Beverage Preparation.

When examining the direction in which the food and beverage preparation automation has taken, there is a definite trend. Systems have gradually shifted towards multi-step integrated processes that are capable of measuring ingredients, preparing them, and delivering them, instead of simple one-step mechanical aid, such as a kettle that switches off when boiling is achieved. Coffee machines were programmed. Juice dispensers were sensor-controlled. Real-time feedback systems were introduced as a means of monitoring commercial food production lines. Trends have been in the direction of reduced human intervention in each successive stage.

Drinks such as pakistani chai have been slower to feel the advantage of this development in part due to the more complex nature of their preparation versus more standardised ones, such as a capsule espresso. Doodh pati



Figure 1.1: Traditional Pakistani Milk Tea

is made with raw liquid ingredients not powder, a multi-phase boiling process, and heat management in real-time. Such requirements present engineering issues not experienced by simpler dispensing systems. The current study on IoT-based smart tea machines confirms that the issue is acknowledged and is under development [4], yet there are few real-life implementations of Smart tea machines in the institutional context of Pakistan

1.1.3 IoT and Cloud Services integration in Vending Systems.

The convergence of competent microcontrollers with cloud database services is one of the most significant technical changes that allow this project. Modern vending machines are not just the mechanical dispensers with a coin slot. Studies indicate that cloud infrastructures and embedded computers allow managing persistent user accounts, remote monitoring, real-time operational control, which could not be previously implemented unless with dedicated server facilities [5]. The ESP32 microcontroller, which

includes Wi-Fi support, the ability to run two cores, and the ability to integrate with a large ecosystem of development libraries has become a viable platform to create systems that interface physical vending hardware to cloud databases directly [6].

In the case of the Chai Station, this connectivity implies that student account, balance and transaction records are stored in Google Firebase Realtime Database - available to any administrator, on any device, and continuing to be available after machine re-boot and being updated in real-time.. It also means that the machine hosts its own web interface without requiring any installed application on the user's phone.

1.2 Problem Description

Preparation of tea in institutions by hand poses some issues at three levels. At the quality level, each session has a different flavor of the output, as there are no parameters, fixed: the ratio of milk to water, how long each boiling stage should last, the amount of tea leaves should be all depends on the taste of the operator. On the hygienic level, there is a risk of contamination of repeated manual contact with common pots, strainers, serving equipment, etc. in communal kitchen spaces, which is hardly manageable on a consistent basis. On the efficiency-level, the process needs a human-focused attention over a long time which in a workplace or department of a university would be that someone is doing not something else eight to fifteen minutes each time they make tea.

The efficiency problem is solved by the commercial vending alternatives currently available in Pakistan but it develops a quality problem. The beverage of powder-mixing machines is significantly different than traditionally brewed doodh pati and in a situation where the expectations of chai drinkers are strong and specific, this trade-off is not palatable to the majority of users [4]. The Chai Station was designed to demonstrate that it is possible to combine both: to make real brewed chai and to make it efficient with an automated system..

1.3 Project Objectives

The primary purpose of this project is to design and implement a functional, IoT-enabled automated tea vending system that delivers traditional Pakistani milk tea from raw ingredients with minimal human involvement. The specific objectives are as follows:

1. **Automated Brewing Architecture:** A physical brewing system is to be designed, which can perform a boiling process with three cycles, as defined by traditional boiling, using sealed and food-grade containers, keeping the proportion of milk and water at an exact ratio.
2. **Sensor Integration & Safety:** To incorporate temperature, flow and limit switches into a coordinated feedback loop governing thermal operation and safe and spill-free dispensing.
3. **Cloud-Based Identity & Finance:** To provide a secure, cloud-based database (Google Firebase) with user authentication and management of digital balance, which would enable students to log in to the machine using institutional credentials.
4. **Interactive Student Platform:** To create a mobile-friendly web-based application that represents the user with a user-friendly interface to view their balance and customize their sugar-level.
5. **Administrative Telemetry:** To create an administrative control panel with password protection, which will enable the operators to control the brew cycles, user accounts, and monitor live machine control.
6. **System Resilience:** To introduce sequential operation logic with non-volatile transaction recovery, balances of students must be hardened against unexpected power outages.

7. **System Validation:** To test the entire system with rigorous hardware, software, and end-to-end integration testing.

1.4 Significance of the Study

In addition to the direct practical value of serving regular chai in an institutional establishment, this project can be important in terms of what it can show us regarding what can be done with available technology. The complete full system of hardware control, web server, cloud database integration, user authentication and transaction safety can be implemented on a single microcontroller, which would only be a fraction of the cost of a dedicated server or industrial controller. This renders the strategy truly scalable to small and mid-sized institutions that have a small technology budgets [7].

On hygienic grounds, the closed ingredient handling and automatic brewing system implies that no hands contact to food-contact surfaces during preparation. This is a practical, but not theoretical, improvement in shared institutional kitchens, which will minimize the risk of contamination.

The project also adds to the existing literature on iot-based smart food and beverage systems, namely, in the field of culturally adapted automated vending, in which the literature has traditionally dealt with Western beverages and foods only.

From a hygiene standpoint, the enclosed ingredient pathway and automated brewing process mean that no hands touch food-contact surfaces during preparation. In shared institutional kitchens, this is a meaningful improvement that reduces contamination risk in a practical rather than theoretical way [8].

The project also contributes to the growing body of work on IoT-based smart food and beverage systems, specifically in the area of

culturally adapted automated vending, where the published literature has historically focused on Western beverages and foods [9].

1.5 Relevance to Sustainable Development Goals (SDGs)

A popular framework of evaluating the societal impact of technological development is the Sustainable Development Goals adopted by the United Nations in 2015. Some of these objectives directly apply to the Chai Station.

SDG 8 Decent Work and Economic Growth: Automation of a repetitive supervised activity releases institutional personnel to more skilled and productive activities. The design and implementation of embedded systems, cloud development, and maintenance services are also demanded and supported through the creation and maintenance of IoT-enabled systems such as the Chai Station [2].

SDG 9 Industry, Innovation and Infrastructure: The system is based on a paradigm of accessible innovation - developing a competent IoT vending solution with locally found parts, open-source software, and free-tier cloud computing that can be used in other institutional contexts throughout Pakistan without significant capital outlay.

1.6 Scope of the Project

The present project deals with the entire design and construction of an independent automated tea vending machine. The machine handles two liquid components water and milk in two sealed containers, which are mixed during filling in an approximate seventy-thirty ratio, tea leaves and sugar are dispensed with the help of servo-controlled

3D-printed systems, there is a three-cycle boiling cycle, and brewed tea is transferred into a holding boiler, and one cup of tea is dispensed to a user, who authenticates by using the web interface.

Firestore is used to perform student authentication and account management. Both the student interface and admin control panel are served by the ESP32. Internet-facing dashboards, payment gateway integration, and multi-unit networking are beyond the scope of the present work and are acknowledged as directions for future work. The machine is designed and tested as a single-unit deployment for a single office, university department, or similar institutional environment.

The overall structure of this report is summarised in Table ??.

1.7 Structure of the Thesis Report

- **Introduction:** Project background, motivation, problem statement, objectives, SDG alignment, and scope.
- **Literature Review:** Examination of existing automated beverage systems, IoT vending platforms, induction heating, temperature sensors, and microcontroller selection with comparative analysis.
- **Requirement Specifications:** Analysis of existing manual tea preparation, proposed system overview, functional and non-functional requirements, and use cases.
- **System Design:** General concepts of High-Level and Low-Level system design, followed by the Chai Station architectural design across hardware and software layers.

- **System Implementation** : Detailed physical construction, electronics wiring, firmware development, and calibration of the Chai Station prototype.
- **Testing and Evaluation** : Hardware simulation, component testing, Firebase integration testing, and end-to-end validation results.
- **Conclusion** : Summary of contributions, limitations encountered during testing, and directions for future development.

Chapter 2

Literature Review

In this chapter, the research and technical work, which are most applicable to the Chai Station project, are discussed. The review is structured into seven thematic areas; automated cooking and beverage systems, IoT-based smart tea machines, cloud-integrated vending platforms, induction heating in cooking systems, sensor-based process control in food applications, embedded microcontrollers of vending, and real-time cloud data integration. Wherever published work is in line with design decisions that have been made in this project, such links are specifically stated. The gap in the existing literature that the Chai Station fills, as the review also names it is the lack of a practical institutionally deployable automated system to brew traditional South Asian milk tea using raw materials under the control of a cloud-connected wireless system.

2.1 Automated Cooking and Beverage Systems

Automation of cooking and beverage preparation is no longer a mere scholarly interest but it is a field of engineering that is becoming more and more practical. In a detailed analysis of automated cooking systems, published by Bautista et al., the authors note that the three key benefits of kitchen automation evident in all the studies that they reviewed are consistent quality output, less reliance on labour, and enhanced hygiene [1]. The same review adds that the main barriers to existing systems are cultural flexibility, the inability of an automated system to generate food with the expectations of a specific culinary tradition, and the engineering intricacy of the multi-step processes, in which multiple physical operations happen in a predefined order.

Arachchige et al. also test the progress of automated systems of food processing and discover that systems based on sensor feedback with programmable timing controllers have significantly more predictable

outputs than agencies based on fixed-duration heating alone [10].. Their results can be directly applied to the brewing logic in the Chai Station, where the three-cycle boiling process is scheduled by crossing temperature thresholds observed by the temperature sensor instead of a specific timer. This sensor-based method eliminates the inconsistency in the boiling time caused by changes in the temperature of the original compounds and the environment.

The food systems application of artificial intelligence discussed by Mavani et al. in an extensive variety of production and processing settings has found real-time sensor integration as the technological platform that supports most AI-enhanced quality innovations in automated food preparation [11]. Although the Chai Station does not utilize AI in its present application, sensor infrastructure that it implements, especially the digital temperature sensing and level detecting functionality, offers the data base such functionality could be based on in a future version..

2.2 IoT-Based Smart Tea and Beverage Machines

The closest related previous literature is presented by two recent studies on the automated tea preparation using IoT technology. Khan et al. introduce a smart tea-vending machine based on IoT that is controlled via an embedded controller which manages a heating cycle and delivers tea to people via a mobile application interface [4]. Their system shows the feasibility of the embedded-control solution to tea vending and proves that mobile-accessible control is better than the fixed-panel interfaces in institutions. They are however designed in a style of powder based tea preparation that does not reproduce the flavor of the doodh pati that is made through tradition-based brewing. The Chai Station overcomes this drawback by employing

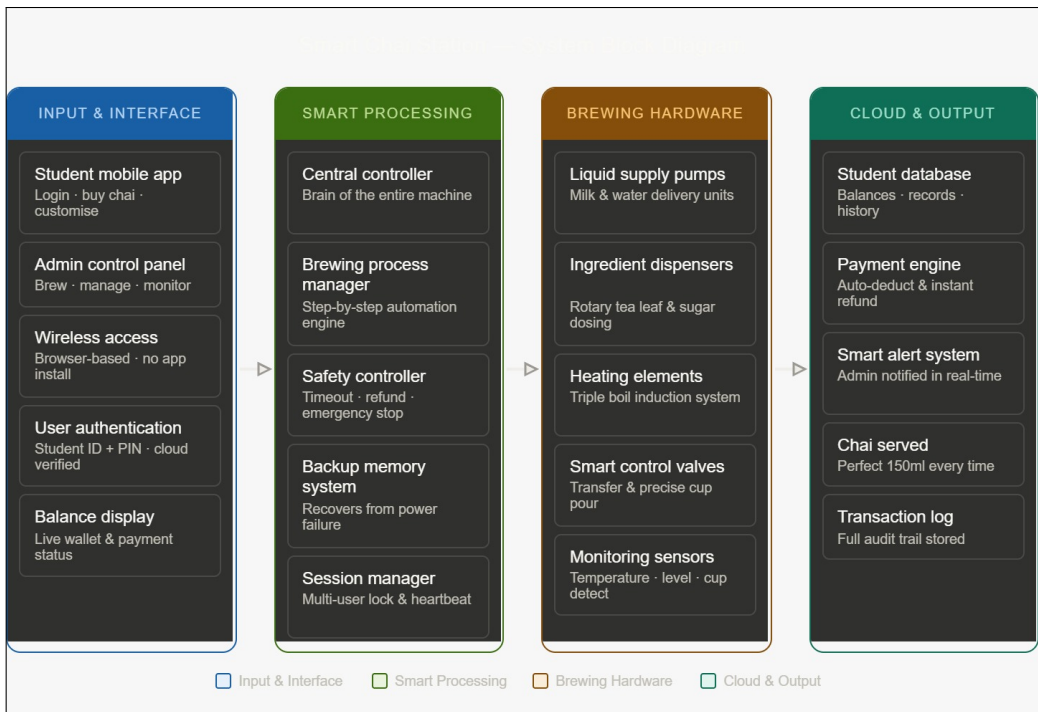


Figure 2.1: Chai Station System Block Diagram

the raw liquid and solid ingredients.

Kumar et al. write about an IoT-based automatic smart tea machine, which mechanizes the additions of water, milk and tea leaves in sequence, using microcontroller-controlled pumps and heating devices [3]. Their work can be used to show that multi-ingredient sequential automated brewing is technically feasible as well as to offer a useful benchmark to compare the design decisions of the Chai Station. The main difference between their work and this project is the introduction of a three-cycle boiling logic, cloud user authentication and balance management, and the entire control panel of the entire administration- something that can now be considered to have provided transition of the system into a working prototype to a system that can be used in real institutions.

Google usage of a beverage dispenser is also addressed by Balakrish-

nan et al. in a system that uses embedded Google and allows remote monitoring and management of a coffee dispenser in the area of smart coffee dispensing [9]. The fact that they use a cloud integration layer to provide real-time status reporting and user interaction can be directly compared to the Firebase integration in the Chai Station, and their latency and reliability results under normal network conditions confirms the possibility of such an architectural decision.

2.3 Selection of Milk-to-Water Ratio for Doodh Pati

One of the earliest design decisions in the development of the Chai Station was determining the correct proportion of milk to water for the brewing batch. Traditional Pakistani doodh pati is known for its rich, creamy consistency and full body, which is achieved through a higher milk proportion than is common in other tea cultures. Rather than relying solely on published recipes, a structured informal taste evaluation was conducted with five participants who each tasted five preparations made with different milk-to-water ratios under identical brewing conditions. Each sample was assessed on three criteria: taste authenticity, creaminess, and overall preference.

Table 2.1: Taste Evaluation Results Across Different Milk-to-Water Ratios

Ratio (Milk : Water)	Tester 1	Tester 2	Tester 3	Tester 4	Tester 5
100% Milk : 0% Water	5 / 10	4 / 10	6 / 10	5 / 10	4 / 10
70% Milk : 30% Water	9 / 10	10 / 10	9 / 10	8 / 10	9 / 10
50% Milk : 50% Water	7 / 10	6 / 10	7 / 10	7 / 10	6 / 10
30% Milk : 70% Water	4 / 10	5 / 10	4 / 10	4 / 10	5 / 10
0% Milk : 100% Water	2 / 10	1 / 10	2 / 10	3 / 10	2 / 10

Scores are out of 10 based on combined taste, creaminess, and authenticity. The 70:30 milk-to-water ratio received the highest average scores across all five testers, closely matching the traditional doodh

pati that participants were familiar with. The 50:50 ratio was considered acceptable but noticeably lighter in body, while the 100:0 preparation was described as too thick and slightly overcooked in taste. The 30:70 and 0:100 preparations were rejected unanimously as lacking the character of authentic chai. Based on this evaluation, a 70:30 milk-to-water ratio was adopted as the standard for all brewing cycles in the Chai Station.

2.4 Cloud-Integrated IoT Vending Systems

Combination of cloud platforms with physical vending hardware has been proved to be the case in various recent studies. Al-Shareeda et al. report about an intelligent pizza vending machine with cloud connectivity and IoT to manage orders, track their status in real-time, and process payments [5]. Their architecture - the embedded hardware controller being connected to a cloud database which is, in turn, accessible by an interface to an administrator is, again, remarkably similar to the design of the Chai Station. The reliability of cloud-hardware synchronisation in the normal conditions of deployment should be of interest to them, and they reported this ability.

Wibowo and Fahmi introduce a contactless and cashless smart vending machine with a mobile device to prove that the integration of mobile web access and account management based on the cloud platform is not only technically feasible but also has good acceptance among users in institutional contexts [7]. Their work validates that eliminating the necessity of handling physical cash which is what the Firebase balance system done by the Chai Station does is a significant element in the feasibility of a vending system to be used in the university and office environment.

A similar model in another area of implementation, an iot-based vending system that is cashless and includes a public health setting,

which Haque et al. apply to analyse the safety of the transactions in their cloud-based vending, has its analysis of the safety requirements of the cloud-based vending directly inform the non-volatile storage recovery mechanism used in the Chai Station [12].

According to Seno et al., a cloud-based smart kitchen automation and monitoring system is a combination of an embedded hardware control with a remote cloud interface to enable a real-time operational monitoring [13]. Their effort confirms their architecture, as the Chai Station admin panel utilizes the architecture with live temperature readings and machine status being pushed to Firebase and shown at the admin interface after every two seconds.

2.5 Automated Cooking- Induction Heating.

The decision to use induction heating to heat both boilers at the Chai Station is justified by the engineering texts on intelligent cooking devices. Chacón-Troya et al. report on an in-depth study of the design of smart induction stoves, the thermal response properties, the fidelity of control, and the benefits of induction heating over traditional resistive and gas heating in controlled cooking conditions [14]. Their results attest to the fact that induction heating offers significantly quicker thermal-response to control signals, which can be significant with a brewing system where the timing of each boil cycle hinges on how quickly the heater reacts to activation.

The fact that the two heaters utilized in the Chai Station are different denotes the various thermal needs of the two stages serviced by the heaters. The primary boiler has an infrared induction heater and this induction heater contributes to the high-intensity heating and rapid heating requirements of the vigorous multi-cycle boiling process. The intermediate holding boiler is fitted with a common induction heater that has lower continuous power to sustain serving temperature. This

dual-heater design came out of the knowledge, which had been validated by Chacón-Troya et al., that cooking phases are inherently different in thermal needs and are appropriate to hardware suited to those needs [14].

2.6 Food System Sensor-Based Process Control.

Patel and Doddamani present a general overview of the use of sensors in the food processing sector, which includes temperature sensor, level sensor, proximity sensor, and flow sensor in a variety of food production settings and environments [8]. The review formed by them determines that the quality and placement of the sensors that serve as feedback in automated food systems is a key factor in establishing reliable process control, a fact that influenced the sensor placement choices at the Chai Station. The temperature sensors are installed directly in the liquid contained in boiler and not measured on the surface or ambient temperature giving more correct and reactive readings of the actual brew temperature..

Buscaratto et al. also analyze the implementation of sensors into automated systems, in general, and food processing specifically, when it comes to the PLC and IoT device integration, in the context of PLC and IoT device integration [?]. Their research on merging conventional programmable controller logic with IoT-connected hardware is applicable to the design of the Chai Station, with the sequential operational logic running on the ESP32 executing a task similar to a PLC as well as the web interface and communicating with Firebase.

Sahara and Aamer discuss the idea of real-time data integration in an IoT-based smart warehouse, comparing the latency and reliability of sensor data transmission to cloud systems in the conditions of constant operations of the facilities [15]. Although the domain of their

application is not the same as the Chai Station, their conclusions about the behaviour of the IoT data integration when subjected to sustained polling (in real-time) can be applied to the live temperature and status monitoring feature of the admin panel.

2.7 Vending and dispensing: Embedded Microcontrollers

The application of the ESP32 microcontroller as the main control unit used in vending applications has been directly confirmed by Wicaksono et al. who explain a complete vending machine design based on the ESP32 platform with the control of the motor, sensors reading, web serving, and database communication involvement in the design of the vending machine [6]. Their achievements in the ESP32 performing multiple tasks at once, between controlling hardware and a web server, validate the appropriateness of the ESP32 to the architecture of Chai Station, with the firmware capable of simultaneously controlling hardware, pump, and servos, and remain receptive to the student and admin web browsers.

The non-blocking firmware architecture employed by the Chai Station that does not rely on blocking delay functions to keep the web server responsive to hardware operations was inspired directly by the observations of Wicaksono et al. in the importance of task concurrency in ESP32-based vending systems [6].

A relevant reference to the design of automated multi-step hardware sequences to include timed actuator operations and sensor-gated transitions is an automated conveyor-based food processing system described by Rambabu et al., constructed using an embedded microcontroller platform, which is relevant in this scenario as well due to its automated nature and the need to design multi-step sequences of actuators and sensors [16]. A relevant example to the

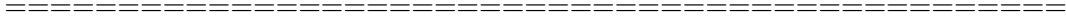
design of automated multi The operations of the timed pump filling, servo dispensing, and sensor-gated valve in the Chai Station are based on the similar architectural pattern.

2.8 IoT Data Systems in real time.

Sahara and Aamer consider the Chai station cloud integration based on a real-time data communication architecture which is studied in systems perspective by Sahara and Aamer [15] and in the periphery computing research by Rakhi in the study by Rakhi [17]. The role of low-latency local processing of control decisions made in time-critical control systems is described by Rakhi in his work on edge-AI-driven real-time control systems, and cloud communication is only used when there is no time-critical control decision, such as status reporting and user management. The Chai Station does precisely this: all time-sensitive control choices are made locally by the ESP32: boiling point detection, pump timing, activation of the valve, etc, and slower and less time-sensitive processes such as authentication and balance control are delegated to Firebase.

Such allocation of duties between the local embedded logic and the cloud data management is an established architectural trend in the IoT systems and is corroborated by numerous references in this review as the most suitable model in the context of vending and cooking automation applications where both the reliability of the operations and their manageability remotely are needed.

This division of responsibilities between local embedded logic and cloud data management is a well-established architectural pattern in IoT systems and is confirmed by multiple references in this review as the appropriate model for vending and cooking automation applications where both operational reliability and remote manageability are required [5] [13].



Chapter 3

Requirement Specifications

In a systematic and tangible manner, this chapter describes the requirements of the Chai Station. It starts with an appraisal of the current method of manual preparation which is to be substituted and its practical limitations analyzed. It is then proposed that the engineering answer to those limitations is the proposed system. This is followed by functional and non-functional requirements and use cases where students and administrators interact with the system. At the end of the chapter, the design methodology that was followed in the project is provided.

3.1 Current System: Manual Preparation of Tea

A manual method of tea preparation, which has not fundamentally changed over the past decades, is already in place in the offices and university departments, where the Chai Station will be deployed. A peon, a staff member who happens to be the one to be given the job to accomplish informally, or any other operator, fills a pot with milk and water in an appropriate proportion depending on experience, adds tea leaves and sometimes cardamom in a quantity dictated by experience, controls the amount of heat by a number of boiling cycles, adds sugar depending on the quantity desired depending on the expressed preference of the individual to whom it is being served, and This is done severally throughout the day.

There are a number of weaknesses associated with this arrangement. The result of each session will be different, as there is no control over any of the parameters, two operators will make chai that will be verifiably different even with the same set of inputs. Studies into automated food systems regularly find this form of operator-dependent variability as a key factor behind the automation of institutional food service [1]. Another issue is hygiene: shared pots, strainers and

serving tools in communal kitchen areas are hard to maintain at a consistent level of cleanliness unless there are stringent measures that are seldom taken above the board.

Probably the simplest issue is the time cost. Preparation of chai to a team cannot take less than the full attention of an individual. This is a tangible and repeated operational expense in an office or university in which that individual has additional responsibilities.



Figure 3.1: Traditional Manual Tea Preparation

3.2 Suggested System: Chai Station

The Chai Station will eliminate human participation in the manual process as it is fully automated with a brewing and dispensing mechanism that has no human interaction with the preparation. The user only interacts with the machine by using his or her phone: by picking the type of sugar and holding his cup but all the cumbersome work of pouring the liquid and boiling, transferring and serving is done by the machine.

The machine is constructed in a metal chassis that has three func-

tional areas arranged vertically. And the upper zone is the brewing zone: the primary boiler is located in this zone on its infrared induction heater, and tea leaf servo dispenser is located directly above the boiler opening such that leaning leaves only flow into the liquid due to gravity. The intermediate holding boiler is located in the middle zone on its standard induction heater, where the main boiler supplies brewed tea to the holding boiler, and it is kept at serving temperature. The bottom zone is the user interface serving zone: the cup outlet, the sugar servo dispenser with its ingredient container, the limit switch, and solenoid valve that empties the intermediate boiler into the cup of the user.

Water and milk are kept in different clean food grade stainless steel containers and pumped into the main boiler in the estimated ratio of seventy percent milk and thirty percent water - the proportions usually used in a batch of the traditional doodh pati. This proportional solution instead of set volume targets offers uniform taste amid batches of varying sizes and varies with the varying pump flow rates of the two liquids

3.3 Requirement Specifications

3.3.1 Functional Requirements

The Chai Station will implement the entire tea preparation and dispensing process. The functional requirements below dictate what the system should be able to do.

The system has to turn on its liquid pumps one by one i.e. milk then water to fill the main boiler to the desired percentage and then turn on the tea leaf servo to blow away the desired number of portions of the leaves to the main boiler. After loading the liquid and leaves, the infrared induction heater should turn on due to constant temperature monitoring of the of temperature sensor and should perform

a boiling cycle of three cycles. The end of each boil cycle is determined when the sensor detects that the temperature of the liquid has exceeded the boiling temperature set, whereupon the heater is temporarily de-energised and the next boil cycle commences. Once the third cycle is verified, the transfer solenoid should open with its calibrated time to permit the flow of brewed tea using gravity only to the intermediate boiler. The normal induction heater will then stabilize the intermediate boiler contents at the serving temperature via temperature sensor feedback control until the tea is dispensed.

On the user side, the system should have a web application - accessible (by any mobile browser connected to the same Wi-Fi network) that will display a login screen where an institutional enrollment ID and PIN can be entered, which will be verified against the Firebase data, where the available balance will be shown, and three sugar options (low, medium and high) will be shown, with the student being guided through the cup placement confirmation process with a countdown clock. The dispensing solenoid has to open after the limit switch recognizes the cup in place, and close after serving time. The system has to empty a balance and release a machine to the next user in case there is no cup inside the waiting window. Individually, an operator should be able to use a password-protected administration panel to initiate and terminate the brewing process, manually activate and deactivate specific hardware components, live boiler temperature and online status, work with student records and balances in Firebase, set the price, and post a notice that appears on the student interface [7].

3.3.2 Non-Functional Requirements

- **Reliability:** The system should be able to perform the entire brewing and dispensing process without breakdown in its normal operation except in the face of multiple cycles.
- **Consistency:** all the cups manufactured at the same level should be

similar in taste, temperature, and approximate volume to the previous cup at the same level..

- **Transaction Safety:** Student balances should be automatically readable after any power failure during an active purchase regardless of the stage of purchase without any user or admin intervention.
- **Hygiene:** The food-contact surfaces should be of food-grade stainless steel or food-safe printed material and contain no exposed untreated metals in the ingredient pathway [10].
- **Usability:** The student interface and the admin panel should be user-friendly by any user with access to a smartphone, without the need to prepare a specialist training. item security: Hardware access controls requiring password authentication should not be available on an ADM-only system.
- **Scalability:** It should be possible to add new student records to Firebase without having to modify the firmware of the machine.

3.4 System Interaction and User Role

The Chai Station system is accessed by three different user roles, which interact with various components of the system.

- **Students (End Users):** Students are the users of the service. All communication with the machine occurs via the web application on their phone - they log in, choose a sugar level, place their cup and collect their chai. Everything is processed in the machine.
- **System Administrator:** The administrator handles the operational aspect of the machine - starting a brew cycle, keeping track of live status, managing student accounts and balances, price, and receiving alerts such as a low-level warning or a interrupted brewing cycle [13].

- **Maintenance Personnel:** The technical employee will be tasked with physical maintenance - refilling ingredient containers, washing brewing vessels and repairing or maintaining any hardware that needs maintenance



Figure 3.2: Humans Interacting with Mobile Web

3.5 Design Methodology

The design method used in the Chai Station is modular and iterative base of development. This methodical process is in line with known practice in the development of embedded systems with the hardware and software developed together and validated jointly at each step of integration required [18].

3.5.1 Requirement Analysis

This started by first analyzing the needs of the two groups of users in detail. The needs of students were focused on simplicity, haste, and natural taste of tea. Administrator requirements were based on complete operational visibility and control without having to be physically at the machine. The requirements were aligned with hardware capability and software functionality prior to any design activity to make sure that all design decisions made could be traced to a particular user requirement.

3.5.2 System Architecture Design

The system was divided into functional modules that are independent of each other: liquid storage and pumping, dry ingredient dispensing, thermal processing and control, fluid transfer, temperature holding, web interface delivery, Firebase communication, and session management. All modules were defined separately then integration planning was undertaken; this made the design easier to manage and testing easier.

3.5.3 Component Selection

The selection of hardware parts was guided by compatibility with the Arduino IDE and the ESP32 development environment, the ability to obtain via local suppliers, food-safety characteristics of all food-contact parts, and the reliability of the parts in published applications. [6].

3.5.4 Microcontroller Selection: ESP32

One of the critical factors that determine the outcome of an Internet of Things embedded system design process is choosing the correct mi-

crocontroller, which will provide the peripheral support, connectivity features, development environment, and processing power necessary to carry out multiple functions simultaneously. Four microcontrollers have been reviewed based on the specifications of the Chai Station.

Table 3.1: Comparison of Microcontroller Options Evaluated for the Chai Station

Feature	ESP32	Arduino Mega	Raspberry Pi 4
Processor cores	2 (240 MHz)	1 (16 MHz)	4 (1.5 GHz)
Built-in Wi-Fi	Yes	No	Yes
Built-in Web Server	Yes	No	Yes
PWM outputs (servo)	16	15	4 (hardware)
ADC channels	18	16	0 (GPIO only)
Firestore library	Yes (Arduino)	No	Yes (Python)
Boot-up time	<1 second	Instant	30–60 sec
Power requirement	3.3V / 250mA	5V / 200mA	5V / 3A
Cost (relative)	Low	Medium	High
NVS (flash storage)	Yes	No (EEPROM)	Yes (SD card)
Selected	Yes	No	No

There were several criteria based on which we chose the ESP32 from among the remaining options [6]. In particular, the Arduino Mega was excluded because it does not support any of its own Wi-Fi features, does not have web server capabilities, and does not have any libraries for working with Firestore, which complicates further development of the project in its current form of implementation using the cloud-based architecture of Chai Station. Raspberry Pi 4 has a relatively boot time of 30 to 60 seconds, there is no ADC by default, as well as higher cost. These features are poorly suited to an embedded application for a vending machine, which should work instantly and stably throughout its entire operation. NodeMCU, which is similar to ESP32, is equipped with only one core, as well as a single ADC channel and fewer PWM channels, making it impossible to perform all tasks at once. ESP32 supports dual-core processing, Wi-Fi, 16 PWM channels, many ADCs for sensors to be added in the future,

NVS for transaction recovery, and extensive IDE for Arduino, which allows us to conclude that ESP32 is the best option in our case. [18].

3.5.5 Prototype Development and Testing

Individual testing of hardware components was followed by integration into subsystems and subsystem validation, followed by the integration of entire systems. This low-level methodology identified most hardware-related problems at the lowest level possible, making problems found during comprehensive testing of the system less complicated.

3.5.6 Final Integration and Evaluation

After subsystem testing and calibration, the entire machine was integrated in its final enclosure and taken through end-to-end testing through several operational cycles. Last calibration corrections were undertaken on observations during this phase and the system was compared with the requirements outlined in this chapter.

Chapter 4

System Design

System design is the stage at which the requirements described in the previous chapter are converted into specific engineering decisions. This chapter covers the complete design of the Chai Station at four levels: the overall system architecture, the hardware component design across the three physical zones of the machine, the software design including the sequential operational logic and web applications, and the Firebase database structure. Design constraints are examined at the end of the chapter.

4.1 System Architecture

4.1.1 Architectural Overview

The Chai Station is designed to have four interacting layers which combine to provide the entire experience of automated brewing and serving.

- **User Interface Layer:** There are two web apps directly served by the ESP32, a student interface with mobile responsiveness, and an administration control panel. They both are served as entire single-page HTML documents to the local network browser. It does not need any additional app installation, or special terminal hardware is required [7].
- **Control and Processing Layer:** The ESP32 microcontroller executes the sequential brewing logic, reads the digital temperature sensors, controls all the actuators via the relay module output, controls session timing and recovery logic, and maintains communication to Firebase.. Its dual-core design enables hardware control and web server functionality to run simultaneously and not block each other over the web server usage [6].
- **Hardware and Execution Layer:**This layer is comprised of all the physical components, pumps, servo motors, solenoid valves,

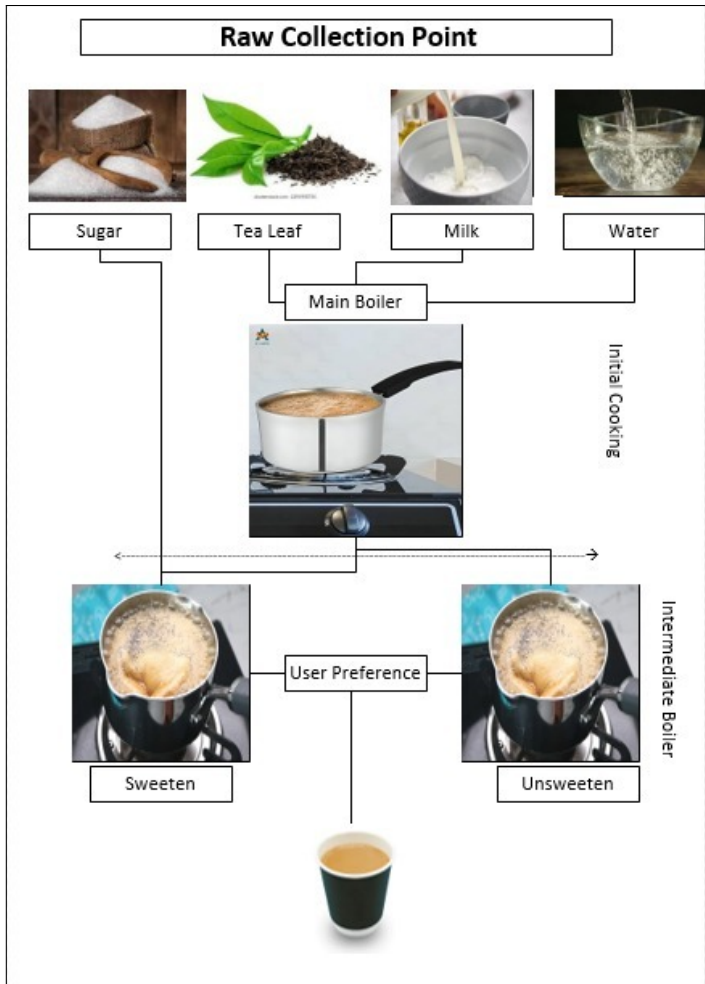


Figure 4.1: System Architecture

induction heaters and sensors. They are managed by the processing layer and offer the actual implementation of every stage of the brewing and dispensing flow [?].

- **Data and Communication Layer:** Google Firebase Real-time Database holds all the permanent data information student account records, transaction state, machine configuration, and machine operational status flags. Modifications to this database are displayed in real time throughout the student interface and the firmware, as well as in the admin panel [5].

4.1.2 System Components and Interactions

The entire tea preparation process is carried out in four stages that are related to the presence of certain hardware engagement in each of the three physical areas in the machine.

- **Liquid Filling:** The milk pump starts initially and removes the milk located in the upper-section storage container into the main boiler until the preset milk-filling time elapses. The order of sequence is then followed, where the water pump adds water. The mixture by volume results in a typical brewing batch of about seventy percent milk and thirty percent water per volume mix up, which is known as a standard brewing batch, though this can vary depending on the brewer, and subsequently the brewer, its production, and its consumption [3].
- **Brewing:** The tea leaf servo in the upper part pumps the required amount of portions into the main boiler. Infrared induction heater is activated with monitoring.. Each time the sensor detects that temperature in the liquid has attained the boiling point, a boil cycle is added. The heater de-energises momentarily to restart. This continues until the boil processes have been completed three times upon which the transfer solenoid is opened to transfer the brewed tea into the intermediate boiler.
- **Holding:** The brewed tea in the main boiler is fed to the intermediate boiler in the middle section which holds the tea at serving temperature (using the standard induction heater under control).
- **Serving:**The authentication process, together with the choice of a sugar level, is followed by placing a cup. The sugar servo installed in the bottom part starts dispensing the corresponding number of portions. The presence of a cup is determined by a limit switch. The dispensing solenoid opens to pour a portion of tea in a cup.

4.2 High Level Design

The High-Level Design describes the organisation of the device into five main modules, which match the four architectural layers outlined above.

The User Interface Module includes all user-related interaction processes like authentication and ordering and all admin-related interaction processes such as monitoring and control of the tea dispenser. The Ingredient Storage and Dispensing Module controls both liquid pumps and both servos. The Brewing and Thermal Control Module is responsible for controlling both the three-step boiling process and the temperature holding procedure. The Firebase Data Module handles all query requests and configurations for the authentication procedure, balance deduction, and state update processes. The Serving and Delivery Module takes care of the processes involved with detecting the cups and pouring the beverage.

4.3 Low Level Design

At the lowest design level, all individual components of the hardware platform communicate with the ESP32 via their designated interfaces types. For example, temperature sensors operate using one-wire buses to communicate their data, with all temperatures being read automatically by the DallasTemperature library in degrees Celsius. Servos require PWM inputs from the ESP32 hardware timers, with the rotation degree per dispensing pulse being configurable in the code. Relay module channels work with digital output pins from the ESP32, allowing all high voltage loads (e.g., pumps, solenoids, and heater elements) to be controlled in isolation with optocouplers. Float sensors and limit switches deliver digital input readings to the firmware that determine their current states [8].

4.4 Hardware Component Design

4.4.1 Enclosure and Physical Layout

The enclosure is made of a powder-coated mild steel frame partitioned by two horizontally welded shelves into three distinct inner zones. All equipment in contact with food is manufactured from food-grade stainless steel. Interconnection between components utilises food-grade silicone tubing with push-fit connectors.

4.4.2 Upper Section: Main Boiler and Brewing Assembly

The main boiler is positioned in the upper section on the infrared induction heater. A sensor probe is inserted through a sealed food-safe port in the vessel wall. The milk and water storage containers sit at this level with their pumps delivering liquid into the boiler from above. The tea leaf servo dispenser, consisting of an servo motor coupled to a 3D-printed rotating pocket wheel, is mounted above the boiler opening so that dispensed material falls into the liquid by gravity.

4.4.3 Middle Section: Intermediate Boiler and Holding Assembly

The intermediate holding boiler which is fully insulated is in the middle section sits on its standard induction heater. A second sensor monitors this vessel. The transfer solenoid valve is fitted in the pipe connecting the main boiler drain to the insulated intermediate boiler inlet at this level, enabling gravity-assisted transfer when activated.

4.4.4 Lower Section: Serving Assembly

In this lower section, there are all user-facing components. Cup outlet is placed at a practical height for placing a cup. Sugar servo dispenser (which has a very similar construction as that of tea leaf dispenser except that it is calibrated for dispensing sugar granules) is placed along with its container. A limit switch is positioned at the outlet hole in order to detect the presence of a cup. Dispensing solenoid valve at the base of the intermediate boiler is also placed in this area.

4.4.5 3D-Printed Pocket-Wheel Dispensers

There are two dispensers of pocket-wheel type. Pocket wheels are cylindrical drums with precise pocket geometry designed and then printed from food-safe PLA material. Rotating through at angle moves one pocket from ingredient hopper into the vessel. Dispenser pockets volume was calibrated through weight measurement per actuation cycle. Sugar dispenser makes one, two, or three revolutions for low, medium, and high-sugar beverages respectively [16].

figure

4.4.6 Dallas Temperature Sensors

Temperature sensor is used in boiler. The DS18B20 communicates through the single-wire interface and provides accurate measurements in degrees Celsius without needing an external calibration formula. The digital output makes it less susceptible to electromagnetic interferences from the relays controlling the induction heaters. This is an important feature as any other analog temperature sensor will not tolerate the noise caused due to the relay switches. [8].



Figure 4.2: 3D-Printed Rotating Pocket-Wheel

4.5 Software Architecture

4.5.1 Sequential Operational Logic

Brewing and Serving Process is controlled via sequential operational logic, which is written as non-blocking switch-case in the main ESP32 code loop. Non-blocking operation of the main code is important, because the ESP32 has to receive HTTP (hypertext transfer protocol) requests from both student and admin browsers all through the brewing process. Blocking operations in any phase would make the web interface unresponsive; and this was observed and confirmed in our tests. [6].

The sequential phases, one by one, are as follows: wait (machine ready but waiting for admin command), fill liquid (liquid is filled in sequence, milk followed by water), dry dispensing (tea leaves are dispensed), boiling (IR induction heating), transfer (transfer solenoid



Figure 4.3: Temperature Sensor

opens), holding (insulated intermediate boiler at serving temperature, student purchasing possible), sugar selection (input from user required), sugar dispensing (servo actuated to dispense sugar), cup detection (limit switch waits for input), serving (serving solenoid actuated), and shutdown (shutdown state).

4.5.2 Firebase Database Design

The Firebase database design consists of two main branches. The student account branch holds the account of each individual student in the form of the record containing the full name of the user, PIN number, and his/her current balance in Pakistani Rupees. This allows for simple authentication as well as batch read operations for the administration panel of the student management table.

The machine states branch holds various states such as operational phase name, flag to mark whether an admin has initiated a brewing

process or not, price per cup, level detection flag based on float sensor value, flag showing interruption of the brew due to power failure and notice field for displaying the message from the administration panel on the student interface [15]. The third temporary branch holds the active transaction details including the identity of the current student transaction as well as the balance prior to deduction, allowing the recovery process following the power failure to find the student and restore the transaction balance in the Firebase database.

4.5.3 Web Application Design

Student web application is loaded from ESP32 internal flash memory as a raw string literal and provided as one HTML file within one HTTP request as the whole page. Eight screens are provided within the single page by changing CSS classes in JavaScript without making any additional requests to the server. Screens include login screen, balance display, balance purchase, selection of sugar, countdown before placing the cup, dispensing animation screen, completion screen, machine busy waiting screen, and level courtesy notice screen. While active, the application sends heartbeat request to ESP32 every eight seconds. In case ESP32 did not receive any request for thirty seconds, the connection will be considered abandoned, transaction balance will be restored in the Firebase database, and machine released back to use [13]. The same way that the student application is hosted, the administration control panel is hosted. However, polling is used to update the operational phase information, temperature readings, and current alert status. It asks the machine for the current state parameters every two seconds. All other operations, such as starting the brewing process, manually triggering components, managing student accounts, changing prices, and publishing notices, have been done by sending simple HTTP requests to the ESP32 firmware handler.

4.5.4 Safety and Power Cutoff Recovery

There are two distinct safety systems that prevent loss of balance due to situations that may not be under the user's control. Session abandonment is managed using the previously outlined heartbeat functionality, which detects if the browser closes and automatically refunds the user. In case of power failure, all the relevant data are stored in the internal non-volatile memory on the ESP32 chip; at every step of the active transaction, the firmware stores the user identity, the pre-purchase balance, and the transaction phase in the internal flash. On every restart, prior to any action, the firmware checks this memory and refills the balance at Firebase if any trace of an unfinished transaction is detected. Thus, even a power loss immediately following a balance withdrawal and before tea dispensation will result in an automatic full refund on power recovery [12].

4.5.5 Hardware Constraints

The ESP32 microcontroller has a limited number of usable I/O pins, each with their own unique hardware attributes for some. Pin assignments were selected to ensure that all peripherals are connected to the correct type of pin without interfering with each other's functioning and without any clashes between the one-wire data bus, the PWM outputs, the relay signals, and digital sensor inputs.

4.6 System Flow Diagram

4.7 Design Constraints

The ESP32 microcontroller has a limited number of usable I/O pins, each with their own unique hardware attributes for some. Pin assignments were selected to ensure that all peripherals are connected

to the correct type of pin without interfering with each other's functioning and without any clashes between the one-wire data bus, the PWM outputs, the relay signals, and digital sensor inputs.

4.7.1 Safety Constraints

All mains voltage devices are controlled via isolated relay module channels. Temperature threshold values in the firmware software disable the heaters when abnormal sensor readings are recorded. The solenoid actuating dispensation can only activate when the limit switch detects the cup.

4.7.2 Food Safety Constraints

The entire food-contact path consists of only food-grade stainless steel or food-safe PLA. No untreated metal or non-food-safe glue is used in any component of the ingredient dispensation path [10].

4.7.3 Firebase Connectivity Constraint

Internet connectivity is required for any operations with Firebase. Errors from failed Firebase requests return a clear message to the firmware software; this prevents the firmware from getting stuck in a fault state. The machine is intended to be deployed within institutional environments, where there is reliable internet availability

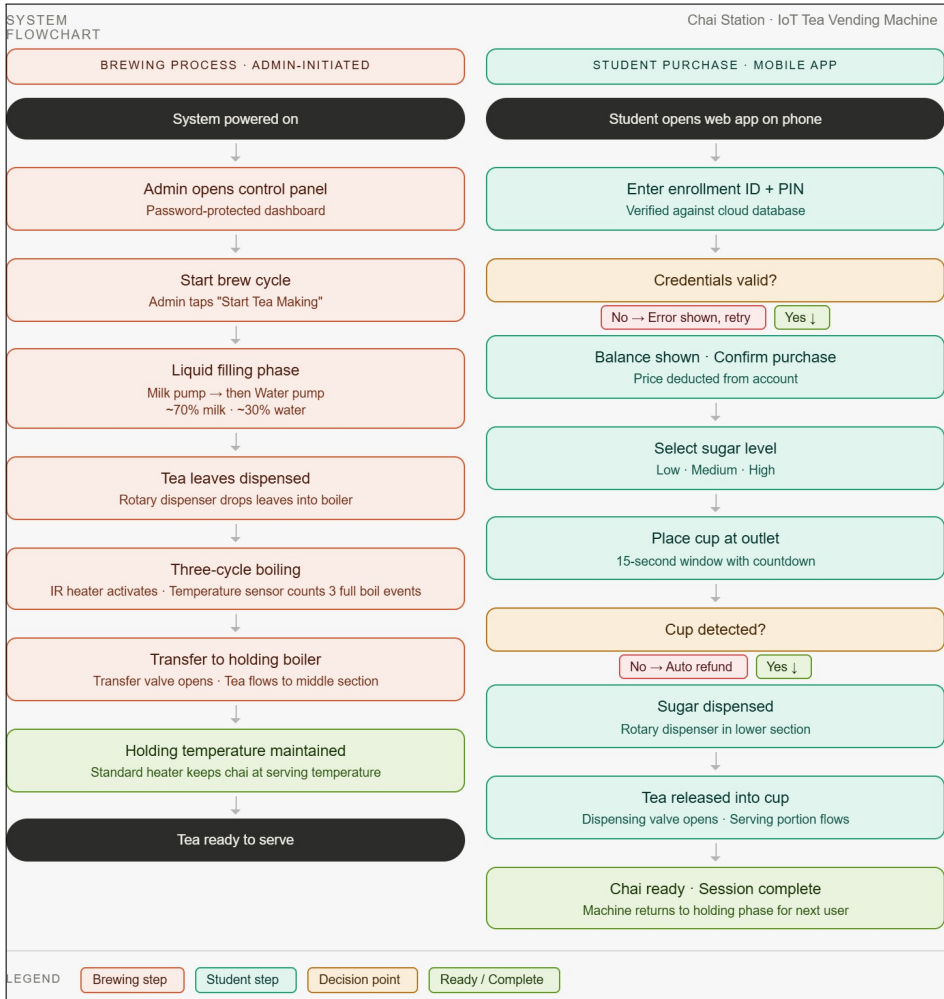


Figure 4.4: Chai Station Complete System Flowchart

Chapter 5

System Implementation

This chapter explains the process of transforming the designs outlined in Chapter 3 into a functional hardware machine. Topics covered include the manufacture of the frame and internal compartments, electronic and wiring assembly, the development environment and important features of the firmware code, and calibration procedures before testing began.

5.1 Physical Construction

5.1.1 Frame and Enclosure

The outer enclosure is constructed from mild steel frame members fabricated by cutting, welding, and bolting them to form a rigid structure that is separated internally into three zones by horizontal shelves welded onto the structure. After manufacture, the frame is then powder coated to protect against corrosion. All food contact vessels (storage vessels and both boilers) are made of food-grade stainless steel. All interconnects between vessels are made of food grade silicone tubing connected via push fit joints. Thus, all fluid path components can be easily disconnected manually for cleaning purposes.

5.1.2 Upper Section Assembly

Main boiler vessel is mounted on the infrared induction heater in the upper section. Temperature sensor is inserted into a food-safe port on the wall of the boiler vessel before assembly. Delivery tubes for milk and water from their storage tanks pass through the cable management to reach their respective inlets on the boiler in this section. Tea leaves servo dispenser (motor placed inside 3D printed body attached to the pocket wheel mechanism) is mounted on a holder above the boiler entrance.



Figure 5.1: Upper Section

5.1.3 Middle Section Assembly

Insulated intermediate holding boiler is mounted on the induction heater in the middle section. Intermediate boiler's temperature sensor is likewise installed. Transfer solenoid valve is fitted to the pipe linking main boiler's drainage point to the intermediate boiler's entrance to enable tea transfer due to gravity when actuated.

5.1.4 Lower Section Assembly

In the lower section, cup outlet, sugar servo dispenser with its storage tank, limit switch, and dispensing solenoid valve are mounted. The lower section was designed to remain uncluttered for easy access while users stand in front of the tea brewer.



Figure 5.2: Middle Section

5.1.5 3D-Printed Dispenser Assembly

The assembly of each 3D-printed dispenser consists of mounting of the servo inside its holder, connecting the pocket wheel to the shaft of the servo, placing the ingredient hopper above the wheel, and tuning the shaft connector until there was no slippage during rotation. Assembled dispensers are shown in Figure 5.4.

5.2 Electronics and Wiring

5.2.1 Power Supply Architecture

Three power rails are employed in the circuitry of the system; 220 V AC is used in induction heaters controlled via relays, 12 V DC is used in pump and solenoid valves circuitry, and 5V DC in ESP32 board and sensor circuitries..



Figure 5.3: Lower Section

5.2.2 Relay Module and Component Wiring

An eight-channel relay module controls access between ESP32 logic output pins and all high-voltage loads. Channels correspond to the milk pump, water pump, transfer solenoid, dispensing solenoid, infrared induction heater, and standard induction heater. Optocoupler circuit stages offer electrical isolation between ESP32 and loads switching circuits [18].

5.3 Tools and Technology Used

ESP32 Microcontroller

This microcontroller serves as the control core for the Chai Station. It manages hardware I/O operations, operates sequential brewing logic, serves a web server, and interacts with Firebase services — all concurrently, through dual-core FreeRTOS operation separating

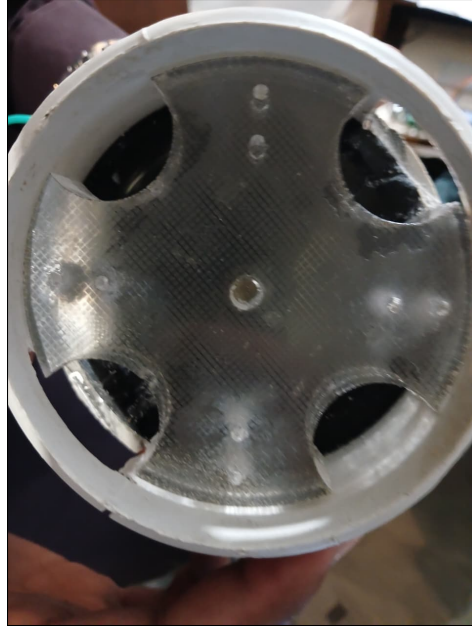


Figure 5.4: 3D-Printed Pocket-Wheel

hardware-critical tasks and web server handling to different processor cores [6]. All firmware development was done in C++ using the ESP32 core provided in Arduino IDE.

Induction Heaters

Two kinds of heaters are used. The main boiler uses infrared induction heater with high power and efficiency suitable for rapid multi-step boiling. Intermediate boiler heater works at low constant power and used to maintain temperature. Controlled with the help of relay modules. [14].

Servo Motors and 3D-Printed Dispensers

Two SG90 servomotors rotate dispensers with pockets inside, controlled by ESP32's PWM outputs. Pocket wheels have been printed from food-safe PLA. [16].

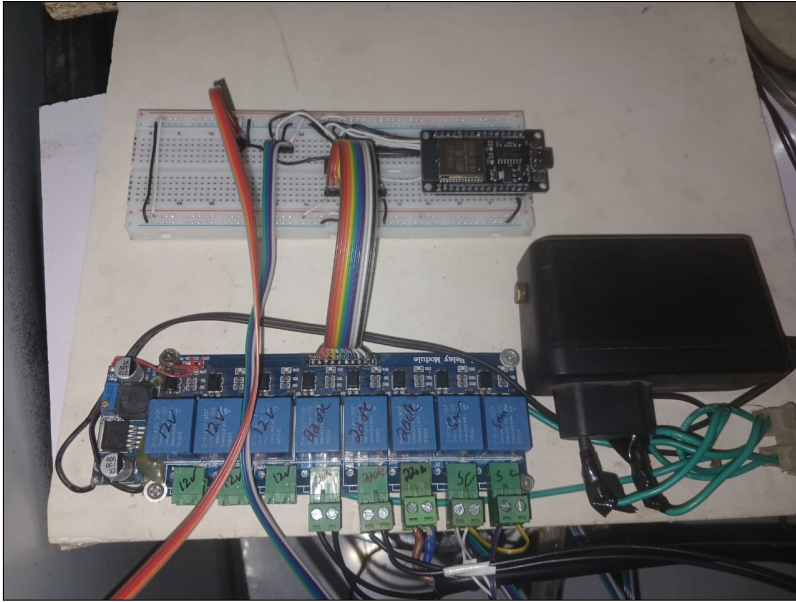


Figure 5.5: Relay's & Power Supply Architecture

Dallas Temperature Sensors

These sensors give temperature readings for both boilers. Communication occurs via one-wire interface and readout performed with DallasTemperature library in degrees Celsius without conversions required [19].

Liquid Pumps and Solenoid Valves

Two 12V submersible pumps are used to transport milk and water from their respective storage tanks to main boiler. There are two solenoids regulating main-to-intermediate boiler transfer and beverage dispensing through valve installed on lower boiler. .

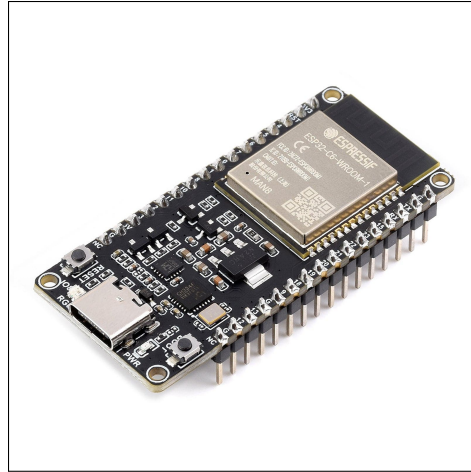


Figure 5.6: ESP32 Microcontroller



Figure 5.7: Servo Motor

5.4 Development and Libraries Used

The code was written in the Arduino IDE in C++. Used libraries are: Wi-Fi, WebServer for networking; FirebaseESP32 for Firebase RTDB API requests; OneWire, DallasTemperature for communication with temperature sensor; ESP32Servo for controlling servos by generating PWM-signal on pin; and Preferences for accessing non-volatile storage.

5.5 Firmware Implementation

5.5.1 Temperature Reading

Reading of temperatures is carried out using the DallasTemperature library. Each poll of the temperature data in the main loop requests temperature readings from both sensors and then compares the results against threshold values to execute the correct heating control logic. Digital interface with the DS18B20 temperature sensors means that there is no interference from relays controlling induction heaters.

5.5.2 Brewing Sequence Logic

All operations are carried out according to a non-blocking switch-case statement. All timing and conditional checks are done by comparing against start timestamps only. No delays are involved; timing is based on the comparison between timestamps. This guarantees high performance even when serving many students [6].

Each transition of phases updates corresponding local variables and sends the name of the phase to Firebase for updating in real time on the admin panel. Firebase RTDB API call takes place asynchronously where possible to reduce additional delay of the control loop.

5.5.3 Session Management and Transaction Recovery

Keep-alive functionality of the web app sends an HTTP request to the firmware every eight seconds during an active session. Timestamp of each such request is recorded by the firmware. When no new request comes in the span of thirty seconds, firmware restores the student's balance to Firebase and resets to the holding phase. It handles the case where a student closes their browser after making payment but not getting their tea yet.

Recovery from non-volatile storage is done by recording the identifier of the student, the value of the balance prior to purchase and the current phase of operation into ESP32's internal flash memory at each step of a purchase transaction. Upon boot, the firmware accesses this storage and sends the stored value of the balance to Firebase before doing anything else [12].

5.6 Calibration Procedures

Pump calibration: Each pump was operated for a variety of durations, and the amount delivered was measured using a graduated measuring jug. Time was adjusted to ensure that the correct seventy-thirty milk-water ratio was delivered consistently across multiple test cycles.

Servo dispenser calibration: For each dispenser, actuations were attempted for various step sizes and step counts per operation. These values were adjusted to give the desired dose of tea leaves and sugars in all three sugar concentration settings.

Transfer timing: The timing of the transfer solenoid was measured by filling the main boiler with the usual batch size and measuring how long it took to empty the boiler through the transfer valve, adding extra time to account for worst-case conditions.

DS18B20 sensor verification: Each temperature sensor was compared with the reference thermometer at various temperatures in the operational range. There was no noticeable systematic offset, verifying that no firmware compensation was necessary.

Chapter 6

System Testing and Evaluation

System testing is the phase where the fully-assembled machine is evaluated according to its design specification, using real-world conditions. This chapter presents the results of the system tests carried out for the Chai Station in four categories: control circuit simulation testing, component testing, software and cloud integration testing, and integration testing.

6.1 Control Circuit Simulation Testing

Before building the control circuit itself, a simulation was constructed in Proteus. This simulation included relay channel assignment, signals sent to each servo, the one-wire behavior of the DS18B20s, and basic pump and solenoid timings.

Various issues in the wiring configuration, such as relay channel directionality and an incorrectly-calculated pull-up resistor value for the DS18B20 sensors, were found and fixed in simulation prior to building the actual hardware, ensuring that these could not harm the circuit at power-up.

6.2 Hardware Component Testing

6.2.1 Pump and Liquid Delivery Testing

Each pump was individually tested prior to integration into the overall control circuit. It was operated for its predetermined duration for ten iterations and the delivered volume was measured for each operation. Both pumps yielded consistent performance over all ten runs, and then the combined fill was conducted, verifying that sequential operation of pumps was working to the required 70:30 milk-to-water ratio within acceptable limits.

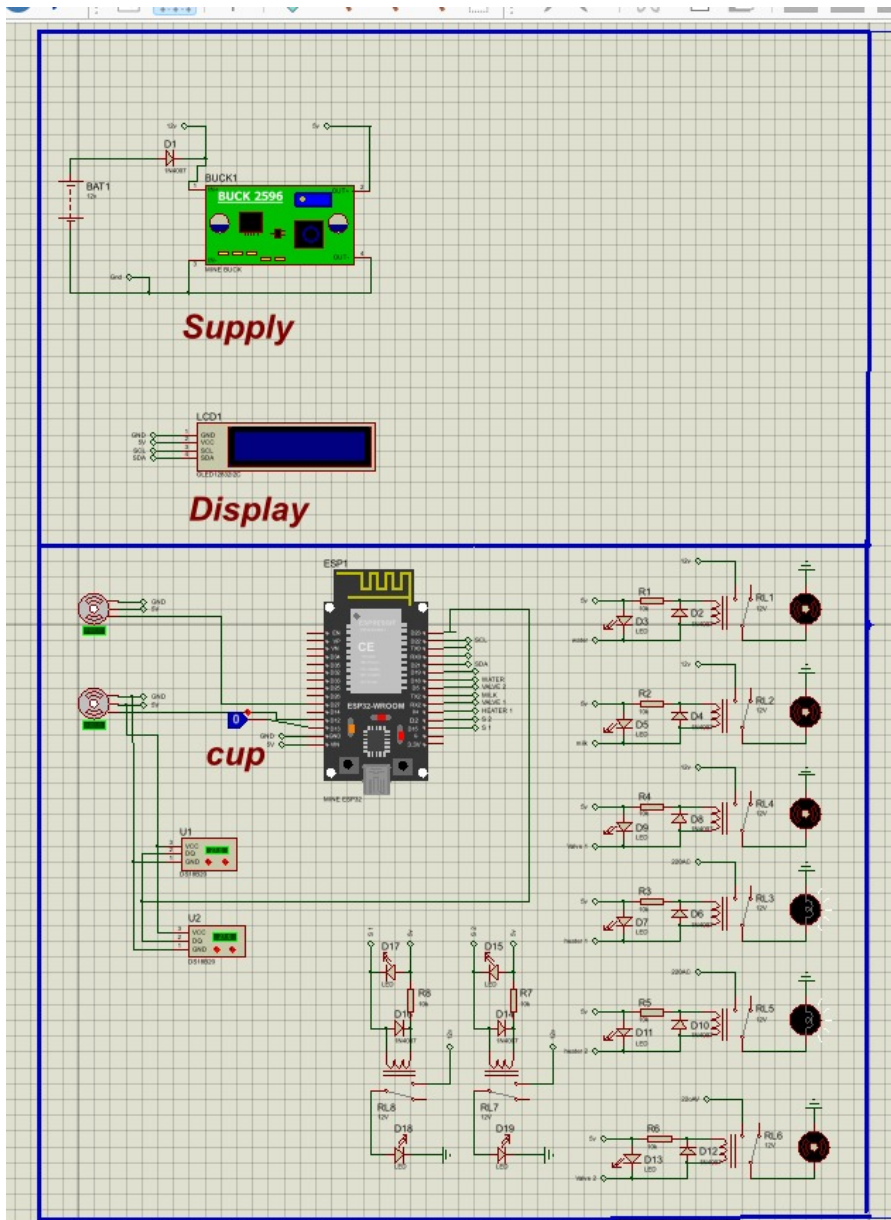


Figure 6.1: Caption

6.2.2 Temperature Sensor Testing

The temperature sensors were tested and compared to a calibrated reference thermometer at four points within their operating range. The sensors showed sensor values as per the reference values in the sensor specification within its accuracy range. Furthermore, no noise changes were noticed in the case where the relay-switched induction heaters were used at the same time, which demonstrated the electromagnetic-immunity of the digital sensors in the circuit environment.

6.2.3 Three-Cycle Boiling Verification

The boiling sequence was experimented by loading the standard batch volume into the main boiler and monitored the firmware output in the Arduino IDE Serial Monitor. During all tests, the number of boil events was three, which were detected and counted before the switch of the firmware to the transfer stage. The infrared induction heater was found to be able to quickly heat the batch to boiling, and the values were consistent and responsive across the board.

6.2.4 Temperature Holding Verification

The medium boiler holding was put to the test more than half an hour without dispensing. DS18B20 values were recorded at half of a minute. The on-off control of the firmware ensured that temperature stay within the set holding band at all times, ensuring that tea brewed would stay at an acceptable serving temperature during longer wait times.



Figure 6.2: 3 Cycle Testing Of Temperatue Sensor

6.2.5 Servo Dispenser Testing

All dispensers underwent fifty actuation cycles with the amount of dispensed mass read on a mass scale in-between every ten actuation cycles. The output of tea leaf dispenser was consistent in all the fifty cycles. The sugar dispenser was experimented at three different levels, i.e., one, two and three steps and mass delivered per cycle was recorded separately. The amount of quantity and consistent output in each level was easily recognizable and dependable, a fact that validated dependable portion control [16].

6.2.6 Solenoid Valve and Sensor Testing

The transfer solenoid was confirmed to fully drain the main boiler within the calibrated open duration across five separate test runs. The dispensing solenoid was tested against the limit switch interlock: it did not open when no cup was present, and opened correctly each

time the switch registered a cup in position. Cup detection was tested with three different cup sizes and two different materials to confirm consistent detection across practical usage scenarios.

6.3 Software and Firebase Testing

6.3.1 Authentication and Balance Testing

Login was tested with valid and invalid credentials across several test accounts. Valid combinations returned the correct student name and balance from Firebase in all cases. Invalid credentials and unrecognised enrollment IDs returned appropriate error messages. Balance deductions were verified by comparing Firebase records before and after each test purchase — the correct amount was deducted and reflected immediately in each case.

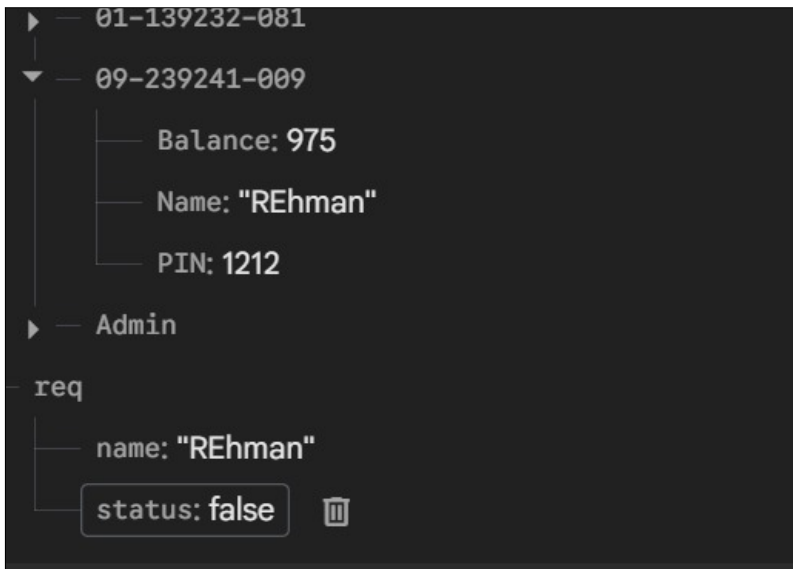


Figure 6.3: Firebase Realtime Database Console Showing Student Records and Machine State

6.3.2 Power Recovery Testing

The mechanism of transaction recovery was also tested by cutting power off just after a deduction of the balance but before dispensing tea. At restart, the system loaded the non-volatile storage data on the transaction saved into the system, and the entire balance was restored to Firebase, and the system was again put into normal operation. This test was carried out three times with power outages at three points of the purchase sequence and proper recovery was ensured in all of them [12].

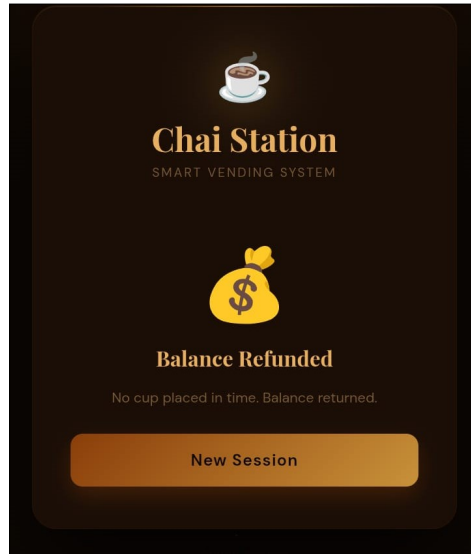


Figure 6.4: Power Recovery

6.3.3 Web Interface Cross-Device Testing

A cross-device testing of the web interface is conducted.

Android (Chrome), iOS (Safari), and Windows desktop (Chrome) were used to test the student web application. The interface loaded, displayed and navigated well on all platforms. The eight screens were checked to change appropriately. The administration panel was

tested.

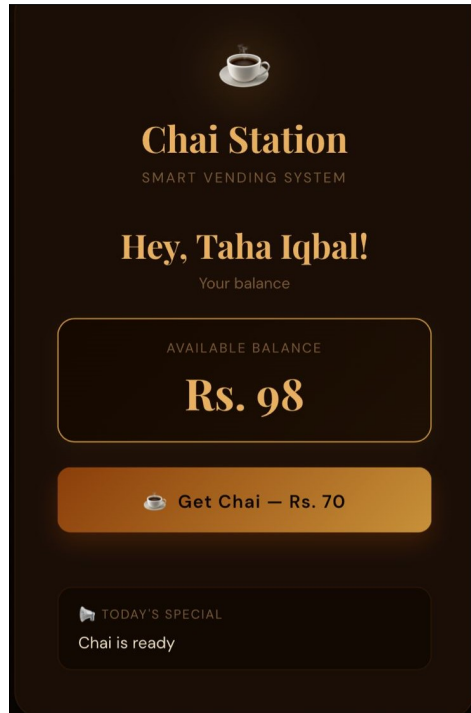


Figure 6.5: Bewring

6.4 Hardware-Software Integration Testing

6.4.1 End-to-End Cycle Validation

The fully assembled machine was used to run ten full brewing and dispensing cycles. Every cycle was initiated by an administration order in the form of a brew in the form of an admin panel and ended with a student verification, the choice of the sugar level, the placing of a cup, and the delivery of a cup of tea dispensed. The brewing process was carried out properly in every ten cycles. Each of the three boil events were counted correctly. Transfer of tea, maintenance of temperature and dispensing of students all went as planned. we were able to evaluate tea quality. The chai was reported to be tasting in

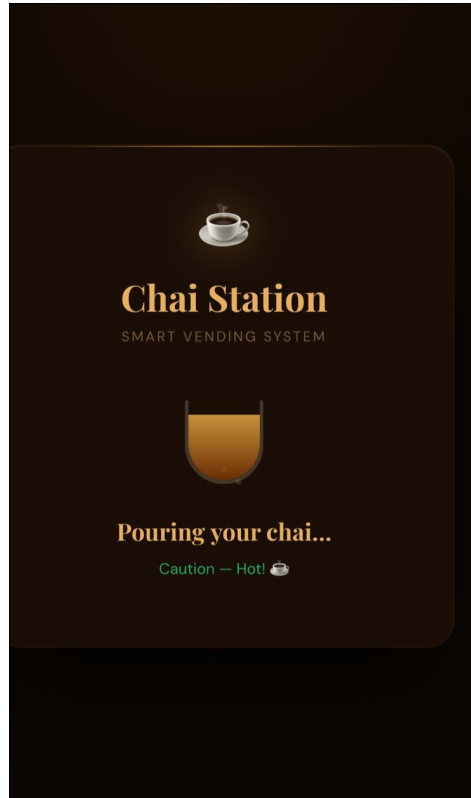


Figure 6.6: Student Web Application Tested Simultaneously

line with traditionally brewed doodh pati in both taste and temperature in each tasting, which is the main quality need of the project.

6.4.2 Concurrent Web and Hardware Operation Testing

The machine was at active hardware states of filling, boiling and transfer when HTTP requests were sent to both student and admin endpoints. All the cases of web interface response were timely, and the non-blocking firmware architecture enforced web server responsiveness at all hardware stages. [6].

6.4.3 Live Operation Testing of the Admin Panel

Live machine operation was carried out to exercise all the functions of the admin panel. Brew initiation, emergency stop, triggering of individual hardware components, student top-up, new student registration, student removal, price update and publishing of notices were all tested. All performed as expected. The display of live temperature and state updated after every two seconds.

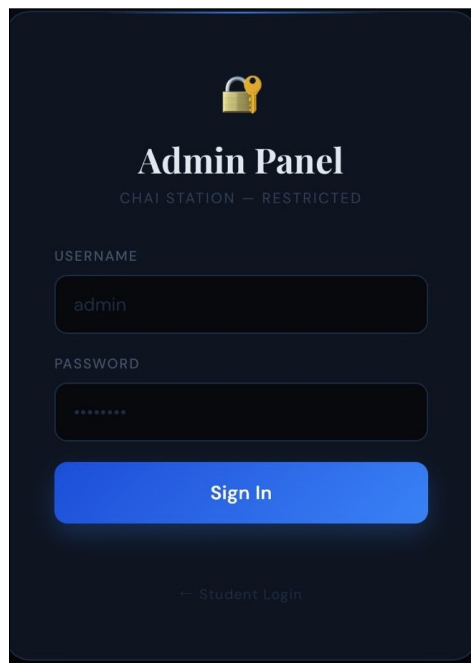


Figure 6.7: Admin Interface

6.5 Limitations Identified During Testing

Discovery of four areas to improve on in the future. The Wi-Fi range of the ESP32 is about fifteen metres with standard office conditions, which would restrict its use in a wider-floor plan without a network extender. The switching of the intermediate boiler heater causes

small temperature swings around the holding setpoint; a proportional control algorithm would decrease this. The dispenser wheels were 3D-printed and displayed slight surface wear in the upper part in long-term high-temperature tests, suggesting that machined stainless steel components would be more durable for high-volume long-term deployments. Admin session management currently uses an in-memory flag rather than a cryptographic token, which is appropriate for a closed institutional network but would require strengthening for any public-facing deployment.

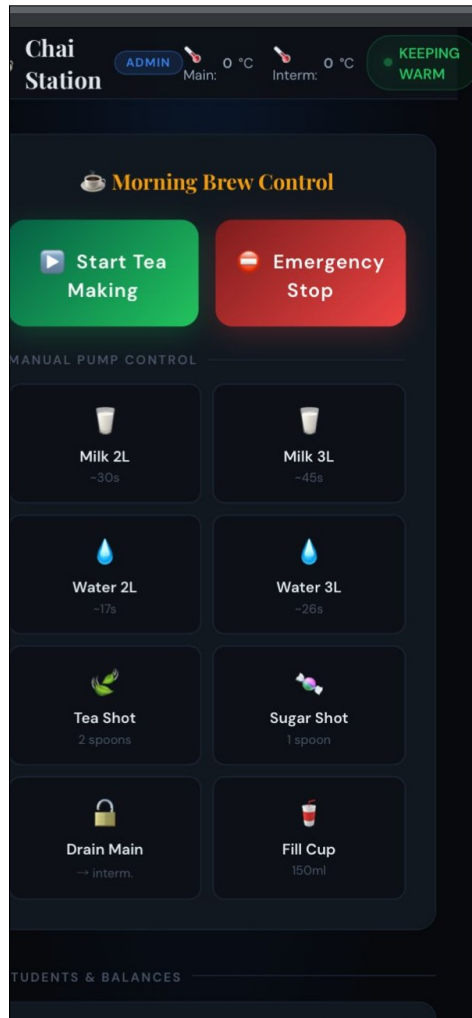


Figure 6.8: Admin Panel Displaying Live Machine

Chapter 7

Conclusion

This thesis has detailed the overall design, development, and testing of the Chai Station - an IoT-based automated tea vending machine that has been installed in order to brew traditional Pakistani milk tea using raw materials and dispense customised cups to users of the institution who authenticate by using a mobile web-based platform. The project was inspired by an actual and realistic need: the current automated vending systems lack the production of true brewed chai, and manual preparation in institutional settings is erratic, unhygienic, and inefficient. The purpose of constructing the Chai Station was to seal that divide, rather than to approximate the result using another approach.

The system is entirely controlled by a single ESP32 microcontroller which also handles hardware control, real-time temperature monitoring, a locally hosted web server, and synchronised communication with Google Firebase Realtime Database. The physical machine is structured into three service areas: an upper brewing area in which the primary boiler and tea leaf dispenser are located to prepare the three-cycle milk tea under infrared induction heating, a middle holding area where the intermediate boiler is found to hold the brewed tea at serving temperature, and a lower serving area where the sugar dispenser, limit switch, and dispensing solenoid dispense individual cups to authenticated students. The whole operation is controlled by a sequential operational logic that does not block and ensures that the web interface remains responsive at each of the hardware stages. Non volatile storage-backed transaction recovery guarantees that in Firebase student balances will be automatically restored after any power outage, no matter which part of a purchase the power outage happened. The ten full brewing and dispensing cycles ensured the quality of tea was stable, the three-cycle boiling was performed properly, Firebase was properly integrated, and web interfaces responded to Android, iOS, and desktop systems.

This project has the following key contributions.

- A working model of an IoT-controlled automated chai vending machine that performs an authentic three-cycle doodh pati brewing process with raw milk, water, tea leaves, and sugar in its proper seventy-thirty ratio.
- Full Firebase Realtime Database implementation with an institutional user management that is persistent, balance tracking in real time, and recovery of transactions during power outages.
- A student web application, mobile-responsive, authenticated by enrollment, three-level sugar personalisation, and heartbeat-based session management to secure balances, even in case of unexpected browser session abandonment.
- Supported by a complete administration control panel that will show real time temperature readings, manual control of hardware, Firebase-powered student database management and operational alerts in real time, all directly served by the ESP32 without a remote server..
- A physically designed three-zone structure with top-to-bottom process flow: brewing at the top, temperature holding at the middle, and user-friendly serving at the bottom - developing a rational, maintainable, and sanitary machine layout.

As the Chai Station has shown, culturally sensitive automation of a daily institutional ritual can be developed on a single inexpensive microcontroller with open-source software and free-tier cloud services, and we hope that the work can serve as a useful starting-point to others working on smart institutional vending solutions in the Pakistani and South Asian environment.

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