Design assignment

Embedded systems engineering

CMPE3001

Unit coordinator Dr. Anuradhi Welhenge

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Group: Bentley (UG & PG) 35

Members:

Mohammad Ma'en Abu-Qamar	Student ID: 21026744
Tashi Lhadon	Student ID: 22155746
Nazanin Rahimi	Student ID: 21510234
Amiru Hangili Muhandiramlage	Student ID: 20818694
Troyee Troyee	student ID: 22663281

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Abstract

For many years vending machines have had a place for off-the-shelf product delivery, but even today they are largely electromechanical systems where intelligence is very limited. The development and implementation of an Intelligent IoT enabled Vending Machine is described as having microcontroller-based control and cashless payment, internet operation, and low energy consumption. The embedded systems architecture makes use of the Arduino Mega 2560, ESP8266 Wi-Fi module, RFID payment system, and sensor verification for autonomous operation and transference of operations data to the cloud server. The power consumption, safety issues and scalability in the future for Artificial Intelligence (AI), Solar Power, and Blockchain are also discussed.

Keywords— Embedded systems, IoT, vending machine, RFID, Arduino, ESP8266, automation, energy efficiency.

Introduction

Vending machines are one of the first examples of autonomous embedded systems used in public environments. They provide a means for users to purchase goods without intervention from a human being through a combination of mechanical control, payment verification, and product dispensing. However, despite decades of application, most existing machines are driven mechanically and exhibit lack of digital communications or adaptive intelligence [1].

Improvements in embedded computing and internet of things (IoT) technologies, have enabled a paradigm shift toward advanced vending solutions whereby intelligent solutions are produced containing sensors, microcontrollers and communication networks. By incorporating intelligence within the system, a vending machine should, with little or no human interaction, monitor stock levels, diagnose faults, perform cashless transactions and vary the energy consumption of the systems [2].

The objective of this paper is to design a Smart Vending Machine Embedded System having IoT connectivity, RFID payment and cloud-based data analytics. Emphasis is placed upon use of low-cost hardware, energy efficiency and scalability of future smart retail systems to enable the required infrastructures to be incorporated [3].

Background

Vending machines have traditionally been a quick way to buy snacks and drinks in public spaces. Over time, their use has expanded to include other items such as fresh food, medicines, and personal care products. This shift has been supported by new technologies like smart sensors, contactless payments, and Internet of Things (IoT) systems, which have made vending machines more efficient and easier to use [8].

They are now a common point of purchase, especially for snack foods, and can be found in schools, workplaces, sports facilities, and train stations [9]. In fact, about 75–80% of schools and universities have vending machines that sell food and drinks. However, research shows that heavy reliance on vending machines is often linked to unhealthy eating habits. Because of this, many researchers suggest redesigning vending machines to encourage healthier and low-calorie choices [9].

The technology behind vending machines has also advanced. One important change has been the use of machine-to-machine (M2M) communication. This includes telemetry, which helps operators monitor stock and manage refilling, and cashless payment systems, which make purchases easier and increase sales. Standards such as the Direct Exchange Uniform Communications Standard (DEX/UCS) and the Multidrop Bus Standard (MDB) were created to support these features [10]. While countries like Japan have widely adopted these technologies, uptake has been slower in Europe and the USA [10].

Despite these improvements, access to sanitary and hygiene products remains limited. Many women struggle to obtain these items when they are urgently needed. In Australia, for example, almost one in four young women have missed school or work because they could not access period products [11]. Traditional options such as supermarkets and pharmacies are not always open, easily accessible, or discreet.

To fill this gap, this project proposes the design of a sanitary product vending machine. The system aims to provide 24/7, private, and affordable access to essential products by combining automation with social responsibility, making it both a practical and socially beneficial solution.

Purpose of the system

The purpose of the system is to create a reliable, automated, and socially beneficial vending machine specifically designed for sanitary and hygiene products. Unlike traditional vending machines that focus on snacks or drinks, this system addresses a real-world social issue: the lack of consistent, affordable, and discreet access to sanitary products.

Key objectives of the system include:

- Ensuring 24/7 availability of products in strategic locations such as universities, hospitals, workplaces, and transport hubs.
- Providing affordability through fair pricing, making essential products accessible to all.
- Integrating smart payment systems (cashless and contactless) to meet modern user expectations.
- Using a design that is both user-friendly and discreet, so users feel comfortable accessing products.

Overall, the system's purpose is more than just technical development. It shows how embedded system design can provide a practical, automated, and efficient solution for daily needs. At the same time, it addresses a social issue by improving access to sanitary and hygiene products in a private and affordable way. By combining technology with social responsibility, the system aims to create a meaningful impact in the community.

Scope of the design

The design work in the project involves complete E2E specification of an intelligent sanitary dispensing vending machine as an embedded system. This includes (i) hardware (control, motion, sensing, comms, UI, power) and its justification (ii) firmware and middleware architecture (Klipper based motion layer on STM32 MCU, ESP8266 web/UI, RFID, cloud telemetry) (iii) core dispense logic and fault handling (iv) security or electrical and mechanical safety (v) energy and power budget (vi) the maintainability aspect and service workflows and (vii) stretch targets or roadmap (IoT analytics, renewable powering, ID-card integrations). Constraints on the project are within the area of Industrial certifications, full-payments gateway PCI reviews, enclosure industrial design and manufacturing drawings and large-scale Fleet ops (vendor SLAs, logistics) which are also earmarked for future work.

Report overview

This report presents the design of a sanitary product vending machine as an embedded system. It is organized to take the reader from the background and purpose of the project through to the proposed solution and its wider impact. The introduction outlines the evolution of vending machines, their growing role in society, and the motivation for developing a system that goes beyond traditional uses.

The report then describes the real-world problem of limited access to sanitary products, including the challenges of affordability, convenience, and discretion, and examines existing solutions currently available. Following this, the design considerations of the system are presented, including cost factors, performance trade-offs, and mechanisms to ensure safe and reliable operation.

Maintainability is also addressed, highlighting features such as modular components and upgrade options that support long-term functionality. In addition, the report identifies features that were not implemented in the current version but could be introduced in future development, such as renewable energy integration or mobile connectivity.

The final part of the report summarizes the key points and reflects on the design process. By combining technical and social perspectives, the report demonstrates how embedded system design can be used to provide a practical solution to a real-world challenge, while also contributing to community well-being.

Problem statement

Real-World context

Access to sanitary and hygiene products continues to be a significant challenge for many individuals. While products are commonly sold in supermarkets and pharmacies, these outlets are not always convenient, affordable, or discreet, particularly in urgent situations. A study by Plan International Australia found that nearly one in four young women have missed school or work because they did not have access to period products when needed [11]. This highlights how lack of access can directly affect education, employment, and well-being.

The problem is not only about affordability and availability, but also about privacy and stigma. Many women and girls report feeling embarrassed when purchasing sanitary products in public, which creates an additional barrier to access [11]. Moreover, access is unequal: students, low-income groups, and those in remote areas often face greater challenges in obtaining these essential items.

Charitable initiatives such as Share the Dignity's "Dignity Vending Machines" have attempted to bridge this gap by providing free period products in schools, universities, and community centers [12]. However, coverage remains limited, and many individuals still face difficulties accessing products when they are urgently needed.

In this context, a sanitary product vending machine provides a practical solution by ensuring products are available 24/7 in strategic locations such as universities, hospitals, and workplaces. It offers convenience, privacy, and affordability, making it an effective response to a real-world social need.

Existing solutions (if any)

Several approaches already exist to improve access to sanitary and hygiene products, but each has clear limitations. The most common option is purchasing from supermarkets and pharmacies. While reliable, these outlets are not always available late at night, during emergencies, or in locations where immediate access is required. They also lack privacy, which can discourage some individuals from purchasing products when needed.

Charitable initiatives have also attempted to address this gap. For example, Share the Dignity in Australia has introduced free Dignity Vending Machines in schools, universities, and community spaces, dispensing period packs at no cost [12]. These machines provide important support but remain limited in number and cannot fully cover the broad demand across workplaces, hospitals, and public transport hubs.

Traditional vending machines have, in some cases, been adapted to sell hygiene products. However, they are not specifically designed for this purpose. They often lack modern features such as contactless payments, stock monitoring, or discreet interfaces. As a result, they are less reliable and less user-friendly compared to purpose-built systems.

This shows that while solutions do exist, none fully meet the needs of affordability, accessibility, and discretion at scale. A dedicated embedded system for sanitary vending machines offers the potential to bridge these gaps by combining automation, convenience, and social responsibility.

Need for the proposed system

There is an evident need for a secure and dedicated contactless format which satisfies those demands for: i) seamless cashless (of RFID or web)/checkout, ii) reliable dispense (and jam resistance) with verification, iii) remote health/stock telemetry, and iv) low energy cost for continuous 24/7 availability, while a modularity, open-components architecture reduces cost (and speeds iteration) and produces safety/maintainability. The design proposed therefore addresses these factors directly.

Design overview

System description

The proposed vending machine system design is derived from conventional models but is enhanced to address the specific needs of its intended environment. Unlike traditional snack and beverage vending machines, this system is purpose-built for sanitary and hygiene products and is optimized for use in public restrooms.

One key modification is the integration of a web application as the primary customer-facing interface, replacing the physical keypad or button panel. This reduces the need for direct contact with shared surfaces, thereby improving hygiene and aligning with the location of deployment. To further improve accessibility, the machine also offers limited free Wi-Fi access (15 minutes per user session), enabling customers to familiarize themselves with the products or payment process if they are unfamiliar with the system, or in a pinch and need to transfer money to complete a purchase.

At the core of the design is the BIGTREETECH Octopus Pro V1.0 motherboard (BTT), which incorporates an ESP8266-based Wi-Fi module for network connectivity. This choice reduces manufacturing complexity and cost by eliminating the need for multiple separate boards. The BTT also offers numerous GPIO interfaces and motor control capabilities, making it suitable for vending operations.

The dispensing mechanism employs a two-motor pulley system inspired by CoreXY 3D printer architecture, which moves an XY carriage or basket to the correct dispensing position. Once positioned, a linear push mechanism driven by a motor and shaft transfers the selected product into the carriage. This combination enables precise, reliable, and scalable product dispensing, supporting a wide range of sanitary products.

High-Level Architecture

The high-level architecture of the proposed vending machine design comprises five major subsystems. The control unit, motion control system, communication module, dispensing mechanism, and power management. These components work together to enable automated product selection, payment verification, and item dispensing.

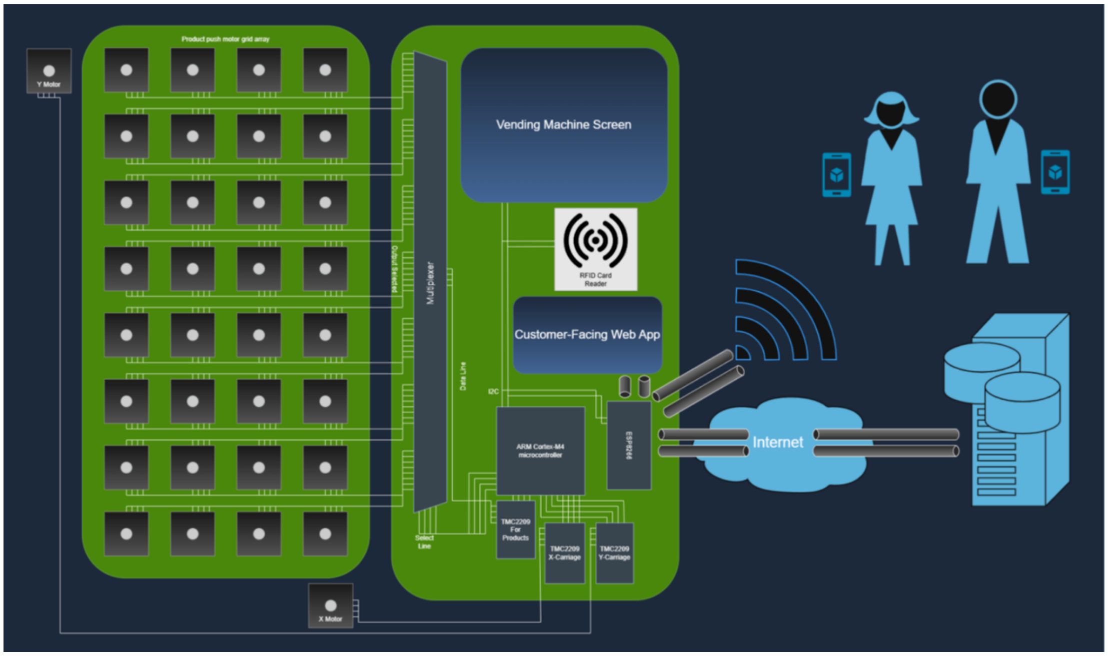
At the core of the system is BTT, serving as the primary controller. It is powered by a 32-bit ARM Cortex-M4 microcontroller that coordinates all mechanical and communication functions. The BTT board drives multiple TMC2209 stepper motor driver modules, which provide smooth and precise control of the XY carriage responsible for positioning and retrieving the selected product. For network connectivity, the system employs an ESP8266 Wi-Fi module. This module manages wireless communication between the vending machine and the cloud server, transmitting order information, payment confirmations, and operational data. Although the ESP8266 can handle lightweight network traffic, the BTT board also supports expansion through add-on processors, such as the Raspberry Pi or Raspberry Pi Zero, allowing for computational offloading of advanced tasks, such as payment encryption or cloud-based analytics.

The dispensing mechanism uses a pair of stepper-driven worm gears that convert rotational motion into linear displacement, enabling reliable and accurate product delivery to the XY carriage. This design minimizes mechanical jamming and ensures consistent dispensing across different product types.

Finally, the power management subsystem regulates voltage for both high-current components (motors and actuators) and low-power modules (microcontrollers, sensors, and communication devices). The system operates primarily on a 24 V DC input with integrated step-down converters for 5 V and 3.3 V logic levels.

This modular architecture not only provides efficient control and communication but also offers scalability and flexibility for future upgrades such as touchscreen integration, cloud-based monitoring, or mobile application support.

Block diagram of the system



Design goals and objectives

The primary goal of the proposed vending machine system is to provide a smart, hygienic, and socially responsible solution for distributing sanitary and hygiene products in public restrooms. The design integrates embedded control, wireless communication, and contactless payment technologies to create a reliable and user-friendly experience.

Design Goals

1. *Hygienic and Contactless Operation*

Replace traditional keypads and buttons with a web-based interface and RFID authentication to minimize physical contact and improve user hygiene in public spaces.

2. *Reliability and Precision*

Use a stepper-motor-driven CoreXY mechanism and worm gear dispensing system to ensure accurate, jam-free product delivery.

3. *Cost-Efficiency and Simplicity*

Utilize the BIGTREETECH Octopus Pro V1.0 motherboard, which integrates motor drivers and Wi-Fi capability, reducing the need for multiple boards and lowering production cost.

4. *Accessibility and Convenience*

Provide short-duration Wi-Fi access to enable customers to browse product information or complete digital payments, ensuring usability for even first-time users.

5. *Scalability and Flexibility*

Enable modular expansion through Raspberry Pi or similar processors, allowing future integration of features such as AI-based stock prediction, touchscreen interfaces, or cloud monitoring.

6. *Energy Efficiency*

Optimize power distribution and employ energy-efficient drivers and logic-level converters to reduce overall power consumption.

Hardware components

List of hardware components

Component	Description	Quantity
BIGTREETECH Octopus Pro V1.0 Motherboard	Main controller board based on a 32-bit ARM Cortex-M4 microcontroller. Provides multiple stepper motor drivers, GPIO pins, and integrated support for communication modules.	1
TMC2209 Stepper Motor Driver Modules	High-precision motor drivers provide silent and efficient motion control for the X, Y, and dispensing motors.	3
NEMA 17 Stepper Motors	Motors are used for the CoreXY carriage movement (X and Y axes) and product dispensing via a linear push mechanism.	66
ESP8266 Wi-Fi Module	Provides wireless connectivity for user web access, order transmission, and cloud-based monitoring. Integrated with the BTT motherboard for seamless operation.	1
RC522 RFID Reader Module	An external RFID reader is used for user authentication and secure cashless transactions. Supports 13.56 MHz RFID cards and tags.	1
Worm Gear and Linear Actuator Assembly	Converts motor rotational motion into linear push movement to dispense selected products accurately.	64
6 – 1 Multiplexer Board	Expands input/output control lines to handle multiple push-motor grids efficiently using fewer microcontroller pins.	1
LCD Screen	Provides visual status indicators or system messages (e.g., “Ready,” “Dispensing,” “Out of Stock”). web-based UI and displayingadvertisements.	1
Power Supply Unit (PSU)	Converts AC to DC and provides regulated power to motors and control circuits, with step-down converters.	1

Relay / MOSFET Switching Modules	Provide isolation and control for high-current components such as motors and actuators.	3
Mechanical Frame and Enclosure	A custom metal or acrylic structure that securely houses all components, ensuringuser safety and accessibility.	1
Wiring, Connectors, and Mounting Accessories	Electrical connections, headers, and fixtures for reliable integration of components.	
End Stop Switches	For knowing when to stop and home the motors	66

Justification for component selection

BIGTREETECH Octopus Pro V1.0 Motherboard

The BIGTREETECH (BTT) Octopus Pro V1.0 motherboard was selected for its cost-effectiveness, flexibility, and extensive hardware support. It features a powerful 32-bit ARM Cortex-M4 microcontroller with a high number of GPIO pins, enabling connections to multiple peripherals. Due to its large open-source community and compatibility with Klipper firmware, minimal custom programming is required to achieve advanced control.

The board natively supports the ESP8266 Wi-Fi module, and many variants include it integrated directly on board. It also provides dedicated, hot-swappable stepper motor driver sockets and interfaces for safety sensors such as temperature probes and voltage monitoring pins. Furthermore, its open-source nature allows for easy firmware modification and future scalability when paired with a Raspberry Pi for additional computational power.

TMC2209 Stepper Motor Driver

The TMC2209 stepper motor driver was chosen for its balance between precision, noise reduction, and affordability. It acts as an interface between the motherboard and the stepper motors, converting digital control signals into precise current pulses that drive the motor coils.

A known limitation of the TMC2209 is that it tends to generate heat under continuous operation. However, since a vending machine performs only short bursts of motion per transaction, thermal buildup is minimal. Compared to alternatives such as the A4988 or DRV8825, the TMC2209 offers quieter operation and smoother motion, contributing to a modern and high-quality user experience.

NEMA17 Motor

The NEMA 17 stepper motor standard was chosen due to its wide availability, strong community support, and proven reliability. It delivers excellent torque-to-size performance, enabling it to dispense a wide range of sanitary products regardless of their weight.

The NEMA 17 form factor also provides easy mechanical mounting and compatibility with existing 3D printer and motion-system hardware. It is cost-effective, readily available from multiple suppliers, and suitable for both the XY carriage and individual product-dispensing mechanisms.

ESP8266 Wi-Fi Module

The ESP8266 is a low-cost yet powerful Wi-Fi module capable of running either a real-time operating system (RTOS) or standalone firmware. It supports full IPv4 communication and can both host a local web interface and connect to a cloud server for transaction processing.

Its seamless integration with the BTT motherboard through UART or I2C communication simplifies hardware design and software development. The ESP8266's strong documentation and open-source libraries further streamline implementation, providing excellent performance for wireless connectivity and IoT integration.

RC522 RFID Reader

The RC522 RFID reader module was chosen for its affordability, reliability, and dual communication options (I^2C or SPI). It enables contactless user authentication, allowing customers to either pay directly using RFID-enabled cards or authenticate through a linked online account.
The inclusion of RFID technology provides flexibility in payment methods, allowing users to choose between paying through the web application or using tap-and-go methods such as EFTPOS cards, thereby enhancing convenience and accessibility.

Worm Gear and Linear Actuator Assembly

The vending mechanism requires converting rotational motion into linear displacement to push and dispense products. A worm gear combined with a linear actuator was selected for this purpose because it provides a strong mechanical advantage, precise movement, and self-locking properties, preventing unintentional product release when powered off.

This configuration ensures smooth and reliable dispensing while maintaining the accuracy necessary for small product sizes.

6-1 Multiplexer Board

The multiplexer board extends the input/output (I/O) capabilities of the BTT motherboard, enabling efficient control of many motors using fewer GPIO pins. This approach reduces hardware costs by minimizing the number of stepper motor drivers required.

Because the vending machine dispenses one product at a time, multiplexing provides a practical balance between performance and cost, eliminating the need for a dedicated driver per motor while maintaining system reliability and cost effectiveness.

LCD Screen

The LCD screen serves as an auxiliary display for the vending machine, providing operational status such as “Ready,” “Dispensing,” “Out of Stock,” or “Out of Order.” It can also display advertising content, generating additional revenue when the machine is idle.

In normal operation, the LCD guides users to the customer-facing web application, ensuring seamless navigation and enhancing the overall user experience.

PSU

The power supply unit converts AC mains input to regulated DC outputs suitable for the control and actuation subsystems. It provides a 24 V main supply for motors and auxiliary 5 V and 3.3 V rails for microcontrollers and communication modules.

A stable PSU is essential for ensuring consistent system performance and protecting sensitive electronics from voltage fluctuations or surges.

Technical specification

Component	Key Specifications	Reference
BIGTREETECH Octopus Pro V1.0	MCU: STM32F446 32-bit ARM Cortex-M4 @ 180 MHz Input Voltage: 12–24 V DC Logic Voltage: 3.3 V Stepper Driver Support: up to 8 (TMC series) Connectivity: UART, SPI, I²C, USB-C, CAN Bus	[1]
TMC2209 Stepper Driver	Voltage Range: 5–29 V DC Max Current: 2 A RMS (2.8 A peak) Microstepping: up to 256 Interface: UART / Step-Dir Features: SilentStep™, StallGuard, CoolStep	[2]
NEMA 17 Stepper Motor	Step Angle: 1.8° (200 steps/rev) Holding Torque: ~ 45 N·cm Rated Current: 1.5 A/phase Operating Voltage: 12–24 V DC Shaft Diameter: 5 mm	[3]
ESP8266	CPU: Tensilica L106 @ 80 MHz Flash: 4 MB Protocols: 802.11 b/g/n (2.4 GHz) Operating Voltage: 3.0–3.6 V Interfaces: UART / SPI / I²C	[4]
RC522 RFID Reader	Frequency: 13.56 MHz (MIFARE standard) Range: ≤ 5 cm Operating Voltage: 3.3 V Interface: SPI / I²C / UART Current: 13–26 mA	[5]

Worm Gear + Linear Actuator	Material: Aluminium alloy/steel gear	
6-to-1 Multiplexer Board	Voltage Range: 3.3–5 V logic Channels: 6-input to 1-output (selectable) Interface: Digital GPIO Purpose: Signal routing and expansion	Nil
LCD Screen	Size: 2.4–3.2 in TFT (typ.) Resolution: 320×240 pixels Interface: SPI / Parallel I/O Voltage: 5 V input, 3.3 V logic	[6]
Power Supply Unit (PSU)	Input: 100–240 V AC, 50/60 Hz Output: 24 V DC, 15 A (360 W) Efficiency: > 85% Protections: Over-current, short-circuit, over-voltage	[7]
Relay / MOSFET Modules	Input Signal: 3.3–5 V logic Switching Voltage: up to 24 V DC Current Capacity: 10 A (typ.)	[8]

Integration of components

The integration of components in the vending machine ensures coordinated operation between the mechanical, electrical, and communication subsystems. Each component is interfaced through the BIGTREETECH Octopus Pro V1.0 motherboard (BTT), which serves as the central control hub for all input and output devices. The integration process involves power distribution, signal interfacing, data communication, and mechanical coordination, as illustrated in the system's block diagram (Figure 1).

Control and Communication Integration

The BTT motherboard serves as the primary processor, controlling signals for motion, communication, and feedback. It connects directly to the TMC2209 stepper motor driver modules, which in turn control the NEMA 17 stepper motors.

- The X and Y motors drive the CoreXY carriage system, allowing precise positioning of the dispensing mechanism.
- The linear actuators connected via worm gears are controlled sequentially to push the selected product into the dispensing basket.

To expand the number of control lines, a 6-to-1 multiplexer and MOSFET switching modules are integrated with BTT, allowing multiple motors to share the same driver channels while still being addressed individually.

The ESP8266 Wi-Fi module communicates with the BTT via UART interface, enabling the vending machine to send and receive data packets such as user selections, payment confirmations, and system diagnostics. ESP8266 also hosts the local web application, providing a contactless interface for product selection and payment. When required, it transmits transaction logs and system data to a cloud database for monitoring and analytics.

The RC522 RFID reader is connected via SPI interface to the BTT board. It enables users to authenticate or make payments using RFID-enabled cards. Once a valid RFID signal is received, the BTT authorizes the dispensing sequence.

Power Distribution and Electrical Integration

The BTT motherboard provides onboard 3.3 V and 5 V rails, but external DC-DC buck converters are implemented to offload power regulation and reduce the electrical load on the motherboard. The main 24 V DC power supply powers the stepper motors, actuators, and relay modules, while the buck converters step down the voltage to 5 V and 3.3 V for the control electronics, sensors, and communication modules.

This separation of power domains improves electrical efficiency and prevents voltage drops or noise from high-current components affecting low-power logic circuits. Proper grounding and fusing are applied throughout the system to ensure electrical safety and stability.

Sensor and Feedback Integration

Sensor integration plays a critical role in maintaining the precise and reliable operation of the vending machine. End-stop switches are installed along the X and Y axes to define “home” positions and prevent over-travel of the carriage, ensuring accurate motion calibration each time the system starts or resets.

Additionally, infrared or optical sensors are positioned at the dispensing chute to detect whether a product has been successfully released. These sensors provide real-time feedback to the BTT motherboard, allowing it to verify successful dispensing, detect jams, or trigger error-handling routines if an item fails to drop. This feedback mechanism ensures safe and dependable operation with minimal user intervention.

User Interface Integration

The vending machine provides two integrated user interface options to enhance accessibility and usability. The primary interface is a web-based application hosted on the ESP8266 module, enabling customers to browse products, select items, and complete payments using their mobile devices. This touchless interface eliminates the need for shared keypads, improving hygiene in public environments.

A secondary LCD screen connected to the BTT motherboard serves as a local display, providing system status messages such as “Ready,” “Dispensing,” or “Out of Stock.” It can also display advertisements or brief usage instructions to assist customers unfamiliar with the system. Together, these interfaces ensure a user-friendly and modern vending experience.

Mechanical and System-Level Integration

Mechanically, the CoreXY motion system ensures efficient movement of the dispensing carriage in both X and Y directions using two synchronised stepper motors. Once positioned, a linear actuator with a worm gear converts rotational motion into linear displacement, pushing the product into the collection slot.

The mechanical frame houses all components, providing stability and ensuring the safety of users and maintenance staff. All cabling is routed through protective conduits and cable sleeves to prevent wear and interference.

System Coordination and Data Flow

When a user interacts with the vending machine, either through the web application or the RFID system, the ESP8266 processes the request and communicates with the BTT motherboard to execute the corresponding command. BTT then activates the relevant motors through the TMC2209 drivers and monitors feedback from the sensors. Once dispensing is confirmed, the ESP8266 updates the transaction log and transmits relevant data to the cloud. The system then resets to an idle state, ready for the next transaction.

Summary

Overall, the component integration establishes a fully embedded and automated vending system that combines mechanical precision, electronic reliability, and digital connectivity. The modular integration of the BTT controller, ESP8266 network module, and peripheral devices provides scalability for future upgrades such as AI-based inventory management, mobile payment systems, or predictive maintenance.

Power supply and consumption analysis

The power system of the vending machine is designed to efficiently supply electrical energy to all control, communication, and actuation components while minimizing losses and maintaining operational reliability. The primary supply is a 24 V DC power source rated at 15 A (360 W), converted from a 240 V AC mains input. The supply voltage is distributed through two main branches: a high-current rail for motors and actuators, and a low-voltage logic rail for control and communication modules.

High-Current Subsystem Analysis

The NEMA 17 stepper motors, controlled by TMC2209 drivers, operate primarily at 24 V DC. Each motor has a phase resistance of approximately 2.8 Ω and is rated for 1.5 A per phase. The instantaneous electrical power consumed by a single motor can be calculated as:

$$P_{motor}=V \times I=24V \times 1.5A=36W$$ Pmotor=V × I=24V ×1.5A=36W

However, because stepper motors are driven by pulse-width-modulated (PWM) control through the TMC2209, the effective RMS current is typically 70 – 80 % of the rated value. Taking a conservative duty factor of 0.75, the average motor power is:

$$P_{avg} = 24V \times (1.5 \times 0.75)A = 27W$$
Pavg =24V ×1.5 ×0.75A=27W

During operation, two motors (X and Y) for the CoreXY system and one linear actuator motor for dispensing may run simultaneously, giving a combined load of approximately:

$$P_{total(motors)} = 3 \times 27W = 81W$$
Ptotalmotors = 3 ×27W=81W

The TMC2209 driver losses are dominated by conduction and switching losses in the MOSFET H-bridges. Each driver dissipates roughly 1 W at idle and up to 3 W when actively switching. Thus, for three drivers:

$$P_{drivers} = 3 \times 3W = 9W$$
Pdrivers=3 ×3W=9W

Including both motors and drivers, the total high-current power draw is approximately:

$$P_{high-current} = 81W + 9W = 90W$$
Phigh−current=81W+9W=90W

Low-Voltage Subsystem Analysis

The BIGTREETECH Octopus Pro motherboard, ESP8266 Wi-Fi module, RC522 RFID reader, and LCD screen all operate at 5V or 3.3V. Step-down conversion is handled by buck converters with about 88 % efficiency (η = 0.88).

Component	Voltage (V)	Current (A)	Power (W)
BTT Mainboard	5	1	5
ESP8266	3.3	.2	.66
RC522 RFID	3.3	.025	.08
LCD Display	5	.25	1.25
Sensors (End stops, IR)	5	.15	.75

The total low-voltage load is:

$$P_{logic} = 5.0 + 0.66 + 0.08 + 1.25 + 0.75 = 7.74W$$
Plogic= 5.0+0.66+0.08+1.25+0.75=7.74W

Accounting for DC-DC conversion efficiency:

$$P_{input(logic)} = P_{logic}\eta = 7.740.88 = 8.8W$$
Pinput(logic)= Plogicη= 7.740.88=8.8W

Hence, the total system power under full operation is approximately:

$$P_{total(active)} = P_{high-current} + P_{input(logic)} = 90W + 8.8W = 98.8W$$
Ptotal(active)= Phigh−current+ Pinput(logic)=90W+8.8W=98.8W

Power Consumption in Sleep Mode

During idle periods (when no vending operation occurs), the system enters a low-power sleep mode. The ESP8266 module supports a deep-sleep current as low as 20 µA, while the BTT motherboard consumes about 100 mA at 5 V for standby functions. The motors and drivers are completely powered down through MOSFET isolation circuits, reducing their current draw to near zero.

Total standby power can be estimated as:

$$I_{sleep(total)} = I_{BTT} + I_{ESP} + I_{RFID} + I_{LCD_{standby}}$$ Isleeptotal= IBTT+ IESP+ IRFID+ ILCDstandby

Substituting the approximate values:

$$I_{sleep(total)} = (0.1A) + (0.00002A) + (0.01A) + (0.05A) = 0.16A$$ Isleeptotal= (0.1A)+(0.00002A)+(0.01A)+(0.05A)=0.16A

At 5 V logic, the total standby power becomes:

$$P_{sleep} = V \times I = 5V \times 0.16A = 0.8W$$ Psleep= V × I= 5V × 0.16A= 0.8W

Thus, in sleep mode, the system draws less than 1 W, a dramatic reduction compared to its 98.8 W active power.

If the machine is active for only 10 % of the time and in sleep mode for 90 %, the average power can be expressed as:

$$P_{avg} = (0.10 \times 98.8) + (0.90 \times 0.8) = 9.88 + 0.72 = 10.6W$$ Pavg= 0.10 × 98.8 + 0.90 × 0.8 = 9.88 + 0.72 = 10.6W

The average daily energy consumption is therefore:

$$E_{daily} = P_{avg} \times t = 10.6W \times 24h = 254.4Wh = 0.254kWh$$ Edaily= Pavg ×t=10.6W ×24h=254.4Wh=0.254kWh

Assuming an electricity cost of \$0.30 AUD per kWh, the daily operating cost is:

$$C_{daily} = 0.254kWh \times \$0.30kWh = \$0.076$$ Cdaily=0.254kWh ×$0.30kWh=$0.076

or roughly 7 to 8 cents per day, which demonstrates the high efficiency of the proposed design.

Software components

Overview of software designs

The software architecture of the proposed vending machine system is structured into multiple layers, with the core control logic built on the Klipper firmware framework. Klipper is an open-source 3D printer firmware originally developed for high-performance, real-time motion control using modern 32-bit microcontrollers. In this project, Klipper is repurposed to control the motion and dispensing mechanisms of a smart vending machine, leveraging its robust stepper motor handling, modular configuration system, and compatibility with the BIGTREETECH Octopus Pro V1.0 motherboard.

At the lowest level, the Klipper firmware runs on the 32-bit ARM Cortex-M4 microcontroller integrated into the BTT Octopus Pro board. It directly controls the CoreXY motor system for precise movement of the XY dispensing carriage, as well as linear actuators for product dispensing. Klipper interprets G-code-style commands that define motion sequences and timing. These commands can be generated externally or triggered via macros and scripts written in Klipper's configuration language. The firmware handles homing procedures, end-stop detection, and coordinates actions with the multiplexer and MOSFET switching modules to manage multiple actuators with minimal GPIO usage.

The ESP8266 Wi-Fi module serves as the user interface controller and communication bridge. It hosts a lightweight web server that delivers a mobile-accessible user interface. Through this interface, customers can browse available hygiene products, authenticate via RFID, and complete cashless transactions. Once a product is selected and payment is confirmed, ESP8266 sends formatted G-code or macro commands to the BTT via UART, instructing Klipper to execute the corresponding movement and dispensing routines. This separation of UI logic and low-level control ensures modularity and improves maintainability.

While Klipper traditionally pairs with a Raspberry Pi for advanced functionality, this design minimizes cost and complexity by having the ESP8266 act as the "host" in a simplified form. However, the architecture allows for future integration of a full Linux-based host (such as a Raspberry Pi Zero or similar) if advanced features like real-time cloud analytics, AI-driven inventory prediction, or complex UI rendering are needed.

The software system is designed to be event-driven and modular, with key tasks such as RFID scanning, payment validation, and command dispatch handled by the ESP8266, and precise motion control delegated to the Klipper-managed microcontroller. Power efficiency is maintained through low-power modes during idle periods, and robust feedback mechanisms (e.g., end-stops and optical sensors) provide fault detection for jammed products or incorrect positions.

By leveraging the proven stability and configurability of Klipper, the system benefits from a well-supported open-source ecosystem while gaining fine-grained control over motion and hardware coordination. This makes Klipper a powerful and efficient foundation for the vending machine's embedded software.

Development Tools and Languages

The development of the vending machine software involves a combination of tools and programming languages tailored to the needs of embedded control, web interfacing, and system integration. Development is split across two main platforms: the BTT motherboard, which runs Klipper firmware on an STM32 microcontroller, and the ESP8266 module, which handles network communication and the user interface.

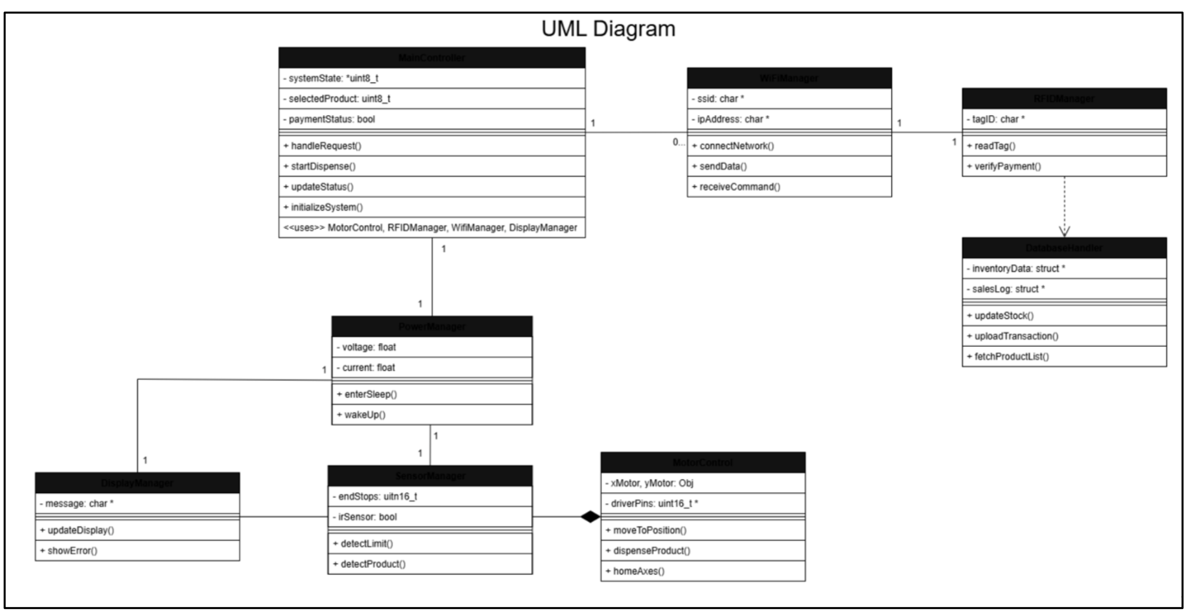
Development Tools for BIGTREETECH Octopus Pro (STM32 + Klipper)
The BTT uses a 32-bit ARM Cortex-M4 microcontroller (STM32F446 or similar), which requires cross-compilation and flashing using the following tools:

- GNU Arm Embedded Toolchain (arm-none-eabi-gcc)
- Make (GNU Make)
- DFU-Util or SD Card
- Neo vim (nvim)
- Serial Debugging Tools

Languages Used:

Platform	Language Used	Purpose
BTT Octopus Pro (Klipper)	Go (host), C (firmware)	Motion control, macros, G-code parsing
ESP8266	Arduino C/C++, HTML, JavaScript	Web UI, Wi-Fi handling, RFID, UART
Configuration Layer	Klipper .cfg scripting	Motor setup, macro definition
Web Interface	HTML/CSS/JS	Frontend for mobile interaction

Software flowchart



Interaction Between Software and Hardware

The software and hardware components of the vending machine are tightly integrated to enable real-time control, communication, and feedback. The BTT motherboard, running Klipper firmware, handles all motion control and peripheral management, receiving commands over UART from the ESP8266 module.

When a user selects a product via the web interface hosted on the ESP8266, the selection and payment confirmation are sent as serial commands to the BTT board. Klipper interprets these commands and activates the appropriate stepper motors via TMC2209 drivers to move the CoreXY carriage and initiate the product dispensing sequence using a worm gear and actuator. End-stop switches provide feedback for carriage position and homing, while optical sensors verify successful dispensing. The RFID reader is polled by the ESP8266, and successful authentication triggers the dispensing process. The power subsystem ensures reliable voltage delivery to both logic and high-current components, while communication between modules uses UART, SPI, and I2C protocols.

This layered architecture allows modular control and reliable operation, combining real-time hardware actuation with cloud-aware, user-facing software.

Constraints and Challenges

Cost Considerations

The cost of installing and running sanitary and hygiene vending machines is an important part of this project. Costs can be divided into upfront purchase costs, ongoing operational expenses, product costs, and revenue considerations.

Upfront Costs

In Australia, vending machines are priced between AUD $2,000–$4,000 depending on their design and features [13]. Machines with advanced technology such as IoT integratsion, contactless payment, and cloud monitoring are more expensive than basic models. However, these features reduce failed sales and make the system more reliable in the long run [8].

Operational Costs

The yearly operational cost of a vending machine is estimated to be around AUD $400–$700, which covers servicing, part replacements, and general maintenance [13]. Power consumption is another ongoing cost, but using energy-efficient systems can help to keep this lower. In addition, regular refilling of sanitary products must be considered as part of operational expenses.

Product Costs

Sanitary products can be purchased in bulk at low prices. Pads and tampons cost around $1–$2 per unit, pantyliners around $0.50–$1.50, hygiene items such as deodorant or wipes between $2–$4, and small emergency kits (containing a pad, tampon, and wipe) around $3–$5 wholesale [14]. Buying in bulk reduces costs and improves overall profit margins.

Pricing and Revenue

This project uses a value-based pricing strategy, where products are sold at slightly higher prices than in supermarkets or pharmacies. Pads and tampons are priced between $2–$4, and emergency kits between $5–$8. Customers are often willing to pay this small premium because of the convenience, privacy, and 24/7 access provided by vending machines [14].

Break-Even and Sustainability

With an average margin of about 40–50%, a machine only needs around 15–20 transactions per month to cover basic costs. In high-traffic areas such as universities, hospitals, and transport hubs, the sales are expected to be much higher, which reduces the payback period and makes the business sustainable [15].

While the upfront costs are relatively high, the low labor requirements, use of smart IoT features, and value-based pricing make sanitary vending machines a cost-effective and profitable solution over time [8].

Performance Trade-offs

When designing and operating sanitary product vending machines, it is necessary to balance performance, cost, convenience, and sustainability. Improving one factor often comes at the expense of another, and these trade-offs must be carefully considered.

Technology vs. Cost

Adding smart features such as IoT connectivity, cashless payments, and real-time inventory monitoring improves performance and customer convenience. However, these features increase upfront costs and may require ongoing software updates and data plans [8]. A trade-off exists between building a highly advanced system and keeping the machines affordable for small-scale operators.

Product Range vs. Machine Capacity

Offering a wide range of products, such as pads, tampons, pantyliners, deodorants, and emergency kits, increases customer satisfaction and inclusivity. On the other hand, including many different products reduces the total stock of each item and requires more frequent restocking. Limiting the variety can lower restocking costs but may reduce customer choice [15].

Convenience vs. Pricing

To ensure 24/7 convenience and privacy, machines are in restrooms and high-traffic areas. This level of convenience allows for slightly higher pricing (value-based pricing model). However, if prices are set too high, some customers may still prefer supermarkets or pharmacies. The trade-off is between keeping products affordable while maintaining enough profit for the machine to be sustainable [14].

Security vs. Accessibility

Machines placed in public spaces must balance accessibility with security. Strong locks, tamper-resistant enclosures, and surveillance can reduce theft and vandalism but also add to the machine's cost and complexity. A balance must be achieved to protect assets without making machines difficult for customers to use.

Energy Efficiency vs. Reliability

Energy-saving components (such as low-power controllers and LED lighting) reduce electricity costs and improve sustainability. However, more aggressive energy-saving measures (e.g., automatic power-down features) may affect reliability and response time when customers need quick access. This trade-off highlights the importance of selecting efficient but dependable hardware.

Performance trade-offs show that not all goals can be maximized at the same time. The final design of the sanitary vending machine must balance advanced features, cost, product availability, pricing, and energy efficiency to achieve a practical, reliable, and sustainable system [8],[15].

Safety and Security Features

System Safety Mechanisms

Safety is an essential aspect of vending machine design, especially when machines are placed in public areas and handle sensitive products such as sanitary and hygiene items. The following mechanisms ensure that the system operates safely for both users and operators:

Electrical and Fire Safety

The machine must comply with electrical safety standards to prevent shocks or fire hazards. This includes the use of certified power supplies, proper grounding, insulated wiring, and protective fuses or circuit breakers. Overheating prevention through ventilation and thermal cut-offs also reduces fire risk [16].

Safe Product Dispensing

The dispensing mechanism should be designed to avoid jamming and prevent injuries. Motors and moving parts are enclosed to ensure that customers cannot accidentally touch them. Optical or infrared sensors confirm successful product delivery and stop the system if a blockage is detected [17].

User Safety and Accessibility

The machine interface must be simple, with a clearly visible display and buttons that can be used by people with limited mobility. Cashless payments reduce the handling of coins and cash, lowering hygiene risks. Emergency shut-off switches may also be included for operator use during servicing.

Tamper and Vandalism Protection

Since machines are in public restrooms and other open spaces, strong locks, tamper-resistant enclosures, and alarms are needed to protect both the machine and users. This not only prevents theft but also reduces the risk of accidental injury caused by forced entry attempts [15].

Hygiene and Sanitation

Because the machine dispenses sanitary products, hygiene is a safety priority. Products should be stored in sealed compartments to protect against contamination. The machine exterior must be easy to clean and made of durable, non-toxic materials. Regular maintenance schedules ensure products remain fresh and safe for use [14].

By combining electrical protection, safe dispensing mechanisms, tamper-proof enclosures, and hygiene safeguards, the sanitary vending machine can provide a safe and reliable service for customers and operators. These safety mechanisms help build trust, protect public health, and ensure compliance with industry regulations.

Fault Tolerance

The vending machine uses a few fault tolerance techniques to guarantee consistent and trustworthy operation:

The Transactional Dispense FSM

Allows the system to securely abort without double-vending by notifying each step of the dispense sequence (move, push, verify) [30, 31].

Procedures for Error Recovery

The system makes one try at dispense after a failed attempt.

Cloud-Based Alerts

Remote diagnostics and maintenance planning are made possible by the local signing of faults and their transmission to the cloud.

Fail-Safe Defaults

To ensure user safety and avoid accidental operation, the system switches to a safe idle state in the case of a communication problem or power outage.

Sensor Redundancy

To minimize false positives, end-stop switches, and optical sensors allow dual-layer feedback to verify product distribution and vehicle place.

Watchdog Timers & Brownout Reset

In the event of software hangs or voltage decreases, the microcontroller's hardware watchdog and brownout detection feature will restore the system to a safe condition. To prevent accidental operation or dangerous behaviours during fault situations, this makes sure that the machine stops all action and locks the dispensing mechanism [32].

Safe Homing

End stops and current-limited homing techniques secure mechanical parts during startup or resets.

Sensor Redundancy
To minimize false positives, end-stop switches, and optical sensors allow dual-layer feedback to verify product distribution and vehicle place

Data and Communication Security

Proper data and communication safety is crucial for the reliable and safe operation of the smart vending machine. The safety measures that can be implemented include the following.

Secure communication networks — Encryption protocols such as SSL/TLS can be used for secure communication between the vending machine, remote server and payment gateway. This ensures the connection of the user to the legitimate site, protects sensitive information such as login credentials and credit card numbers, and ensures the integrity of the data during transit. [20]

Protection of user data — As contactless or cashless payment is one of the key features of this design, the PCI DSS (Payment Card Industry Data Security Standard) must be followed to prevent the storage or exposure of credit/debit card details. It is also crucial that user transactions are logged anonymously, to avoid the exposure of the personal identity of customers. [21]

Secure Input Handling: All user input such as product selections, quantity choice, QR codes or payment codes must be validated against expected data formats. Input sanitization must be done by rejecting unexpected inputs, which is especially important to prevent buffer overflows, code injection or command injection. [22]

Strong authentication credentials (if possible, biometric verification or multi-factor verification) must be applied for all privileged operations, such as access to system controls, maintenance settings or firmware updates. It is also advisable to adhere to the principle of least privilege (by restricting user permissions to only actions required for the operation) and verify all key modifications using digital signatures to prevent unauthorized changes.

Other measures include ensuring immediate encryption of sensitive data such as pins and ensuring that the input devices are safe from tampering. It is also important to prevent misleading user inputs, by using clear prompts and implementing time-outs when repeated wrong inputs are made. [23]

Hardware Protection Measures

Comprehensive tamper protection and physical security measures are essential to prevent theft and vandalism of the vending machine. This can include a tamper resistant enclosure made of reinforced metal, concealed locks and internal hinges. Anti-theft anchoring is necessary to prevent the forced relocation or theft of the machine. Magnetic and vibration sensors can be used to detect unauthorized access or strong impacts. Electronic locks with RFID access or pins are useful to secure sensitive areas, such as cash compartments, control panels and product compartments. Maintenance logs that monitor service sessions, and physical separation of different compartments can also help to minimize security risks during routine refills and maintenance. In the event of tampering or forced opening, a dedicated alarm as well as an alert to the operator must be activated to ensure a quick security response.

Another aspect is the protection of sensitive electronic components and safety features, to ensure reliability and durability of the machine. Integrated voltage regulators and fuses can be used to protect against power fluctuations and surges. Cooling vents and continuous temperature monitoring is required to prevent overheating of electronic components, especially during sustained operation. Short circuit protection through resettable fuses can be done to prevent extensive systemic damage during electrical faults. The exterior enclosure and the seals are engineered to IP54 standards to ensure dust and moisture resistance needed for operating in semi-outdoor environments. Another layer of protection is the EMI/RFI Shielding, which is intended to protect the microcontroller and payment system from electromagnetic interference. Including a backup power supply allows the machine to send emergency alerts and complete active transactions during short power outages.[24]

Data hardware security is also crucial for the safe and reliable operation of the machine. PCI-Compliant Payment Terminals can be used to encrypt sensitive transaction data upon entry. Using secure microcontrollers with built-in encryption allows for safe storage of sensitive data needed for core operations. It also prevents unauthorized firmware modifications. Secure Boot and Firmware Locks can ensure that only the authentic firmware is executed during startup. Isolating the payment unit from the main control logic also helps to limit access and potential damage if one subsystem is compromised. [25]

Maintainability

Maintainability is an important factor for ensuring that sanitary product vending machines can operate reliably over time. This means the machine should be designed in a way that makes it simple to service, repair, and upgrade without major disruption. For example, using modular components allows faulty parts such as motors, sensors, or payment readers to be replaced individually instead of replacing the entire system.

Clear documentation and a modular software design also make it easier to update features like payment methods or stock monitoring as technology improves. In addition, smart diagnostic tools and remote alerts can help operators quickly identify issues such as low stock or mechanical faults, reducing downtime. Planning for long-term sustainability—by using energy-efficient hardware, widely available spare parts, and easy-to-clean materials—ensures that the vending machines remain reliable, cost-effective, and adaptable to future needs.

Ease of Upgrades and Replacements

Modular mechatronics

The stepper drivers (TMC2209) are pluggable; the motors, the worm/linear gear train assemblies, and the sensor pods are field replaceable with keyed connectors.

Config first motion layer

Klipper runs a human-readable .cfg to change pins, limits, currents, and kinematics without recompiling [11]– [13].

Swappable comms

The ESP8266 carrier can be swapped out for an ESP32 or Pi Zero 2 W host if a richer crypto / UX front end is desired, without affecting the MCU motion stack.

Service access

Hinged front service door; harnesses are labelled; QR goes to a health page per unit and error codes for guided triage.

Diagnostic and Debugging Tools

Both software and hardware tools are included in the system to facilitate effective maintenance and diagnostics:

Local Debug Console

For on-site diagnostics, a USB/UART console offers secure, read-only access. To enable specialists to inspect and control every machine from a single location, the equipment transmits its error records to a central system.

Cloud Logging

Transaction logs, fault events, and system uptime parameters are stored for monitoring and analytics by Firebase or comparable cloud services.

Logs & Error Codes

SKU/bin identifiers are connected to time-tagged fault events. For remote testing, a QR code on the LCD connects to a web-based health page.

Serial Debugging

Real-time recordings of motion commands, sensor conditions, and error messages are provided by the BTT board's and the ESP8266's UART-based output.

Documentation and Code Modularity

Because of its modular software structure and thorough documentation, the system is made to be effortlessly maintained and updated in the future.

Hardware Schematics

To assist with updates, repairs, and troubleshooting, wiring diagrams, pin maps, and assembly drawings are provided. Cleaning and refilling tasks are outlined in standard operating procedures (SOPs).

Configuration Files

Without recompiling the firmware or changing the main code, Klipper.cfg files allow for simple modifications to settings like motor speed, pin mapping, and dispense time [33].

Inline Documentation

To facilitate debugging and collaboration, each function in the code has comments explaining its inputs, outputs, and purpose.

Modular Codebase

The firmware is divided into modules for communication, motion control logic, finite state machines (FSM), and hardware abstraction layer (HAL) drivers. Updates to one module won't impact the others [34].

Long-term Support Considerations

Reliable, documented components

The BTT Octopus Pro and TMC2209 have robust documentation from many vendor and community sources [7], [8]. The ESP8266 and MFRC522 chipsets have long-lived toolchains and datasheets [9], [10].

Standards compliance

DEX/UCS for auditing and document export and MDB/ICP for payment "peripherals" ensure both multi-vendor compatibility and independence of vendors [4]– [6].

Supply chain feasibility

Multi-sourced parts must be selected (like NEMA17 steppers, buck modules, TFT LCDs). BOM alternates and pin-compatible drivers must also be kept.

Security lifecycle

Periodic firmware revision is needed (ESP8266/MCU), credential re-issue, TLS on cloud linked; migration to ESP32 with secure hardware if needed.

Stretch Goals and Future Development

Future models of the vending machine will come with a few advanced features, even though the existing design satisfies basic demands including cashless payments, product dispensing, and trustworthiness. These consist of integrating solar panels for sustainable energy, tracking stocks in real time via a mobile app, and applying advanced analytics for restocking predictions.

Integration with institutional ID cards for sponsored or cashless access, multilingual support, and accessibility improvements like voice assistance are other possible improvements. Future generations of the system should be more intelligent, accessible, and sustainable because of to these upgrades.

Additional Features Not Implemented

Although the sanitary product vending machine design covers the essential requirements of product dispensing, cashless payments, and reliability, several advanced features were not implemented in the current version due to time, cost, and technical limitations.

1. Renewable Energy Integration

Using solar panels or energy-harvesting methods could make the machine more sustainable and reduce electricity costs. However, this requires additional hardware, space, and higher upfront investment, which were not feasible for the prototype stage.

2. Mobile App Connectivity

A companion mobile application that allows users to locate nearby machines, check stock availability, or receive digital receipts was considered. This feature was not implemented because it requires more complex software development and backend integration.

3. Advanced Data Analytics

While the machine can track stock levels, more advanced analytics such as user purchase trends, predictive restocking, or dynamic pricing were not included. These features would require cloud services and larger-scale data collection.

4. Voice Assistance and Accessibility Features

Accessibility could be improved by adding voice instructions or touchless interaction options for people with disabilities. However, the current design prioritized a simpler interface to reduce costs and complexity.

5. Multi-Language User Interface

Supporting multiple languages on the display would make the machine more inclusive in diverse environments such as universities and transport hubs. This feature was excluded in the prototype to keep software development focused on core functionality.

6.Integration with Institutional ID Cards
Linking the vending machine to student or staff ID cards for payment or free product distribution (e.g., sponsored by a university) was considered but not implemented due to the need for secure integration with third-party systems.

These additional features were identified as valuable for improving sustainability, inclusivity, and user experience, but were not implemented due to cost, time, or technical complexity. They remain strong candidates for future development stages.

Planned Improvements

Fleet view
DEX/UCS out + REST MQTT bridge; stock alarm, jams, temperature.C48; vendor KPIs

Payment
Add MDB Cashless device & approved gateway, add NFC wallets + entitlement IDs

Per SKU dispense macros
Klipper macros to change push distance/force capability in product bin.

Scalability

The scalability of the smart vending machine design facilitates its continuous growth and evolution to effectively meet future demands. The modular hardware architecture and the use of standard interfaces enable new components to be seamlessly integrated into the existing system. This includes upgrades such as the addition of new product racks, display modules, incorporating new sensors and payment units, renewable energy integration and touchscreen interfaces. The flexibility of software allows the addition of new features such as multilingual user interfaces, voice commands and new APIs. Through IoT-based networks, multiple smart vending machines can be integrated and monitored through a single central Cloud platform. This is useful for large scale deployment of the design across multiple locations and development of mobile applications with real-time product availability. [28, 29]

Integration with Emerging Technologies

resolar + MPPT + LiFePO4 pack + complimentary gear for low duty non-refrigerated operation. (idle <1 W, active c. 100 W bursts; good duty cycle) AI Analytics; demand prediction, stock mix optimization, alarm jam/error signature detection. Edge upgrades: swap out ESP8266 host for ESP32/Pi Zero for better crypto, WebAuthn, camera-based verification of bays (or CAN bus expansion). Public programs alignment: telemetry hooks for Government/NGO programs which support menstrual equity programs (eg Vic statewide deployments). [2]

Conclusion

The design and development of the IoT-Enabled Sanitary Product Vending Machine highlights the ability of embedded systems engineering to address both technical problems and important social needs. Embedded systems engineering is demonstrated through the incorporation of the BIGTREETECH Octopus Pro motherboard with ESP8266 Wi-Fi module and RC522 RFID reader to provide a fully automated, cashless and energy-efficient public hygiene system. The modular embedded system architecture enables accurate motion control, reliable communications, secure payment handling and lower maintenance and energy costs.

The design process reflected the need for interdisciplinary cooperation, showing that hardware integration, firmware writing, safety assurance and user-centric thinking can all be addressed.

One of its key successes has been the team's ability to solve problems in a systematic and iterative manner to create a scalable prototype that is consistent with modern IoT objectives such as remote monitoring, cloud analytics and low power operation.

Further than the engineering achievements of this project, it also demonstrates a positive contribution towards social improvement. The provision of discrete, cheap, 24/7 accessible sanitary products help support menstrual equity and has a positive effect on the community's wellbeing. Future improvements such as solar energy use, AI-based stock management systems and institutional ID connections can broaden the scope for simplicity and inclusive design.

The project has shown that it provides for required design outcomes of embedded systems engineering, and that technology when applied in a thoughtful manner can allow a development of both technical efficiency and social responsibility. Everyday automation therefore can be transformed into an effective public service.

Summary of Key Points

By designing an embedded smart vending machine for sanitary and hygiene supplies, this project tackles a critical societal demand. A BIGTREETECH Octopus Pro motherboard, an ESP8266 Wi-Fi module, and an RC522 RFID reader are all connected within the system to guarantee reliability and cashless distribution. Using a transactional finite state machine (FSM), watchdog timers, and cloud connectivity, the MPU primarily handles motion sequences, sensor feedback, user interaction, and fault recovery. Additionally, the system's modular firmware structure and diagnostic tools preserve its versatility, flexibility, and energy efficiency, offering both technological safety and societal advantages.

Reflection on Design Process

The initial phase in the design process was to determine an applicable social need and transform it into technical specifications. By choosing components that combined affordability, performance, and safety, an effective system architecture with integrated sensor feedback, FSM-based dispensing logic, and fault tolerance mechanisms was produced.

The division of work across operations, software, and hardware allowed for effortless collaboration throughout testing and efficient development. Through collaborative development and progressive conversations, the team improved the project's technical and user-cantered features, guaranteeing that the final product is usable, accessible, and comfortable.
Overall, it can be said that the design expanded our awareness of cooperation, system integration, and embedded systems development, moreover, giving us invaluable knowledge for upcoming engineering work.

Final Remarks

In conclusion, through automation, connectivity, and user focus, the sanitary vending machine project effectively illustrates how embedded innovations, and the Internet of Things can deal with significant social problems. However, MPU which is at the hub of this system, uses a transactions-based finite state machine and a modular firmware architecture to handle motion control, sensor feedback, and breakdown recovery.

The design guarantees both technical reliability and public accessibility with embedded diagnostics, watchdog timers, and cloud-based logging. Moreover, future improvements like predictive analytics, mobile app interaction, and integration of renewable energy will turn the system into an entirely smart and ecological public utility, boosting technological progress and having a positive influence on the community.

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Appendices

Appendix A - Table of contribution

Task	Mohammad AQ	Tashi L	Nazanin R	Amiru HM	Dhrubo T
1. Introduction		x			
1.1 Background			x		
1.2 Purpose of the System			x		
1.3 Scope of the Design				x	
1.4 Report Overview			x		
2. Problem Statement		x			
2.1 Real-World Context			x		
2.2 Existing Solutions			x		
2.3 Need for the Proposed System				x	
3. Design Overview	x				
3.1 System Description		x			
3.2 High-Level Architecture	x				
3.3 Block Diagram of the System			x		
3.4 Design Goals and Objectives	x				
4. Hardware Components	x				
4.1 List of Hardware Components			x		

4.2 Justification for Component Selection	x				
4.3 Technical Specifications	x				
4.4 Integration of Components					x
4.5 Power Supply and Consumption Analysis	x				
5. Software Components	x				
5.1 Overview of Software Design	x				
5.2 Development Tools and Languages	x				
5.3 Software Flowchart	x				
5.4 Interaction Between Software and Hardware	x				
6. Constraints and Challenges					
6.1 Cost Considerations			x		
6.2 Performance Trade-offs			x		
7. Safety and Security Features		x			
7.1 System Safety Mechanisms			x		
7.2 Fault Tolerance					x
7.3 Data and Communication Security				x	
7.4 Hardware Protection Measures				x	
8. Maintainability			x		
8.1 Ease of Upgrades and Replacements				x	
8.2 Diagnostic and Debugging Tools					x
8.3 Documentation and Code Modularity					x
8.4 Long-term Support Considerations				x	
9. Stretch Goals and Future Development					x
9.1 Additional Features Not Implemented			x		

9.2 Planned Improvements		x			
9.3 Scalability				x	
9.4 Integration with Emerging Technologies		x			
10. Conclusion					x
10.1 Summary of Key Points					x
10.2 Reflection on Design Process					x
10.3 Final Remarks					x
11. References	x				
12. Appendices	x				
13. Formatting and compiling		x			

Appendix B – Assignment Brief

Curtin University

EMBEDDED SYSTEMS ENGINEERING CMPE3001
Department of Electrical and Computer Engineering

Embedded Systems Design Assignment

Your task is to write the design document for an embedded system. You can choose from the list below or chose your own embedded system design. The design assignment can be handed in individually or as a group of **at most five**. Here are the requirements for this assignment:

- Problem Statement
- General plan for the implementation of the design
- Hardware components of your design (including technical details of the components)
- Software components of your design (software flow of the program, can be represented in terms of flow charts or pseudo code)
- Constraints and challenges of your design in terms of functionality, cost, performance, size, power and energy
- Safety and security features
- Maintainability features implemented in your design
- Inclusion of stretch goals and future development of your idea

Marking Sheet for Design Assignment

Date and Session Time: ____________________

Names and ID Numbers: ____________________
(Please do not forget to write your student ID number)

Task	Assessment Criteria			Allocated Mark
	0%–35%	35%–70%	70%–100%	
Structure and content flow	Poor structure and content flow	The structure and content flow were good but there was room for improvement	Excellent structure and content flow with a beginning, middle and end	/15
Technical Content	The report does not include all the components and the content is not well written	The report includes all the components and the content is well written	The report includes all the components, reasons for selection of the components and the content is well written.	/60
Quality of writing	There were a lot of typos and grammatical errors	The quality of writing was good but there was room for improvement	The writing was clear to understand and without any grammatical errors	/15
The quality of References	Not many references were used, or the references are outdated	Several references used but there is a lack of variety or some are outdated	A lot of up to date and varied references were used in the consistent referencing style	/10