

PROJECT PROPOSAL: CLOSED-LOOP HIGH-ACCURACY UNIVERSAL DRINK SYSTEM

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Project Proposal for ECE 445, Senior Design, Fall 2026

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18 September 2026

Team No. 50

Contents

1. Introduction.....	3
1.1 Problem.....	3
1.2 Solution And Visual Aid.....	3
1.3 High Level Requirements.....	4
2 Design.....	5
2.1 Block Diagram and Mechanical Drawings.....	5
2.2 Subsystem Overview.....	5
2.2.1 User Interface and Main Controller Subsystem.....	5
2.2.2 Ingredient Dispensing Subsystem.....	6
2.2.3 Load-Cell Measurement Subsystem.....	6
2.2.4 Adaptive Dispensing and Fault-Detection Subsystem.....	7
2.3 Subsystem Requirements.....	7
2.3.1 User Interface and Main Controller Subsystem Requirements.....	7
2.3.2 Ingredient Dispensing Subsystem Requirements.....	8
2.3.3 Load-Cell Measurement Subsystem Requirements.....	8
2.3.4 Adaptive Dispensing and Fault-Detection Subsystem Requirements.....	8
2.4 Tolerance Analysis.....	9
3. Impact and Standards – Ethics, Safety, Societal Impact, and Standards.....	9
3.1 Ethics.....	9
3.2 Safety.....	9
3.3 Societal Impact.....	10
3.4 Standards.....	10

1. Introduction

1.1 Problem

Preparing mixed beverages with a consistent ratio of ingredients requires precise control over the amount of liquid ingredients. Many autonomous beverage machines rely on predetermined pump activation time to dispense the different liquids. This method assumes that the pump will maintain a constant flow rate.

In reality, there are many factors that would affect the flow rate, such as the difference in liquid viscosity, reservoir level, tubing condition, and the pump performance. This means that activating the pump for the same amount of time does not guarantee that the pumps dispense the same amount of liquid each time. Even a tiny dispensing error can result in an altered ratio of a mixed drink.

The goal of this project is to develop an automated beverage dispensing system that measures the amount of liquid actually delivered to the cup and uses that measurement as feedback. This allows the system to compensate for the different factors that affect flow rate instead of relying on preprogrammed pumping times.

1.2 Solution And Visual Aid

Our proposed solution is a closed-loop automated beverage dispensing system capable of managing at least four independently controlled liquid ingredients. Dispensing is driven by 12 V peristaltic pumps that deliver liquid directly into a cup positioned on a load-cell weighing platform, with an ESP32-S3 microcontroller serving as the central control unit.

During operation, the controller continuously monitors real-time changes in mass via the load cell and compares them to the targeted ingredient quantities. To prevent overshoot, the system dynamically adjusts pump operation by running continuously during the initial stage, then throttling the flow rate or applying brief pump pulses as the target mass is approached. Furthermore, the ESP32 estimates flow rates by analyzing mass changes over time, enabling real-time adaptation to variables such as pump wear, fluid viscosity, tubing resistance, and reservoir level fluctuations.

User interaction is managed through a local web interface hosted directly on the ESP32. Through this interface, users can select preconfigured recipes or customize beverages, set precise ingredient amounts, initiate or halt dispensing operations, and monitor system status in real time.

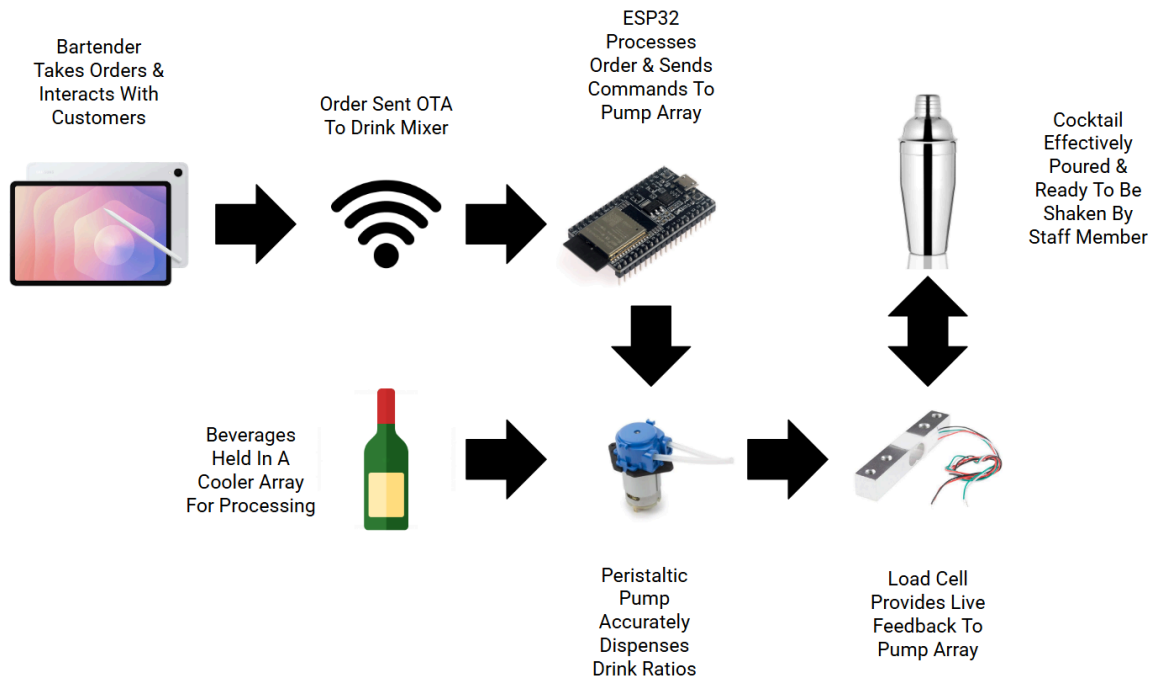


Figure 1 Visual Aid: A high-level block diagram illustrating the data and product flow for the average use case.

1.3 High Level Requirements

Requirement	Quantitative Analysis
Dispensing Accuracy	For requested ingredient quantities between 20 g and 150 g, the system shall dispense each ingredient within $\pm 5\%$ of the requested mass or ± 2 g.
Flow Rate Adaptation	The system will have a dispensing accuracy requirement during flow rate changes of up to $\pm 20\%$ relative to the initial calibrated flow rate of any off-the-shelf pump.
Fault Detection	If a pump is activated but the measured cup mass does not increase sufficiently, the system will stop dispensing and report a fault within 5 seconds. The system will also prevent dispensing when no cup is detected on the load-cell platform.

2 Design

2.1 Block Diagram and Mechanical Drawings

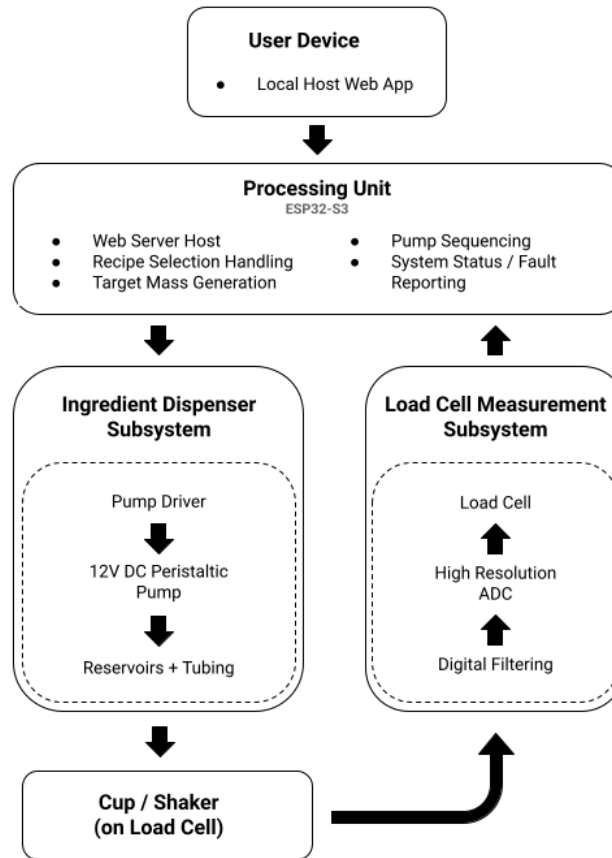


Figure 2 High level block diagram of cumulative subsystems.

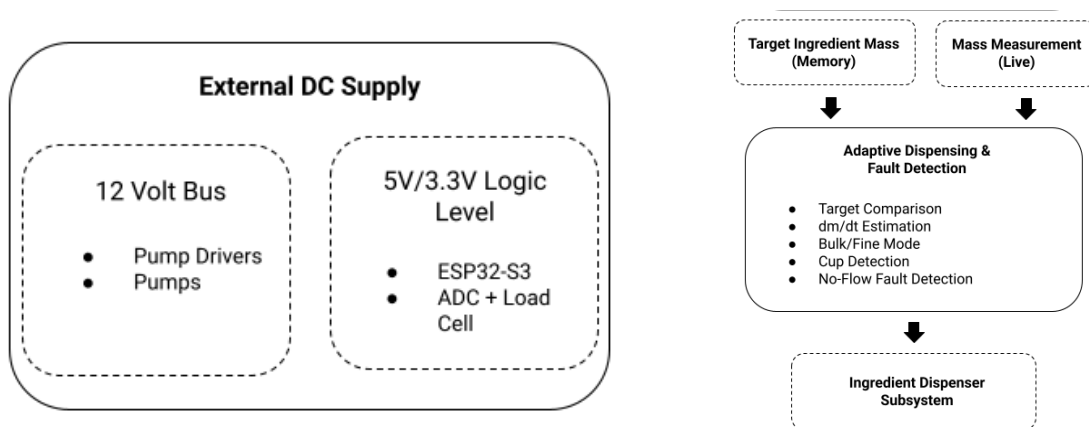


Figure 3 Breakdown of the power management system and expansion on processor functionality.

2.2 Subsystem Overview

The system is divided into four primary subsystems: the User Interface and Main Controller Subsystem, Ingredient Dispensing Subsystem, Load-Cell Measurement Subsystem, and Adaptive Dispensing and Fault-Detection Subsystem. These subsystems work together to receive a requested beverage, dispense the selected ingredients, measure the amount of liquid delivered, and adjust pump operation using closed loop feedback.

2.2.1 User Interface and Main Controller Subsystem

The User Interface and Main Controller Subsystem serves as the central control hub for system operations and provides the primary interface for user interaction. An ESP32-S3 microcontroller hosts a local web server, allowing users to access the control interface over WiFi via a web browser on a smartphone, tablet, or personal computer. Through this interface, users can select preconfigured beverage recipes or define custom mixtures, specify target ingredient masses, initiate or interrupt dispensing cycles, and monitor real time system status.

Upon receiving user selections, the ESP32-S3 processes the commands, determines the required ingredient sequence, and sets target mass values for each pump cycle. The controller continuously reads mass data provided by the Load-Cell Measurement Subsystem and passes these values to the Adaptive Dispensing and Fault-Detection Subsystem algorithm. Based on computed control decisions, the ESP32-S3 outputs control signals to the Ingredient Dispensing Subsystem to independently activate, pulse, or deactivate each peristaltic pump.

2.2.2 Ingredient Dispensing Subsystem

The Ingredient Dispensing Subsystem is responsible for the physical delivery of liquid from the ingredient reservoirs into the user's cup. Designed with at least four independently controlled channels, each fluid line comprises a dedicated liquid reservoir, food grade tubing, a 12 V peristaltic pump, and corresponding pump driver circuitry. Because the ESP32-S3 microcontroller cannot directly supply the required drive current, each channel incorporates a MOSFET switching circuit to interface the low-power control signals with the high current pump loads.

During a dispensing cycle, the subsystem operates under direct control from the main controller. For bulk liquid transfer, the pumps run continuously when the measured mass is significantly below the target threshold. As the target mass is approached, the Adaptive Dispensing and Fault-Detection Subsystem modulates the control signals to deliver brief pump pulses, minimizing volume overshoot and ensuring precise ratio delivery. Real time feedback regarding the delivered liquid mass is concurrently provided by the Load-Cell Measurement Subsystem.

2.2.3 Load-Cell Measurement Subsystem

The Load-Cell Measurement Subsystem provides real time, high precision mass feedback to enable accurate closed-loop control of the liquid dispensing process. The subsystem incorporates a strain-gauge load cell configured in a platform setup to measure the real-time weight of the cup and its contents. Analog signals from the load cell are digitized using a high resolution analog to digital converter (ADC), which transmits converted mass measurements to the central ESP32-S3 microcontroller.

To ensure reliable measurement accuracy during fluid delivery, the subsystem establishes an initial mass baseline prior to dispensing, accounting for varying cup weights or residual contents. During operation, digital filtering techniques are applied to mitigate mechanical vibrations and dynamic liquid sloshing noise. The filtered mass data allows the ESP32-S3 to compute instantaneous flow rate estimates, dynamically tracking dispensing progress and providing essential feedback to the control subsystem to terminate pumping precisely at the target ingredient weight.

The estimated mass flow rate ($dm/dt \approx \Delta m / \Delta t$) is calculated by evaluating the rate of change of the measured mass over a discrete sampling time interval Δt :

$$dm/dt \approx \Delta m / \Delta t$$

With the measured dispensed mass is approximately $m_{\text{dispensed}} = m_{\text{current}} - m_{\text{initial}}$

2.2.4 Adaptive Dispensing and Fault-Detection Subsystem

The Adaptive Dispensing and Fault-Detection Subsystem implements closed loop feedback algorithms within the ESP32-S3 microcontroller to achieve target dispensing accuracy and maintain safe operating conditions. By continuously comparing real time load-cell mass data against target ingredient quantities, the subsystem dynamically regulates pump activation, transition timing, and duty cycle modulation.

To optimize dispensing efficiency while preventing target overshoot, the control algorithm operates in two primary phases: continuous bulk delivery and pulsed fine delivery. During initial activation, the pump runs continuously to transfer the majority of the required liquid volume. As the measured cup mass approaches the target threshold, the controller transitions to a pulsed drive scheme, applying brief PWM or discrete voltage pulses to incrementally deliver fluid until the specified mass is reached within $\pm 5\%$ or ± 2 g accuracy.

Simultaneously, the subsystem performs real time flow rate estimation by computing discrete mass changes over time ($dm/dt \approx \Delta m / \Delta t$). This dynamic tracking allows the algorithm to adjust pump timing and compensate for variance caused by fluid viscosity, supply line resistance, or hydraulic head fluctuations up to $\pm 20\%$ of the initial baseline calibration.

Safety and integrity checks are continuously executed throughout the dispensing process. If no cup presence is verified by the baseline load-cell reading prior to routine execution, dispensing operations are inhibited. Additionally, if an active pump fails to produce an expected increase in measured mass within 5 seconds, the subsystem flags a fault condition, immediately terminates pump drive signals, and alerts the user through the local web interface.

2.3 Subsystem Requirements

2.3.1 User Interface and Main Controller Subsystem Requirements

1. **Requirement 1:** The user interface will provide options to select predefined beverage recipes or specify custom ingredient ratios
2. **Requirement 2:** The user interface will provide controls to initiate and manually terminate dispensing operations.
3. **Requirement 3:** The user interface will display real time system status, including current dispensing state, measured ingredient mass, and fault conditions.
4. **Requirement 4:** The central controller will output independent control signals for at least four distinct ingredient dispensing channels.
5. **Requirement 5:** Upon receipt of a stop command or detection of a fault signal, the controller will deactivate all active dispensing channels within 100 ms.

2.3.2 Ingredient Dispensing Subsystem Requirements

1. **Requirement 1:** The dispensing channel will operate with electrical and channel isolation, preventing cross activation or inadvertent operation of adjacent channels during dispensing.
2. **Requirement 2:** The pump driver circuitry will support both continuous high volume fluid delivery and short duration pulse width modulated (PWM) or discrete pulsed actuation for fine volume control.
3. **Requirement 3:** Dedicated switching interface circuitry will isolate the main controller logic and safely switch the high current drive loads required by the peristaltic pump.
4. **Requirement 4:** The fluid pathway will transport liquid independently from its dedicated reservoir to the dispensing point without premature intermixing of separate ingredients.
5. **Requirement 5:** Upon deactivation of a channel control signal by the main controller, the targeted pump drive output will stop all operation.

2.3.3 Load-Cell Measurement Subsystem Requirements

1. **Requirement 1:** The subsystem will sample and transmit digitized mass readings to the main controller at a sampling frequency of at least 10 Hz during dispensing.
2. **Requirement 2:** The subsystem will update real time mass measurements with a total latency of no more than 100 ms to enable timely pump shutoff and pulsing control.
3. **Requirement 3:** Digital filtering applied to the mass signal will reduce steady state measurement noise to within ± 0.5 g during active fluid delivery.
4. **Requirement 4:** The subsystem will detect the presence of an empty cup on the load-cell platform for any mass exceeding a minimum threshold of 10 g.
5. **Requirement 5:** If the measured mass drops below the detected cup baseline threshold during active dispensing, the subsystem will report a cup removal event to the controller.

2.3.4 Adaptive Dispensing and Fault-Detection Subsystem Requirements

1. **Requirement 1:** The subsystem will continuously compare the measured dispensed mass against the requested ingredient mass during active dispensing.
2. **Requirement 2:** The subsystem will estimate the real-time liquid mass flow rate based on measured mass changes over discrete time intervals.
3. **Requirement 3:** The controller will dynamically transition from continuous pumping to pulsed delivery as the target quantity is approached to minimize overshoot.
4. **Requirement 4:** For requested ingredient quantities between 20 g and 150 g, the control system will dispense within $\pm 5\%$ of the requested mass or $\pm 2\text{g}$
5. **Requirement 5:** The control system will maintain dispensing accuracy when the pump flow rate varies by up to $\pm 20\%$ from its initial calibrated baseline.
6. **Requirement 6:** The subsystem will not operate if no cup is detected on the weighing platform.
7. **Requirement 7:** If the active pump fails to produce a sufficient increase in measured cup mass, the system will stop dispensing and report a fault condition within 5 seconds.
8. **Requirement 8:** The subsystem will immediately stop pumping if the cup is removed during a dispensing cycle.
9. **Requirement 9:** Upon completion of a dispensing cycle, the subsystem will compare the final measured mass with the expected target mass and verify compliance with accuracy tolerances.

2.4 Tolerance Analysis

A quantitative tolerance analysis cannot be completed at this stage because the system has not yet been physically assembled or tested. The main sources of error in the project, such as pump flow rate variation, load-cell measurement noise, tubing effects, vibration, splashing, and residual liquid flow after the pump is turned off, depend on the completed physical setup. Since experimental values for these effects are not currently available, any numerical tolerance calculation would rely on assumptions rather than measured system behavior. Once the prototype is assembled, these sources of variation can be measured and used to evaluate whether the system satisfies the required dispensing accuracy of $\pm 5\%$ or $\pm 2\text{ g}$, whichever is larger.

3. Impact and Standards – Ethics, Safety, Societal Impact, and Standards

3.1 Ethics

The primary ethical consideration for this project is ensuring that the system accurately reports what it has dispensed and does not present an incorrectly prepared beverage as successful. The system will therefore use the load-cell measurement to compare the actual amount dispensed with the requested amount and will report a fault when appropriate. The user should be able to clearly determine whether the requested beverage was prepared successfully rather than relying only on the commanded pump times.

Although the system is intended as a general purpose beverage dispenser, all demonstrations for this project will use non-alcoholic liquids. If the design were adapted for commercial use with alcoholic beverages, additional ethical and legal considerations such as responsible serving and age restrictions would need to be addressed. Adapting the system for commercial use with alcoholic beverages would require addressing all associated ethical considerations regarding alcohol consumption, responsible service, and regulatory compliance.

3.2 Safety

The primary safety concern is the combination of liquids and electronic components. Reservoirs, tubing, dispensing nozzles, and the cup area will therefore be physically separated from the control electronics as much as possible. Electrical connections will be enclosed where practical, and the system will use low-voltage DC power. Flyback protection will also be included in the pump driver circuits to protect the electronics from voltage spikes generated when the pumps are switched.

The control system will include additional safety behavior to reduce the risk of spills. Dispensing will not begin unless a cup is detected by the load-cell subsystem. If the cup is removed during operation, the controller will stop the active pumps. The system will also detect a possible blocked tube, empty reservoir, disconnected tube, or pump failure when a pump is running but the measured cup mass is not increasing as expected. In this condition, dispensing will be stopped and a fault will be reported to the user.

3.3 Societal Impact

The integration of automated, closed-loop feedback in liquid dispensing systems enhances process consistency, minimizes material waste, and reduces operational error compared to open-loop timed dispensing methods. Beyond beverage preparation, this mass based control architecture demonstrates general applicability across various engineering domain applications, including automated laboratory liquid handling, precision chemical mixing, and pharmaceutical reagent dispensing. However, the deployment of such automated systems necessitates appropriate human oversight, regular calibration, routine maintenance, and rigorous sanitation protocols to maintain long-term reliability and operational safety.

3.4 Standards

Although the prototype developed for this project is not intended for commercial certification, several industry standards and regulatory frameworks inform its design. Wireless communication between the ESP32 microcontroller and user devices operates within the IEEE 802.11 WiFi standard. For commercial deployment, this subsystem would require compliance with Federal Communications Commission (FCC) regulations regarding intentional radiators. Electrical hardware and printed circuit board (PCB) layouts adhere to standard engineering practices, incorporating proper power and signal isolation, trace sizing, grounding, and inductive load protection. Furthermore, to address fluid contact, food grade materials and tubing are utilized in the prototype, while full commercial realization would necessitate alignment with established food safety, sanitation, and electrical safety standards.