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SpiceBot

The Development of a Solenoid-Controlled
Dispensing Machine and User Interface

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Abstract

Om die toeganklikheid en doeltreffendheid van huishoudelike kookkuns te verhoog, is 'n nuwe masjien ontwikkel en gebou wat tot vier verskillende speserye van verwisselbare houers afgee soos deur die gebruiker versoek deur 'n mobiele toepassing. Die stelsel bestaan uit sewe verskillende dele: die fisiese bouvorm, elektromagnetiese aansturing, ingeboude beheer, Bluetooth-konneksie, LED-beligting, 'n gebruikerskoppelvlak in die vorm van 'n mobiele toepassing en 'n kragstroombaan. Die onderdele is geïntegreer in 'n volledig funksionerende prototipe wat aan alle vereistes voldoen het.

To increase the accessibility and efficiency of domestic cooking, a novel machine was developed and built that dispenses up to four different spices from interchangeable containers as requested by the user through a mobile application. The system consists of seven different parts: the physical build, electromagnetic actuation, embedded control, Bluetooth connectivity, LED lighting, a user interface in the form of a mobile application, and a power circuit. The parts were integrated into a fully-functioning prototype that fulfilled all requirements when assembled.

Contents

List of Figures

List of Tables

Nomenclature

Acronyms and Abbreviations

API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
CAD	Computer-Aided Design
CIE	International Commission on Illumination
CSS	Cascading Style Sheets
CSV	Comma-Separated Values
GPIO	General Purpose Input/Output
HTML	Hypertext Markup Language
IDE	Integrated Development Environment
ISM	Industrial Scientific Medical
LED	Light Emitting Diode
LSB	Least Significant Bit
MWBP	Mobile Web Best Practices
MOSFET	Metal Oxide Silicon Field Effect Transistor
PCB	Printed Circuit Board
RGB	Red Green Blue
SPICE	Simulation Program with Integrated Circuit Emphasis
UI	User Interface
URL	Uniform Resource Locator
UART	Universal Synchronous/Asynchronous Receiver/Transmitter
WCAG	Web Content Accessibility Guidelines

Constants

g $9.81\mathrm{m/s^2}$

Variables and Functions

μ	Coefficient of Static Friction
Θ	Thermal Resistance
B	Button Set
d_B	Button Distance
$\frac{di}{dt}$	Derivative of Current
f_M	Measurement Frequency
F	Force, general
F_b	Balloon's Spring Force
F_c	Solenoid's Counter Spring Force
F_g	Weight
F_k	Spring Force
F_p	Required Pulling Force
F_s	Frictional Force
H	Trace Height
I	Current
I_{colour}	LED Current for a Single Colour: Red, Green or Blue
I_n	Current of Element in n
I_{out}	Output Current
I_Q	Quiescent Current
k	Spring Coefficient
L	Inductance
m	mass, milli
M	Measurement Set
n	The RGB Set (Red, Green, Blue)
N	Normal Force
P	Power
P_D	Power Dissipation
R	Resistance
R_{colour}	Resistance for a Single Colour: Red, Green or Blue
$R_{\Theta ja}$	Thermal Resistance, Junction-Ambient
S	Weighted Sum
T	Temperature Rise
T_A	Ambient Temperature
T_{jmax}	Maximum Device Temperature
V	Voltage
V_{in}	Input Voltage
V_{cc}	Source Voltage
V_{colour}	LED Voltage for a Single Colour: Red, Green or Blue
V_n	Voltage of Element in n
V_{R_n}	Voltage of Element in n's limiting resistor
V_{ULN}	Voltage of ULN2803
V_{out}	Output Voltage
W	Trace Width
x	Displacement

1. Introduction

1.1 Problem Summary

Domestic cooking has proven health benefits and is, for many, a necessary part of life. However, it can be time-consuming and inconvenient. Studies have found a correlation between home-prepared food and dietary quality among participants [1], yet worldwide diet quality declines. Poor diet has been considered a leading cause of poor health [2].

Despite the benefits, home cooking can take a considerable amount of time, of which not everyone has access. Studies have found the amount of time allocated to food preparation can vary based on age, employment status and other factors, suggesting people may not have enough time to cook (as in the case of employed persons) or that aging could lengthen the cooking process [3].

Within food preparation, measuring dry ingredients was pinpointed as an area with untapped potential for optimisation. Cooking with spices has usually required an elongated process comprised of opening jars, finding the right measuring spoons and measuring the correct amount before closing and putting away the jars. The many steps required greatly reduces the efficiency of home cooking. For some people, like those with limited mobility (who may already be at risk for several health concerns), it may present unnecessary challenges. For example, grip strength (a requisite for performing these tasks) can decline with age, health conditions and many other factors [4], suggesting those most in need of the benefits of home cooking can find the task the most difficult.

1.2 Project Aims

The project aimed to alleviate a portion of the time and effort required in domestic cooking by automating the jar opening, dispensing and measuring through the development of an app-controlled spice-dispensing machine.

User experience, feasibility and potential for future work–especially with a view toward possible commercialisation–were the top three design considerations. Modularity and scalability were also considered.

2. Problem Definition

2.1 Data Analysis

A brief market study was developed to validate the problem, inform the physical design and target possible locations where a machine might be most useful.

A small dataset of common dry ingredients and their measurements ordered by frequency was created for various cuisine types by scraping recipes listed at `AllRecipes.com`. The data was acquired over two days, and categories were chosen arbitrarily. The categories and the number of recipes examined can be seen in Table 2.1.

Table 2.1: Recipes Analysed

Date Acquired	Cuisine Type	Number
6-Apr-2020	African	305
6-Apr-2020	American	406
6-Apr-2020	Chinese	389
8-Apr-2020	European	403
6-Apr-2020	Indian	399
6-Apr-2020	Italian	413
6-Apr-2020	Mexican	411
8-Apr-2020	Breakfast	411
8-Apr-2020	Gourmet	403
8-Apr-2020	Quick and Easy	411
Total		
Categories		10
Recipes		3951

2.1.1 Method

After analysing the HTML structure of AllRecipes, Python code was written to build the URLs required to navigate the first 20 pages of a category, and library functions were used to retrieve the nested recipe URLs on each page, open the URLs and return the ingredients.

The remaining list was then filtered by custom keywords; all ingredients not measured in teaspoons or tablespoons, most fresh and wet ingredients were removed, and vulgar fractions was converted. The data was then split into two CSV files listing the measurements and names of dry ingredients, respectively, with the entries ordered from most to least frequent and the frequencies of each entry recorded.

The frequency of names was then graphed by cuisine and used to inform the physical design. The frequency of measurements was used as a weighting to inform the button layout in the user interface. A diagram of the code can be seen in Figure 2.1.

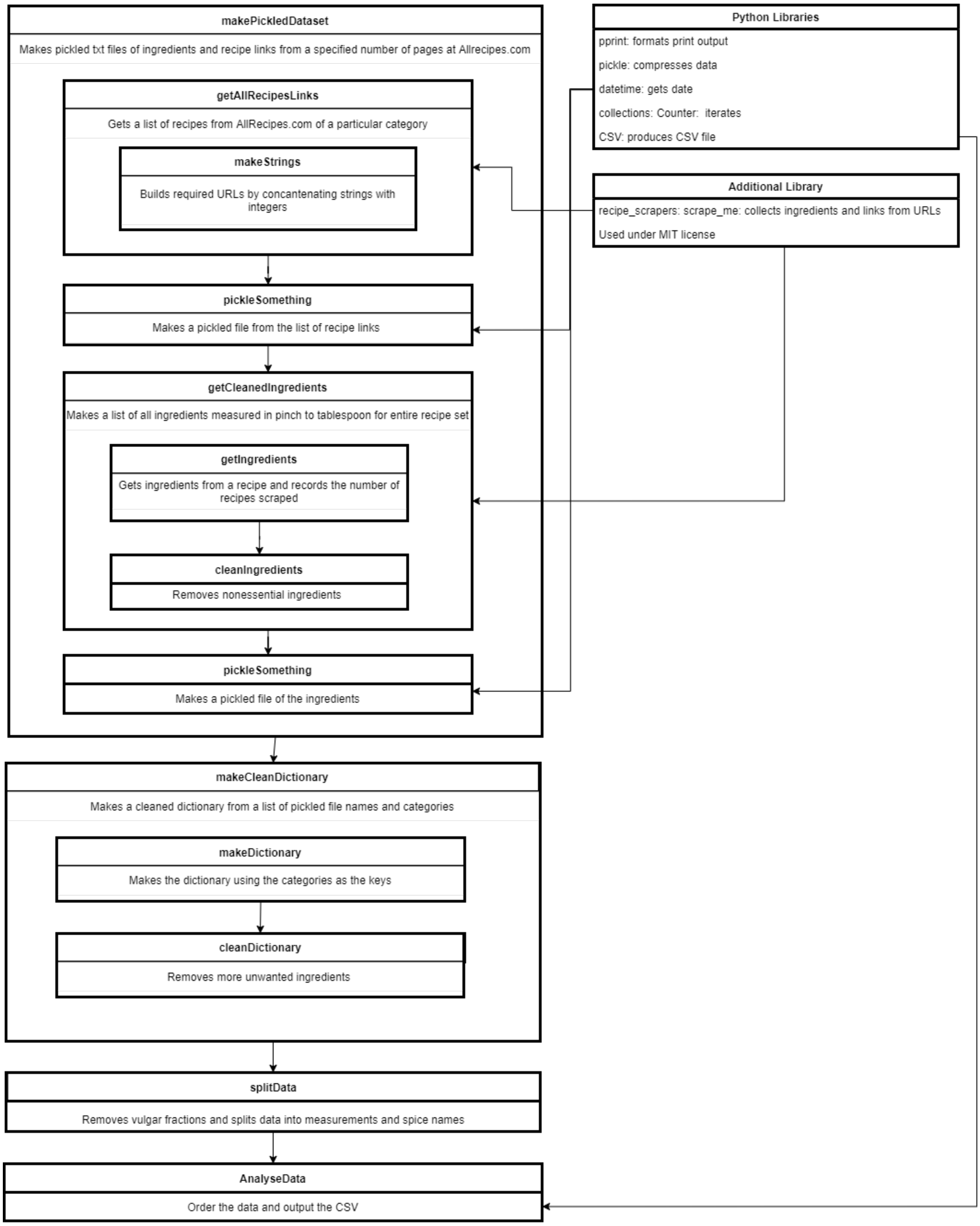


Figure 2.1: Diagram of the code used to acquire the ingredients dataset.

2.1.2 Spice Name Processing

Given the categories showed a large variation of ingredient names (roughly 120 different spices per the approximately 400 recipes examined for each category), the lists were manually truncated to include only ingredients used in five per cent or more of recipes within a category. Each truncated list was then graphed to give a visual sense of how often a particular spice is used, as seen in Figure 2.2.

2.1.3 Analysis

Quick and Easy had the least number of commonly used spices, three, suggesting that measuring and dispensing dry ingredients is indeed a limiting factor of perceived convenience.

On average, eight dry ingredients were used in five per cent or more of the examined recipes, with four spices carrying the majority in nine of ten categories. Therefore, it was decided designing the machine to accommodate at least four dry ingredients at a time, ideally with the containers being easily changeable to allow for multiple runs, would provide a fairly satisfactory user experience without over-complicating the mechanics with repetition.

Salt was the most commonly used dry ingredient by a significant margin.

2.1.4 Limitations

The acquired data has a limited source and sample set, and it does not take into account the broad spectrum of typical user behaviors such as cross-cultural palettes, cooking without recipes, limited recipes or using recipes from other sources. However, the study aimed only to support a general hypothesis about what a typical user might prefer and to refine the problem definition. Expanding the dataset would have required analysis, code rewrites and lengthy execution times for each website considered and would not have remedied the limitations, which could be better addressed by beta testers after completion, beyond the current scope of this project.

2.2 Requirements Definition

Based on the data analysis, it was decided the machine should have the ability to process four, easily interchangeable containers of dry ingredients at a time without excessive motion required for the measurements, and it must work with salt. The containers should be free of electrical components, and the user interface should be accessible. The machine should be designed to be compliant with standards insofar as is feasible within the project scope, and the control code generalized to allow for future alterations without significant rewrites. Electrically it should be as simple as possible to reduce cost and the possibility of component failure. The spices should be isolated from the mechanics as much as possible to avoid mechanical inconsistency and wear.

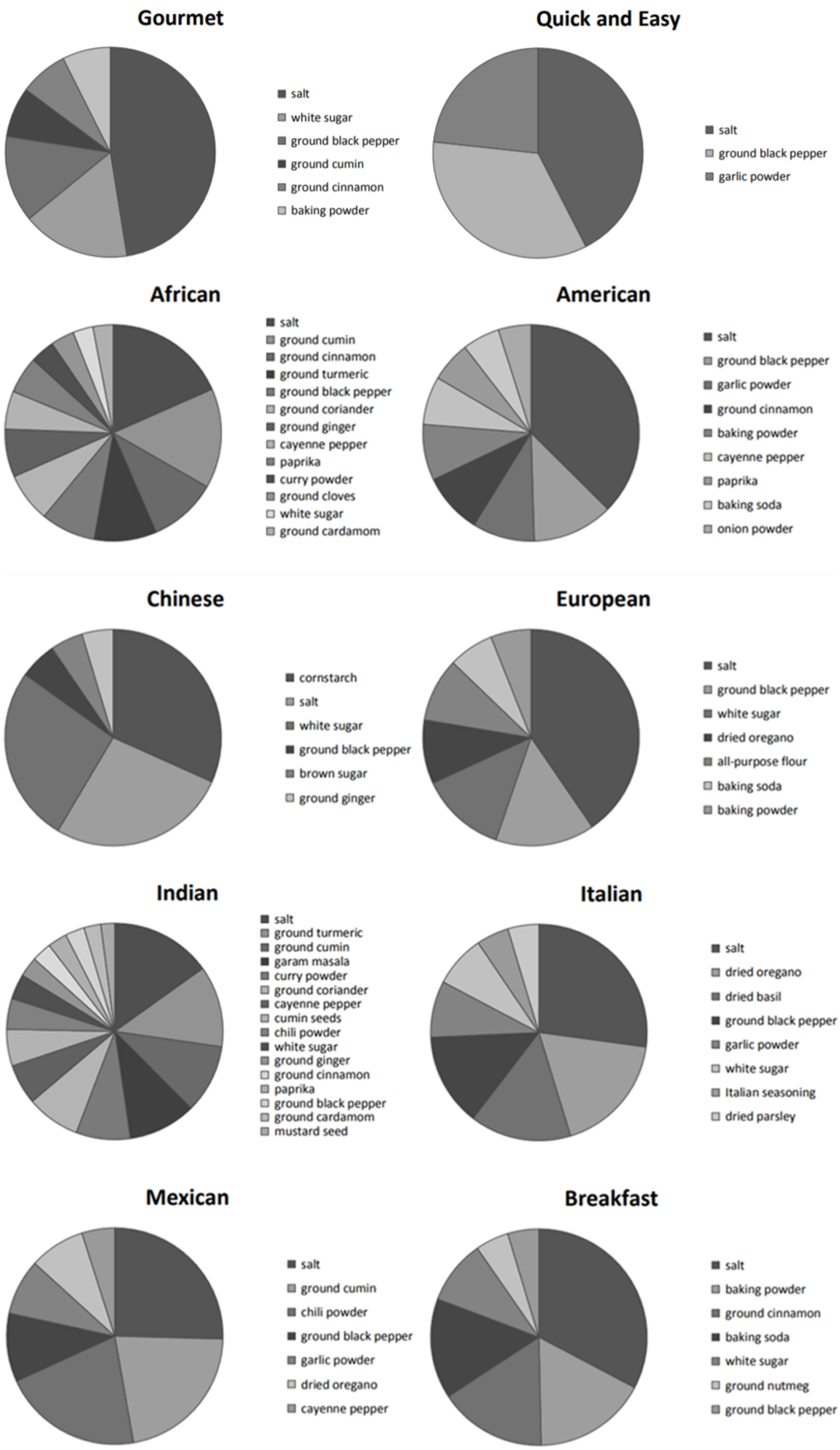


Figure 2.2: Frequency of spices according to cuisine.

3. Technical Solution Summary

3.1 System Diagram

The solution consists of interchangeable containers each with a cavity that simultaneously shuts and empties via solenoid actuators. The actuators are switched via MOSFETs by a microcontroller that receives UART signals through a Bluetooth module, which interacts with a mobile application that provides the user interface (UI). Indicator LEDs are also included. The system diagram can be seen in Figure 3.1.

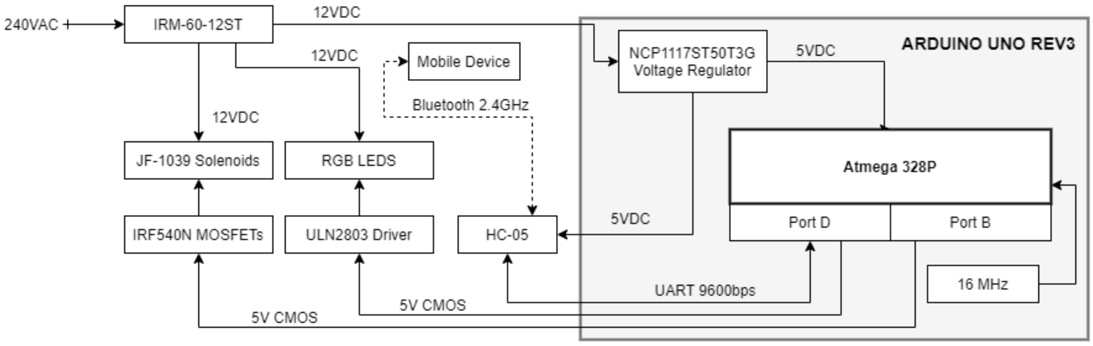


Figure 3.1: System diagram

3.2 System Details

3.2.1 Mechanical Design

Containers with an elastic bladder and drawer-like mechanism are each controlled by a 25N solenoid actuator solidly mounted to a base. The solenoid simultaneously pinches the bladder shut while removing the closure at the base, dispensing a set volume. The motion repeats until the correct amount has been dispensed, while the elastic bladder isolates the granules from the mechanics, as seen in Figure 3.2. The action is meant to resemble scooping with a small measuring spoon and scraping off the excess.

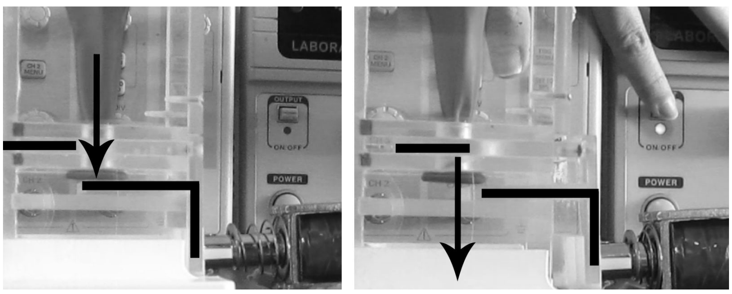


Figure 3.2: Container dispensing. When the drawer is pushed in, the spices are blocked from the bottom. When open, the bladder is pinched from the top, and the spices flow out the bottom.

3.2.2 Electromagnetic Actuation

Solenoid action is driven by IRF540N Power MOSFETs controlled by an Atmel ATmega328P microcontroller and was developed with the Arduino Uno Rev3 development board.

3.2.3 Embedded Programming

The control protocol relies on bitmasking designer-defined register addresses for control, and implements pointers to functions for tick retrieval and delay commands. Implementation was performed in this way to allow the code to be adapted to different microcontrollers an pinouts with limited rewrites to the main control, apart from peripheral and serial setup. It also limits the required computing power. As written, implementation on the Arduino Rev3 with use of their `delay`, `millis`, and `Serial` functions takes 2280 bytes for the programme and 214 bytes for global variables.

3.2.4 Bluetooth Connectivity

The control code is triggered through user input to a mobile application via an HC-05 Bluetooth module, which interfaces with the ATmega328P via UART. Bluetooth commands are sent using functions from `Flutter Bluetooth Serial`, which is an extension for Flutter, Google's development software for UI design.

3.2.5 User Interface and Mobile Application

The mobile application was written in Dart programming language and used the Flutter software with the Android Studio IDE. Using Dart allows for both IOS and Android compatibility. The application is optimised for Android 6.0, API Level 23: Marshmallow, comprising 83.3 per cent of Android devices currently in use. The minimum required Android platform is Android 4.3 API Level 18: Jelly Bean, comprising 98.2 per cent of currently used devices.

3.2.6 LED Indicators

To connect the UI with the physical device visually, 5mm RGB LEDs indicate power and connection status, and container selection. The LEDs are driven by a ULN2803 integrated circuit (IC) connected to the 12V supply. The IC consists of eight Darlington pair drivers.

3.2.7 Power

The absolute maximum voltage is determined by the maximum allowable current to the LEDs (30mA for the leads in series with 560Ω) at 19V. The solenoids set the maximum current requirement at greater than 2A. Their 12V rating was used as the operating voltage. An IRM-60-12ST power supply converts 240VAC to 12VDC and can supply up to 5A. Fuses and decoupling capacitors were also included.

3.3 The User Experience

When plugged in, the power LED blinks, indicating power to the device. The user then opens the mobile application on a Bluetooth-enabled phone, and the device connects. The power LED then changes to continuous light, indicating a proper connection.

Once connected, the user can first select the number of teaspoons and then the appropriate container on the measurement screen. When the container button is tapped, the screen changes to display the currently-programmed number of teaspoons, and the corresponding physical container lights up in a colour corresponding to the button on the UI. The user relies on the spice container's labelling, coupled with the illumination and colour, to determine they have measured the correct spice.

In the case of error, measurements can be cleared by double-tapping the relevant container button and overwritten simply by selecting new measurements and tapping the container button again.

Once the user is finished selecting spices, the dispense button is pressed. The container lights turn off and the solenoids begin dispensing in set increments, one at a time in a rotational pattern while a "Dispensing" waiting screen appears on the mobile device, preventing any more commands from being sent.

Once the dispensing sequence is complete, the microcontroller sends the "finished" command back to the mobile device, which clears the buttons and returns to the measurement screen. The user is then free to dispense again.

A summary of the entire process can be seen in Figure 3.3.

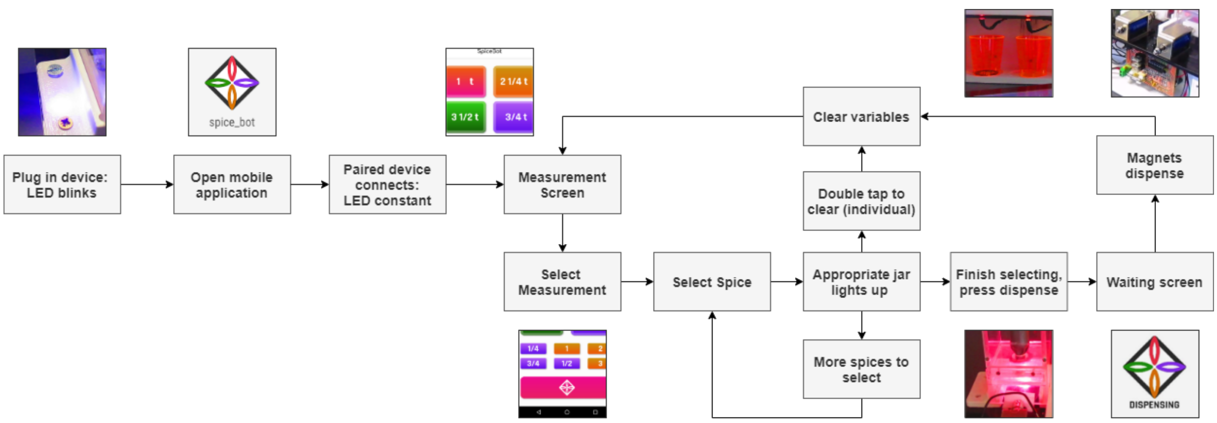


Figure 3.3: Diagram of the user experience.

4. Literature Review

4.1 Mechanics

4.1.1 Equations

According to Newton's first law of motion, a body will not move along a particular axis if the sum of the forces along that axis equals zero. Solving the forces according to the law can determine if any motion will occur.

Where two surfaces meet, there is an uneven distribution of normal and frictional forces that can maintain equilibrium along an axis, even when a force is applied. Frictional force (F_s), acts tangent to contact surface and is related to normal force (N) through $F = \mu N$. The maximum amount of force needed to overcome the frictional force and cause motion is the coefficient of static friction (μ). Once the applied force equals F_s, the object is said to be slipping, and movement will start.

Spring force is governed by Hooke's Law, F_k=-kx where x is the amount by which the spring is elongated or compressed and k is a constant related to the spring's stiffness [5].

4.1.2 Application

Because the solenoids were sold with a force rating, the above equations were used to determine if the solenoids were strong enough to overcome the forces maintaining equilibrium and move the dispensing mechanism in Section 5.2.2.

4.2 Switching

4.2.1 Switching Inductive Loads

An inductor's voltage is related to the rate of change in the current as per the equation $V = L\,\frac{di}{dt}$. When the current drops suddenly, as is the case when switching off a circuit, the collapse of the solenoid's magnetic field can cause a large voltage spike. This spike can damage components or cause memory corruption.

Diodes or transorbs can be used to prevent the spike by providing a path that allows the inductor to use its own current in a "fly-back" loop until the energy is dissipated. Literature notes that diodes should be rated for at least the maximum current carried by the inductor and have a reverse voltage higher than the inductor's driving voltage [6].

4.2.2 Transistors

The MOSFET has three terminals: drain, gate, and source. When a MOSFET is used as a switch, if the input gate-source voltage is higher than the threshold voltage, the transistor is "on" and "off" if the input is less than the threshold. When "off," the MOSFET is in cutoff mode. When the gate voltage increases, the transistor starts in saturation and moves to non-saturation if the voltage increases enough. When in non-saturation, the drain-source voltage across the transistor is low, meaning the voltage drop will occur across the load [7].

4.2.3 Application

Research into the switching of inductive loads informed diode and MOSFET selection in 5.1.2. The voltage spikes were also simulated and measured during development (Section 5.2.2). Information concerning MOSFETs was used to inform a general understanding of circuit functionality.

4.3 Connectivity

4.3.1 Bluetooth

Bluetooth advertises itself as using an unreliable medium (radio) reliably. It operates in the 2.4 GHz ISM frequency band along with all other devices defined by the IEEE 802.15.4 standard (WiFi is also among these). Data corruption due to packet collisions and latency are among the biggest concerns. Bluetooth avoids data corruption by using adaptive frequency hopping. It divides the frequency band into smaller channels and avoids noisy ones, sending very small packets very quickly along with multiple copies of the same message [8]. Bluetooth has transport and middleware protocols with several members each, and each device has a unique 48-bit address [9]. Bluetooth requires a license for use in commercial products that is acquired after undergoing a qualification process. Qualification can be achieved without testing if an already-qualified Bluetooth end product is used without modification [10].

4.3.2 UART

The 8251 Universal Asynchronous Receiver/Transmitter (UART) defines the programming interface for serial communication. It transmits a single bit at a time starting with the least significant bit (LSB) and continues in 5-8 bit data increments (depending on settings) appended by a start bit (low), stop bit/bits (high), and optional parity. It includes status and command registers, as well as transmit and receive buffer registers [9].

4.3.3 Application

Information concerning the functionality provided a general understanding of the HC-05's operation, and the 48-bit address was coded into the mobile application. Information concerning the qualification process was considered for future work and aided in choosing components. Both Atmel and ARM (the two considered microcontrollers brands) are qualified partners [11], and the HC-05 module is qualified [12]. Though it is likely more comprehensive integration would be considered for future work, continued use of the HC-05 could expedite production in the interim.

Knowledge of UART transmission was considered when developing the protocol. Data and commands were encoded together in single characters where possible to allow for possible optimisation with regard to response times.

4.4 Colour Theory

4.4.1 Colour Spaces

Intentional colour selection and precise, standardised colours are required for industry-level branding considerations, as well as for standards in many fields including aerospace materials, traffic signage and food quality [13]. Such precision, however, is not always easy to achieve. Colour perception varies based on an individual's visual acuity as well as the physical limitations of the displaying medium [14]. The RGB coding commonly used in defining a colour, therefore, does not represent a set colour but rather a percentage of a colour space–for example HP/Microsoft's sRGB or Adobe RGB 1998–which can include a different range of colours, or gamut. Different colour spaces exist; this means the same colour code will display differently across devices with different colour spaces[15][16].

4.4.2 Standardisation

In 1931, the International Commission on Illumination (CIE) used linear transforms to change the RGB code into the XYZ colour space and produce the 2D chromaticity graph, representing all colours in the visible spectrum [17]. The graph is commonly used in colour matching. Matching is done using spectrophotometers [18] or sensors with feedback algorithms [19], through visual inspection by people who have recently passed acuity examinations such as the Farnsworth Munsell 100 Hue Test [20], or by using colours from libraries with well-defined matching systems such as from the Munsell or Pantone libraries.

4.4.3 Application

Colour theory was researched after a direct translation of the RGB code to LED currents produced a purplish-white light, and research showed the relationship between current and LED output is not linear[19]. The chromaticity graph superimposed with the LED's gamut was used to estimate the relative percentage of each coloured light needed to produce the UI colours and inform the iterations. Pantone's online test on colour differentiation [21] was used to provide a rough calibration in place of a formal test.

4.5 Power Dissipation

4.5.1 In Components

General electrical equations relating power to voltage and current such as $P{=}VI$, and Ohm's Law, $V{=}IR$, were used to calculate the power in various scenarios. Similarly, relationships between power dissipation (P), temperature difference (T) and a component's thermal resistance exist (Θ) with $T = P\Theta$. Components have maximum values for these parameters. If exceeded, the component may break or not function properly, unless more heat is dissipated through a heat sink [7].

4.5.2 In Printed Circuit Boards

The IPC-2221 is the standard document for determining required trace width (W) and height (H) for a given current carrying capacity (I) and maximum temperature rise (T), with the calculation defined as $I = 0.048T^{0.44}(WH)^{0.725}$ [22].

However, some have urged caution with considering the document a universal standard, with arguments that the calculations are vague and not conservative [23]. Other factors, such as distance between traces, can also play a role. The phenomenon relating the heat dissipating from traces to the current being carried is known as Joule heating. It is balanced by radiative cooling of the trace's exposure to ambient temperature [24].

4.5.3 Application

Power calculations and heat dissipation became a serious consideration once it was known the solenoids were going to source 2A, as the large current could lead to component failure if improperly designed. Power calculations also indicate the amount of electrical resources needed to run the appliance, and the correct power source (using a wall plug as opposed to a battery, for example) was chosen based on the calculations. KiCad's calculator was used to determine the heat and power dissipation of high current-carrying traces in Section 5.2.8. It relies on the IPC-2221 equation.

4.6 Compliance

4.6.1 Safety

The SANS61140:26/IEC6114:2016 Standard: *Protection against electric shock – Common aspects for installations* provides requirements for safe design as well as appliance classification. It notes that 8VDC is the threshold for touch reaction. Touchable current exposure must be lower than 2mA under normal conditions and 10mA under fault conditions, and it classifies appliances based on their level of insulation and electrical isolation [25].

4.6.2 Accessibility

The Web Content Accessibility Guidelines 2.0 [26] and Mobile Web Best Practices 1.0 [27] both list numerous guidelines for ensuring a mobile application is not cumbersome technically or uncomfortable for the user.

4.6.3 Application

With reference to the IEC6114:2016, the device contains no exposed connections external to the protected casing. The metal solenoid casings were grounded as fault protection, and a power supply with a Class II rating was chosen. The accessibility guidelines were used to inform the design of the user interface and were tested in Section 6.5.3.

4.7 Previous Work

4.7.1 Spice Dispensing Examples

Before development of the SpiceBot, previous solutions were also considered, including the TasteTro, which uses motors to dispense the spice [28], but it looked overly complicated with preset spice blends and twenty containers. A video of another automated spice dispenser also exists [29], but the containers are mechanically complex and cannot be stacked on the shelf. Personal experience with an industrial filling machine showed free flowing powder to be messy, and the interaction of particles with mechanics produce significant wear to mechanical parts.

4.7.2 Other Examples

Reloading machines for measuring and dispensing ammunition powders were more seriously considered than the spice examples, given the context would necessitate quick and careful measurement. Of the products found, dispensing mechanisms that worked by a rotating ball valve [30] seemed to have the most advantages as they require one motion and are quick to dispense, but very fine powders get stuck in the seams of the valve on similar products. Also, a way to separate the containers from the control in a modular fashion could not easily be found.

4.7.3 Application

Examples from previous work gave insight into the level of complexity currently required to solve the dispensing problem and set a benchmark for complexity reduction.

5. Design

5.1 Component Selection

Bearing in mind project development was occurring in the middle of the Covid pandemic with a strict time schedule, components were limited to those locally available with same or next day delivery. Solenoids were exempted from this restriction, but also were available locally. The complete bill of materials is available in Appendix C.

5.1.1 Physical Build

The initial container design originally assumed a 3D print fabrication using polylactic acid (the available material), and a working prototype of a single container was printed. The final design used perspex because it provided smoother surfaces and allowed for the mechanics to be visible during demonstrations. Concerns with service delivery were also considered; the workshop's printer had been prone to multiple breakages at the beginning of the year. Machining takes too much time to be considered a viable emergency option, so it became the primary choice instead.

5.1.2 Solenoid Circuit

Solenoids

The JF-1039B solenoids were chosen because of their availability, 10 mm stroke length and 25N capabilities. The 400mA solenoids were mismarked, however; tests and labeling show them to require a current of 2A and not 400mA as advertised, with measured resistances of 5.6Ω. Lab tests showed the minimum voltage and current required to overcome the force of the included spring as 5V, 800mA.

As the only solenoids available with 10mm stroke, they were still used to complete the design because of the advantages previously listed, though the 2A rating did place limitations on the design. The control code was written to dispense only one container at a time rather than simultaneous dispensing. Wire thickness and PCB track width also had to be considered.

Solenoid Driver

The 2A current requirement likewise greatly reduced the number of available drivers to switch the solenoids. Previously, power MOSFETs, specialised solenoid driver chips, automotive H-bridge drivers and Darlington pairs had been considered; yet only power MOSFETs could be found with an applicable current rating. IRF540N were chosen because they had the highest possible current rating 33A [31] of the ones available, both for thermal considerations and durability during prototyping phase. During design A2SHB MOSFETs were briefly considered, but despite their smaller size did not provide any significant space-saving advantages on the printed circuit board, so the higher ratings of the IRF540N were preferred.

Based on the research concerning safe switching, 1n4007 diodes were originally considered because they were familiar and have a reverse voltage rating of 1000V [32]. Once the current was determined to be greater than 1A, they were swapped for their 3A equivalent 1n5408 diodes. These diodes, however, are large in size; the surface mount 1N5822-SS34 were found also with a 3A tolerance and voltage rating of 40V [33]. They were chosen because they did save a significant amount of space, and simulations showed the voltage spike to be under the rating.

5.1.3 Microcontroller and Development Boards

The Arduino Uno Rev 3, Raspberry Pi, STM334R8 and Adafruit Feather nRF52 Bluefruit LE were considered, with main considerations being availability, familiarity, current tolerance, the presence of an on-board Bluetooth module, complexity and the potential for future work.

Adafruit Feather was considered because of its small size, the presence of an on-board Bluetooth module and a familiar, ARM Cortex M4 microcontroller. However, it was only available internationally. Raspberry Pi was briefly considered likewise for the same ARM controller and Bluetooth module, but was deemed too complex for the required functionality. Both the Feather and Raspberry Pi also lacked 5V pins, which were needed for the given MOSFET selection.

Arduino Uno and STM334 were considered most seriously because they were easy to acquire. The Arduino Uno Rev 3 with the Atmel ATMega328P microcontroller was chosen because the ATMega offered 12 digital pins with 40 mA per pin maximum rating and a single UART [34]. The application required one UART and 10 pins, and the higher current tolerance allowed for a simpler test circuit.

The STM334R8 was more familiar and at the time was thought to have more comprehensive documentation, but it also had a limited current tolerance of 20mA per pin across its 51 GPIO and 80mA maximum current output for the whole board, along with a considerable amount of functional circuitry that would not be used [35]. Moreover, given the STM334R8 has the Arduino Uno headers built into the board, the Uno's limited capability did not appear to pose any risk, and the ATMega's simpler architecture (smaller registers, less control registers, shorter memory addresses) made it faster to develop a working prototype.

5.1.4 Bluetooth

The HC-05 Bluetooth module was chosen because it was available and had a UART interface, which was familiar. The inexpensive tablet that was going to be used for development and demos also had a proven track record of working well with inexpensive Bluetooth headphones, whereas the tablet had only been used in public places with Wifi (another option) and with limited reliability. Considering the strict time frame, the option already shown to be reliable with the non-negotiable hardware was chosen.

5.1.5 User Interface

Touch screens and mobile applications were considered, with buttons considered briefly but quickly dropped because of mechanical bounce and the potential for debris collecting in the seams around the button sides. Touch screens were expensive and did not appear to have the same image quality as a mobile device, so mobile was preferred. Using mobile would also expand the potential for SpiceBot both as a mobility assistant.

Flutter and Dart were used for the mobile development because they are cross platform and the syntax was similar to CSS which was previously known. The API is also well documented.

5.1.6 LED Indicators

LEDs

In order to offer a visual association between the physical device and the UI, LED indicators were added to display power, connection status and container selection. Blue LEDs (5mm) were originally considered. These were later replaced by 5mm common cathode RGB LEDs with a diffused lens so the colours could be matched to the UI.

LED Driver

Originally discovered while searching for solenoid drivers, the ULN2803 Darlington pair driver IC was chosen because it had a maximum current tolerance of 500mA per channel and included eight driving circuit[36]. Eight channels would account for every digital output pin not used in the solenoid circuit, allowing for easy expansion. Literature also showed it could be swapped out for a MOSFET-equivalent circuit without significant changes to the circuitry [37]. This seemed appealing as it would mean the entire SpiceBot could be driven by MOSFETs, potentially reducing the required silicon in later designs.

5.1.7 Power

Regulation

An LM7805 linear 5V regulator was originally considered to power the Arduino, but was later dropped in favor of the NCP117 regulator already supplied on the Arduino board. The NCP117 included thermal protection and current limiting, and was designed to use the copper PCB as an additional heat sink, with the ability to take up to 20V maximum input voltage [38]. Power was therefore supplied through the V_{in} pin using an IRM-60-12ST, which measured at 12.2 unloaded.

Additional 12V regulation with LM7812 regulators was considered to increase the range of potential power supplies but abandoned given their maximum current tolerance of 1A. The 3A equivalent regulators were not available nationally. The maximum voltage for the IRF540N MOSFETs is 100V and 30V for the ULN2803; the limiting factor for unregulated input would therefore be the absolute maximum current of 30 mA for the brightest LED (in series with 560Ω). Assuming an LED voltage of 2.5V, the absolute limiting voltage to the circuit was determined to be 19.3V.

Additional Circuitry

A 3A cartridge fuse was included at the input, and a 500mA resettable fuse was placed before Arduino's V_{in} pin. Decoupling capacitors of 10uF (tantalum) and 100nF (ceramic) were included near the input, as well as 1uF tantalum and 100nF ceramic near V_{in}, also for decoupling. Powering the Arduino through V_{in} bypasses the diode used for polarity protection [39]. Due to the limited polarity protection, power input occurs through a PCB terminal block, and the cord to the SpiceBot is not meant to be removable.

5.2 Detailed design

The design consists of seven main subsystems including the physical build, microcontroller protocol, user interface and four circuits: solenoids, LEDs, power and UART connections. The complete schematic can be found in Appendix D.

5.2.1 Physical Build

Development

Development of the physical concept focused primarily on reducing the complexity of the device both electrically and mechanically, both to increase the feasibility of the project within the strict time frame and to make it more attractive for future work.

As seen in Table 5.1, conceptual development occurred with various ideas, each aimed at reducing an aspect of complexity.

The balloon was chosen in the rough prototyping phase because it isolated the powder from the mechanics, had the potential for modularity, and the vibration of the stretching elastic might serve to dislodge any stuck powder. Also it was initially thought that the elasticity could function as a spring, though this is unnecessary with solenoid control. Various prototypes were built and tested as proof of concept.

Once tests proved conceptually, CAD files were drawn (Appendix E). The containers were made rectangular with the intention they be easily stackable. Ideally, the balloon would be replaced with a more suitable material like nitrile, silicone, or surgical tubing, possibly with attached O-ring. Double pinching the bladder with a modified dispensing arm could also be attempted.

Table 5.1: Concepts Considered: Dispensing

Summary	Description	Reasoning	Issues
Rotating cylinder with "open flower design"	A ring of pistons tethered to the edge of an inverted pyramid push upward, opening the pyramid's triangular panels and dispensing the spice, a tray of jars rotates to align each container with the dispense mechanism	Starting design	Complex, containers not removable
Industrial example	A rotating corkscrew dispenses a set amount of spice	Proven example	Complex, containers not removable, difficult to clean
Ball valve	A rotating ball with cavity collects and dispense the spice	Less complex	Containers not removable, powder not isolated
Rolled bag with scraping propeller	A lining gets pulled upward via pulleys mounted near the bottom of a container, the top mound gets scraped off via a rotating propeller	Removable containers	Complex
Balloon or bag with driving wedge and control base	A cap with a wedge-shaped attachment simultaneously pinches a balloon shut while opening the bottom	Removable containers, Isolates powder from majority of the mechanics	

5.2.2 Solenoid Circuit

Development

During the prototyping phase, several control options consisting of various combinations of motors and solenoids were considered, again with an emphasis on reducing complexity, as seen in Table 5.2.

Using all solenoids was initially considered but abandoned because no solenoids of a suitable price and stroke could be found. Potential drivers and development boards were considered in tandem with the motor designs. During the research into the motor design, affordable solenoids were found and eventually chosen because they were of a similar price point to a motor. Solenoids could also be mounted solid, reducing potential stability, alignment and disturbance rejection concerns caused by the dispensing motion.

The estimated force required to dispense the container (F_p), neglecting the mass of the plunger and the spring feedback (F_c), was roughly calculated to determine feasibility, according to the free body diagram in Figure 5.1.

Salt, being the heaviest listed among the most common ingredients, was used for the calculations. First, the balloon's spring force was calculated. The balloon could hold about 50g of salt, and stretched approximately 1 mm when hanging vertically, resulting in a spring constant (k) of 490.5, by substituting Equation 5.2 into Equation 5.1 and applying Hooke's Law (Equation 5.3).

Table 5.2: Concepts Considered: Controlling the dispensing arm

Summary	Description	Complexity	Concerns
All solenoids	Each container controlled by a single solenoid	4 pulses	Suitable solenoids could not be found
Rotating hook controlled by solenoid	A motor rotates a solenoid controlled hook that hooks the correct container open	1 rotation, 1 pulse	Cad complexity of the solenoid valve
3D printer design	Two motors move in the x and y direction to select and push the dispensing mechanism, similar to a 3D printer	2 linear motions	CAD complexity, noise
Music box design	A barrel with dispersed, raised bumps rotates (selection) and is pushed forward and backward by a motor moving in the y direction (dispense)	1 linear motion, 1 rotation	CAD complexity, noise
Cam design	A rotating cam pushes the dispensing arm in and out	1 rotation	Spice selection not possible for more than two
Scotch Yoke design	A rotating scotch yoke pushes the dispenser in and out, or a solid scotch yoke pushes the dispenser of a rotating spice rack in and out	2 rotations, CAD can be basic shapes	Control arm has a lot of wasted space, potentially larger motor size for the spice rack
1 motor and solenoid	similar to scotch yoke design, but with a solenoid replacing yoke	1 rotation 1 pulse	Noise, concerns about alignment, feedback and disturbance rejection
All solenoids	Original design as above	4 pulses	Larger required current

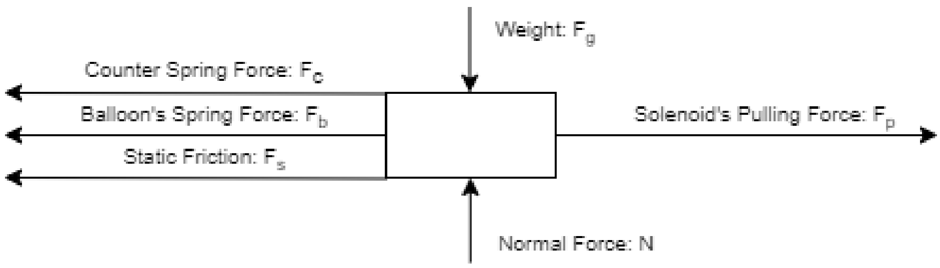


Figure 5.1: Free Body Diagram.

$$0 = \sum F \tag{5.1}$$

$$0 = mg = F_b \tag{5.2}$$

$$F_b = -k(x) \tag{5.3}$$

The mass (m) multiplied by the gravitational constant (g = *9.81* m/s^2) determine the weight, which opposed F_b to maintain equilibrium in the vertical direction when the balloon was hanging vertically. This allowed k to be estimated.

Once the spring constant was found, F_b was determined for the free body diagram by assuming a displacement of 0.01 m, equal to the length of the solenoid's stroke.

The solenoid's spring force (F_c) was neglected.

The force of static friction is given by Equation 5.4.

$$F_s = \mu N \tag{5.4}$$

The maximum coefficient of static friction found for various materials was 1.35 [40], so the coefficient was estimated at 1.35 to account for potentially uneven surfaces.

Equation 5.1 was again applied in the vertical direction, this time for the forces in the free body diagram, to determine the Normal force (N). The mass was assumed to be a conservative 100g (to account for both the salt and the mass of the dispensing part), producing a weight (F_g) of 0.1(9.81), or 0.0981N.

The pulling force ($\mathrm{F_p}$) required for a given mass, therefore, was determined by applying Equation 5.1 as expanded in Equations 5.5 and 5.6.

$$\sum F = F_p - F_s - F_b - F_c = F_p - \mu N - kx - 0 = 0 \tag{5.5}$$

$$F_p = 1.35(0.981) + (490.5)(0.01) = 6.23N \tag{5.6}$$

The resulting $\mathrm{F_p}$ was determined to be 6.23 N. Given the estimated required force was more than four times less than 25N, with margin added, the solenoids were purchased.

Solenoid Circuit

The solenoid circuit is a basic MOSFET circuit with flyback diodes. The 10k resistor ensures proper switching; the additional resistor at the output pin was added as per a recommendation from the Arduino documentation to include 1kΩ resistors at the output, as the voltage division was still above the MOSFET threshold voltage [41].

The voltage spike caused by switching the inductive load was simulated both with and without the Schottky diode (Figure 5.2) to determine its effectiveness, using a 5.6Ω resistor in series with a 3mH inductor, corresponding to the measured resistance and inductance of the solenoid.

Power dissipation of the IRF540N was simulated to be 0.2W while conducting with 4W spikes during switch on and 18W spikes during switch off that last approximately 0.6 ms (Figure 5.3). Given the power dissipation occurs over a short duration (Equation 5.7 for

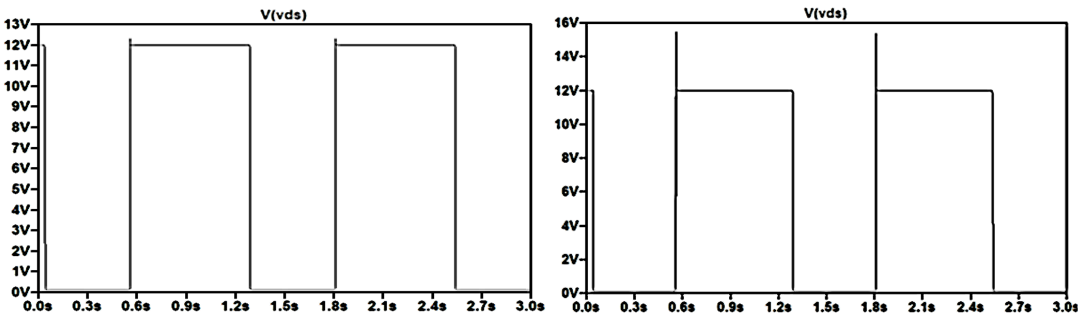


Figure 5.2: SPICE simulation of V_{DS} with and without the Schottky diode.

one 500ms pulse and one 750ms rest), a heat sink was not added. The maximum number of pulses per run is 15, or approximately 1.65W.

$$18(0.6m) + 4(0.6m) + 0.2(500m) + 0(750m - 1.2m) = 0.11W \tag{5.7}$$

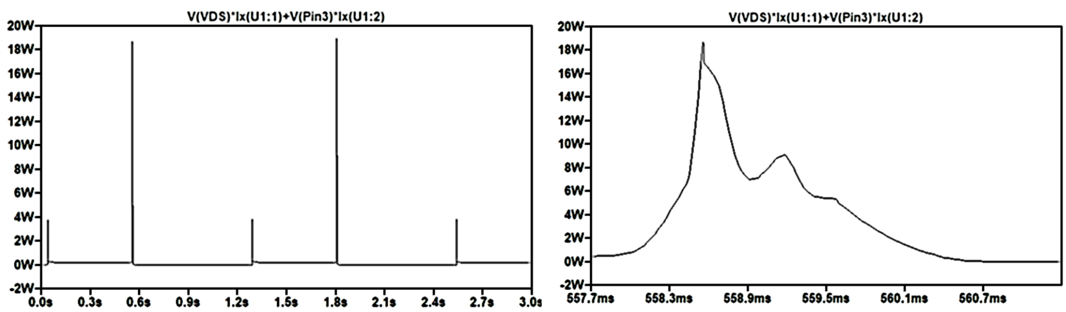


Figure 5.3: SPICE simulation of IRF540N's power dissipation.

5.2.3 Microcontroller Protocol

The algorithms and accompanying protocol were developed with the intention of being general and computationally simple, in preparation for future work which could potentially include design for scaled production where the choice of microcontroller might change. Code setup also aided in prototyping, where the pin position and solenoid timing could be changed in the definitions, without altering the code.

The control code assumes an inputted string of uint8_t characters to correspond with the UART transmission. The first four bits of each character designate which type of character it is; the last four characters provide the value. The code parses the characters by matching the first four to to determine the type, then processing the last four bits according to the information they provide. Characters prefixed with 0x4 indicate commands, a 0x5 prefix indicates an address, and a 0x3 prefix indicates a number. The 0x3 prefix corresponds to the ASCII code for the same number. A list of the current control codes can be seen in Table 5.3 and the address codes in Table 5.4.

Once the command is determined, the information is processed and the appropriate control register is bitmasked with the provided address. The addresses are one hot encoded so as

Table 5.3: Command Codes: 0x4_

Hex	Character	Command	Description	Sender	Receiver
0x43	'C'	Connect	Connect to SpiceBot	Mobile Device	Microcontroller
0x46	'F'	Finish	Return to Measurement Screen	Microcontroller	Mobile Device
0x4C	'L'	Light	Light the Container	Mobile Device	Microcontroller
0x4D	'M'	Measure	Dispense the Spices	Mobile Device	Microncontroller

Table 5.4: Address Codes: 0x5_

Hex	Binary	UI Colour	UI Location	Physical Location (Left to Right)
0x58	0b0101 1000		Top Left	First Container
0x54	0b0101 0100		Top Right	Second Container
0x52	0b0101 0010		Bottom Left	Third Container
0x51	0b0101 0001		Bottom Right	Fourth Container

to ensure only one solenoid or light is active at a time. In the case of the measurement sequence, the SpiceBot assumes the first two characters are allocated to address 0x58, the next two are for 0x54, followed by two for 0x52 and a final two characters for 0x51. The two characters represent the fractional (number of 1/4 teaspoons) and integer number of teaspoons to be dispensed. If a value is zero, the character sent will be 0x30. The code then uses bitshifting to produce characters for functional logic, according to the following listing.

The command sequences have no delineators, apart from ending with the newline character, 0x0A. A list of the possible sequences can be seen in Table 5.5.

Table 5.5: Command Sequences

Hex	Description
0x43 0x0A	Connect to SpiceBot
0x46 0x0A	Return to measurement screen
0x4C 0x5_ 0x0A	Light the container at the following address
0x4D 0x3_ 0x3_ 0x3_ 0x3_ 0x3_ 0x3_ 0x3_ 0x3_ 0x0A	Dispense the following amounts

The protocol assumes a block of four bits has been allocated for the lights control in a single register; the same for the solenoids and a single bit for the power light. Only the same type of control need be in the same register; for example, the four bits controlling the lights must be in the same register, but not the lights and solenoids together. The four bits for the lights, for example, must not be split over two registers.

If the designer defines the control register addresses for the lights, addresses for the solenoids, register sizes, the index of the least significant bit, and an address of a tick retrieval function, the control functions should work with minimal setup. A diagram of the code can be seen in Figure 5.4.

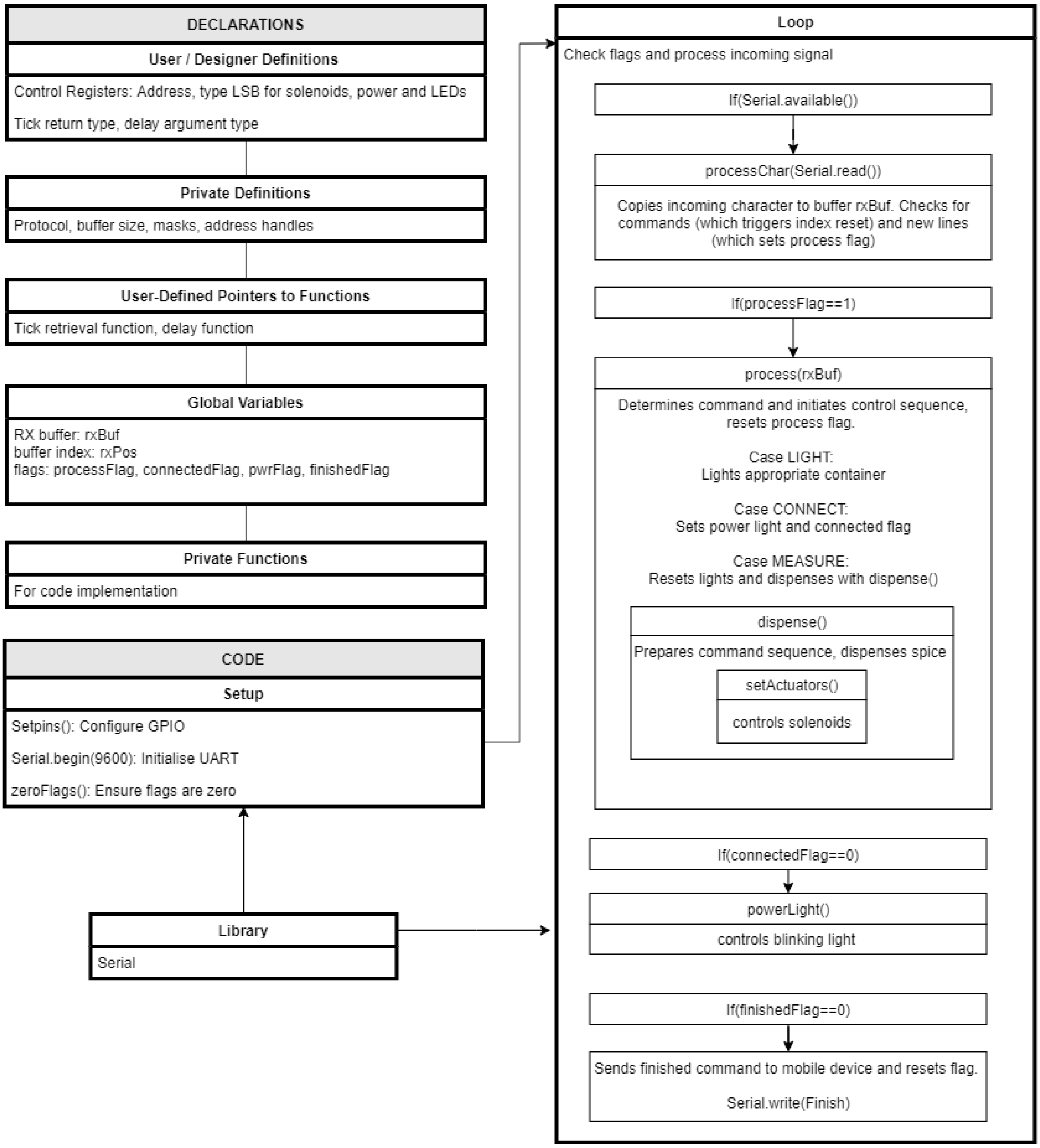


Figure 5.4: Diagram of the microcontroller code.

5.2.4 Bluetooth

The settings of the HC-05 module were left unchanged, with a password of "1234" and a baud rate of 9600 for data transmission.

5.2.5 User Interface

Visual Development

UI design focused primarily on convenience, visual appeal and accessibility. Colours were chosen to be bright and then adjusted until they achieved a minimum contrast ratio 3.0:1, in order to comply with for accessibility recommendations for visual deficiencies. Available Google Fonts were searched and a shortlist created, with Rajdhani chosen for the buttons and Comfortaa chosen for the SpiceBot title. Both were used under OpenFonts license. The user interface, which consists of a measurement and waiting screen, along with the application icon, can be seen in Figure 5.5.

Figure 5.5: The SpiceBot user interface and app icon.

Functionality

Given the layout's symmetrical nature and the limited number of potential combinations for button presses, button placement could be optimised. The number of buttons was reduced from an original design of fifteen to eleven buttons and was arranged in a general format. The layout was then printed, and each button labelled. The distance from the centre of each button center to every other button's centre was measured, rounded to the nearest 0.5 cm to simplify calculations. The obtained distances were then used to estimate the distance (d_B) of each possible sequence of button presses. Using the measurement data from the previously-obtained CSV files, the distance of each sequence was then weighted according to the measurement frequency (f_M), as seen in Equation 5.8.

$$S = \sum_{M} \sum_{B} d_B(1 - f_M) \tag{5.8}$$

B = {0x51, 0x52, 0x54, 0x58}
M = {1/4, 1/2, 3/4, 1, 1 1/4, 1 1/2, 1 3/4, 2, 2 1/4, 2 1/2, 2 3/4, 3, 3 1/4, 3 1/2, 3 3/4}

To illustrate, one teaspoon was the most commonly used measurement with a frequency of 0.32 (the number of teaspoon appearances over the total number of appearances of all measurements), so the distance from 1 tsp to each of the four container buttons was noted and summed, and the sum weighted by (1-0.32). Several configurations for the location of 1 tsp and the other measurement buttons were considered. The configuration with the lowest score was used in the final design. A summary of the calculations can be seen in Table 5.6.

Table 5.6: Possible Button Configurations

Name	Button Arrangement	Weighted Sum (S)
Set 1	1-2-3; 1/4-1/2-3/4	8591
Set 2	1/4-1-2; 1/2-3/4-3	8202
Set 3	1/4-1-2; 3/4-1/2-3	8114
Set 4	1/2-1-2; 3/4-1/4-3	8114

Set 3 seemed a more intuitive configuration of the two lowest-scored configurations and was therefore chosen for the user interface.

Since SpiceBot aims to optimise a mundane task and has the potential to be used often, calculating the most convenient button placement was deemed a valuable addition for enhancing the user experience.

Code Structure

The user interface was developed as a Flutter application using Dart in Android Studio. The main programme returns `MyApp` which contains a stateless widget that sets up the application's navigational structure, removes the debug banner (since the application is still in debug mode and is not officially published) and returns a `MaterialApp`. Returning a `MaterialApp` gives the application access to Google's Material library. `MaterialApp` contains a home page which extends a stateful widget that returns the `MyHomePage` State Class. This class contains the code to be transmitted to the microcontroller as well as the build widget, which returns a scaffold representing the design of the screen. The general layout of stateless and stateful widgets are standard to a Flutter application.

The returned scaffold, which comprises the styling and functional code, was developed specifically for the SpiceBot. `Expanded` widgets were used within a `SafeArea` to ensure compatibility across devices by giving the buttons proportional rather than fixed sizes within a screen area known not to be obstructed by the physical shapes of devices. A boolean was used to determine which screen is shown, the waiting or measurement screen. A diagram of the complete code structure can be seen in Figure 5.6

Code Logic

Integer and fractional variables were declared for each container as well as a general set to record the current button state. When a measurement button is pressed (fractional or integer), the value is copied to the respective variable. It is then copied to the specific container variable when a container button is pressed, and the general result is cleared. This variable is directly displayed within the user interface. When dispense is pressed, the values of the specific container variables are converted to unsigned characters and transmitted one at a time via Bluetooth serial functions to the microcontroller. "Size" variables are also declared for each container and as general variables to control the visibility of the "t" (for teaspoons) seen on the measurement screen. A summary of the code logic can be seen in Figure 5.7.

5.2.6 LED Indicators

Development

Several ideas were considered to indicate user selection including containers of varying resistances, containers with a cam shape that corresponds to mechanical buttons, and hall effect sensors. In all of these concepts, however, a particular container would correspond to one spice, and the control code and user interface would require a database of the corresponding codes and spice names that could be programmed.

Including such a database would either increase the rigidity of the product (only pre-programmed containers would be recognised) or increase the complexity for the user (they would need to learn to program each individual spice container). Neither of these options seemed desirable, as the results from the data analysis suggest that users would prefer a wide range of spices, including specialty items, some of which would be rarely used. It would be increasingly inconvenient, especially in the case of new spices or spices with limited use. Increasing the required setup of the product through programming would also limit the user base by making it less accessible.

Further analysis suggested the user's main priority in its simplest form is to identify the container selected on the interface with the container on the machine. This could be achieved by lighting up the container of choice, which could be manually labelled by the user. Lighting arbitrary containers would fulfill the user's requirement without limiting the range of spices that could be serviced, or increasing the administrative tasks required for use.

Circuit

The ULN2803 switches common cathode RGB LEDs from 12V. A SPICE model could not be found for the ULN2803 so functionality was confirmed by building a single channel according to the datasheet circuit diagram (Figure 5.8).

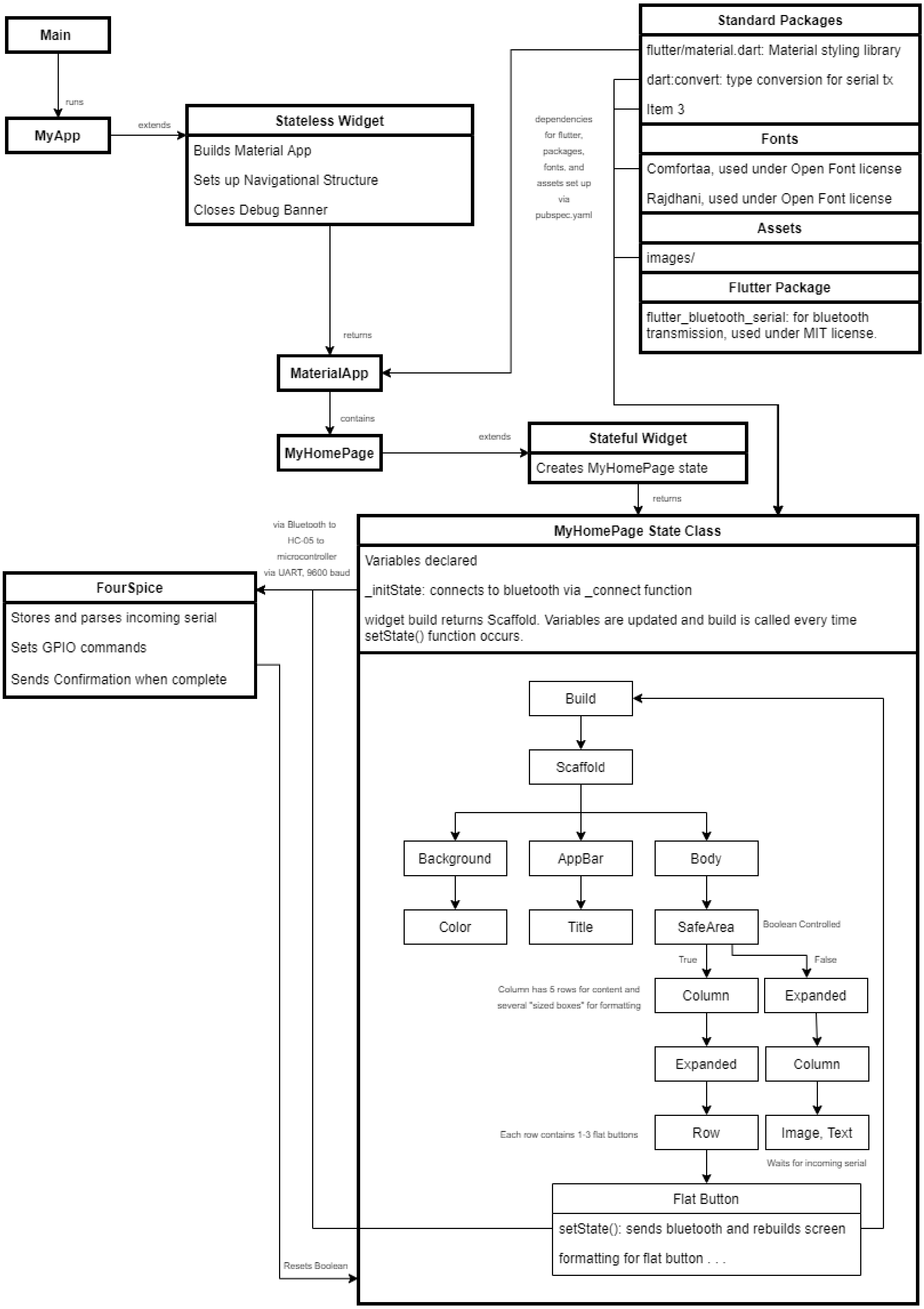


Figure 5.6: Structure of the mobile application.

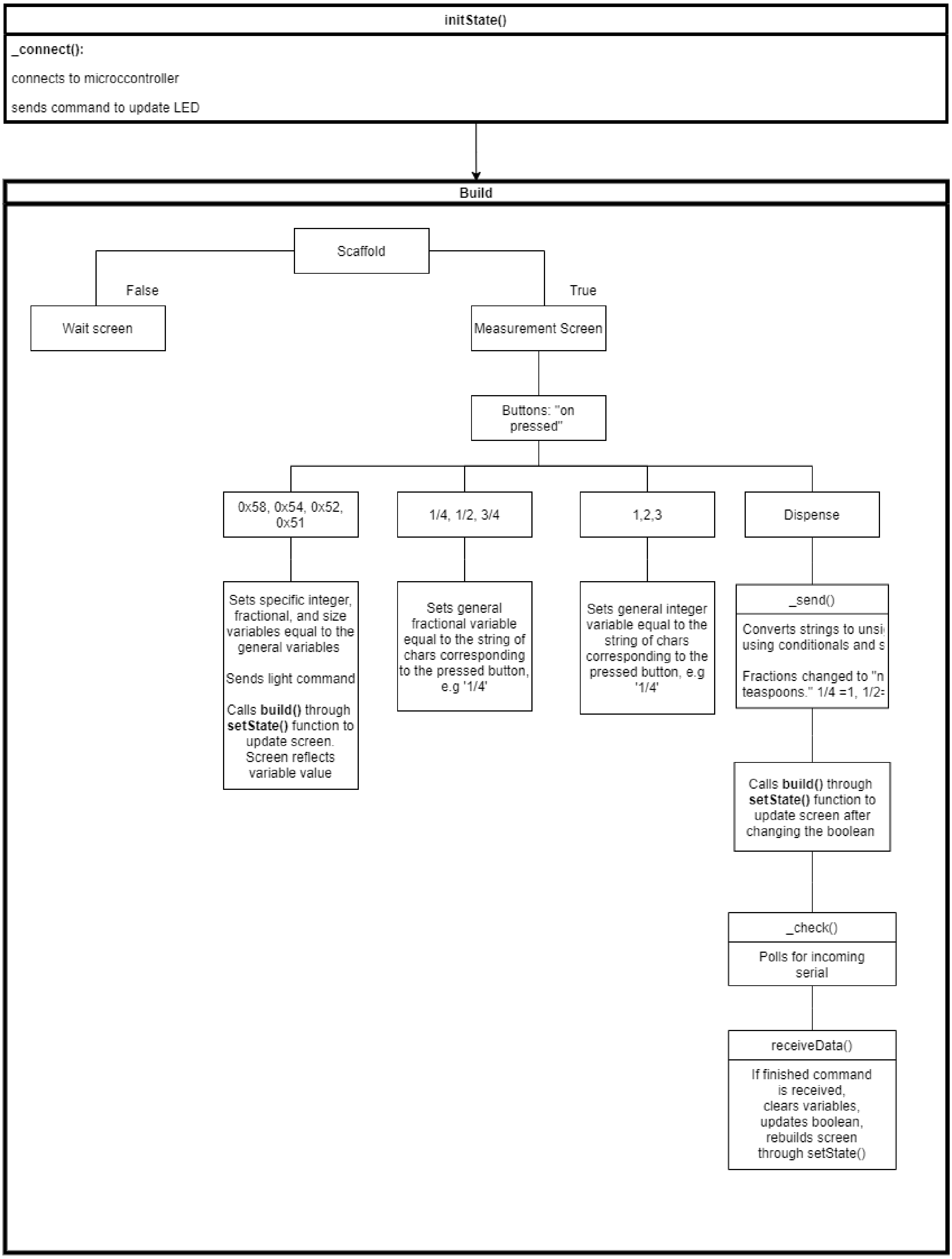


Figure 5.7: The mobile application's functional logic.

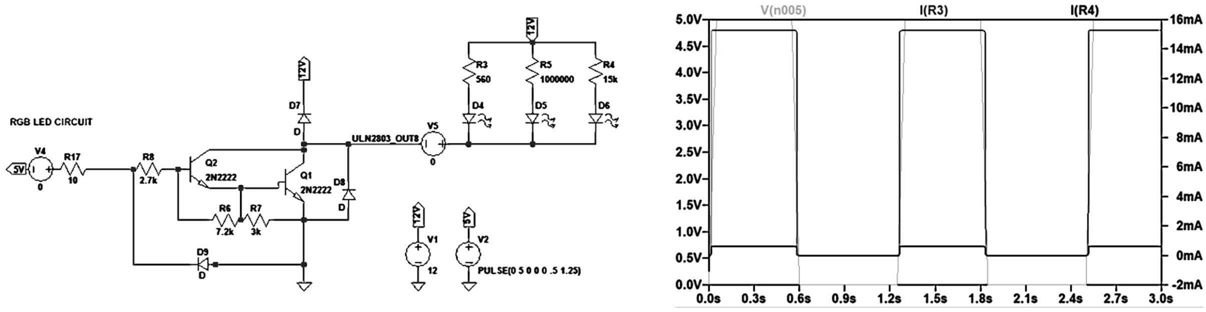


Figure 5.8: SPICE model and output.

Maximum Current Calculations

The LEDs were designed to draw a maximum current of less than 20mA per colour at 12V; the datasheet recommends 20mA per colour with an absolute maximum rating of 30mA per colour [42]. Values of 2.5V for red and 2.75V for green and blue were used for calculations. The resistance was therefore calculated according to Equation 5.9.

$$R_{colour} = \frac{V_{cc} - V_{colour} - V_{ULN}}{I_{colour}} \tag{5.9}$$

Resistors of 10Ω were used between the output pins and driver as an entry point for current measurements. The driver has at its input a 2.7kΩ resistor included in the chip. The resistor number on the input corresponds to the microcontroller pinout (for example, R2 is the resistor to pin D2).

Current and Colour

Colours were chosen to mirror the user interface. The UI colours will vary across mobile devices according to the physical limitations and colour calibration settings of each device. Therefore, extremely precise matching cannot be achieved, and is also not required given the application. Reducing the bill of materials instead became the primary design goal.

The original colour palette was reduced to the web-safe palette (216 colours) to produce a larger difference between the red, green and blue hues. The dominant wavelengths for each colour as listed in the datasheet were graphed on the CIE-1931 chromaticity graph (Figure 5.9), producing the colour gamut for the LED. A coordinate from within the gamut shows the possible colours that can be produced by the LED.

Mixing Ratios

The mixing ratio was determined by experimenting with a mix of calculated resistors and potentiometers. The chromatography graph and reduced colour palette were used to inform the iterations. Comparison of the user interface was performed by visual inspection after receiving a score of 0 on the Pantone colour test, indicating a relatively acceptable colour-calibrated monitor and visual acuity. Results of the experimentation showed that all twelve LED inputs could be set using a combination of open circuits and three standard

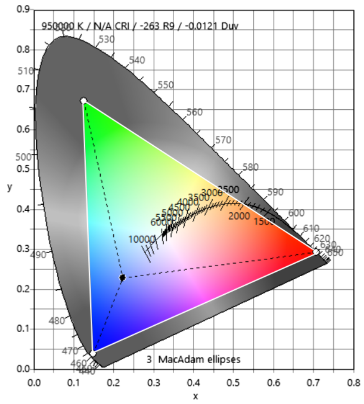


Figure 5.9: The CIE-1931 graph as restricted by the LED.

resistor values (560Ω, 15kΩ, 1kΩ) as seen in Table 5.7, with a fourth resistor (1.8kΩ) added to reduce the current to the power LED.

Table 5.7: LED Mixing Ratios

LED	UI Colour	UI RGB Code	Reduced Code	Resistors (Ω)	Currents (A)	LED Result
0x58		238 049 072	255 000 105	560 Open 15k	0 16m 576u	
0x54		222 117 000	255 102 000	560 15k Open	16m 577u 0	
0x52		037 152 000	000 255 000	Open 560 Open	0 15m 0	
0x51		137 046 242	102 000 204	560 Open 1k	16m 0 9m	
PWR		137 046 242	102 000 204	1k Open 1.8k	8.9m 0 4.8m	

Since the Power LED was to remain illuminated through the duration of the user experience, a similar ratio to 0x51 was used with reduced current.

Power Dissipation

The power dissipation for each LED (P_D) was determined by measuring the voltage (V_{R_n}) across the current limiting resistor (R_n) and LED (V_n) for each colour (Set n = red: r, green: g, blue: b), and inputting the values into Equations 5.10 and 5.11, Ohm's Law.

$$\sum_n I_n V_n = P_D \tag{5.10}$$

$$\lim_{x \to R_n} \frac{V_{R_n}}{x} = I_n \tag{5.11}$$

5.2.7 Power

The NCP117 regulator is in a SOT-223 package, capable of handling up to 20V input through the V_{in} pin. Power dissipation is internally limited, according to Equation 5.12.

$$P_D = \frac{T_{j,max} - T_A}{R_{\theta ja}} \tag{5.12}$$

Assuming the SpiceBot may function in kitchens that are not air conditioned, the power dissipation for an ambient temperature of 25C as well as 45C was calculated, with $T_{j,max}$ = *150C* and R_{ja} = *160 C/W* as per the regulator's datasheet [38]. This results in a maximum allowable power dissipation of 781mW under normal ambient temperatures and 656mW at 45C. Rearranging the terms in Equation 5.13 produces Equation 5.14 with an assumed quiescent current of 6mA (the worst case recorded on the datasheet).

$$P_D = V_{in}(I_{out} + I_Q) - V_{out} I_{out} \tag{5.13}$$

$$I_{out} = \frac{P_D + I_Q V_{in}}{V_{out} - V_{in}} \tag{5.14}$$

Various input voltages were graphed at 0.5V increments up to the maximum allowable voltage (19V) to determine the allowable current draw without a heatsink (Figure 5.10).

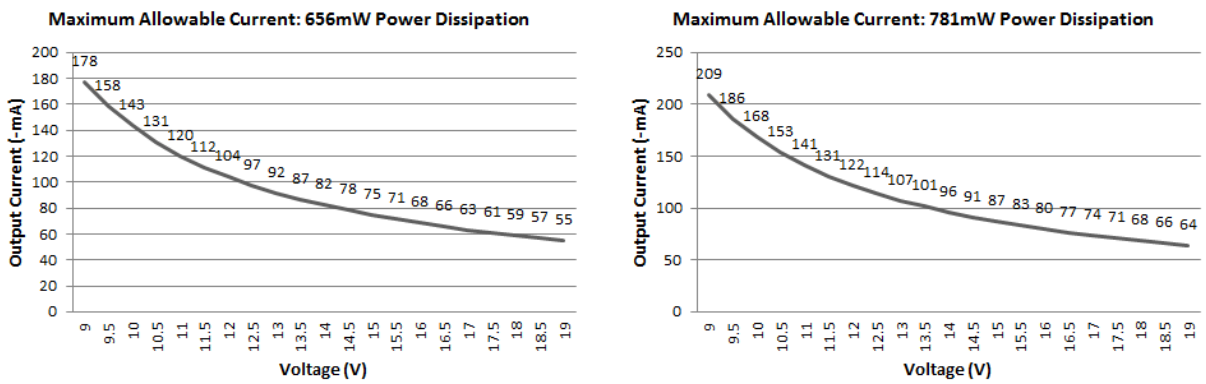


Figure 5.10: Allowable current draw for the NCP117 regulator without a heatsink.

The 500mA fuse had a measured resistance of 0.6Ω, with a measured voltage drop of approximately 30-32mV during operation. The current draw of the Arduino is therefore calculated at approximately 50mA, under the allowable ratings.

5.2.8 Printed Circuit Board

The printed circuit board (PCB) was designed as an Arduino shield with 20 mil traces for signals and LED currents, each with a minimum 14 mil clearance. Fifty mil traces were used for the 12V power line and for the connections between the solenoid and MOSFETs, and 30mil for the HC-05's 5V supply. KiCad's PCB calculator, which uses formulas from the IPC-2221 standard, was used to confirm the minimum trace width for amperage assuming a 10C temperature rise, and margin was added. Footprints were acquired from Eagle, Adafruit and Mouser's SamacSys libraries. The formula was then used to determine the expected temperature rise, with the results in Table 5.8.

Table 5.8: Temperature Rise

Track Width (mil)	**Maximum Expected Current** (A)	**Temperature Rise** (C)
50	2.2	5.6
30	0.03	0.14

Power dissipation, voltage drop and resistance were also recorded by using Eagle's trace length measurements in the KiCad calculator. The voltage drops were considered to ensure they would not significantly affect the circuitry (Table 5.9).

Table 5.9: Power Loss

Width (mil)	**Measured Length** (mm)	**Resistance** (Ω)	**Voltage Drop** (V)	**Power Loss** (W)
50	2.2	0.081	0.231	0.658
30	0.03	0.045	0.088	0.174

A diagram of the component layout can be seen in Figure 5.11. Resistors were arranged in numerical order where possible, with numbers mirroring the Arduino pinout.

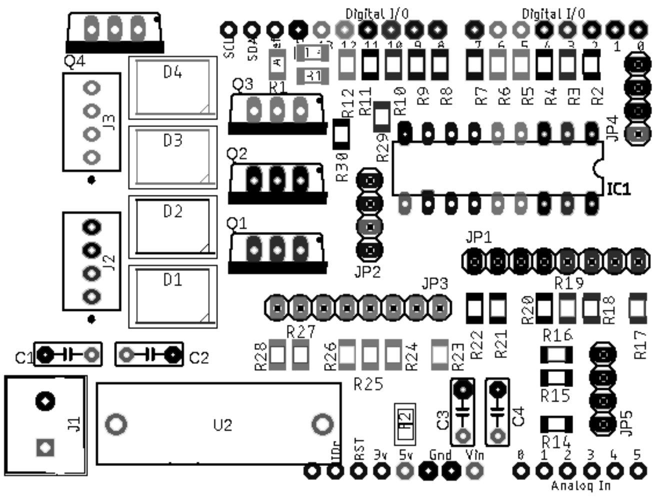


Figure 5.11: Component layout.

6. Integration and Testing

6.1 Physical Build

6.1.1 Prototyping

Several prototypes were built to test the dispensing container. Cardboard was initially used because it was inexpensive and a weak material; material failure in the different cardboard models quickly showed the stress points that would need to be considered in the final design. These points were discussed with the people building the final model and determined the screw placement in the dispensing part. A summary of the built prototypes can be seen in Figure 6.1.

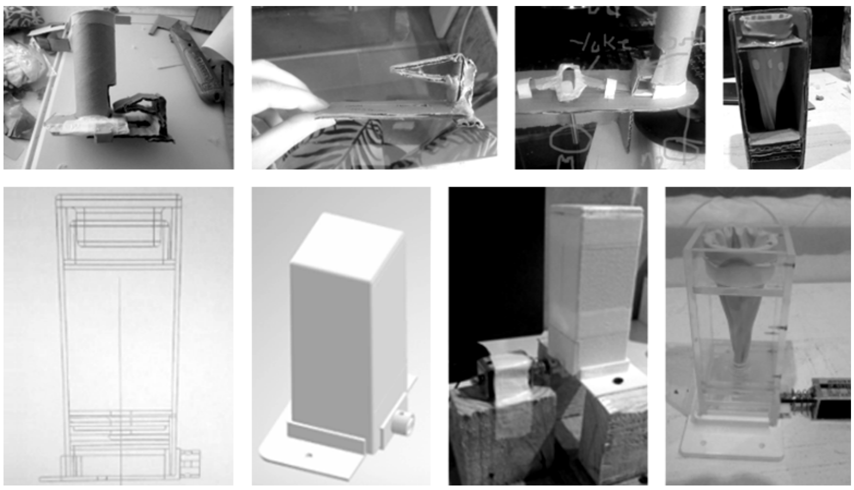


Figure 6.1: Summary of built prototypes.

6.1.2 Dispensing Test

Each container was tested by sending a command for four pulses to all four containers and then measuring the result. Containers were then emptied and the test repeated four times, with salt. Four pulses were sent because the volume was small and the scale not sensitive enough to measure small amounts. The test aimed to prove consistent measuring of a set volume each time. The dimensions of said volume were not designed.

6.1.3 Electrical Safety Test

Potential points of contact (solenoid wires, near the LED bulb), as well as the earthed solenoid casings were tested with a multimeter. No live wires were found.

Table 6.1: Dispensing Test Results

Trial	0x58	0x54	0x52	0x51
1	2g	2g	2g	2g
2	2g	2g	2g	2g
3	2g	2g	2g	2g
4	2g	2g	2g	2g

6.2 Solenoids

6.2.1 Incremental Integration

The solenoids were first tested individually attached to a 12V bench supply. The switching circuit was then tested on a breadboard with resistor 8.2 10W and measured with an oscilloscope. A solenoid, again attached to the bench supply, was tested with one container. When tests indicated positive results, the solenoid and container were integrated with the MOSFET switching circuit on the breadboard, as seen in Figure 6.2. The solenoids were then soldered into the final installation.

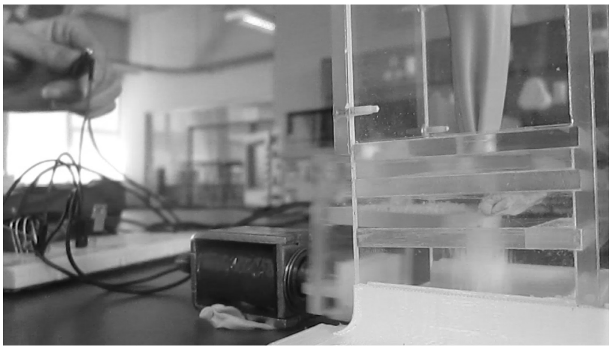


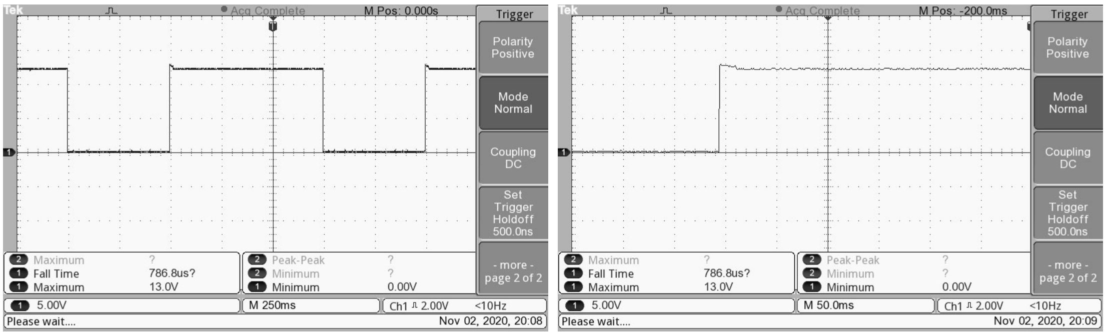
Figure 6.2: Solenoid with switching circuit test.

6.2.2 Voltage Spike Measurement

Two pulses (1/2 teaspoon) were requested, with the oscilloscope triggering on a pulse width greater than 505ms (the rest time between pulses was programmed at 750ms, as per previous chapters). Voltage measured across VDS was recorded using the oscilloscope probe attached to the MOSFET case. The maximum measured voltage was 13V, as per the results in Figures 6.3a and 6.3b

6.2.3 MOSFET Temperature Measurement

The maximum command sequence (3 3/4 teaspoons to a single container) was sent and the temperature recorded afterward by touching the case with a thermocoupler attached to a multimeter. The case measured 26C before use and 27C after, with another test showing 26C before and after use.



(a) (b)

Figure 6.3: Oscilloscope result (a) and detail (b) of the voltage spike caused from switching off the inductive load.

6.3 Microcontroller

6.3.1 Integrating the Mechanics and Code

The code was developed using incremental functions with printf output, followed by integration with the HC05 module using Arduino's printSerial functionality to debug. Further development used an LED circuit (LEDs in series with 1k resistors connected to each GPIO) to test the LED and solenoid control, and power light. It was then installed with screws. The solenoid pulse width was conservatively programmed at 500ms with 750ms rest time. Times can be changed in the macro definitions.

6.3.2 Functional Test

Microcontroller code was tested with random sequences during development using the LED circuit. Additional tests were performed on the working SpiceBot, as per the results in Table 6.2.

Table 6.2: Dispensing Test Results

Test Description	Sequence	Pulses Recorded	Assessment
All functioning	1/4;1/4;1/4;1/4	1;1;1;1	Pass
Different measurements, fractions	1/4;1/2;3/4;1	1;2;3;4	Pass
No spices	0;0;0;0;	0;0;0;0	Pass
Integer-fraction combination + skips	1 1/4;0;1 1/2;0;	5;0;6;0	Pass
Integers + skips	0;2;0;3	0;8;0;12	Pass

6.4 Connectivity

Bluetooth connectivity was first established with a simplified version of the protocol through a single LED using a Bluetooth terminal programme. The user interface was then developed and the simple test repeated with the android app. The full protocol was then implemented and tested using the LED test circuit previously mentioned.

The HC05 module was connected to the PCB with wires soldered to the PCB and terminating in 1pin DuPont connectors. Connection was done in this way because code updates could not be flashed to the Arduino with the module connected (the upload fails). It also allowed for positional adjustment of the antenna, if needed.

6.4.1 Connectivity Distance Test

The range of the Bluetooth module was tested by sending dispense commands to the SpiceBot and increasing the distance between the phone and the SpiceBot between each command. The device was placed on one end of the Stellenbosch E&E lab and commands sent while walking the length of the lab, with the distance measured according to number of floor tiles passed. The SpiceBot was able to receive commands to the opposite end of the lab at 135 tiles away, or approximately 34 meters. Further distance was not measured as this distance seemed to more than encompass the length of most kitchens.

6.5 User Interface

6.5.1 Development

The user interface was developed during testing using the Android emulator of a Nexus 6. Once Bluetooth connectivity was established, development continued with a Vodacom VFD 1100 tablet. Both were API level 23: Marshmallow. The tablet was used in the final tests and demos.

6.5.2 Functionality Test

The user interface was tested with random sequences during development and while performing other tests. No errors were found.

6.5.3 Accessibility Test

The User interface was compared against selected points within Mobile Web Best Practices (MWBP) 1.0 [27] and Web Content Accessibility Guidelines (WCAG) 2.0 [26] as per table 6.3. Minimum colour contrast was measured by inputting the hex codes into a testing website.

Table 6.3: Accessibility Guidelines Addressed

Document	Guideline	Response
MWBP	No frames, tables or embedded objects	None used.
MWBP	Colour information relayed in additional ways	container selection can also be determined by illumination
MWBP	Minimum colour contrast of 3.0 for large text (AA rating)	Button contrast ratios: Pink:4.06; Orange:3.15; Green:3.77; Purple:5.62
MWBP	Tested on device and emulator	Tested on emulated Nexus and physical Vodacom tablet
MWBP	Limit to user requested content	Bluetooth connectivity settings handled by phone; only dispensing commands provided with limited buttons
MWBP	Minimise keystrokes	Optimal button placement determined.
WCAG	No images of text, background audio, flashes or animations	None used. Dispensing animation originally considered, dropped because of the guideline
WCAG	Compatible	Code compatible with 98 per cent of Android and some IOS devices through Dart language and programme setup
WCAG	Provide status message	Includes waiting screen.

6.6 LEDs

The LEDs were individually tested on a breadboard at 12V and then connected to the ULN2803 using a bench supply for input and source voltage. Each lead was soldered to wire and wrapped in heat shrink. Once wired, each lead tested individually with 560 Ohms at 12V before being installed into the final SpiceBot. Testing of leads was done because the LEDs were subject to breakage during installation and are also sensitive to electrostatic discharge. Once installed the LEDs were tested again on the breadboard before being wired to PCB (Figure 6.4).

Figure 6.4: Lighting test.

The 1MΩ resistors included in the schematic were added to allow for colour changes without PCB alterations and were initially left open. They were later added in a troubleshooting attempt but were not necessary; the fault was improper grounding and was resolved.

Measured voltages across the LED during breadboard tests were higher than the estimates used to design the resistor values, varying from 3.66V to 4.65V depending on colour and current draw.

Table 6.4: LED Measurements

LED	V_{R_r}	V_{R_g}	V_{R_b}	R_r	R_g	R_b	I_r	I_g	I_b	V_r	V_g	V_b	P_D (mW)
0x58	8.56	0	8.06	560	∞	15k	15.3m	0	537u	3.66	0	4.15	58.18
0x54	8.56	8.29	0	560	15k	∞	15.3m	552u	0	3.65	3.92	0	57.96
0x52	0	7.53	0	∞	560	∞	0	13.4m	0	0	4.65	0	62.78
0x51	8.49	0	7.75	560	∞	1k	15.2m	0	7.8m	3.71	0	4.44	91.02
PWR	8.66	0	7.84	1k	∞	1.8k	8.7m	0	4.36m	3.54	0	4.26	49.2

6.6.1 LED Functionality Test

The power light functionality and container selection lights were observed during a demonstration of the SpiceBot, with each container selected and the results obtained by visual inspection.

6.6.2 Delay Measurement

The switching delay between button press and light illumination was obtained by measuring the frames in the video between press and light. According to the film test, the delay is approximately 0.28s.

6.7 Power

Capacitors and fuses were soldered to the PCB; the regulator was already installed. Offcut wires from another power supply were used to connect the power supply to the PCB to ensure proper current carrying capacity. Input voltage was measured at 12.2V.

6.7.1 Device Voltage and Current Measurements

The input voltage of the power supply was measured to be 12.20V at no load, with the multimeter probes touching the terminal block. The current draw was measured at 0.08A at startup when disconnected from the mobile application, at 0.13A when the lights are selected, and approximately 2A when dispensing. Assuming 0.13A as the nominal value, the power dissipation is estimated to be approximately 1.6W.

6.7.2 Regulator Temperature Measurement

The temperature of the regulator was measured at 30C after five minutes of demonstrating random sequences.

6.8 Printed Circuit Board

The PCB is a double-sided board with 35 micron copper thickness and a substrate thickness of 1.6mm of FR-4 material. The board was milled on a ProtoMat S103, soldered at 341C with lead-based solder. The PCB can be seen in 6.5; a diagram of the traces can be seen in Appendix F.

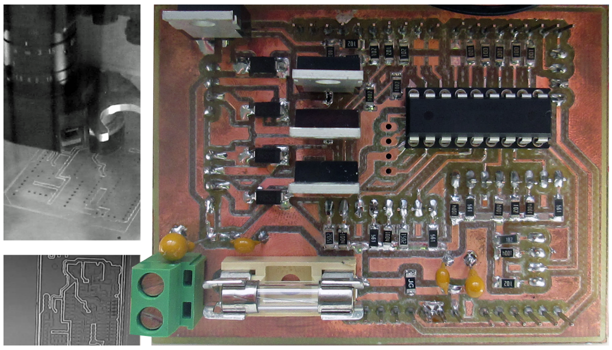


Figure 6.5: Final PCB and its fabrication.

6.9 Final Build

The subsystems were integrated into the final working design, as seen in Figure 6.6. Spices dispense from the front, with the solenoids, circuitry, power and connectivity displayed in the back. Holes were added to the casing for ventilation.

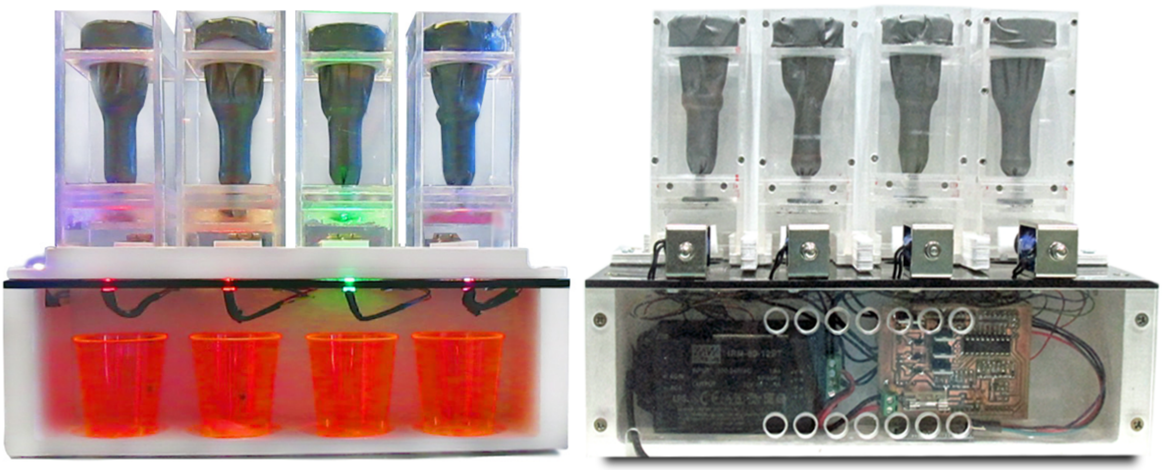


Figure 6.6: Image of working SpiceBot, front and back.

7. Conclusions

7.1 Analysis of Test Results

SpiceBot passed all functional tests and delivers on the initial requirements, as seen in Table 7.1.

Table 7.1: Response to Initial Requirements

Initial Requirements	Response
Four, easily interchangeable containers free of electrical components	Four, easily interchangeable containers free of electrical components supplied
Works with salt	Passed tests with salt
Accessible user interface	UI implemented with reference to accessibility recommendations as above
Standard compliance	As above
Generalised code	Implemented generalised register level code
Electrically simple	Solenoid and lighting circuitry
Isolated spices	Elastic bladder isolates the mechanics

7.2 Recommendations and Future Work

If commercialisation is to be considered, SpiceBot could benefit from further optimisations to the container and base design, as well as material upgrades, with an emphasis on making the containers airtight, durable, and with an increased volume. Decreasing the timing, which was deliberately set to be slow, could also be considered, as well as further component integration. Increased insulation between the circuit and user would be needed for full compliance to safety standards, and the Bluetooth qualification process would need to be started.

Though commercial patents were found, it appears they solve the problem differently and more complexly; therefore, intellectual property protection may want to be considered. Other applications, such as dispensing sugars for tea or medicines could also apply. Personal work on the SpiceBot would be toward attempts at modifications for use in zero gravity and the aerospace culinary field, where powders and crumbs are restricted.

7.3 Final Remarks

Immense consideration was given to producing a simple, effective solution to spice dispensing. Such a solution was found, developed and built as SpiceBot, which both fulfills current requirements and shows significant potential for future work.

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Appendix A: Project Schedule

The project schedule started with a general outline of tasks and potential completion dates (Figure A.1), with tasks assigned as nodes on a mind map. Tasks were worked concurrently and the progress for each task recorded on the map. Every week the map was assessed for node priority based on the results of previous tasks, and the schedule was recalculated with the most critical nodes being allocated the most time, using the general outline as a guide. A copy of the map can be seen on the next page.

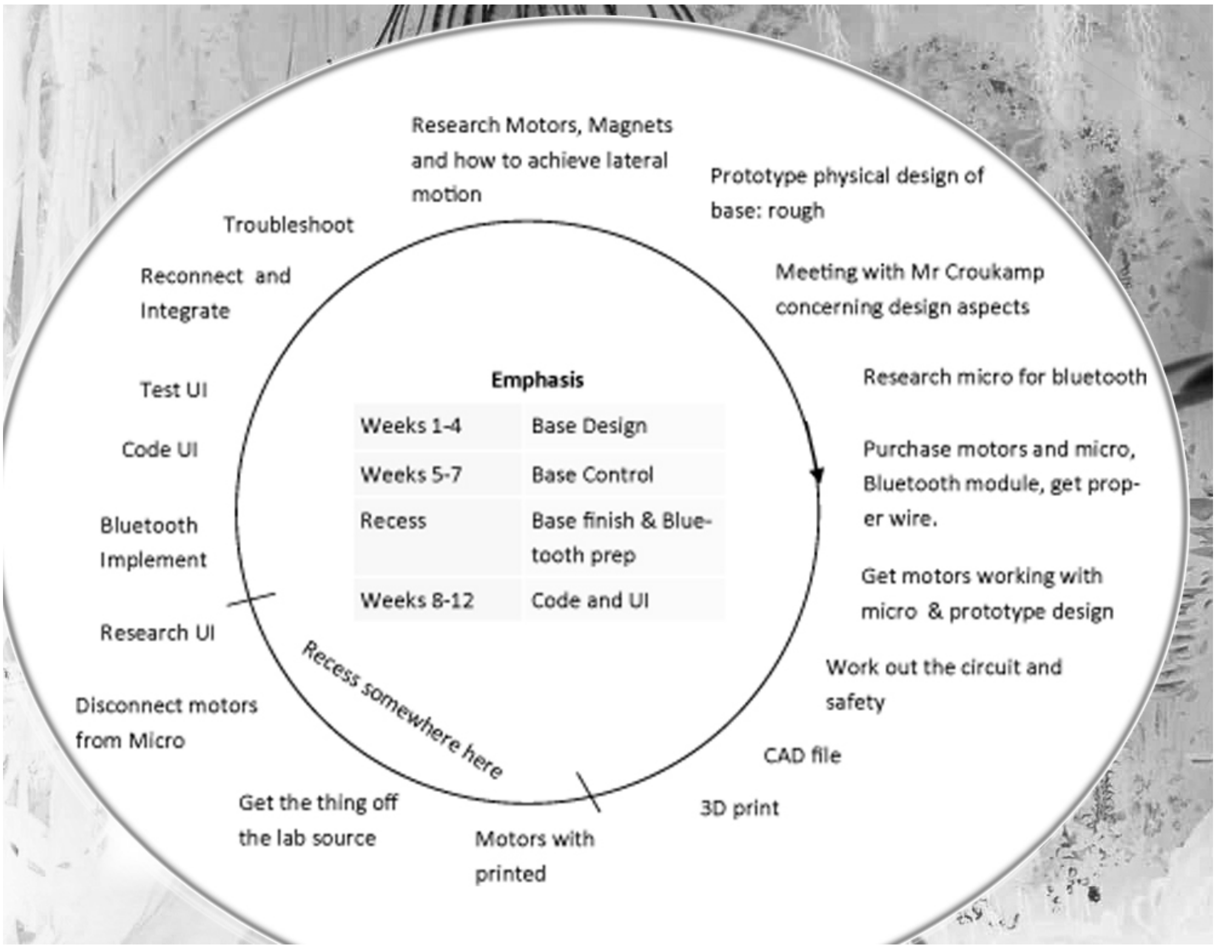
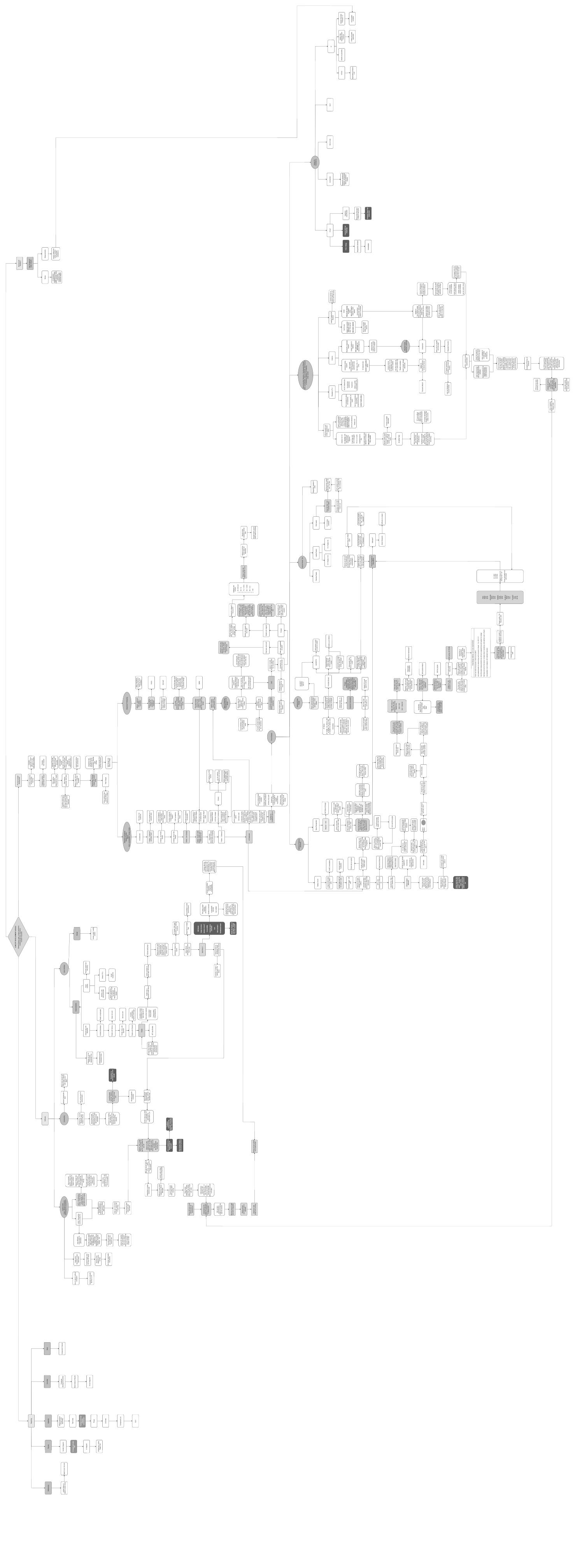


Figure A.1: Preliminary schedule.



Appendix B: Outcomes Compliance

ELO 1: Problem solving (identify, formulate, analyse and solve complex engineering problems creatively and innovatively)
Solving complex engineering problems requires in-depth fundamental and specialized engineering knowledge; and problems have one or more of the characteristics:
1. are ill-posed, under- or over-specified, or require identification and refinement;
2. are high-level problems including component parts or sub-problems;
3. are unfamiliar or involve infrequently encountered issues;
The solutions have one or more of these characteristics:
1. are not obvious, require originality or analysis based on fundamentals;
2. are outside the scope of standards and codes;
3. require information from variety of sources that is complex, abstract or incomplete;
4. involve wide-ranging or conflicting issues: technical, engineering and interested or affected parties.

Response
The problem, "design something that dispense spices," was high-level, ill-posed and under-specified and required data analysis to refine. It contained seven sub-problems of physical design, actuation, programmatic control, connectivity, user interface design, lighting and power. As per the literature review and design chapters, the original solution began as abstract concepts and was developed based on analysis of fundamental theory from a variety of sources, and involved the conflicting issue of providing a technical solution simple enough to please a nontechnical user.

ELO 2: Application of scientific and engineering knowledge (apply knowledge of mathematics, natural sciences, engineering fundamentals and an engineering speciality to solve complex engineering problems)
Mathematics, natural science and engineering sciences are applied in formal analysis and modelling of engineering situations, and for reasoning about and conceptualizing engineering problems.

Response
Natural science and mathematical formulations were used for calculations hypothesizing about the solenoid functionality (free body diagram and accompanying calculations). Knowledge of engineering science was used to make decisions concerning component selection and design, with accompanying calculations (power dissipation, allowable currents and voltages).

ELO 3: Engineering design (perform creative, procedural and non- procedural design and synthesis of components, systems, engineering works, products or processes)
The design problem must conform to the definition of a complex engineering problem (refer to ELO 1) and should be a major electrical and/or electronic engineering design problem.

Response
The problem was complex as stated in ELO 1, with seven subsystems that needed to be integrated, inclusive of circuit design, high and low-level programming (python, mobile application design and register-level C code) and embedded systems. Creative procedural and nonprocedural design, such as developing LED colours with minimal component requirements and determining optimal button placement for the user interface, were used.

ELO 4: Investigations, experiments and data analysis (demonstrate competence to design and conduct investigations and experiments)
The balance of investigation and experiment should be appropriate to electrical and/or electronic engineering. Research methodology to be applied in research or investigation where the student engages with selected knowledge in the research literature of electrical and/or electronic engineering.

Response
Data analysis was performed to investigate and refine the problem statement. Research literature was used to inform design decisions and set up simulations and experiments (as in the case of switching inductive loads and designing LED currents). As seen in Chapter 6, Integration and Testing, the solution was developed incrementally, with test circuits, functions, and experiments to confirm functionality.

ELO 5: Engineering methods, skills and tools, including information technology (demonstrate competence to use appropriate engineering methods, skills and tools, including those based on information technology)
A range of methods, skills and tools appropriate to electrical and/or electronic engineering including: 1. Discipline-specific tools, processes or procedures; 2. Computer packages for computation, modelling, simulation, and information handling; 3. Computers and networks and information infrastructures for accessing, processing, managing, and storing information to enhance personal productivity.

Response
Analysis via force calculations and a free body diagram, were used for solenoid design. SPICE simulations were used to confirm circuit functionality. Coding included python, dart and c languages was written. Github repositories were used for version control of code; Atlassian Bitbucket repository was used for version control of a Latex-formatted report. Autodesk Eagle was used for schematic and PCB design, and their functionality was used to produce accurate trace lengths for power calculations. Autodesk Inventor Professional was used for the modelling the physical design. The mind map was incrementally developed to manage and integrate the separate subproblems.

ELO 6: Professional and technical communication (demonstrate competence to communicate effectively, both orally and in writing, with engineering audiences and the community at large)
Material to be communicated is in an academic or simulated professional context. The audience for the report and presentation is engineering peers and management, while the

poster is aimed at lay persons, using appropriate academic or professional discourse. The long written report (10 000 to 15 000 words plus tables, diagrams and appendices) covers material at exit-level. Methods of providing information include the conventional methods of electrical and/or electronic engineering.

Response
The 40-page report covers the project from an engineering perspective, with strong emphasis on research, technical design, implementation and testing. The poster was designed to be more visual in nature with greater emphasis on the user experience and applicable features, which would be of greater interest to lay persons.

ELO 8: Individual work (demonstrate competence to work effectively as an individual)

Response
All research, decisions, design and implementation was conducted individually, except for those mentioned in the citations or acknowledgments.

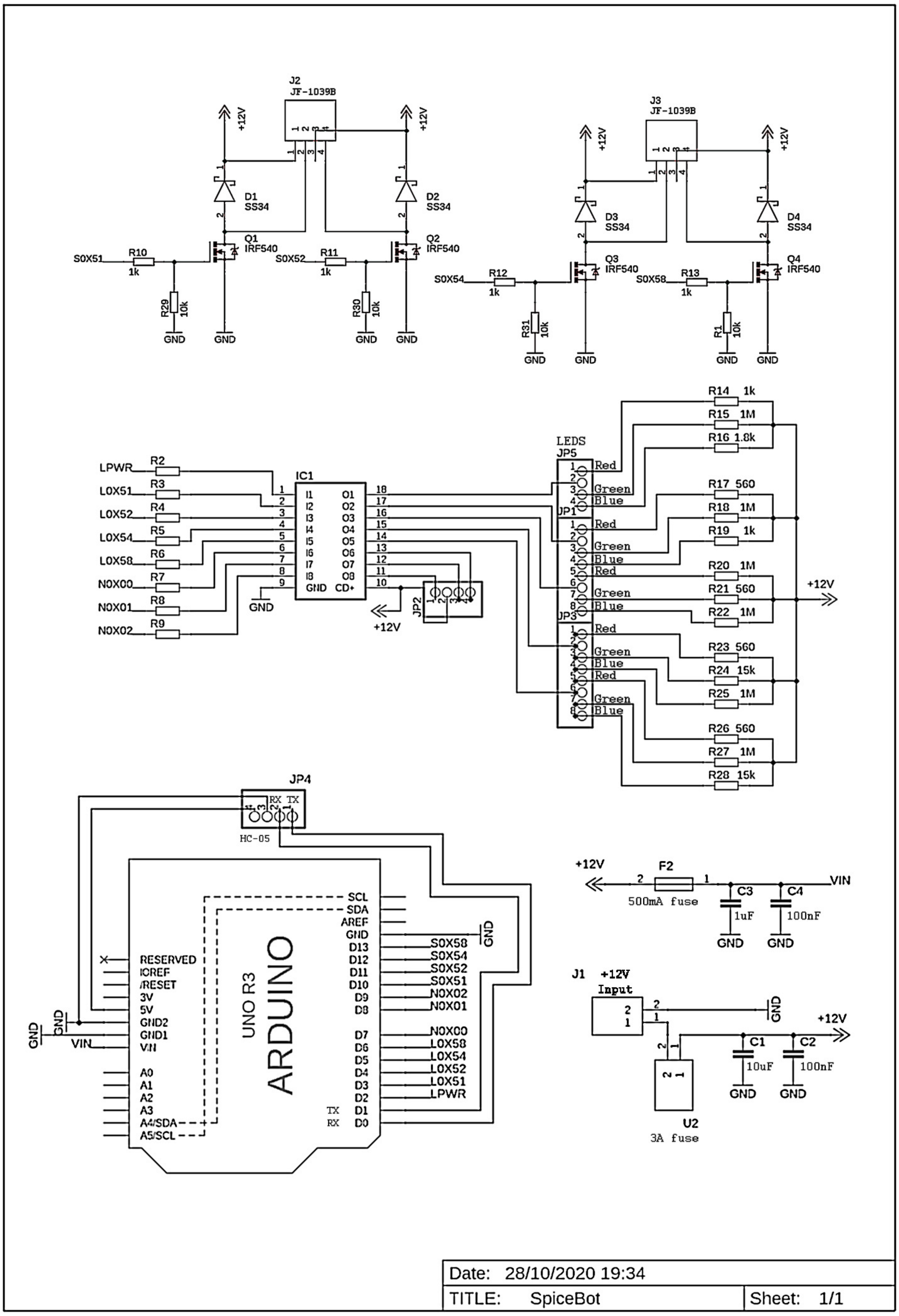
ELO 9: Independent learning ability (demonstrate competence to engage in independent learning through well-developed learning skills)
Operate independently in complex, ill-defined contexts requiring personal responsibility and initiative, accurately self-evaluate and take responsibility for learning requirements; be aware of social and ethical implications of applying knowledge in particular contexts.

Response
Social and ethical implications of applying knowledge were considered in terms of compliance with standards, particularly in terms of accessibility and electrical shock avoidance; design considerations included a responsibility toward ease of use and future work rather than unintelligible bloatware filled with unnecessary complexity.
The project topic was self-formulated. Completion of tasks was self-controlled with no adviser-mandated scheduling requirements. A working prototype was developed and designed, components sourced, and the product tested and built with little precedent and by the required due date, despite the challenges of the Covid pandemic.

Appendix C: Bill of Materials

Qty	Value	Part	Pkg	Description
2	100nF		Radial	Ceramic Capacitor
1	10uF		Radial	Tantalum Capacitor
1	1uF		Radial	Tantalum Capacitor
4			DO-214AB	SMT Schottky Diode, 40V 3A
4		JF-1039B		Solenoid, 10mm stroke, 25N, 2A
4		IRF540N	TO220	Power MOSFET
6	1k		1206	Resistor
1	1.8k		1206	Resistor
4	10k		1206	Resistor
2	15k		1206	Resistor
4	560		1206	Resistor
5			5mm	Common Cathode RGB LED
1		2803AWG	DIP	8-Channel Darlington Driver
1		BKHTC15M		PCB Fuse Holder Block
1	3A		Cartridge	Fuse
1	500mA		1206	Resettable Fuse
1		Rev3		Arduino Uno
1		HC-05		Bluetooth Module with pins
4				Female DuPont Connector
1				2 way Buchanan Series 5.08mm Pitch Terminal Block, Cage Clamp, Screw Termination
1		IRM-60-12ST		240VAC-12VDC Power Supply

Appendix D: Schematic



Appendix E: CAD Drawings

Figures A.3 - A.6 show the technical drawings for a container and single testing base. All dimensions are in mm.

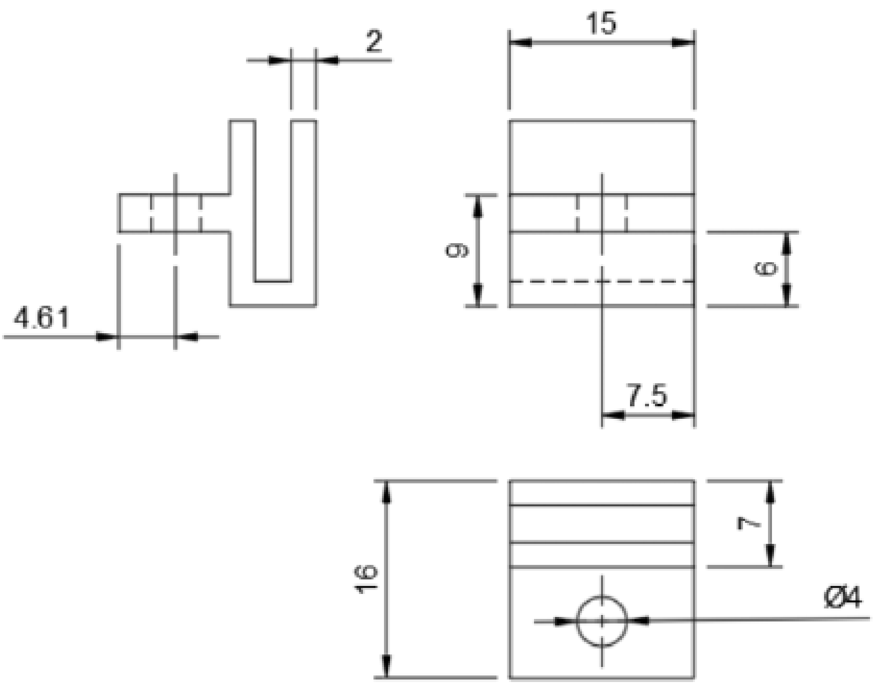


Figure A.2: Solenoid Attachment.

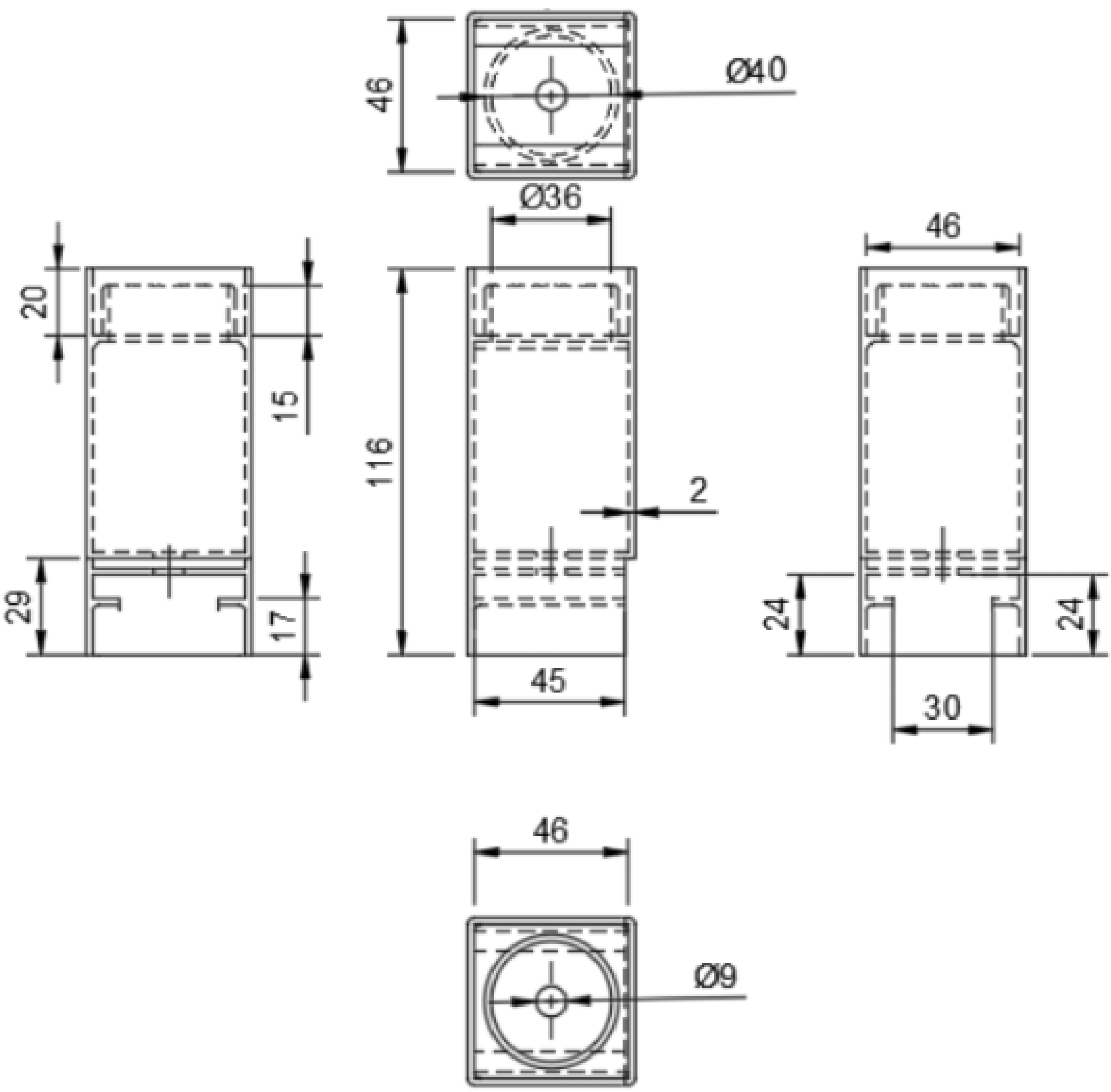


Figure A.3: Container.

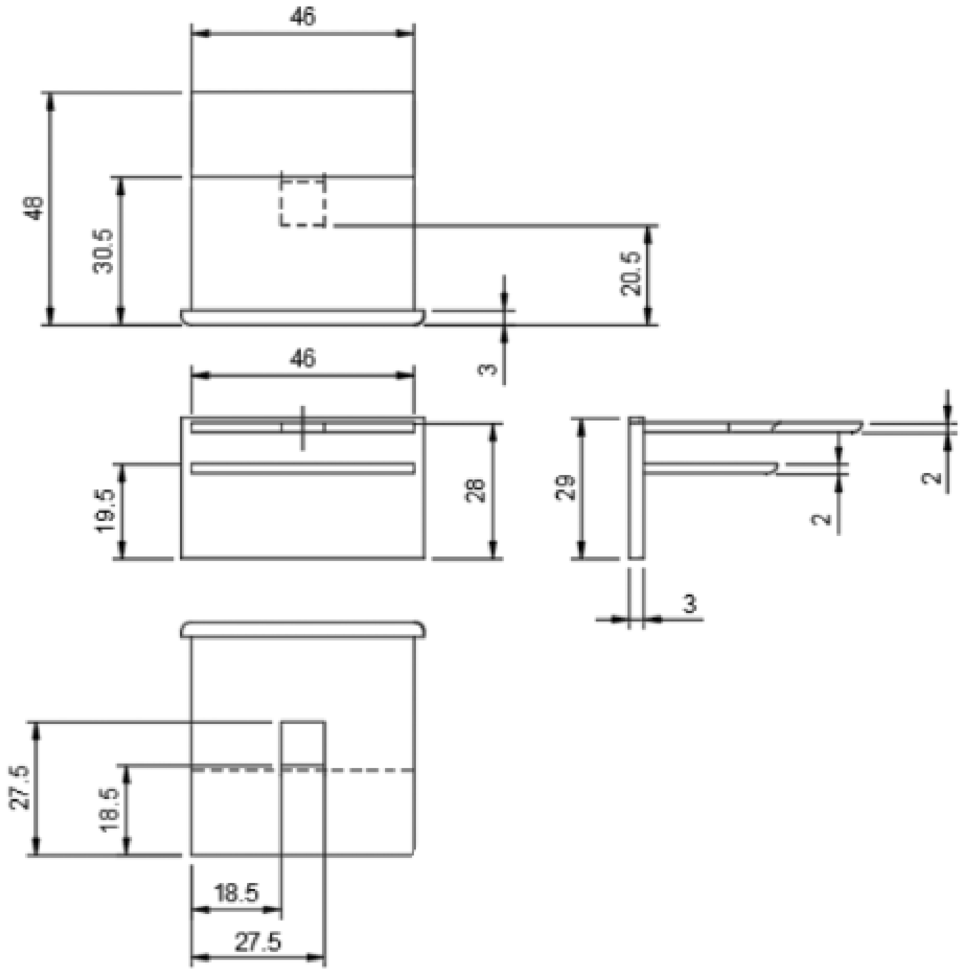


Figure A.4: Dispensing Arm.

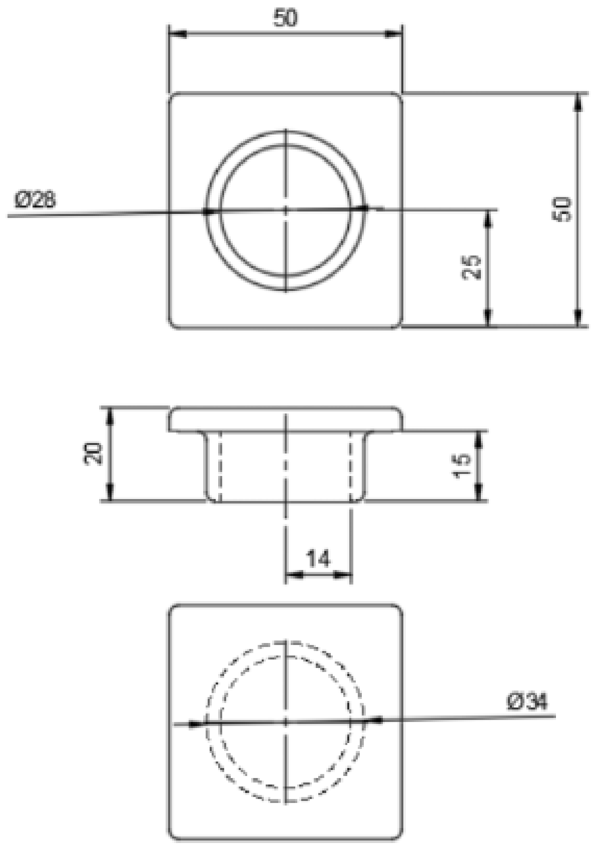


Figure A.5: Top.

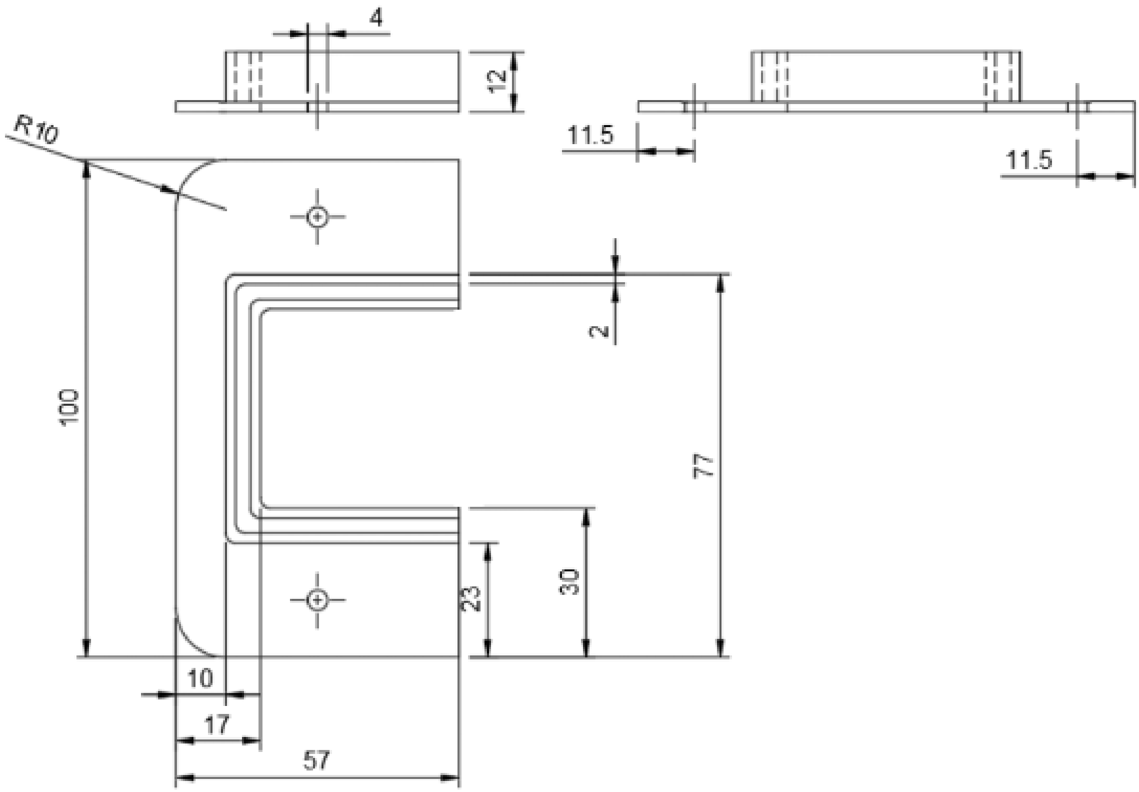


Figure A.6: Testing Base.

Appendix F: Printed Circuit Board

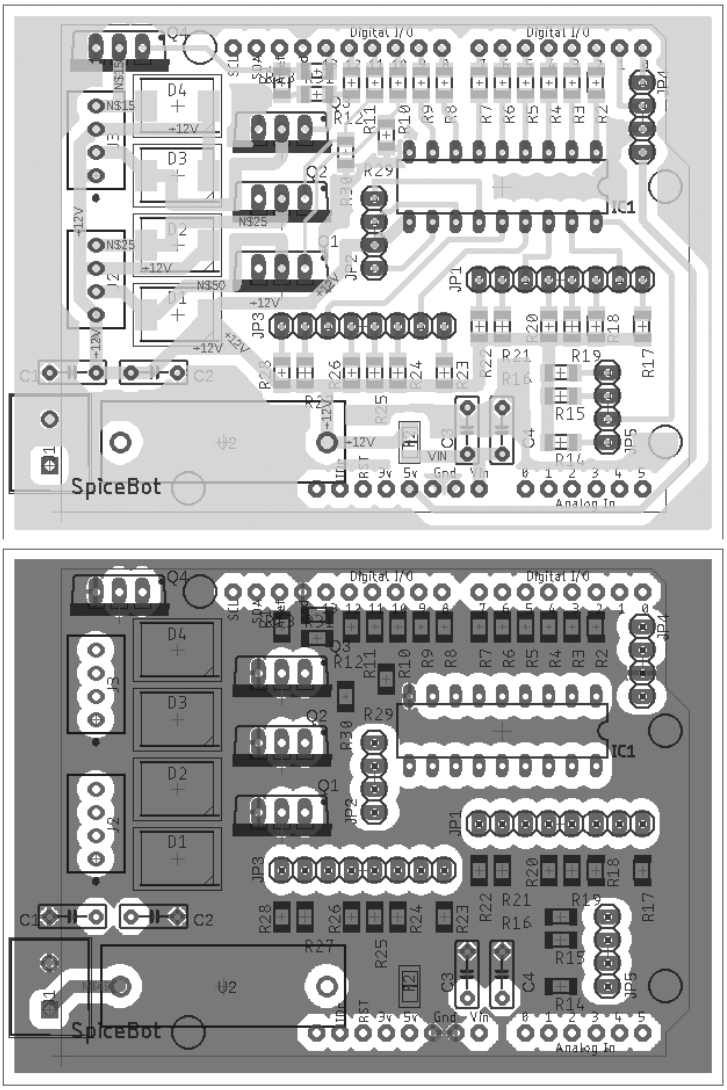


Figure A.7: PCB top and bottom, with traces.