PrimoWhip - Axiomatic Design of an Automatic Cream Whipper

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Abstract

Whipped cream is a popular food topping that's made by aerating high-fat dairy cream to a light and fluffy texture. This report presents the design of an automated cream whipper that delivers cream at a desired consistency without the need for human oversight. Several approaches for stopping the whipping process at the ideal texture were considered, including torque measurement, load sensors, and viscosity sensors. The chosen solution consists of a glass with a lid, a motor with a whisk attachment, a current sensor, and a current-activated switch to stop the motor when the cream reaches the desired thickness. Testing was conducted using 75 mL of cream for each test, and the system's performance was evaluated based on the volume expansion (overrun) of the cream. Results indicate the device consistently achieved an overrun of approximately 59.4% with a sample standard deviation of 0.042. The probability of failure was 1.238%, and the information content was 0.018, meeting the target of 50% overrun. The system demonstrated effective containment, consistent performance, and reliable automated stopping, meeting all functional requirements. This design offers a hands-free, user-friendly solution for whipping cream effortlessly.

1 Introduction

Whipped cream has been used in recipes since at least the 1530s [1]. In Iceland, whipped cream is most commonly used as a topping or ingredient in various desserts such as cakes, pies, waffles, pancakes and hot chocolate. While whipped cream can be easily prepared using handheld mixers or stand mixers, these methods require ongoing user attention to prevent the cream over-whipping. For this reason, many small-scale kitchens and homes could benefit from an automated, hands-free solution that consistently delivers properly whipped cream without the constant need for oversight. The aim of this project is to develop a compact, automatic cream whipper that consistently whips the cream to the ideal consistency and then stops automatically, eliminating the need for user monitoring. This prototype uses a sensor-based approach to detect changes in the cream's consistency by measuring the motor's current which increases with increased stiffness. This lets the device stop automatically when the cream reaches the ideal thickness, offering a safe and reliable solution. This report covers the design, development, and testing of the cream whipper prototype, focusing on its ability to reach the desired cream thickness consistently across different cream volumes. Using Axiomatic Design Theory, the design is aligned with customer needs, keeps functions independent, operates efficiently, and reduces complexity.

2 Prior Art

Handheld mixers and whisks are tools that are commonly used to whip cream. They require constant manual effort and at least one hand to remain occupied throughout the process. This not only limits multitasking but also increases the risk of inconsistent results due to human error. Stand mixers, like the one shown in figure 1, allow users to do something else while the cream is whipping. However, the user must be careful to routinely check the status of the cream so that the cream does not over-whip which can result in the cream turning into butter.

Figure 1: A Classic Stand Mixer [2]licensed under CC BY 2.0

Nitrous oxide (N_2O)-based whipped cream dispensers provide a different approach by instantly aerating the cream using pressurized N_2O gas. A classic N_2O whipped cream dispenser can be seen in figure 2.

Figure 2: Whipped cream dispenser [3]licensed under CC BY 2.0

These gas dispensers are convenient and easy to use. Despite their convenience, these dispensers can have significant drawbacks. Users must frequently purchase and dispose of single-use N_2O cartridges, contributing to environmental waste. Additionally, because N_2O can be used as a recreational drug, some individuals might not want to keep such items in their home, such as parents to young children or people with substance abuse issues.

The Primowhip improves upon these solutions by addressing their shortcomings. It offers a hands-free operation with no user monitoring necessary. Unlike stand mixers, which require periodic checks, the user only needs to pour in the cream and press a button. The system ensures consistent whipping without intervention. Unlike N_2O dispensers, The Primowhip requires no refill of any item (other than cream), and it does not have any mind-altering potential.

3 Methodology

The design process for the Primowhip is based on Axiomatic Design Theory. This design theory was chosen for its ability to ensure that the Primowhip meets costumer needs while also minimizing the complexity of the design. By following this methodology, the Primowhip achieves a more reliable and efficient design. The Axiomatic Design Theory is a design methodology developed by Suh Nam-pyo at MIT that's grounded in the application of two fundamental axioms. It guides the design process by systematically ensuring that decisions align with the following axioms:

- Axiom 1: The Independence Axiom. Maintain the independence of the functional requirements (FRs). This ensures that each functional requirement can be met without impacting others
- Axiom 2: The Information Axiom. Minimize the information content of the design. This leads to simpler, more reliable designs by reducing complexity and potential sources of error [4].

The design begins by identifying the Functional requirements (FR) and the corresponding design parameters (DP). These are developed directly based on the costumer need. The coupling between the FRs and DPs is evaluated using a design matrix. Coupling between an FR and a DP is denoted with an X, if the effect of a DP on an FR is miniscule, it is denoted with a lower case x. If the design matrix is diagonal, the design is entirely uncoupled, and satisfies the independence axiom.

3.1 Customer Needs and Design Mapping

The customer need is identified as:
CN: A hands-free cream whipper that automatically stops at the desired consistency without requiring the user to monitor.
Based on this costumer need the Functional Requirements (FRs) and their corresponding Design Parameters (DPs) were established, as shown in Table 1.

Table 1: FR-DP mapping.

ID	Functional Requirement	Design Parameter
1	Contain cream	Container with lid
2	Automatically aerate cream	Motorized whisk
3	Stop whipping at $\leq 50\%$ overrun	Electrical current safety switch

In the dairy industry, overrun refers to the volume expansion of cream caused by the incorporation of air during the whipping process [5]. An overrun of $\leq 50\%$ was selected as testing indicated this level of aeration was a sufficient consistency for whipped cream. The FRs and DPs were mapped in a design matrix as shown in Equation 1.

$$\begin{Bmatrix} \mathrm{FR}_1 \\ \mathrm{FR}_2 \\ \mathrm{FR}_3 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 \\ 0 & X & 0 \\ 0 & 0 & X \end{bmatrix} \begin{Bmatrix} \mathrm{DP}_1 \\ \mathrm{DP}_2 \\ \mathrm{DP}_3 \end{Bmatrix} \tag{1}$$

The diagonal structure of the matrix confirms that the design matrix is uncoupled and therefor satisfies the Independence Axiom. This guarantees that each FR is affected by only one DP. This simplifies the system and enhances the reliability of the design [4].

4 Design

The Primowhip prototype is designed for simplicity and ease of use. Figure 3 shows an overview of the system and how the main components relate to the Functional Requirements (FRs).

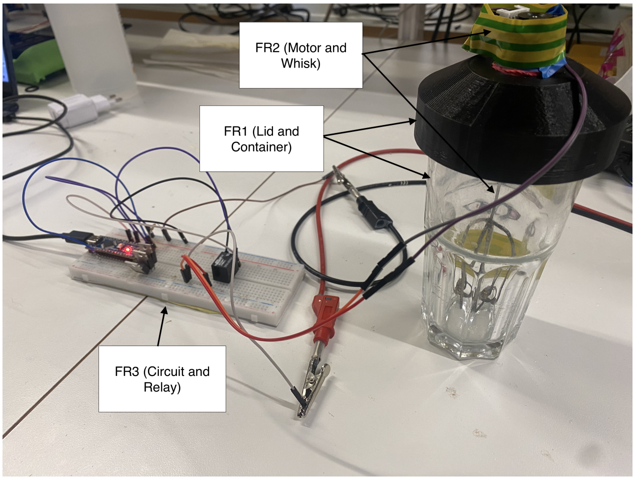


Figure 3: The Primowhip system with corresponding FRs and DPs

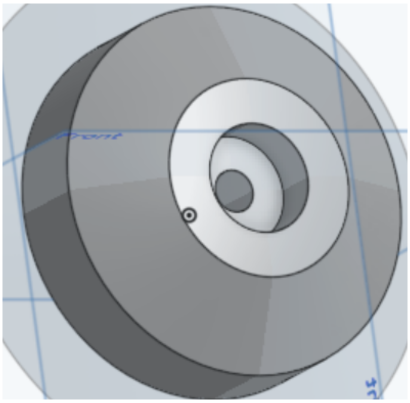
FR1 (Lid and Container) includes the black lid and glass container that hold the cream during whipping. FR2 (Motor) shows the motor connection that drives the whip inside the container. FR3 (Circuit and Relay) highlights the Arduino and circuit components on the breadboard, which control the motor and trigger the automatic shut-off.

4.1 Lid and Container Design

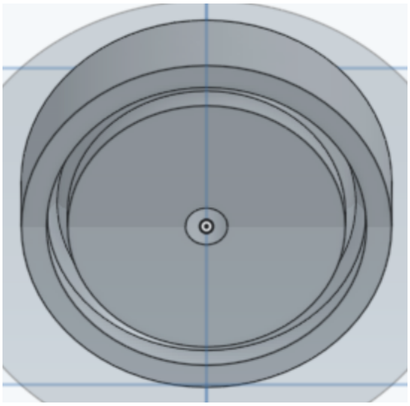
The lid and container design is key to keeping the motor and whisk in place while the Primowhip is in use. The lid is custom-made and 3D-printed to fit perfectly on the glass container that holds the cream. The lid was designed using the Onshape CAD software and printed using a Prusa mk4 3D printer. Figure 4 shows the front and underside views of the lid.

In addition to holding the motor in place, the design incorporates two soft 3D-printed rings around the motor. These rings help reduce vibration during operation, which not only improves the user experience by minimizing noise but also enhances the overall durability of the system. By absorbing vibrations, the rings prevent excessive wear on the components. The technical drawing of the lid can be found in the appendix.

This design effectively balances motor stability, noise reduction, and durability, ensuring the system performs reliably during the cream-whipping process.



(a) The lid viewed from the top

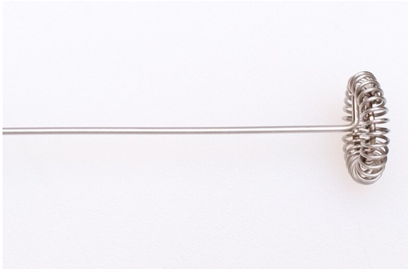


(b) The lid viewed from the bottom

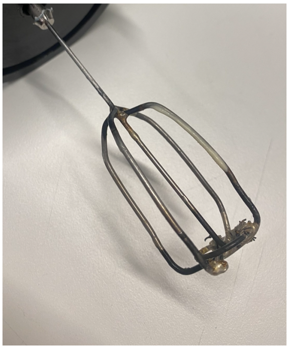
Figure 4: The 3D printed lid for the Primowhip viewed from the top and bottom, the biggest radius is 44mm.

4.2 Motor and Whisk Design

The core of the Primowhip prototype is a 6V DC-motor. The motor drives a whisk attachment that is connected to the motor shaft. This whisk component is originally a milk frother that was modified to improve its functionality for cream whipping. The modifications to the milk frother were done using silver solder to attach additional parts, which enhance its performance. These improvements ensure that the whisk efficiently mixes the cream, achieving the desired consistency. Figure 5 shows the original and modified milk frother components: (a) the original frother and (b) the modified version used in the Primowhip prototype.



(a) Original Milk Frother [6] CC0 license.



(b) Modified Milk Frother

Figure 5: Milk Frother Modification

4.3 Sensor Selection and Control System

Using the principle that as viscosity increases, the motor experiences higher torque and draws more current, a current sensor and relay system are employed to monitor the cream's consistency and automatically stop the motor when the desired consistency is reached. This is achieved through a shunt resistor and an Arduino-based monitoring system, which tracks the current levels and triggers the automatic shut-off feature when a preset current threshold (1.1 A) is exceeded. The relationship between motor torque and current is given by Equation 2.

$$T = K_T I \tag{2}$$

Where T is the torque of the motor, I is the current, and K_T is the torque constant of the motor [7]. The design leverages the motor itself as a viscosity sensor, simplifying the system while ensuring reliable performance. Figure 6 shows the circuit diagram. The diagram illustrates the control mechanism for the cream whipper system.

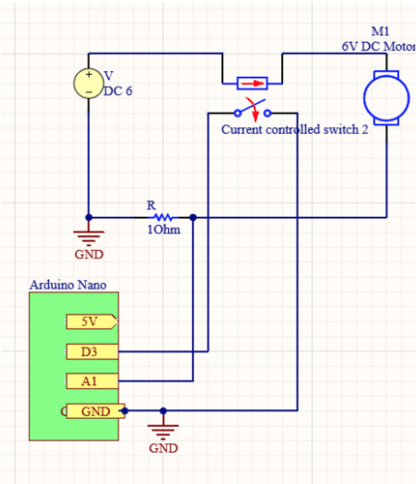


Figure 6: Design of the control system for the cream whipper

The system is powered by a 6V DC power supply, which drives both the motor and the rest of the circuit. A 6V DC motor operates the whisk, and its current draw is monitored to determine the optimal stopping point for the whipping process. A 10-ohm shunt resistor is incorporated to measure the current flowing through the motor. The voltage drop across this resistor is proportional to the motor's current and is read by the Arduino via its analog pin (A1). The Arduino processes this input to calculate the current and control the motor's operation via a relay. If the current exceeds 1.1 A three times in a row, the Arduino triggers the relay to cut power to the motor and stop the whipping process. The Arduino code is provided in the appendix.

5 Experiments and Results

Two experiments were carried out to evaluate the performance of the Primowhip cream whipper. The first tested how accurately the system measures the current to automatically stop the motor when needed. The second test looked at how well the device achieves the right cream consistency, aiming for at least 50% overrun. The goal was to ensure the whipper stops at the right time and gives the cream the perfect texture.

5.1 Ammeter Calibration Test

An ammeter calibration test was performed to ensure the accuracy of the current measurements in the cream whipper system. The ammeter relies on a shunt resistor for current measurement, and its accuracy under load conditions was assessed. The test was conducted using a 6V system with a motor load, simulating the whipping process with 75 mL of water. Twelve measurements were taken, comparing the measured current to 0.50A that were fed into the circuit for testing. The graph of amperage versus time remaining is shown in Figure 7 below, illustrating both the measured amperage and the given current of 0.50 A.

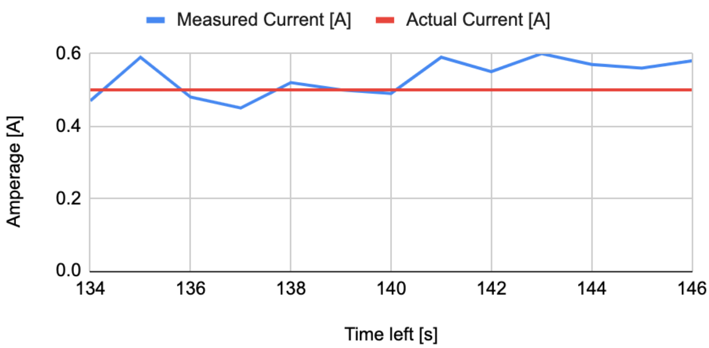


Figure 7: Amperage vs. Time Remaining

From the twelve measurements the average measured current was 0.535 A and the standard deviation was 0.052 A. The discrepancy (percantage error) is calculated as 7%. The 7% discrepancy in the ammeter readings is acceptable for the operational range of the system. This ensures that the motor's current consumption is measured accurately, which is essential for the cream whipper's automatic shut-off feature to work correctly.

5.2 Cream Overrun Test

The goal of the cream overrun test is to ensure that the cream whipper can automatically stop once the cream reaches the optimal texture (less than or equal to 50% overrun), without any user intervention. The tests focus on measuring the increase in cream volume, which indicates whether the cream has been whipped enough. To test the performance of the Primowhip cream whipper, a series of trials were conducted using 75 mL of cream for each test. The mass of 50 mL of unwhipped cream was measured to be 54±0.2 g. Ten test runs were performed, and each run involved the following steps:

- Filling the cream whipper with 75 mL of cream.
- Activating the automated whipping process and letting the device run until the automatic stop feature was triggered.
- Measuring the mass of 50 mL of whipped cream immediately after the stop function was triggered.
- Measuring the volume expansion (overrun) by comparing the initial weight of the cream to the weight of the whipped cream.

The volume expansion of the cream was calculated for the nominal, max and min values with Equation 3.

$$V_{\text{exp}} = \frac{V_{\text{whipped}}}{V_{\text{unwhipped}}} \tag{3}$$

Where V_{exp} represents the volume expansion, V_{whipped} is the specific volume of whipped cream and $V_{\text{unwhipped}}$ is the specific volume for unwhipped cream. 10 experiments were carried out. The results of the tests are shown in Table 2, which summarizes the mass of the whipped cream and the volume expansion for each test. The table shows three volume expansion values for each test: nominal, maximum, and minimum, which help understand the range of variability in the cream's overrun.

Table 2: Summary of Measured Mass and Volume Expansion.

ID	Measured mass of 50mL whipped cream (g)	Volume expansion nominal	Volume expansion max	Volume expansion min
1	32.70 ± 0.2	1.6514	1.7267	1.5795
2	33.40 ± 0.2	1.6168	1.6900	1.5469
3	33.70 ± 0.2	1.6024	1.6747	1.5334
4	34.50 ± 0.2	1.5652	1.6353	1.4983
5	35.00 ± 0.2	1.5429	1.6116	1.4772
6	35.40 ± 0.2	1.5254	1.5932	1.4607
7	34.10 ± 0.2	1.5836	1.6548	1.5156
8	32.80 ± 0.2	1.6463	1.7214	1.5748
9	33.30 ± 0.2	1.6216	1.6952	1.5515
10	34.10 ± 0.2	1.5836	1.6548	1.5156

The nominal volume expansion values are relatively close to one another, indicating that the device performed consistently across trials. The maximum and minimum values show some variation, which is expected due to the nature of the whipping process. Table 3 shows a statistical analysis of the volume expansion ratios. The Information Content (IC) is calculated using Equation 4

$$IC = -\log_2(1 - P_f) \tag{4}$$

where P_f represents the probability of failure.

Table 3: Statistical metrics for volume expansion ratios.

Metric	**Nominal**	**Maximum**	**Minimum**
Mean	1.594	1.642	1.547
Sample SD	0.042	0.043	0.040
Probability of failure	1.238%	0.053%	12.006%
Information Content	0.018	0.001	0.185

Figures 8-10 show a normal distribution using the computed standard deviations and means.

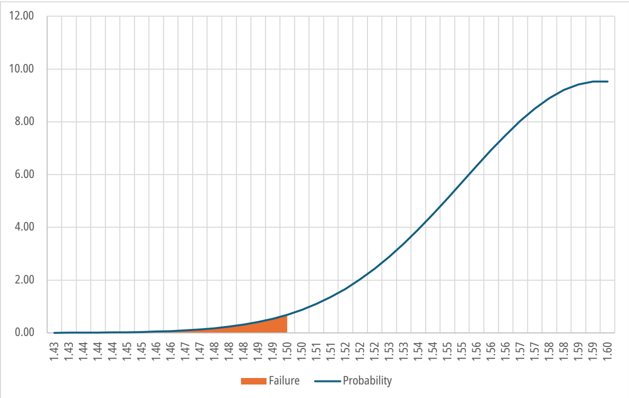


Figure 8: Probability distribution for volume expansion, based on measured values

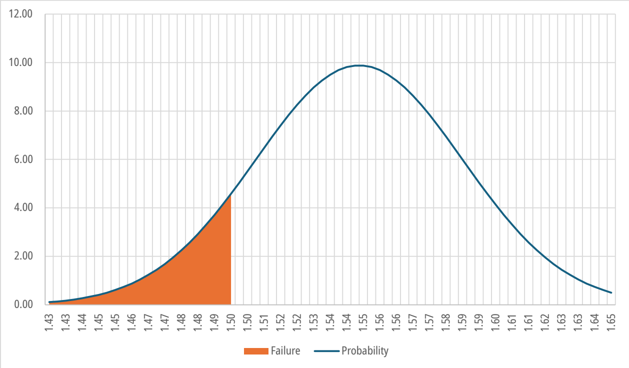


Figure 9: Probability distribution for volume expansion, based on worst case scenario in terms of uncertainty in measurements.

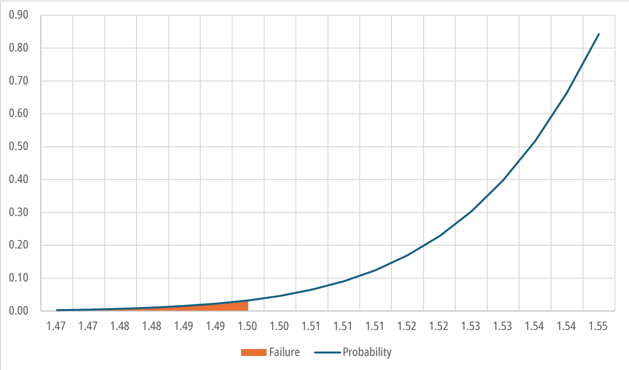


Figure 10: Probability distribution for volume expansion, based on best case scenario in terms of uncertainty in measurements.

5.3 Test Results and Requirement Fulfillment

The test results confirm that the cream whipper meets its Functional Requirements (FRs) with the corresponding Design Parameters (DPs) shown in Table 1. FR_1 is met by the container and lid which securely holds the cream during the whipping process. The cream overrun test proved that no cream was spilled or leaked. This result confirms that the DP_1, the container with lid, functions as intended. FR_2, automatically aerate cream, is fulfilled by the motorized whisk. In the cream overrun test the whisk efficiently aerated the cream for all 10 test runs. That confirms that DP_2, the motorized whisk, meets the necessary performance standards. Finally, FR_3, stop whipping at $\geq 50\%$ overrun, is met through the use of DP_3, the electrical current switch. The performance of this safety switch was validated during the cream overrun test, with results showing that the system effectively stopped the whipping process at the correct stage. The nominal volume expansion values across the tests ranged from 1.5254 to 1.6514, corresponding to an overrun between approximately 52.5% and 65.1%. These results show that the electrical current switch functions as intended, stopping the whipping process when the overrun is close to the target.

6 Conclusion

The Primowhip cream whipper automatically stops at the perfect whipped cream consistency, fully meeting the customer need. All functional requirements of the Primowhip cream whipper were successfully met. The device effectively contained the cream during operation, automatically aerated it to the desired consistency, and stopped the whipping process at the correct point, ensuring consistent results. This demonstrates that each aspect of the design worked as intended. The ammeter calibration test showed the current sensor is accurate enough to stop the motor at the right time, while the cream overrun tests confirmed that the device consistently whips cream to the target texture. By applying Axiomatic Design Theory, the system was simplified and its reliability improved. The diagonal design matrix proves this, and the total information content of the system is just 0.018 bits. the Primowhip cream whipper is easy to use, consistent, and reliable. Future improvements could focus on increasing precision and expanding its use for larger cream batches or other mixtures.

7 Appendix

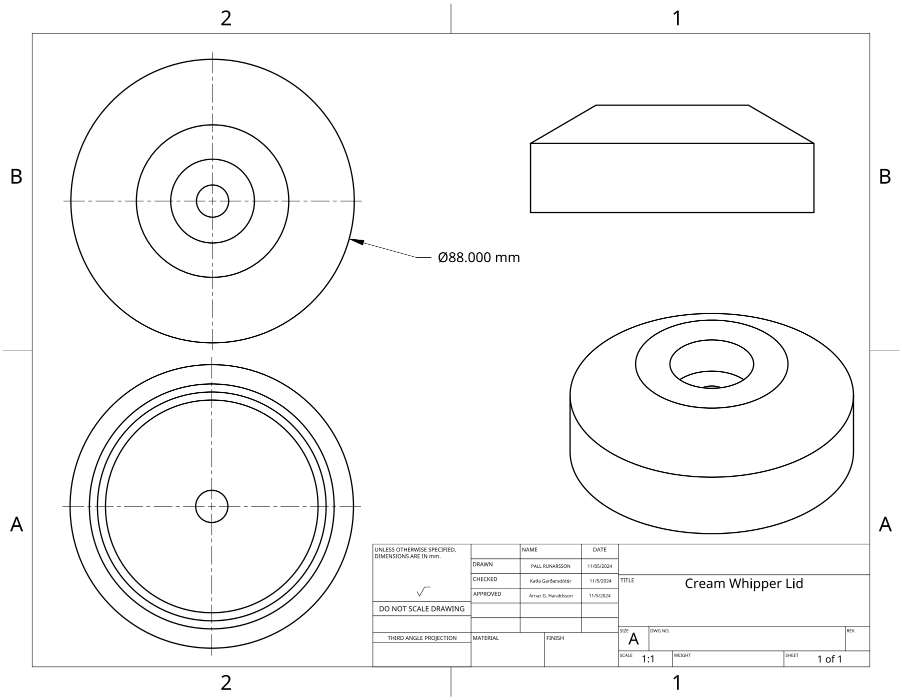


Figure 11: Design of lid for glass

Below is the Arduino code for controlling the cream whipper:

```
#include <Arduino.h> // Include the Arduino library

// Pin numbers defined
const int pinD3 = 3;
const int pinA1 = A1; // Define A1 pin as A1

// Constants for ADC to current conversion
const float referenceVoltage = 5.0;  //5V logic
const int adcMax = 1023;
const float voltsToAmps = 1.0 / 1.2; // Conversion factor: 1A per 1.2V

// Threshold current value in amperes
const float currentThreshold = 1.1;
const int consecutiveLimit = 3; // Number of consecutive readings needed to stop the motor

void setup() {
  // Initialize the serial communication
  Serial.begin(9600);

  // Set pin D3 as an output to turn on and off cream whipper
  pinMode(pinD3, OUTPUT);

  // Set pin D3 to HIGH (5V)
  digitalWrite(pinD3, HIGH);
  Serial.println("Pin D3 set to HIGH (5V)");

  int consecutiveHighCurrent = 0; // Counter for consecutive high current readings

  // 150-second countdown so cream whipper won't run forever if you put unwhippable liquids in it
  for (int i = 150; i > 0; i--) {
    // Read the value from A1
    int adcValue = analogRead(pinA1);

    // Convert ADC value to voltage
    float voltage = (adcValue * referenceVoltage) / adcMax;

    // Convert voltage to current
    float current = voltage * voltsToAmps;

    // Print countdown time and current value
    Serial.print("Time left: ");
    Serial.print(i);
    Serial.print(" seconds, Current: ");
    Serial.print(current);
    Serial.println(" A");

```

```
    // Check if current exceeds the threshold
    if (current > currentThreshold) {
      consecutiveHighCurrent++;
    } else {
      consecutiveHighCurrent = 0; // Reset counter if current is below
        ↪  threshold
    }

    // Stop the motor if threshold is exceeded 3 times in a row
    if (consecutiveHighCurrent >= consecutiveLimit) {
      digitalWrite(pinD3, LOW);
      Serial.println("Motor stopped due to high current!");
      break; // Exit the countdown loop
    }

    delay(1000); // Wait 1 second
  }

  // Ensure pin D3 is set to LOW (0V) at the end
  digitalWrite(pinD3, LOW);
  Serial.println("Pin D3 set to LOW (0V)");
}

void loop() {
  // Nothing to do here
}
```

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