System design of smart ADL tools for the hand rehabilitation of people with stroke

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ABSTRACT: This paper is meant to explain the research process and system design of smart ADL tools contained in a toolbox. The toolbox is a collection of devices designed for everyday use and also as tools to aid in the rehabilitation of stroke patients. The main focus of this research is system design and improvement of two of these devices - Tumble Tooth and Squeeze and Release. A toothbrush and a cup with rehabilitative functions, respectively.

Key words:

1 INTRODUCTION

A stroke, also known as a brain attack, is a medical condition in which part of the brain is deprived of its blood supply [1]. There are multiple reasons for this, but the most common is the blockage of the artery leading to a cut supply of oxygen to some part of the brain. Depending on the part of the brain affected, there may be different outcomes. Most common effects, however, are loss of some cognitive functions and limb impairment. It is crucial to react quickly to prevent further damage and maintain the remaining body functions [2]. Therefore, the rehabilitation process after the stroke is one of the most important processes to reduce the consequences of it [3]. There are multiple ways of rehabilitation that are boring, repetitive, and require a lot of self-motivation. Therefore, even though the survival rate of stroke is constantly increasing [4], there is still another issue that needs attention. It's what happens after. Patients usually don't have enough motivation to practice and exercise, which makes their mobility limited and causes many problems in everyday life [5] [6]. The solution that is presented in this report is the Toolbox, including everyday-use devices that contain rehabilitation functions. Therefore, the patients can seamlessly exercise while performing everyday tasks. In this paper, the system design of two of the devices included in the Toolbox is presented. The Tumble Tooth - electric toothbrush and the Squeeze and Release - drinking cup. Moreover, the improvements of the systems are presented.

2 RESEARCH QUESTIONS

The goal of this research is to identify potential improvements in device design and system architecture. Each device, as a subsystem, will later compose a complex system of different ADL devices that will collaborate with each other. Considering that every patient must exercise for about 30 minutes daily, using all the ADL devices will help to make the process unnoticeable for the patient while still having a positive impact on the motor skills. Both devices analyzed in this paper are used for the rehabilitation of stroke patients. For these and other previously designed devices to function properly and be most efficient, a system and subsystem architecture have to be designed. This research focuses on the subsystems' architecture. Analyzing the existing system will help gain insight into its functions and potentially improve them.

2.1 Main research question

How can the design and system integration of ADL-based dual-function rehabilitation tools—specifically the Tumble Tooth and Squeeze and Release—be improved to enhance therapeutic synergy, user engagement, and functional recovery in stroke patients?

2.2 Research sub-questions

1. What specific motor and cognitive functions are targeted by the Tumble Tooth and Squeeze and Release devices, and how effectively do they address these rehabilitation goals?
2. How do stroke patients physically and cognitively

interact with each device during use, and what are the main usability barriers or facilitators?
3. How can these tools be functionally or therapeutically integrated into a unified system that enhances rehabilitation outcomes beyond individual device use?
4. What design improvements or shared features can be proposed to enhance the communication, adaptability, and therapeutic efficiency of the toolbox as a whole?

3 METHODOLOGY

This research is particularly focused on the understanding of the rehabilitation processes and individual rehabilitation potential.
It adopts a mixed qualitative-analytical approach, combining human-centered design, reverse engineering, and systems integration analysis to evaluate and improve the Tumble Tooth and Squeeze and Release devices[7]. The specific tools will be analyzed and explored to discover how they can be functionally integrated into a seamless therapeutic system for stroke patients[8]. The two particular ADL-based tools that were previously discussed. Due to limited direct access to stroke patient participants and the tools, the analysis was carried out using expert reviews and simulation scenarios. Additionally, for a long time, user trials and real-time biomechanical data collection were not included in this study; all of these are suggested for later stages of research.

3.1 Research Design Overview

In this step, the existing designs and their interaction are analyzed. That way, it becomes clear how the devices currently work and communicate. This is an important step to see potential gaps and extra features to be added.

3.2 Functional Analysis of Devices

Later, the device's functions, subsystems, and materials are analyzed. Here, the functional diagram is used. It is important to understand not only the main function of the device but also how the device interacts with the user before and after using it [9]. This presents a completely new view on the rehabilitation device's functionality.
In the next Figure 1 and Figure 2, the functional diagrams of the Tumble Tooth and Squeeze and Release are shown. For visibility, the figures are also included in the AppendixA

Figure 1: Tumble Tooth functional diagram

Figure 2: Squeeze and Release functional diagram

As it is shown in the diagrams, the devices perform their designated functions only when they're being used. That means (depending on the device, of course) most of its time, the device is in "sleep mode". The Toolbox is designed to be a box that includes all of the tools and stores them between uses. However, with this approach, all the tools have to be returned after every use. This makes the usage difficult and requires a lot of effort. As an example, one can look at brushing the teeth. If the Toolbox hub is placed in the kitchen on the base floor and the Tumble Tooth is being used in the bathroom on the first floor, going downstairs just to place the toothbrush back in the toolbox would interfere with the evening routine.

4 LITERATURE REVIEW

People who have had a stroke have to go through a tedious rehabilitation process to maintain basic bodily functions. After leaving the clinic, they are advised to practice daily for at least 30 minutes on their own [10]. Lack of promising results and no possibility of improvement of motor skills causes patients to lose motivation to practice and rehabilitate [11]. Current devices included in the toolbox are promising; however, they have never gone through extensive testing and real-life application [12]. This has to be done to create the best version of the system architecture and make the toolbox ready for users. It is a difficult task as the devices of everyday use are not easily replaceable for people. Users mostly have their preferences and are likely to come back to their previous device [13]. Therefore, the main focus should be on making them easy and comfortable to use and look compelling and pleasing to the human eye. What can be done without extensive testing and including the stroke patients, is a systematic approach to that problem.

4.1 Device's main purpose

The research approaches a system design of two tools included in the Toolbox: Tumble Tooth - an electric toothbrush, and Squeeze and Release - a squeezable drinking cup. They both provide functions that seamlessly blend into their original features and serve rehabilitation purposes. It is important to mention the differences between the tools that directly target different types of movements and exercises [14].

4.2 Tumble tooth

The TumbleTooth is a device developed by a master's student of Twente University [15]. It is a toothbrush with an additional rotational degree of freedom added at the toothbrush head. Not only does the toothbrush head rotate with high RPMs (revolutions per minute), but the base can also slowly rotate into different positions (in the pitch direction, see Figure 3) thanks to a servo motor installed inside. The MPU 6050 - an accelerometer and gyroscope - made sure that the feedback from a user's hand rotation is gathered. Later, the information was sent via WiFi to analyze the feedback. The device communicates and charges via a USB-C port on the Toolbox hub (the main hub for all the tools). Through this device this way, the user can practice the wrist rotational movement and stability.

Figure 3: TumbleTooth toothbrush

Below, in Figure 4, a FAST diagram of the Tumble Tooth toothbrush is shown. Using this tool helps to visualise the exact processes that allow for wrist rehabilitation using the Tumble Tooth. It mobilizes brainstorming and systematic thinking.

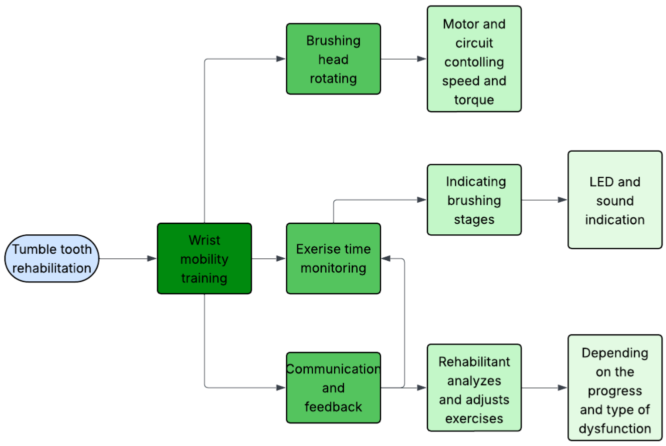


Figure 4: TumbleTooth FAST diagram

4.3 Squeeze and release

Squeeze and Release is a cup designed specifically for patients after a stroke. It targets the most frequent daily activity, which is drinking, with an average of 10 times per day [16]. It is a functional ADL device that also trains grip strength and accuracy. Using a colored LED scale, it indicates the strength of the grip. This way, it can be used to drink and practice gripping objects with specific force simultaneously. The picture of the cup in Figure 5. As an additional sub-system, a Place-mat was designed - an interactive mat for practising arm coordination. It indicates place positions on the surface that have to be followed by the patient.

Figure 5: Squeeze and Release cup

Same as for the Tumble Tooth, in Figure 6 a FAST diagram is shown.

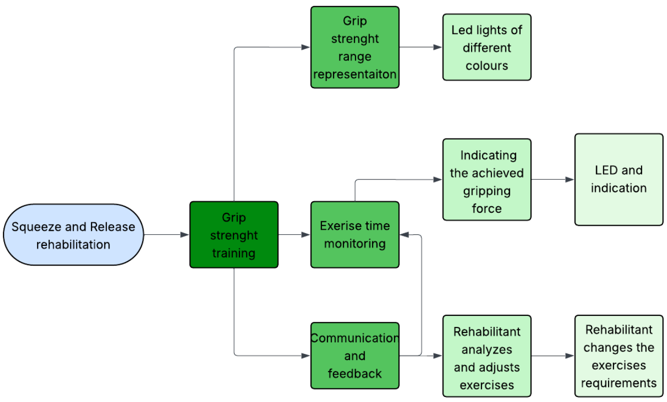


Figure 6: Squeeze and Release FAST diagram

5 SQUEEZE AND RELEASE POTENTIAL IMPROVEMENTS

5.1 Tools Designation

Both of the tools have been designed for a specific purpose. Because of that, they also have a predefined and assumed location where they are used. For Tumble Tooth, it's the bathroom, and for the Squeeze and Release, kitchen. Therefore, however, as we can observe in real life, people generally perform those actions in multiple places [17]. People often drink outside their home (drinks at a friend's place or a coffee at the bar). Even when they drink at home, they often choose multiple rooms - kitchen, living room, garden, or even bathroom. For teeth brushing, the habit is similar. Nowadays, with multiple distractors around us, we brush our teeth in the bedroom, while watching the news, or even in the kitchen. These situations were not taken into account while designing the Toolbox. Therefore, multiple devices are not adjusted to be used outside of their designated area, and that could make the experience less seamless. Moreover, all the existing devices have to be plugged into the Toolbox hub in order to be charged or the gathered data analyzed. That means if any of the devices' batteries drain, the user is forced to transport it to the hub (which is currently placed in the kitchen of the patient's house) and plug the device in.

Another important aspect to mention is that the tools included in the Toolbox mostly allow for performing only one exercise. That means, to provide the patient with the complex set of exercises, multiple tools have to be used, and that increases the risk of rehabilitation being unsuccessful.

5.2 Design Improvement Proposals

Based on the previous analysis, a few improvements can be suggested.

Naturally, in the future development of the Toolbox, the tools' functionalities should be adjusted not only for the rehabilitation process itself but also for the storage and charging of the tools. Preferably, all the devices should be able to communicate via gateways and WiFi protocols instead of cables and SD cards. The functions of the devices shouldn't be dependent on or influenced by the location where they're used.

Moreover, in the future, all the tools should perform multiple functions. To decrease the complexity of the system and improve seamless operation, the patient should be able to exercise efficiently. That means one tool should contain two or even three exercises for different arm parts affected by stroke. Ideally, one device that could exercise all necessary functions for a specific patient. If the tool provides multiple exercises, the therapist should be able to create a plan for a specific patient and activate only the necessary ones.

Another suggestion for improvement, which would drastically increase the total exercising time, would be to implement the LTE communication modem in some of the devices. That way, the patient can exercise at work, school, at a friend's house, or even while commuting. As an example, the Squeeze and Release cup could be used as a travel cup where the user could train the grip on the way to work in the metro or other transportation means.

All these improvements can be a part of future research and implementation. In Chapter 6, a proposed design of the functions integration is presented.

6 SQUEEZE AND RELEASE WRIST MOBILITY TRAINING IMPLEMENTATION - TILT AND DRINK DEVICE

Squeeze and Release cup in cooperation with the Place-mat (an interactive mat detecting proper placement of the cup in different, highlighted spots) is a great tool to train both arm movement coordination and grip strength. However, the cup itself contains components that could potentially be used to exercise more motor skills without modifying the cup too much. In this section, the development process of a sub-system called Tilt and Drink for the Squeeze and Release cup will be presented. Implementing the device into Squeeze and Release seems to be the most efficient option as the cup is one of the most often used Toolbox's devices (approximately 10 times daily).

6.1 Motivation

After researching the Toolbox system, it was discovered that not every tool is multifunctional enough to exercise multiple motor skills at once. Tumble Tooth - wrist mobility, Mouse and Squeeze and Release - grip strength, Spatula - correct grip [18]. These tools are all contained in the Toolbox, and they perform different functions. As mentioned in Chapter 5.1 - Tools Designation - knowing that all these tools provide separate functions, it becomes clear that the integration of multiple functions into one tool would decrease the total number of tools. That would further decrease the complexity of the Toolbox and potentially make the experience more seamless [19].
Moreover, the current Squeeze and Release cup contains the circuit board with components that will allow for that modification without significantly altering the current system.
This particular tool would address a common issue among stroke patients, which is difficulties with drinking [20]. Many patients look for ways to cope with this problem using a straw, drinking from a bottle, or other methods. This tool will teach the patient how to do it correctly and improve the wrist mobility and coordination.

6.2 Main functions

The main function of the described sub-system is to detect the patients' wrist rotation during the drinking process and inform the patient using a buzzer if the required angle is reached. Wrist movement exercise is already provided by Tumble Tooth, and implementing it in another device shows that multiple functions can be implemented in one device, decreasing the total number of devices and therefore the complexity of the system. Below in Figure 7, the visual representation of the Tilt and Drink device function is shown:

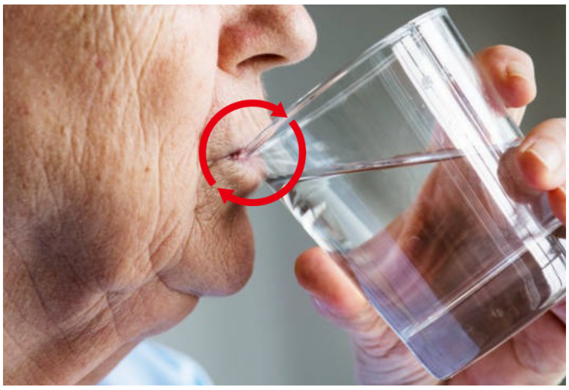


Figure 7: Wrist rotation while drinking from a glass

A detailed FAST diagram of the Tilt and Drink device added to the Squeeze and Release cup can be found in Figure 8

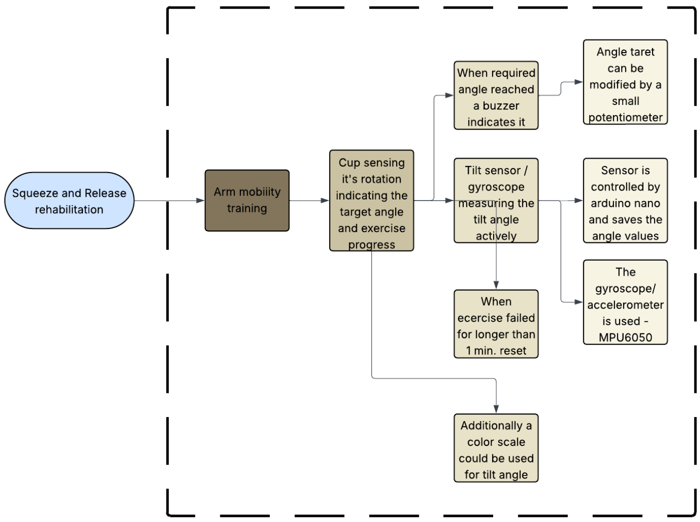


Figure 8: Tilt and Drink device FAST diagram

On the next page, in Table 1 can be found with all the functions of the device.

Function	Indicator/ Range
Notification when tilt angle (set via pot) is reached	2000 Hz buzzer
Potentiometer sets angle in specific range	between 5° and 90° in 18 steps
Device activates when movement is detected	for movement >2 G (force)
Indicates when turned on	simple 3-tone melody on activation
After reaching angle threshold, sleeps	5 s (COOLDOWN)
After 1min inactivity, goes into deep sleep	low, 0.5s, 100Hz tone
Alert re-arms only after device returns to near-horizontal	angle $<5°$
Device turns off when potentiometer switched to leftmost position	low, 0.5s, 100Hz tone

Table 1: Overview of device functions and indicators

6.3 Technical information

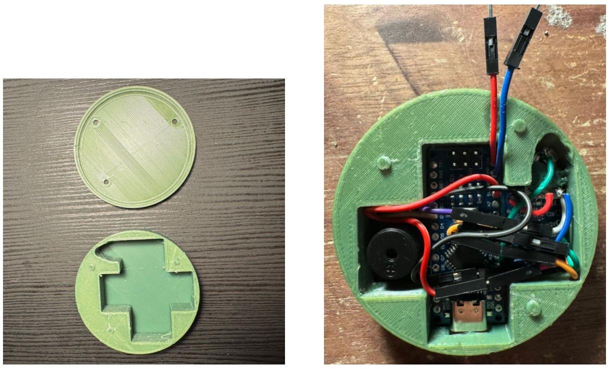
The sub-system contains 4 components. They are listed on the next page in the Table 2, with their functions.

The angle target can be adjusted by a very small potentiometer accessible by the therapist through a hole in the device casing. That way, the tilt angle target can be increased or decreased depending on the patient's progress.
The battery powering the current device is outside the casing, as in the future design, the idea is to implement the function into an already existing device. It was not possible for this prototype to be integrated with the Squeeze and Release cup, as all of the functional cups are currently used in a research project. However, the 3D printed design case allows for attachment to the bottom of any regular-sized (150ml-200ml) plastic cup. A regular-sized exemplary assembly is shown in Figure 9 below.

Figure 9: Tilt and Drink device attached to the cup

6.4 Process and assembly

After determining the main function of the new design, a prototype was made. All the electronics were assembled on the prototyping Arduino board, which is easy to modify and therefore suitable for rapid prototyping [21]. The Arduino code was written (included in Appendix A), and the system was tested. After successful tilt detection, the buzzer indicating the right tone at the right angle, the 3D case design was made and printed. Below, in Figure 10 are the pictures of the 3D printed device case and the electronics placed inside:



(a) 3D printed Tilt and Drink device case

(b) Electronics fit into the case

Figure 10: Pre-assembled Tilt and Drink device

6.5 Future use and improvements

A few features could be added to the current design of the Tilt and Drink device.
First of all, as mentioned before, the device is currently built as an extra attachable box, which can be potentially removed or damaged by the patient. Moreover, it is not waterproof, so it has to be either removed from the cup or carefully washed every time. Therefore, the main goal is to implement the device into the already existing Squeeze and Release cup using the hardware already installed.

Component	Function	Technical data
Arduino Nano	Controlling the device	USB-C interface
MPU6050 Accelerometer	Detecting the tilt angle	$\pm 16\, g$, $\pm 2000\, \mathrm{deg/s}$
3-pin Buzzer	Indicating the reached tilt target	0–2500 Hz
Potentiometer	Lets the therapist change the tilt target	$500\, \mathrm{k}\Omega$
3d printed case	Allows for seamless integration	PLA material

Table 2: Overview of Tilt and Drink sub-system components

Also, currently, the device doesn't take into consideration different alterations of hand movements. In other words, some patients might have problems with hand control or the hand tremor (involuntary, rhythmic hand movements) very often happening with diseases like Alzheimer's, Parkinson's, or dementia [22]. In that case, the devices' sensitivity should be altered. Preferably with an analog device (like a potentiometer) so that the therapist or the patients do not have to make changes in the code.

As the cup would be used approximately 10 times per day and more rehabilitative functions would be implemented in the design, the cup could automatically switch between the exercises during the day depending on the exercises that the particular patient needs and the significance of the needs. For example, one patient would exercise the grip strength 5 out of 10 times while the rest would focus on the wrist mobility and other exercises. Another individual's ratio would differ depending on the needs [23].

One more improvement would be to change the buzzer into a speaker, and while the talk is completed, initiate a more satisfying and natural sound for a human ear. The buzzer might sound too rough for some patients.

7 CONCLUSIONS

From the performed analysis and research, multiple conclusions can be drawn. First of all, the devices included in the toolbox can have multiple features added in order to achieve more than one rehabilitation target using only one device.

Secondly, it is very clear that the Toolbox Hub should be either removed completely or replaced with a wireless communicating gateway.

Lastly, each device should have its own universal charging system, which can be used in multiple locations.

This research has shown how much improvement could still be made in the rehabilitation sector and proved that rehabilitation doesn't have to be tedious and difficult in order to achieve great results.

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A APPENDIX A

Figure 11: Tumble Tooth functional diagram

Figure 12: Squeeze and Release functional diagram

```cpp
#include <Wire.h>
#include <MPU6050.h>
#include <avr/sleep.h>
#include <avr/power.h>

// Pin definitions
#define BUZZER_PIN 3          // PWM output
#define POT_PIN A0            // Analog input
#define INTERRUPT_PIN 2       // MPU6050 INT -> digital 2

MPU6050 mpu;

enum State { OFF, ACTIVE, COOLDOWN };
State deviceState = OFF;
unsigned long lastActiveTime = 0;
const unsigned long INACTIVITY_TIMEOUT = 60000;  // 1 minute inactivity

// Melody
const int melody[] = { 262, 330, 392 }; // C4, E4, G4
const int melodyLen = sizeof(melody) / sizeof(int);

// Alert re-arm flag
bool alerted = false;

void setup() {
  Wire.begin();
  Serial.begin(115200);

  // Init MPU6050
  mpu.initialize();
  if (!mpu.testConnection()) {
    Serial.println("MPU6050 connection failed");
    while (1);
  }

  // Motion interrupt setup
  mpu.setMotionDetectionThreshold(2);
  mpu.setMotionDetectionDuration(10);
  mpu.setIntMotionEnabled(true);
  pinMode(INTERRUPT_PIN, INPUT);

  pinMode(BUZZER_PIN, OUTPUT);
  power_all_enable();
}

void wakeISR() {
  // Empty ISR to wake from sleep
}

void goToSleep() {
  noTone(BUZZER_PIN);
  set_sleep_mode(SLEEP_MODE_PWR_DOWN);
  sleep_enable();
  attachInterrupt(digitalPinToInterrupt(INTERRUPT_PIN), wakeISR, RISING);
  sleep_cpu();
  sleep_disable();
  detachInterrupt(digitalPinToInterrupt(INTERRUPT_PIN));
}

// Read tilt angle (X vs Z plane)
float readTiltAngle() {
  int16_t ax, ay, az;
  mpu.getAcceleration(&ax, &ay, &az);
  float gx = ax / 16384.0;
  float gz = az / 16384.0;
  return abs(degrees(atan2(gx, gz)));
}

// Read potentiometer step 1..18
int readPotStep() {
  int raw = analogRead(POT_PIN);
  return map(raw, 0, 1023, 1, 18);
}

// Convert step to angle
int stepToAngle(int step) {
  return step * 5;
}

// Play startup melody
void playMelody() {
  for (int i = 0; i < melodyLen; i++) {
    tone(BUZZER_PIN, melody[i], 200);
    delay(250);
  }
  noTone(BUZZER_PIN);
}

void loop() {
  int potStep = readPotStep();
  int targetAngle = stepToAngle(potStep);

  // Leftmost pot special mode
  if (potStep == 1) {
    // 0.5s low tone indicator
    tone(BUZZER_PIN, 100, 500);
    delay(500);
    noTone(BUZZER_PIN);
    // Wait until pot moved off leftmost
    while (readPotStep() == 1) {
      delay(100);
    }
    delay(50);  // debounce
    // Wake on pot change
    alerted = false;
    deviceState = ACTIVE;
    lastActiveTime = millis();
    playMelody();
    return;
  }

  switch (deviceState) {
    case OFF:
      goToSleep();
      alerted = false;
      deviceState = ACTIVE;
      lastActiveTime = millis();
      playMelody();
      break;

    case ACTIVE: {
      unsigned long now = millis();
      if (now - lastActiveTime > INACTIVITY_TIMEOUT) {
        deviceState = OFF;
        break;
      }
      float currentAngle = readTiltAngle();
      // If not alerted yet and angle threshold reached
      if (!alerted && currentAngle >= targetAngle) {
        tone(BUZZER_PIN, 2000);
        delay(500);
        noTone(BUZZER_PIN);
        alerted = true;
        deviceState = COOLDOWN;
        lastActiveTime = millis();
      }
      // Re-arm: reset alert when returned near horizontal (<5°)
      if (alerted && currentAngle < 5.0) {
        alerted = false;
      }
      break;
    }

    case COOLDOWN:
      // Ignore inputs for 5 seconds
      delay(5000);
      deviceState = ACTIVE;
      lastActiveTime = millis();
      break;
  }
}
```

Figure 13: Tilt and Drink device arduino code