

CLOSED-LOOP HIGH-ACCURACY UNIVERSAL DRINK SYSTEM

ECE445 DESIGN DOCUMENT - FALL 2026

Project #50

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1 Introduction

1.1 Problem

Preparing mixed beverages consistently requires accurate control of the amount of each ingredient being dispensed. Many automated beverage dispensers rely on running a pump for a predetermined amount of time and assume that the pump delivers liquid at a constant flow rate. In practice, however, the amount dispensed during a fixed time interval can change because of differences in liquid viscosity, reservoir level, tubing conditions, and normal variations in pump performance. As a result, a system that relies only on timing may repeatedly over-dispense or under-dispense an ingredient, producing incorrect drink ratios and inconsistent final beverages. This problem becomes more significant when several ingredients must be combined accurately, since errors from multiple dispensing stages can accumulate in the final drink. In addition, a purely time-based system has little ability to determine whether liquid was actually delivered, whether the cup is present, or whether a dispensing failure has occurred. Therefore, there is a need for an automated beverage dispensing system that can determine how much liquid is actually delivered rather than assuming that pump activation time directly corresponds to the desired quantity.

1.2 Solution

Our design utilizes four independently regulated 12 V peristaltic pumps to transfer liquid ingredients into a container rested upon a strain-gauge platform. To isolate motor activation, weight measurement, and user operation, the system is organized into distinct submodules. Pump control is driven by a Seeed Studio XIAO ESP32-C3, whereas a primary ESP32-S3 situated inside the enclosure base manages force-sensing readings, overall state logic, and an integrated web application.

Serving as the central processing unit, the ESP32-S3 acquires digitized mass samples via the load-cell conditioning circuit to track container weight throughout the process. Rather than assuming static flow performance over fixed timing intervals, our implementation leverages dynamic force feedback. For each fluid component, the main processor compares the measured mass increase against the target threshold to determine whether continued pumping is required.

Actuation is delegated to the secondary XIAO ESP32-C3 module. Upon receiving a request from the primary MCU, the pump controller engages the designated peristaltic channel. Operation is restricted to a single channel at any instance to ensure added weight is mapped accurately to the active line. Distributing the electronics places switching hardware close to the motors while maintaining the central ESP32-S3 near the base sensors and communication interface.

At the start of an ingredient phase, the ESP32-S3 records a baseline weight and calculates the necessary mass delta. During initial delivery, continuous pump engagement rapidly supplies the bulk volume. The MCU tracks the mass delta over time to calculate the instantaneous flow rate. As the target threshold approaches, the system transitions into pulsed operation, reducing volume increments to minimize settling overshoot and enhance precision.

Active sensing resolves inaccuracies associated with open-loop, time-dependent dispensing setups. Physical variations in fluid viscosity, head pressure, line degradation, and motor performance alter flow volume during fixed time windows. By reading real-time mass changes, the controller avoids relying on assumed flow constants, adjusting pulse cycles directly from physical volume added.

In addition to volumetric tracking, force measurements serve a diagnostic and safety function. Initial weight readings confirm container placement prior to starting dispensing. While running, the control logic expects a positive mass slope; sudden weight drops or missing flow increments indicate anomalies such as container removal, fluid depletion, line obstructions, or motor failures, triggering an immediate shutdown sequence.

User interaction occurs through an embedded HTTP server running on the ESP32-S3. Through this interface, users select recipes, adjust component volumes, initiate dispensing cycles, and monitor real-time system status including active channels, batch progress, and error alerts.

Because the portal is served locally, external clients can connect directly via standard web browsers on mobile or desktop devices without dedicated software.

Once an ingredient target is reached, the ESP32-S3 halts the corresponding channel and proceeds to the next phase. Following completion of all recipe steps, final container weight is cross-checked against the predicted total before signaling successful completion. By pairing the XIAO ESP32-C3 motor driver with the primary ESP32-S3 controller, the architecture partitions control tasks into a cohesive feedback control loop. All experimental validations will be conducted exclusively using non-alcoholic liquids.

1.3 Visual Aid

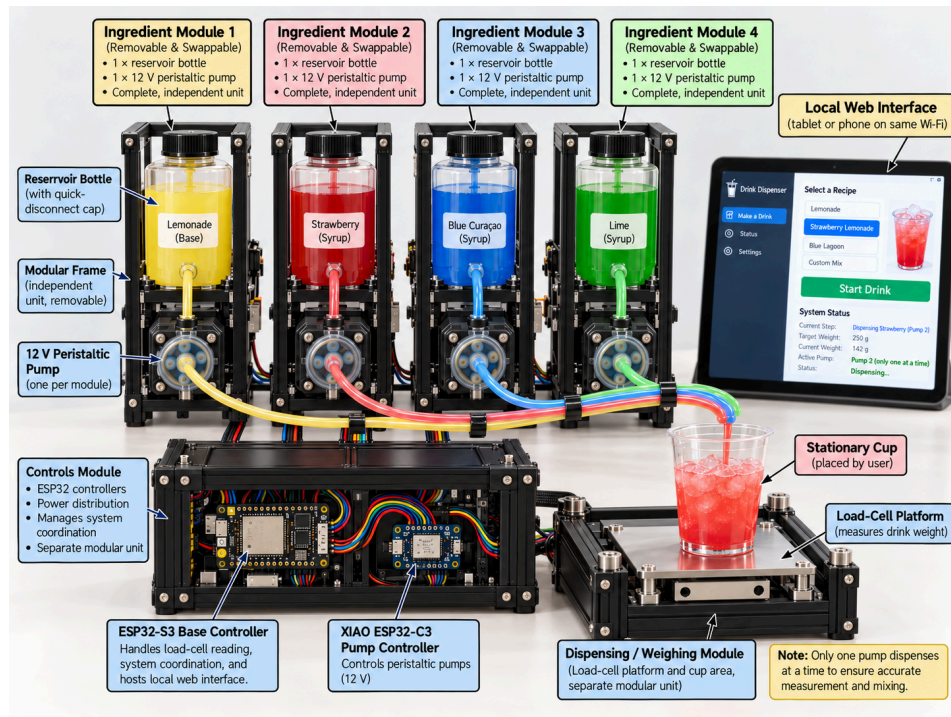


Figure 1. AI-generated conceptual rendering of the proposed modular drink dispensing system. Generated using ChatGPT (OpenAI) based on the authors' design specifications. The figure is intended to illustrate the proposed physical layout and is not a photograph of the completed system.

The above rendering clarifies the structural configuration rather than showcasing the physical prototype. The physical framework incorporates four independent fluid channels, each equipped with an isolated reservoir, a 12 V peristaltic pump, and dedicated fluid conduits. This modular division permits individual ingredient lines to be serviced or reconfigured without disrupting adjacent pathways.

Fluid lines link directly to a distinct control module housing both the XIAO ESP32-C3 motor driver and the primary ESP32-S3 microcontroller. While the secondary XIAO ESP32-C3 governs pump actuation, the central ESP32-S3 manages sequence state logic, gathers mass data from the load-cell assembly, and serves the embedded web application. External wireless clients, such as tablets or smartphones, connect to this local portal to choose recipes, modify ingredient targets, manage dispensing execution, and review real-time operating metrics.

Throughout dispensing, fluid from the active channel is transferred via its respective pump assembly into a vessel positioned atop the load-cell sensor. Restricting actuation to a single pump ensures observed weight deltas correspond precisely to the active ingredient line. The primary ESP32-S3 processes continuous force measurements to verify target delivery before initiating subsequent recipe phases. Partitioning fluid reservoirs, drive electronics, and sensor hardware simplifies diagnostic routines, enhances safety, and facilitates system expansion.

1.4 High-level Requirements

ID	Requirement
HL1	For each requested ingredient mass from 20 g to 150 g, the final dispensing error will be no greater than the larger of $\pm 5\%$ of the target mass or ± 2 g. At least 9 out of 10 trials for each tested target mass shall satisfy this requirement.
HL2	The system will continue to satisfy HL1 when the effective mass flow rate changes to approximately 80% or 120% of its calibrated baseline, without requiring manual adjustment of a fixed dispensing time.
HL3	To ensure safe operation, dispensing will automatically stop if no receiving vessel is identified on the sensor pad or if the container is abruptly removed during a cycle. Furthermore, the control logic must identify absent or insufficient fluid delivery, terminating the active sequence and alerting the interface within 5 seconds of detection.
HL4	Our initial prototype implementation incorporates two dual-channel fluid pathways, where each distinct line features a dedicated reservoir, an isolated 12 V peristaltic pump, and individual conduit routing. Expanding upon this modular architecture, the system framework easily accommodates supplementary dispensing channels following identical structural patterns.

2 Design

2.1 Block Diagram

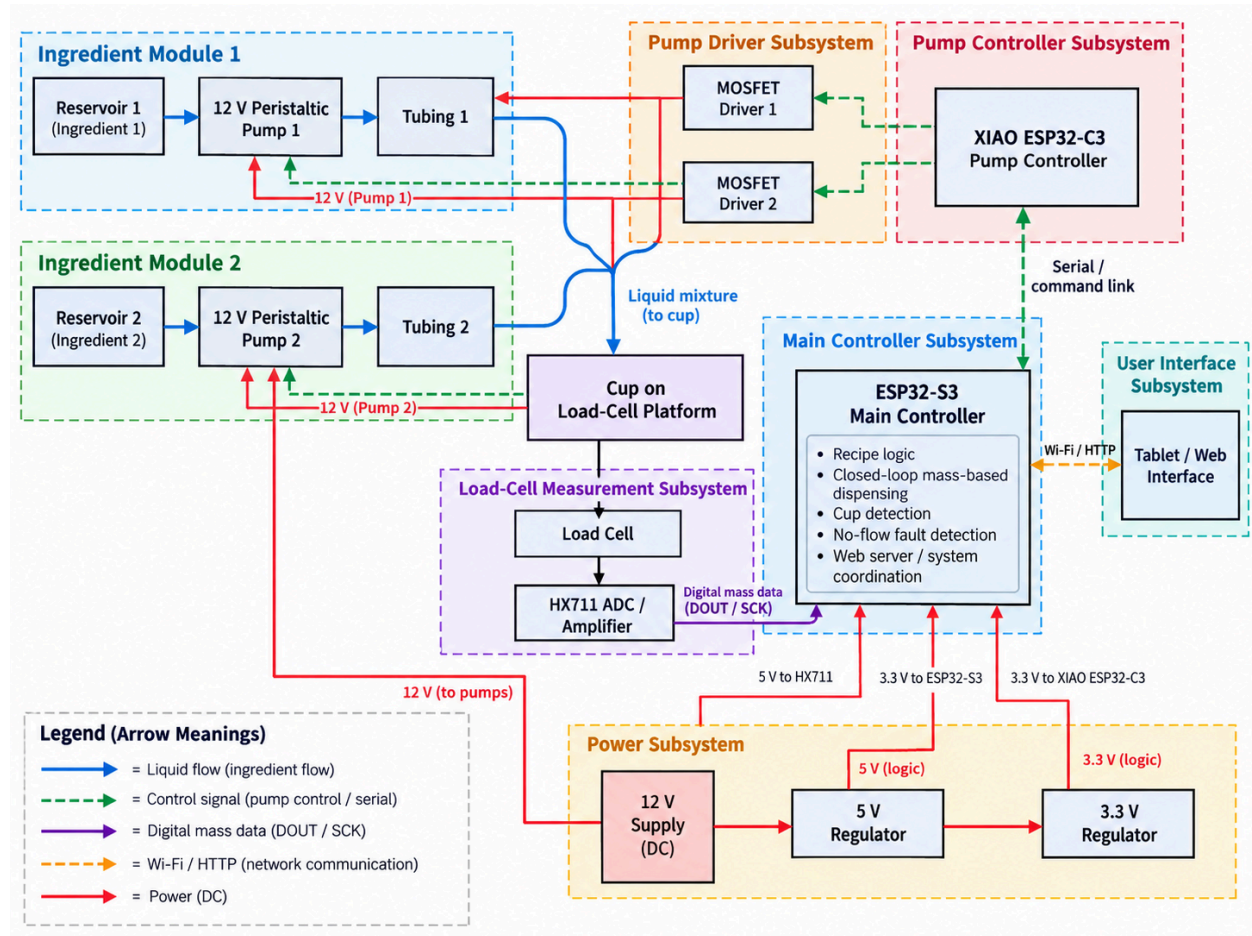


Diagram 1: High-level block diagram of the project

2.2 Subsystem Descriptions

To isolate system operations, the architecture of the Closed-Loop High-Accuracy Universal Drink System is partitioned into seven distinct modules: the User Interface Subsystem, Main Controller Subsystem, Pump Controller Subsystem, Pump Driver Subsystem, Ingredient Dispensing Subsystem, Load-Cell Measurement Subsystem, and Power Subsystem. Each component fulfills a targeted task while communicating power, drive signals, force readings, and fluid transfer across module boundaries. Coordinated interaction between these modules permits

recipe selection, dual-channel volume dispensing, real-time mass acquisition, and closed-loop feedback management.

Although financial limitations restrict the present implementation to two active fluid lines, every channel incorporates identical standardized pump, driver, container, and tubing assemblies. Consequently, expanding the system framework with supplemental dispensing lines requires no structural modification to the core control logic.

2.2.1 User Interface Subsystem

The User Interface Subsystem serves as the primary mechanism for human interaction with the automated dispenser. An embedded HTTP server deployed on the ESP32-S3 hosts a local web portal, allowing external clients to establish connection via any Wi-Fi-enabled smartphone, tablet, or desktop computer. Within this web interface, operators can choose preset drink recipes, customize component volume targets, execute dispensing cycles, halt ongoing operations, and observe real-time operational state metrics and diagnostic error flags.

Communication between the User Interface Subsystem and the Main Controller Subsystem occurs wirelessly over standard Wi-Fi protocols. Incoming operational requests are transferred directly to the main processor, while real-time mass progression, sequence status, and fault alerts are transmitted back to update the web dashboard. Because actuator execution remains isolated from the frontend, browser disconnections or page updates will not disrupt ongoing closed-loop dispensing managed locally by the ESP32-S3.

2.2.2 Main Controller Subsystem

Centered around the ESP32-S3 microcontroller, the Main Controller Subsystem orchestrates primary system operations. It maintains selected recipe data, sequences ingredient delivery orders, designates volume targets, handles load-cell data processing, enforces container and fault detection routines, and manages the closed-loop feedback algorithm.

Prior to starting a dispensing sequence, the ESP32-S3 acquires recipe choices from the User Interface Subsystem and confirms container presence via readings supplied by the Load-Cell

Measurement Subsystem. Upon cycle initiation, the main MCU transmits actuation commands to the Pump Controller Subsystem while continuously sampling digitized mass values.

Actuation is restricted to a single channel at any instance to ensure observed weight changes correlate directly to the active component. At the start of an ingredient phase, the ESP32-S3 logs the initial vessel weight as a baseline. Transferred fluid mass is subsequently derived by calculating the delta between real-time load-cell metrics and this reference baseline.

During initial delivery, continuous pump engagement rapidly supplies the bulk volume. As the target threshold approaches, the MCU transitions into short pulsed cycles to minimize settling overshoot. The ESP32-S3 tracks mass changes over time to account for variations in dynamic flow performance. This feedback strategy permits the system to adapt dynamically to variations in fluid viscosity, head pressure, line degradation, or pump output rather than assuming static timing constants.

Furthermore, force readings serve a diagnostic and safety function. Abrupt container removal or missing mass increases during active pump command phases trigger safety logic, prompting the ESP32-S3 to halt delivery, send a shutdown directive to the Pump Controller Subsystem, and issue error alerts to the User Interface Subsystem.

2.2.3 Pump Controller Subsystem

Centered around a secondary Seeed Studio XIAO ESP32-C3 module, the Pump Controller Subsystem manages localized actuation for both fluid channels. This dedicated MCU decodes operational instructions transmitted from the Main Controller Subsystem, establishing whether the assigned line must run continuously, enter pulsed modulation, or deactivate.

Upon validating an incoming directive, the secondary processor asserts logic-level switching signals to the active line within the Pump Driver Subsystem. System execution strictly isolates activation to a single peristaltic pathway at any given moment. Restricting motor operation ensures that observed force increments on the load platform map directly to the active component line.

Offloading low-level drive signals to the auxiliary module isolates switching hardware close to the motors. Consequently, the primary ESP32-S3 remains dedicated to real-time force acquisition, feedback state calculations, recipe sequencing, anomaly monitoring, and hosting the embedded web server.

2.2.4 Pump Driver Subsystem

The Pump Driver Subsystem acts as the high-power switching interface separating the low-voltage control outputs of the Seeed Studio XIAO ESP32-C3 from the 12 V peristaltic pump motors. Each dedicated dispensing line features an isolated N-channel MOSFET switching stage. The secondary MCU drives the respective gate terminals, permitting precise modulation of the high-current supply paths required for motor actuation.

To safeguard against inductive voltage spikes generated during rapid motor deactivation, each channel incorporates a parallel flyback diode circuit across the pump terminals. Additional inline gate resistance and gate-to-source pulldown resistors minimize switching transients while ensuring that driver channels remain securely latched in an off state during microcontroller initialization or undefined logic conditions.

In terms of system interconnections, the Pump Driver Subsystem accepts digital control inputs from the Pump Controller Subsystem, draws regulated 12 V DC power from the Power Subsystem, and outputs switched drive signals to actuate the motor assemblies residing in the Ingredient Dispensing Subsystem.

2.2.5 Ingredient Dispensing Subsystem

The Ingredient Dispensing Subsystem executes the physical transfer of fluid media from dedicated supply vessels to the target container. In the present prototype implementation, this framework incorporates two isolated fluid pathways, each comprising an independent fluid reservoir, a 12 V peristaltic pump assembly, and dedicated line routing.

Fluid lines maintain complete physical isolation until terminating at the central dispensing area above the vessel platform. This prevents cross-contamination between distinct channels while

enabling modular servicing and maintenance of individual lines. Furthermore, this modular architecture facilitates seamless scalability, allowing supplemental dispensing channels to be integrated by replicating the core reservoir, pump, conduit, and driver hardware assemblies.

Upon receiving switched 12 V DC power from the Pump Driver Subsystem, the designated pump draws liquid from its corresponding source vessel, driving fluid through the peristaltic tube assembly and into the receiving vessel positioned on the strain-gauge mount. System execution avoids relying on open-loop, time-dependent dispensing; rather, actual volume delivery is continuously acquired via the Load-Cell Measurement Subsystem, which provides real-time force feedback to the Main Controller Subsystem.

2.2.6 Load-Cell Measurement Subsystem

The Load-Cell Measurement Subsystem supplies real-time mass data essential for driving closed-loop dispensing feedback. A receiving vessel resides on a dedicated platform coupled to a strain-gauge load cell, where variations in vessel mass yield proportional low-level differential voltage signals. These analog signals are subsequently conditioned, amplified, and digitized using an HX711 analog-to-front-end conversion module.

Digitized mass metrics are routed directly to the primary ESP32-S3 microcontroller via a two-wire DOUT/SCK digital communication interface. Prior to active execution, the strain-gauge platform undergoes a calibration routine using known reference weights to map raw digital output readings directly into calibrated mass units. System calibration relies on establishing a tare baseline from an unweighted platform before applying standard reference weights to calculate accurate scaling factors.

The central processor evaluates gross mass measurements to verify initial container placement on the sensing pad. Upon starting an active dispensing phase, the system captures a baseline weight reference, determining added fluid volume by computing the difference between continuous load-cell metrics and this reference. Furthermore, the main MCU evaluates these mass changes over time to monitor instantaneous flow rates, govern the transition from continuous bulk flow to short pulsed delivery, confirm container presence, and identify potential no-flow conditions.

By deriving container detection, volume tracking, and fault monitoring directly from strain-gauge force readings, the physical architecture eliminates the need for auxiliary optical proximity sensors or inline fluid flowmeters.

2.2.7 Power Subsystem

The Power Subsystem supplies all necessary operating voltages across system modules. A central regulated 12 V DC supply energizes the peristaltic motor assemblies via the Pump Driver Subsystem. Secondary low-voltage regulation stages provide stable power rails to drive the primary ESP32-S3, secondary Seeed Studio XIAO ESP32-C3, HX711 front-end digitizer, and associated digital control logic.

Consequently, the Power Subsystem interfaces directly with the Pump Driver Subsystem, Pump Controller Subsystem, Main Controller Subsystem, and Load-Cell Measurement Subsystem. The power routing network is designed to sustain transient motor startup current demands without inducing voltage dips or instability on the digital rails during active Wi-Fi transmissions or switching operations.

To prevent noise coupling into sensitive strain-gauge signal paths, motor return currents are separated from the analog measurement ground while preserving a unified reference potential. Decoupling capacitors are placed in close proximity to control and sensing ICs to suppress power supply transients. These design choices ensure continuous logic stability while delivering isolated high-current paths for motor actuation.

2.3 Subsystem Requirements

The following criteria establish the operational performance metrics required for each individual module within the final prototype. These specifications address quantifiable functional responses, encompassing volumetric accuracy, motor control, force-sensing capabilities, anomaly management, and power supply regulation. Except where explicitly noted, all operational parameters apply uniformly across both active dispensing channels.

2.3.1 User Interface Subsystem Requirements

ID	Requirement
UI1	Through the local web interface, operators shall select desired beverage recipes and specify individual component mass targets ranging between 20 g and 150 g, with the system actively validating input parameters to discard out-of-bounds quantities prior to initiating cycle execution.
UI2	Operators shall be capable of initiating or aborting dispensing cycles via the web dashboard, which must continuously report the active component channel, real-time process state, sequence completion metrics, and diagnostic error flags. The rendered interface data shall refresh at a minimum frequency of 2 Hz.
UI3	Browser disconnections or client page reloads must neither trigger unwanted motor operation nor impede the primary processor from identifying and mitigating system anomalies.

2.3.2 Main Controller Subsystem Requirements

ID	Requirement
MC1	2Actuation shall remain strictly limited to a single fluid channel at any instance, with the system capturing a reference weight baseline prior to initiating delivery for each respective component.
MC2	For each requested ingredient mass from 20 g to 150 g, the final dispensing error will be no greater than the larger of $\pm 5\%$ of the target mass or ± 2 g. At least 9 out of 10 trials for each tested target mass shall satisfy this requirement.
MC3	The control system will continue to satisfy requirement MC2 when effective fluid flow rates shift to roughly 80% or 120% of the baseline calibration, achieving this without requiring manual modifications to predetermined dispensing durations.
MC4	During initial delivery, continuous pump engagement rapidly supplies the bulk volume, transitioning into short pulsed cycles as the target threshold approaches to minimize overshoot.
MC5	To guarantee operational safety, the main processor shall halt actuation in the absence of a verified vessel, abort execution immediately upon container displacement, and identify fluid delivery failures, issuing a system alert within 5 s of anomaly detection.

2.3.3 Pump Controller Subsystem Requirements

ID	Requirement
PC1	The dedicated XIAO ESP32-C3 microcontroller must provide autonomous regulation across both fluid channels, strictly preventing concurrent dual-channel operation throughout standard dispensing routines.
PC2	Upon receiving a legitimate start, halt, or modulation directive, the secondary XIAO ESP32-C3 microcontroller must transition the corresponding driver control signal within 100 ms.
PC3	To prevent unintended activation, the dual drive channels must maintain an inactive state throughout initialization, system resets, standby periods, and error states.

2.3.4 Pump Driver Subsystem Requirements

ID	Requirement
PD1	Each driver circuit must provide isolated power control to its corresponding 12 V DC peristaltic actuator, ensuring strictly independent actuation across distinct fluid lines.
PD2	To prevent micro-controller restarts or spurious channel triggering, each driver stage must reliably maintain steady-state motor energization alongside rapidly pulsed actuation cycles during high-precision dispensing routines.
PD3	Upon receiving a deactivation directive, the assigned drive channel must preserve total electrical inactivity throughout standby periods, sequence halts, system resets, and unhandled fault states.

2.3.5 Ingredient Dispensing Subsystem Requirements

ID	Requirement
ID1	Our initial prototype framework incorporates two isolated fluid pathways, where each individual line features a dedicated supply reservoir, an independent 12 V peristaltic pump assembly, and separate conduit routing.
ID2	Actuation of a designated fluid path shall induce liquid transfer strictly through that active line, preserving total physical isolation between both conduits prior to their convergence at the primary discharge zone over the vessel platform.
ID3	Throughout the operational span of 20 g to 150 g, each fluid line must accurately dispense specified quantities without exhibiting observable fluid escaping from any conduits or mechanical joints.

2.3.6 Load Cell Measurement Subsystem Requirements

ID	Requirement
LC1	The Load-Cell Measurement Subsystem must deliver updated mass readings to the central ESP32-S3 microcontroller at a minimum sampling frequency of 10 Hz.
LC2	Following completion of the calibration routine, static weight readings obtained across the active testing range shall maintain an accuracy margin within ± 0.5 g relative to known standard masses.
LC3	Under static load conditions without active fluid transfer, baseline mass fluctuations reported by the sensor platform must not exceed ± 0.5 g across a continuous 5 s window.
LC4	To ensure accurate vessel identification, the main processor tracks gross container weight, while referencing an independent zero baseline to quantify the precise volume of each added fluid component.

2.3.7 Power Subsystem Requirements

ID	Requirement
PW1	The Power Subsystem must deliver a stable 12 V DC operating voltage to drive the peristaltic pumps while supplying regulated low-voltage rails for the primary ESP32-S3 microcontroller, auxiliary Seeed Studio XIAO ESP32-C3 module, HX711 digitizer, and supporting control circuitry.
PW2	During continuous pump activation, startup transients, and pulsed modulation cycles, the regulated low-voltage rails powering the digital logic must maintain stability within $\pm 5\%$ of specified nominal thresholds.
PW3	Actuation of the motor assemblies must not induce system resets, disrupt serial communication lines, or introduce force reading instabilities exceeding the ± 0.5 g baseline variation defined in requirement LC3.

2.4 Subsystem Verifications

To confirm compliance with the module specifications established in Section 2.3, the following verification protocols will be executed. All experimental dispensing evaluations will strictly utilize water or equivalent non-alcoholic liquids. For trials assessing volumetric precision, measured output quantities will be validated against an independent calibrated balance to evaluate variance from target values.

2.4.1 User Interface Subsystem Verifications

ID	Verification Procedure	Success Criterion
UI1	Input valid ingredient quantity targets at 20 g, a mid-range value, and 150 g through the user interface. Next, submit target values under 20 g and over 150 g to evaluate input validation.	The system successfully accepts valid target parameters while discarding out-of-bounds input values prior to starting execution.
UI2	Initiate an active dispensing cycle and verify that the interface dynamically reports the active line, process stage, execution completion, and system error indicators. Subsequently, transmit an abort request while fluid transfer is underway.	Visualized interface elements accurately reflect internal controller state variables, refreshing at a minimum frequency of 2 Hz, while transmission of an abort request immediately terminates active fluid delivery.
UI3	Initiate an active dispensing cycle, then reload or disconnect the client browser session from the web application.	Spurious motor energization is completely prevented, ensuring that automated dispensing routines and safety fault tracking proceed without interruption.

2.4.2 Main Controller Subsystem Verifications

ID	Verification Procedure	Success Criterion
MC1	Execute a dual-component dispensing sequence while simultaneously logging drive control signals alongside initial zero-reference metrics prior to introducing each fluid line.	Actuation remains strictly isolated to a single fluid pathway at any instance, with the primary controller sampling a baseline zero-reference weight prior to starting delivery for every component phase.
MC2	Execute dispensing sequences for specified component weight targets at 20 g, a mid-range parameter, and 150 g across every fluid line. Conduct 10 evaluation trials per target setting and verify actual output quantities against an external calibrated balance.	Minimum performance metrics require at least 9 out of 10 evaluation trials per target setting to demonstrate a final dispensing variance bounded within the larger of $\pm 5\%$ of the target mass or ± 2 g.
MC3	Determine the baseline volumetric delivery rate, then induce physical variance to establish operational throughputs at roughly 80% and 120% of this benchmark. Execute the MC2 verification protocol across these altered flow states without modifying preprogrammed runtime windows.	Volumetric delivery reliably satisfies the precision criteria specified in requirement MC2 across both adjusted throughput rates.
MC4	Capture drive control signals alongside continuous vessel weight metrics throughout a standard	During initial delivery, continuous pump engagement rapidly supplies the bulk volume, transitioning into short pulsed cycles as the

	dispensing routine.	target threshold approaches to minimize overshoot.
MC5	Execute three distinct anomaly evaluations: initiate fluid delivery without a receiving vessel placed on the sensing platform, abruptly displace the container midway through active sequence execution, and activate a motor channel under zero-flow or fluid depletion conditions.	Dispensing fails to initiate without a verified vessel, container displacement immediately aborts execution, and fluid delivery failures prompt a system fault alert within 5 s of anomaly detection.

2.4.3 Pump Controller Subsystem Verifications

ID	Verification Procedure	Success Criterion
PC1	Issue individual actuation directives to the first and second peristaltic channels while concurrently monitoring respective control line outputs.	Actuation proceeds strictly for the designated fluid channel, ensuring concurrent operation across multiple pathways is completely prevented throughout standard execution.
PC2	Transmit initiation, termination, and modulation directives from the central ESP32-S3 microcontroller to the auxiliary XIAO ESP32-C3 unit while capturing command propagation delays and signal transitions using a logic analyzer or oscilloscope.	Upon receiving a legitimate directive, the secondary processor must transition the corresponding driver control signal within 100 ms.

PC3	Observe drive control signals across both channels during microcontroller initialization, soft resets, standby states, and active fault conditions.	Throughout each of the four designated operational states, both output channels consistently preserve a fully deactivated status.
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2.4.4 Pump Driver Subsystem Verifications

ID	Verification Procedure	Success Criterion
PD1	Issue individual actuation directives to the first and second peristaltic channels while concurrently monitoring respective control line outputs.	Actuation proceeds strictly for the designated fluid channel, ensuring concurrent operation across multiple pathways is completely prevented throughout standard execution.
PD2	Operate each pump continuously and then repeatedly pulse the pump during a simulated fine dispensing sequence.	The commanded pump follows both continuous and pulsed operation without controller reset or activation of the other pump.
PC3	Monitor pump voltage or current during idle, reset, stop, and fault conditions.	The corresponding pump remains electrically inactive whenever its channel is commanded OFF.

2.4.5 Ingredient Dispensing Subsystem Verifications

ID	Verification Procedure	Success Criterion
ID1	Visually examine the completed system framework, verifying that each dual fluid line remains physically isolated from its supply vessel to the primary discharge point.	Two independent channels are present, each containing its own reservoir, pump, and tubing path.
ID2	Fill the two reservoirs with visibly different test liquids and activate each channel separately.	Liquid from each channel remains separate until reaching the common dispensing location above the cup.
ID3	Execute fluid delivery sequences spanning target masses from 20 g to 150 g across both active pathways while continuously checking conduit interfaces and mechanical joints for signs of leakage.	Both channels successfully deliver liquid over the tested range with no visible leakage from tubing or fittings.

2.4.6 Load Cell Measurement Subsystem Verifications

ID	Verification Procedure	Success Criterion
LC1	Record timestamps of consecutive mass measurements received by the ESP32-S3 for at least 10 s.	Continuous mass readings are delivered to the primary MCU at an average sampling frequency of no less than 10 Hz, maintaining steady update intervals throughout standard execution.

LC2	Place several known reference masses across the expected operating range on the calibrated platform and compare the reported value with the reference mass.	Measurement error is no greater than ± 0.5 g at each tested mass.
LC3	Place a stationary representative cup/load on the platform and record the measured mass for 5 s without dispensing.	The measured mass remains within ± 0.5 g of its steady value during the observation period.
LC4	Place a cup on the platform, record its gross mass, then dispense the first and second ingredients while logging the baseline used for each stage.	Cup presence is determined from gross mass, and a separate baseline is used to calculate the delivered mass of each ingredient.

2.4.7 Power Subsystem Verifications

ID	Verification Procedure	Success Criterion
PW1	Measure the pump supply and regulated logic rails at their outputs using a multimeter before operating the system.	The expected 12 V pump supply and required regulated logic voltages are present and correctly connected to their intended subsystems.
LC2	Measure each regulated logic rail while the system is idle, while each pump starts, during continuous pumping, and during pulsed operation.	Each regulated rail remains within $\pm 5\%$ of its nominal voltage during all test conditions.

LC3	Run 10 consecutive dispensing cycles while monitoring controller operation, communication, and steady-load mass readings during pump switching.	No ESP32-S3, XIAO ESP32-C3, or HX711 reset or communication failure occurs, and pump switching does not cause load-cell variation greater than ± 0.5 g.
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2.5 Supporting Material

The following figures provide additional technical detail for the control, electrical, sensing, and mechanical portions of the system that are not fully shown in the high-level block diagram.

2.5.1 Control Sequence

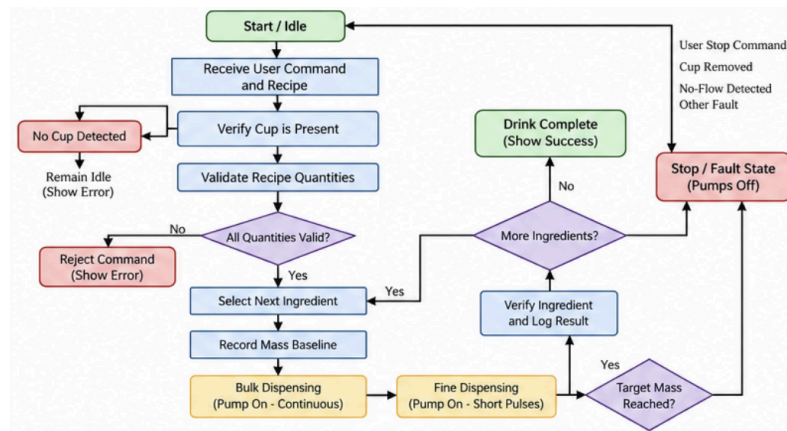


Figure 3: Proposed control sequence used by the ESP32-S3.

Before dispensing begins, the system verifies that a cup is present and validates the requested ingredient quantities. A stable mass baseline is then recorded for the active ingredient. The controller initially operates the selected pump continuously during bulk dispensing and transitions to shorter pump activations as the measured mass approaches the target. Once the ingredient mass is verified, the controller either captures a new baseline for the next ingredient or reports that the drink is complete. A stop command, cup removal, no-flow condition, or other detected fault overrides the normal sequence and disables pump operation.

2.5.2 Pump Driver Circuit

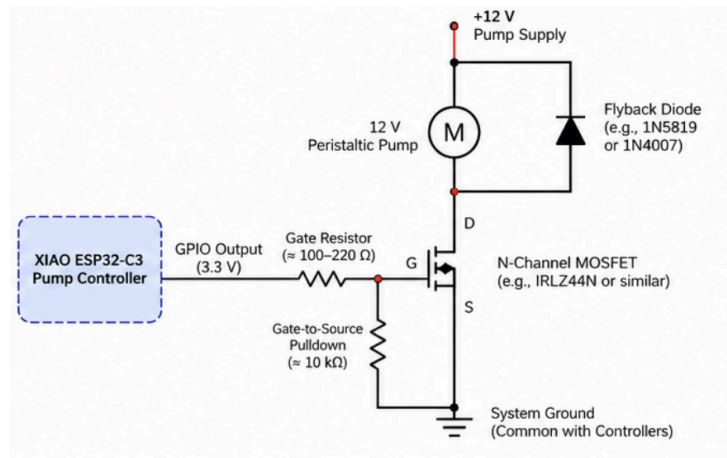


Figure 4: Proposed pump-driver circuit for one ingredient channel.

Because the XIAO ESP32-C3 cannot directly supply the voltage and current required by the 12 V peristaltic pump, an N-channel MOSFET is used as a low-side electronic switch. The pump is connected between the 12 V supply and MOSFET drain, while the source is connected to ground. The XIAO ESP32-C3 controls the MOSFET gate through a series resistor, and a gate-to-source pulldown ensures that the pump remains off when the control signal is undefined. A flyback diode across the pump provides a path for inductive current when the motor is switched off. An identical driver circuit is used for the second ingredient channel.

2.5.3 Load Cell Measurement Path

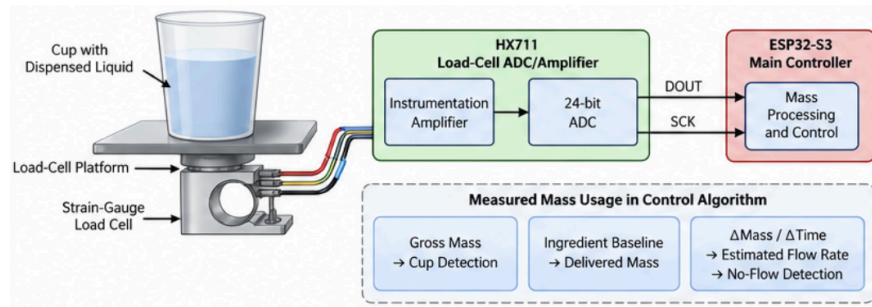


Figure 5: Load-Cell Measurement Path.

The load-cell and HX711 provide digital mass measurements to the ESP32-S3 for cup detection, ingredient mass tracking, flow-rate estimation, and no-flow detection. The technical design and system architecture were developed by the project team; ChatGPT (OpenAI) was used only to assist in generating the figure.

2.5.4 Mechanical / Modular Arrangement

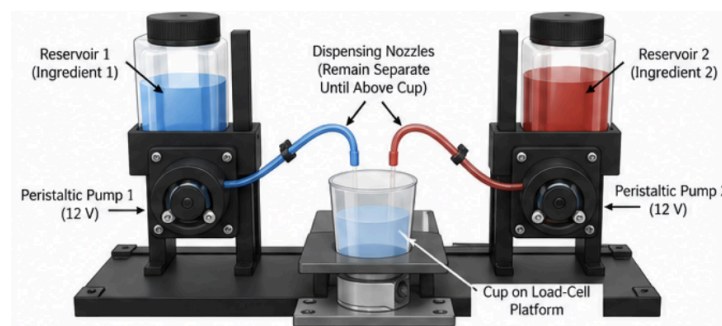


Figure 6: Mechanical Arrangement of the Two-Ingredient Prototype.

Two independent ingredient modules dispense through separate tubing paths into a cup positioned on the load-cell platform. The system layout is designed to keep pumps, reservoirs, and electronics mechanically isolated from the weighing platform to reduce measurement

interference. The technical design and system architecture were developed by the project team; ChatGPT (OpenAI) was used only to assist in generating the figure.

2.6 Tolerance Analysis

The most critical performance requirement of the system is the ability to dispense the requested amount of each ingredient within the specified mass tolerance. For requested ingredient masses between 20 g and 150 g, the maximum allowable error is

$$T(m) = \max(0.05m, 2g)$$

where m is the requested ingredient mass. The most restrictive case occurs for target masses from 20 g through 40 g because 5% of the target is less than or equal to 2 g. Therefore, the system must be capable of maintaining a total dispensing error of no more than ± 2 g in the worst case. For comparison, a 100 g target permits ± 5 g of error and a 150 g target permits ± 7.5 g. This dispensing requirement was established in the previous project document. The major sources of error near the end of a dispensing cycle are the load-cell measurement uncertainty, the amount of liquid delivered while the controller is responding to the latest measurement, residual liquid delivered after the pump is turned off, and the uncertainty associated with the final fine-dispensing pulse. A conservative worst-case error model is therefore

$$E_{total} \leq E_{measurement} + q_{fine}(t_{measurement} + t_{actuation}) + E_{tail} + E_{pulse}$$

where q_{fine} is the effective mass-flow rate while approaching the target.

Using the subsystem limits selected for the design gives the following error budget:

Error Source	Design Limit	Maximum Contribution
Load-cell measurement error	± 0.50 g	0.50 g
Measurement/filtering delay	≤ 0.10 s	$0.10q_{fine}$

Controller/pump response delay	$\leq 0.10 \text{ s}$	$0.10q_{fine}$
Residual liquid after shutoff	$\leq 0.25 \text{ g}$	0.25 g
Final pulse uncertainty	$\leq 0.25 \text{ g}$	0.25 g

For the total error to remain within the worst-case 2 g requirement,

$$0.50 + 0.10q_{fine} + 0.10q_{fine} + 0.25 + 0.25 \leq 2$$

which gives

$$1.00 + 0.20q_{fine} \leq 2$$

and therefore

$$q_{fine} \leq 5 \text{ g/s}$$

Thus, if the effective flow rate during the final approach to the target is limited to 5 g/s or less, the combined measurement, response, residual-flow, and fine-pulse errors remain within the required ± 2 g tolerance.

The design must also remain accurate when pump flow changes by approximately $\pm 20\%$ from its calibrated value. To guarantee that the worst-case $+20\%$ flow condition still satisfies the 5 g/s limit,

$$1.20q_0 \leq 5$$

where q_0 is the nominal effective flow rate during fine dispensing. Therefore,

$$q_0 \leq \frac{5}{1.20} = 4.17 \text{ g/s}$$

The controller should therefore transition from continuous bulk dispensing to fine pulsed dispensing early enough that the effective near-target delivery rate is approximately 4.17 g/s or

lower under nominal conditions. Even if the actual flow then increases by 20%, the resulting flow remains at or below 5 g/s and the worst-case error budget remains within ± 2 g.

Because the two ingredient channels are operated one at a time and a new mass baseline is recorded before each ingredient, the dispensing errors of the two pumps do not directly add together when determining the accuracy of an individual ingredient. The same tolerance analysis therefore applies independently to both implemented channels.

This analysis demonstrates that the closed-loop dispensing approach is feasible provided that the load-cell error, control delays, residual flow, and fine-pulse behavior remain within the allocated limits. These values are design limits rather than completed measurements and will be confirmed experimentally during subsystem verification. If testing shows that the near-target flow is too high, the ESP32-S3 can transition to fine dispensing earlier or command shorter pump pulses so that the effective final delivery rate satisfies the derived 5 g/s maximum.

3 Cost & Schedule

3.1 Bill of Materials

Part Name	References	Needed	Order Qty	Cost
3.3 μ H Inductor	L1	1	2	
0.1 μ F Ceramic Capacitor – low-voltage	C1,C2,C3,C6,C8, C15,C20,C26,C27, C29	10	15	\$0.45
0.1 μ F Ceramic Capacitor – MP2338 input	C12,C19	2	7	\$0.85
0.1 μ F Ceramic Capacitor – A4988 charge pump	C33,C35	2	7	\$0.70
0.1 μ F Ceramic Capacitor – 24 V motor rail	C31,C34	2	7	\$0.77
0.22 μ F Ceramic Capacitor	C28	1	6	\$0.84
10 μ F Ceramic Capacitor – low-voltage	C4,C5,C7,C25	4	9	\$1.17
10 μ F Ceramic Capacitor – regulator input	C10,C11,C17,C18	4	9	\$2.79
22 μ F Ceramic Capacitor	C13,C14,C21,C22	4	9	\$4.23
22 nF Ceramic Capacitor	C9,C23	2	7	
470 pF Ceramic Capacitor	C16,C24	2	7	
100 μ F Polarized Capacitor	C32	1	6	\$2.34
0.1 Ω Current-Sense Resistor	R34,R35	2	7	
100 Ω Resistor	R3,R4,R5,R6,R17, R22,R27	7	12	
3.3 k Ω Resistor	R9,R10,R25,R26	4	9	

5 kΩ Resistor	R36	1	6	
8.2 kΩ Resistor	R2,R32	2	7	
9.09 kΩ Resistor	R16,R24	2	7	
10 kΩ Resistor	R7,R8,R14,R21,R28,R29	6	11	
20 kΩ Resistor	R1	1	6	
24.9 kΩ Resistor	R33	1	6	
25 kΩ Resistor	R30	1	6	
49.9 kΩ Resistor	R12,R19	2	7	
51 kΩ Resistor	R15,R23	2	7	
100 kΩ Resistor	R13,R20	2	7	
191 kΩ Resistor	R11,R18	2	7	
MMBT3906 PNP Transistor	Q1	1	6	\$0.60
SMD Momentary Pushbutton	SW1–SW4	4	9	\$3.19
1×4 2.54 mm Header	J1,J2,J4,J5,J6,J7,J9	7	12	
1×2 2.54 mm Header	J3,J8	2	7	
MCUs & Peripheral ICs			Combined Estimate	\$15
Total				\$32.93

Table 1: Itemized cost estimates based on research as of 2 October, 2026. Combined real values are expected to exceed \$45.00 to produce the base and peripheral modules not including the cost of manufacturing the PCBs and respective stencils.

3.2 Schedule

Week of	Project Tasks	Assigned Member
Oct 5	Design Review	Team
	Finalize PCB layout based on review advice.	Aiden
	Finalize shopping list and begin order placement.	Kevin
	2nd Round PCB Order	Team
Oct 12	Breadboard Demo	Team
	Begin PCB assembly	Aiden
	Begin hardware verification as needed.	Kevin
	3rd Round PCB Order	Team
Oct 19	Continued hardware assembly in CAD.	Aiden
	Complete verifications and begin web-app development.	Kevin
Oct 26	Shop/manufacture parts as needed by CAD designs.	Aiden
	Continue project testing in software.	Kevin
	4th Round PCB Order	Team

Nov 2	Individual Progress Reports	Aiden, Kevin
	Continue team assignment as needed to meet deadlines.	Team
Nov 9	Team Contract Assessment	Team
	Have all necessary models produced for project modules.	Aiden
	Final touches on UI development and app features.	Kevin
Nov 16	Mock Demo & Presentation	Team
	Finalize last-minute debugging.	Team
Nov 23	FALL BREAK	
Nov 30	Final Demo & Presentation	Team
Dec 7	Final Paper Submission	Team

Table 2: High-level schedule and team assignments week-by-week.

4 Impact Discussion & Engineering Standards

4.1 Societal Impact

The Closed-Loop High-Accuracy Universal Drink System is intended to improve the consistency, safety, and efficiency of automated liquid dispensing. Unlike systems that rely only on fixed pump activation times, this design measures the mass actually delivered to the cup and adjusts pump operation using real-time feedback. This allows the system to compensate for changes in liquid properties, reservoir level, tubing conditions, and pump performance. Cup detection, cup-removal detection, and no-flow detection also reduce the likelihood of spills, incorrect mixtures, and undetected dispensing failures.

From an economic perspective, improved dispensing accuracy can reduce ingredient waste caused by over-dispensing and inconsistent portions. The use of relatively low-cost microcontrollers, peristaltic pumps, and load-cell sensing also provides a way to implement closed-loop dispensing without requiring more expensive industrial flow-measurement equipment. However, continued operation would require periodic cleaning, calibration, tubing replacement, and other maintenance.

From an environmental perspective, accurate portion control can reduce unnecessary liquid waste. The closed-loop control method may also allow the system to compensate for gradual changes in pump or tubing performance rather than requiring immediate replacement when the original flow rate changes. At the same time, the system contains electronic components, pumps, tubing, and other materials that will eventually require disposal. A future commercial version should therefore emphasize replaceable fluid-path components, durable electronics, and appropriate electronic-waste disposal.

Socially, the system can provide more repeatable beverage preparation while reducing repetitive manual dispensing tasks. The configurable web interface allows ingredient quantities and recipes to be adjusted for different user preferences instead of limiting the dispenser to fixed recipes. If the system were deployed commercially or internationally, applicable sanitation, electrical, wireless, and food-equipment regulations would need to be evaluated for the intended location.

4.2 Engineering Standards

Several engineering and regulatory standards are relevant to the proposed system, even though commercial certification is outside the scope of the prototype.

Because the ESP32-S3 provides a local Wi-Fi interface, **IEEE 802.11-2024** is relevant to the wireless communication portion of the system. IEEE 802.11 defines the medium access control (MAC) and physical-layer (PHY) specifications used for wireless local-area networking [1]. The standard is currently active and incorporates updates to the IEEE 802.11 wireless LAN specification.

A commercial wireless product marketed in the United States would also be subject to applicable **FCC Part 15** requirements. Part 15 establishes requirements for radio-frequency devices, including intentional radiators such as wireless networking equipment [2].

Because liquid passes through tubing and other components before being dispensed, **NSF/ANSI 51-2025, Food Equipment Materials**, is relevant to the selection of food-contact materials. The standard applies to materials and finishes used in food equipment, including beverage dispensers, tubing, gaskets, sealants, and valves [3]. Therefore, fluid-path components in a future system intended for beverage consumption should be made from materials appropriate for food-contact applications.

A future commercial implementation could also consider **IEC 60335-2-75:2024**, which addresses the safety of commercial electrical dispensing appliances and vending machines used to prepare or deliver food and beverages [4]. The standard includes both AC- and DC-powered equipment and addresses hazards associated with dispensing appliances. Its principles are relevant to electrical protection, enclosure design, servicing, and preventing users from contacting energized components.

The **2026 FDA Food Code** provides additional guidance for the sanitary operation of retail and food-service equipment. The Food Code is a model intended to help governmental jurisdictions develop food-safety regulations rather than a certification standard itself [5]. Its principles

reinforce the importance of maintaining clean food-contact surfaces and fluid paths and preventing contamination of dispensed beverages.

4.3 Ethics

An important ethical responsibility of this project is ensuring that the system does not indicate that a beverage was prepared successfully when a dispensing failure has occurred. The load-cell feedback is therefore used to determine the amount actually delivered rather than assuming that commanding a pump for a certain period guarantees successful dispensing. If the measured result indicates a dispensing fault or an unacceptable result, the system should report that condition instead of presenting the preparation as successful.

This approach is consistent with the **IEEE Code of Ethics**, which emphasizes protecting public health and safety and being honest and realistic when stating technical claims and estimates [6]. These principles are especially relevant when reporting the accuracy and reliability of the prototype.

The **ACM Code of Ethics and Professional Conduct** similarly emphasizes avoiding harm, honesty and trustworthiness, and evaluating the potential risks of computing systems [7]. Applied to this project, these principles require the team to report dispensing failures accurately, test foreseeable failure modes, communicate limitations of the prototype, and avoid overstating demonstrated system performance.

These ethical principles also apply when presenting experimental results. Individual failed trials should not be excluded simply because they negatively affect the reported dispensing accuracy. Likewise, capabilities demonstrated by the two-channel prototype should be distinguished from features that could be implemented in a future expanded system.

All course demonstrations will use non-alcoholic liquids. If a future version were designed to dispense alcoholic beverages, additional legal and ethical concerns involving age restrictions, responsible serving, and applicable licensing requirements would need to be addressed before deployment.

4.4 Electrical and Mechanical Safety

The primary electrical safety concern is the close proximity of liquid-handling components to powered electronic circuitry. The prototype therefore separates the reservoirs, tubing, dispensing area, and load-cell platform from the control electronics where practical. Exposed electrical connections will be enclosed or otherwise protected from accidental contact with liquids.

Although the system operates from relatively low DC voltages, the 12 V pump supply can provide enough current to cause wiring, connectors, or PCB traces to heat during a short circuit. Appropriate conductor sizing, protected connections, current limiting or fuse protection, and inspection for damaged wiring should therefore be used. Electrical power will be disconnected before servicing pumps, wiring, tubing, or other internal components.

Each pump-driver circuit also incorporates flyback protection to provide a current path for the inductive motor when the pump is switched off. The MOSFET drivers, power wiring, and logic electronics will be designed so that pump switching does not expose the microcontrollers or load-cell electronics to damaging voltage transients.

Mechanical hazards are relatively limited because the moving portions of the peristaltic pumps are enclosed during normal operation. The pumps should nevertheless not be operated with their protective housings removed, and fingers, clothing, or tools should be kept away from exposed moving components during maintenance.

The control system provides an additional layer of functional safety. Dispensing is prevented when a cup is not detected, cup removal causes active dispensing to stop, and insufficient measured mass increase during pump operation results in a no-flow fault. These features reduce the risk of continued dispensing during abnormal conditions.

4.5 Safety and Risk-Mitigation Procedure

Before each laboratory test or demonstration, the reservoirs, tubing, electrical wiring, pump connections, and control electronics will be inspected for visible damage, loose connections, or leakage. Initial fluid-path testing will be performed with water before other demonstration

liquids are introduced. The load-cell system and cup-detection behavior will also be checked before automatic dispensing is enabled.

During testing, the system will operate from an appropriately rated low-voltage DC supply with suitable over-current protection. Reservoirs and tubing connections will be positioned so that a leak is unlikely to drain directly onto exposed electronics. Energized pump-driver circuitry and wiring will remain enclosed or inaccessible during normal operation. The user will retain access to the software stop function, while electrical power can be disconnected manually if unexpected operation occurs.

If a leak or spill occurs, pump operation will be stopped and electrical power disconnected before the spill is cleaned or components are handled. The system will not be powered again until affected electrical components have dried and been inspected for damage. Pumps, tubing, and internal wiring will not be serviced while the system is energized.

Food-contact reservoirs, tubing, and dispensing components will be cleaned before and after demonstrations and will not be used when visible contamination, residue, or material degradation is present. Demonstration liquids will be non-alcoholic. These procedures complement the automatic cup-detection, cup-removal, and no-flow protections incorporated into the control system.

5 Sources

[1] IEEE, *IEEE Standard for Information Technology—Telecommunications and Information Exchange Between Systems Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Std. 802.11-2024, 2025.

[2] Federal Communications Commission, *Radio Frequency Devices*, Code of Federal Regulations, Title 47, Part 15.

[3] NSF International, *Food Equipment Materials*, NSF/ANSI 51-2025, 2025.

[4] International Electrotechnical Commission, *Household and Similar Electrical Appliances—Safety—Part 2-75: Particular Requirements for Commercial Dispensing Appliances and Vending Machines*, IEC 60335-2-75:2024, 4th ed., 2024.

[5] U.S. Food and Drug Administration, *Food Code 2026*. U.S. Department of Health and Human Services, 2026.

[6] IEEE, “IEEE Code of Ethics,” *IEEE Policies*, sec. 7.8.

[7] Association for Computing Machinery, *ACM Code of Ethics and Professional Conduct*, 2018.