Design and Implementation of a Smart Toothbrush for Individuals with Dementia

by

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Abstract

Dementia in general and Alzheimer Disease in particular are one of the most challenging health conditions in our century. Experiencing cognitive decline, resulting in relying on others for daily living activities and impairment in basic mental tasks are the main symptoms. There are yet no proven treatments to slow or prevent Alzheimer's Disease or dementia progression; thus, Alzheimer's patients eventually need full-time care. To help patients to stay at their own home longer and ease the caregiver burden, Smart Assistive Technology (SAT) products may be beneficial. One of the basic activities that Alzheimer's patients in particular need help with, are basic hygiene needs such as brushing their teeth. In this thesis, a smart toothbrush has been designed and implemented as a pilot study towards development of an SAT for basic hygiene functions of Alzheimer's patients. The design includes hardware and software. The hardware includes 9-Axis (gyro, accelerometer, compass) motion sensor, temperature sensor, individually addressable red, green, blue (RGB) light emitting diodes (LEDs), voice module and other electrical components, while the software includes real-time monitoring of several dependent and independent tasks using a parallel algorithm to assist the users. The real-time monitoring system of the designed prototype assists the users by visual and auditory means. It is anticipated the designed prototype will assist people with dementia, and hopefully prolong the time they can be cared for at home; it may also be used for oral hygiene education and instruction in general.

Contents

List of Figures

List of Tables

List of Abbreviations

AD	**A**lzheimer's **D**isease. 8
ADC	**A**nalog-to-**D**igital **C**onverter. 53, 54
ADL	**A**ctivities of **D**aily **L**iving. 2, 6, 10
BOP	**P**ercentage **B**leeding **o**n **P**robing. 7, 8
CAL	**C**linical **A**ttachment **L**evel. 7, 8
CP	**C**hronic **P**eriodontitis. 8, 9
CPU	**C**entral **P**rocessing **U**nit. 35, 67
GI	**G**ingival **I**ndex. 7, 8
IATs	**I**ntelligent **A**ssistive **T**echnologies. 2, 10, 11
IC	**I**ntegrated **C**ircuit. 29
IMU	**I**nertial **M**easurement **U**nit. 18, 21, 29, 38
LCD	**L**iquid **C**rystal **D**isplay. 19, 35, 82
LED	**L**ight **E**mitting **D**iode. ii, 18, 22, 23, 25, 26, 29, 35, 43, 44, 78
NFC	**N**ear **F**ield **C**ommunication. 16
NHIRD	**N**ational **H**ealth **I**nsurance **R**esearch **D**atabase. 9
OLED	**O**rganic **L**ight **E**mitting **D**iode. 19, 35
PCB	**P**rinted **C**ircuit **B**oard. 21–25, 32, 33, 37, 38

PI	**P**laque **I**ndex. 7, 8
PPD	**P**robing **P**ocket **D**epth. 7, 8
RGB	**R**ed **G**reen **B**lue. ii, 18, 22, 23, 25, 26, 43, 78
SAT	**S**mart **A**ssistive **T**echnology. ii

Acknowledgments

I would like to begin by thanking my advisor (Prof. Z. Moussavi), my committee, my parents, and all the people who have supported me along the way.

This thesis is dedicated to my loving parents and brother.

Chapter 1

Introduction

Dementia, in particular Alzheimer's Disease, is a global growing concern of the 21^{st} century. Alzheimer's Disease is an irreversible brain disorder that gradually impairs memory and cognitive skills; thus, limiting the individual's executive functioning and affecting the individual's life significantly [1]. Since Alzheimer's Disease is mostly developed later in a person's life, the increased lifespan and change in lifestyle has led to an increase in the number of people diagnosed with Alzheimer's. Researchers estimate that 1 in 85 individuals worldwide will be diagnosed with Alzheimer's Disease by 2050 [2].

Dementia has a significant and growing impact on Canadians. Approximately 9 seniors are diagnosed with a dementia type (including Alzheimer's) every hour in Canada [3]. There are currently more than 6.9% of Canadians, with the ages of 65 years and over, suffering from dementia [3]. The total annual health care costs for Canadians with dementia is estimated to double in the next 10 years compared to 10 years ago [3] increasing the need for management and institutionalization.

There are as yet no cures or proven treatments to prevent Alzheimer's progression [4]. Almost all patients with Alzheimer's or other types of dementia may end up in a nursing home when the disease is advanced [5]. Family and friend caregivers in Canada spend approximately 26 hours per week supporting a person living with dementia. It has been projected that total health care costs and out-of-pocket caregiver costs of dementia will be $16.6 billion by 2031 in Canada [3].

Progressive cognitive decline and memory loss are some of the main symptoms of Alzheimer's disease, which lead to impairment in activities of daily living (ADL[1]), and increases the caregiver's burden. The disabling condition of dementia includes physical, cognitive, and behavioral problems. Intelligent assistive technologies (IATs) are required to provide multi-level support to patients and to their caregivers. Also, patients with Alzheimer's disease have specific needs and limitations, which may be different from those with other age-related cognitive disturbances or disabilities [6]. Moreover, patients at a mild stage of Alzheimer's have different needs and limitations from those at an advanced stage [7].

Current approaches focus on managing symptoms and slowing the progression of dementia [1]. Any advancements in Assistive Technologies for progressive dementia patients will be beneficial as it may improve patients' life quality, minimize the associated costs and help them stay in the comfort of their home longer. Oral hygiene is an essential part of ADL that advanced Alzheimer's patients often have difficulty performing properly. There is not yet any smart toothbrush specifically designed for people with Alzheimer's disease in the market. In this study, we have focused on one basic daily living need, teeth brushing, that individuals with moderate to advanced

[1]ADL is self-care activities which includes eating, toileting, bathing, brushing teeth and etc.

stages of progressive dementia often have trouble performing independently.

We have designed and implemented a Smart Toothbrush that can help individuals with progressive dementia brush their teeth independently. The designed Smart Toothbrush has software and hardware for real-time monitoring of the users' actions while brushing their teeth, and is able to assist them via visual and auditory cues. Based on our team's experience with Alzheimer's research through clinical trials over the past ten years, Alzheimer's patients at moderate or advanced stages of the disease have impaired visual object recognition, but can still recognize different colors. Also, they are still able to understand and follow verbal simple instructions. Thus, we assigned specific colors to different stages of brushing teeth, such as picking up the toothbrush, opening the water tap, brushing different sides of the teeth, etc. At each stage, the smart toothbrush gives an audio command to the user on what to do next. It also monitors the users' actions by using different sensors such as the accelerometer, gyroscope, magnetometer, etc. If the user does not act as instructed, the audio command will be repeated or changed accordingly.

The main objectives of this work were:

i. Development and validation of electronic circuits for recording and measuring users' actions while brushing their teeth (described in Section 3.1).

ii. Development and validation of an algorithm to monitor the measured actions for completing the teeth brushing procedure (described in Section 3.2).

The target population of our design is people with any type of dementia at a relatively advanced stage.

1.1 Organization of this Thesis

The thesis is organized in five chapters.

The general research problem and the main objectives of this work were presented in this chapter.

General literature review on dementia including stages of the disease, risk factors, patient's need in the advanced stage, etc. and literature review on oral hygiene's assistive technologies are presented in Chapter 2.

The concept and the prototype's design of a smart toothbrush for people with dementia capable of guiding users for brushing teeth by visual and auditory hints are presented in Chapter 3. Finally, Chapter 5 presents the main conclusion of this work and recommendations for future studies.

Chapter 2

Background

2.1 Dementia and Alzheimer's Disease

Dementia is a brain disease that ranges from mild to severe stages, with the symptoms including impairment in judgments and logic, forgetting memories and loss of cognitive functions to such an extent that it will make the patients incapable of performing most of their normal daily routines [1]. One of the most common types of dementia is Alzheimer's Disease, which includes progressive cognitive decline, memory loss, memory impairment, language and behavioral deficits (eventually leading to complete loss of mental functions and death) [8], [9].

2.1.1 Stages of the Disease

The brain changes due to Alzheimer's may even begin 20 years before showing any significant symptoms [10]. The progression rate of Alzheimer's Disease depends on the age of the patient but varies amongst individuals [1]. The progression of Alzheimer's

Disease can be divided into four main stages as pre-dementia, mild, moderate and severe dementia [1].

The pre-dementia stage symptoms may look similar to those due to stress, and they are unreliably distinguished from normal aging [11], [12]. Deterioration of episodic memory and a slight impairment in verbal and visuospatial functions are some of the first symptoms, but there is no error in sensory or motor performance at the pre-dementia stage [1]. Normally at this stage, there is no diagnosis given [12].

During mild stages of Alzheimer's disease, the progression of memory loss impairs recent declarative memory more than other capacities such as short-term memories [13].

During the moderate stage, the progression of memory loss is continuous and obvious. Because of the difficulty of creating new memories, Alzheimer's patients look as if they live in the past [14]. At this stage, they are able to handle basic ADL, but they may need help in some activities such as grooming and dressing [13], [14]. Alzheimer's patients commonly lose insight into their condition at this stage [1]. Towards the end of this stage, Alzheimer's patients are more likely to be placed in nursing homes because of their significant cognitive decline, aggression, depression and incontinence [5].

Once patients progress to the advanced stage, long-term memories are also affected and patients have difficulty handling basic ADL [1]. Communication skills such as generating words or phrases are significantly impaired [13], [14]. Caregivers experience great difficulty caring for their patient at home because of behavioral disturbances [13], [15].

2.1.2 Risk Factors

There are various risk factors such as age, gender, education, genetics, etc. for Alzheimer's Disease [1]. The chance of getting Alzheimer's is significantly increased by aging [16]. According to [9], between the ages of 65 and 74 years, around 5% of people have Alzheimer's, but the risk increases to 50% for people over 85 years of age. Women are more susceptible Alzheimer's compared to men [16]. There is a theory that a higher education level allows the creation of more synaptic connections in the brain [1]. As a result, a higher education level creates a "cognitive reserve" in the brain that enables a person to compete with the progression of Alzheimer's and to hide the symptoms for a longer period of time [9]. Coexisting health problems such heart disease, high blood pressure, type 2 diabetes or high cholesterol are associated with an increase in the chance of developing Alzheimer's Disease [1].

New studies show that gum disease is associated with developing dementia. Researchers have shown that chronic inflammatory diseases are associated with an increased rate of cognitive decline in Alzheimer's Disease [17]. It has been shown that the dental health of Alzheimer's patients is poorer compared to their age-matched control group, and there is a direct relationship between dementia severity and dental health level [18], [19].

According to [19] the mean values of the periodontal parameters for Alzheimer's patients at a severe stage were higher than that of age-matched healthy individuals. Periodontal parameters include plaque index (PI), gingival index (GI), probing pocket depth (PPD), clinical attachment level (CAL) and percentage of bleeding sites (%BOP). These parameters values have been shown in Table 2.1.

Table 2.1: Comparison between the periodontal parameters from normal individuals group to severe group (mean ± SD).

Parameter	Normal	Mild AD	Moderate AD	Severe AD
PI	1.37 ± 0.29	1.96 ± 0.18	2.62 ± 0.12	3.47 ± 0.27
GI	0.64 ± 0.21	1.15 ± 0.21	1.68 ± 0.22	2.31 ± 0.26
PPD	2.39 ± 0.5	3.18 ± 0.35	3.99 ± 0.32	5.58 ± 0.58
CAL	2.76 ± 0.55	1.58 ± 0.37	4.52 ± 0.38	5.58 ± 0.58
%BOP	29.17 ± 5.43	37.09 ± 5.24	55.44 ± 7	67 ± 12.36

It has been theorized that dental health level may be impacted by the reduced ability of self-care of Alzheimer's patients as the disease progresses [20], [21].

Chronic periodontitis (CP) is a type of peripheral infectious/inflammatory condition, which can lead to increasing the chance of losing teeth [22]. Researchers reported that periodontitis could increase the risk of developing dementia [23]. Periodontitis is common in seniors, and it may become more common in the Alzheimer's population because of a decrease in the level of self-care [24].

There is some evidence that supports the role of systemic inflammation in cognitive decline, but the relationship between periodontitis and cognitive decline is still unclear [24].

Nevertheless, one study showed that people who had gum disease in addition to mild or moderate Alzheimer's Disease, experienced a faster rate of cognitive decline [24]. Thus, treatment of periodontitis may be considered as a plausible treatment to avoid further decline of Alzheimer's patients.

Although short-term studies have shown that CP may lead to increased cognitive impairment in Alzheimer's Disease patients [19], [24], long-term studies have provided less clear evidence regarding the relationship between CP and Alzheimer's Disease [8], [25], [26].

A retrospective cohort study has been done using the National Health Insurance Research Database (NHIRD) of Taiwan [27]; They investigated whether patients with CP were more likely to develop Alzheimer's in long-term. Their outcomes support the idea that infectious diseases, even with low-grade inflammation such as CP, may lead to significant progress of Alzheimer's Disease [28]. In [27], they have shown that the risk of developing Alzheimer's for people with 10-year CP problem was 1.707-fold increased compared to those with no CP issues. These findings indicate that prevention in progression of periodontal disease is necessary for its plausible effect on Alzheimer's progression.

By analyzing the human postmortem brain tissue sample from the Neurological Foundation of New Zealand Human Brain Bank, researchers found a bacteria associated with chronic gum disease, (Porphyromonas gingivalis) in the brains of Alzheimer's patients [29]; the cause of death for the control cases was unrelated to any neurological condition. In addition, toxic proteases from that bacterium, called gingipains, were identified in the brain of people with Alzheimer's [29]. Moreover, researchers found that all patients with cardiovascular disease had Porphyromonas gingivalis arterial colonization [30]. The level of gingipain immunoreactivity in the brains of normal individuals was reported lower in comparison to brains of people with Alzheimer's [29]. Porphyromonas gingivalis can access the brain through teeth cavity infection [29]. When Porphyromonas gingivalis is inside the brain, it can spread from neuron to neuron via various methods and move through neural pathways gradually [31].

The study reported in [29] provides evidence that Porphyromonas gingivalis and gingipains in the brain play an important role in the development of the Alzheimer's Disease.

2.1.3 Patient's Challenges at Advanced Stage of Alzheimer's

Caring for patients with Alzheimer's at an advanced stage of the disease is challenging for families and caregivers at their home.

The main objective for late-stage Alzheimer's care is the maintenance of the quality of life of the person with dementia (physically, mentally and emotionally). In this study, we focused on patients' oral hygiene as a small step to increase the quality of life of patients.

2.2 Literature Review on Oral hygiene's Assistive Technologies

Intelligent assistive technologies (IATs) have the potential to provide new solutions and tools for dementia care. People with Alzheimer's Disease often have difficulty performing ADL independently or even with assistance. To address some of these difficulties, Intelligent Assistive Technologies (IATs) have been developed. Assistive technology can help people with dementia in maintaining or improving the quality of their daily living activities [32].

Assistive technologies are becoming an inseparable part of life for people with Dementia. In [33], it is discussed that the number of IATs applications for dementia is being doubled every five years globally. A systematic review on IATs with applications for dementia care identified 539 IATs with current or potential applications [33]. However, none of the devices provide a solution for Alzheimer's patients to brush their teeth.

The first smart toothbrush system for a healthy user was presented in [34], [35], where the toothbrush brush movements were monitored using magnetic and accelerometer sensors.

In the design presented in [34], a MMA7260 3-axis accelerometer, an ENC-03MA 2-axis gyroscope and an HMC1055 3-axis magnetic sensors were used. An MSP430 microcontroller was used to measure the movements of the toothbrush and transmit the measured data to a personal computer. The real-time data received from the toothbrush could be then monitored. However, for extracting clinically relevant information a non real-time program was used.

In another design of smart toothbrushes for healthy users [35], the tooth brushing pattern classification algorithm was used for checking whether the user has brushed different sections of the mouth. The mouth was mapped into eight sections and the signal received from the toothbrush was analyzed to identify the brushed parts. The classification algorithm used in this research was not explained in detail. Normally the brushing procedure is done in front of a mirror. The most important challenge during classification was calculating the absolute heading information of the toothbrush concerning a mirror which was located in front of the user [35]. The heading of an object is the compass direction in which the object is pointed.

In the design presented in [36], an HMC6042 2-axis and an HMC1051Z 1-axis were used as magnetic sensors for measuring magnetic fields. Also, a 3-axis accelerometer sensor called MMA7260 was used in their design for monitoring toothbrush movements. Researchers mapped the mouth into sixteen brushing regions and classified the posture of the toothbrush into four positions. They defined a specific range of roll angles for each posture. The classification algorithm checked the heading, pitch, and roll of the toothbrush, and using data from the accelerometer and magnetic sensors classified the brushed regions. That toothbrush was tested on a group of young and dentally healthy participants with a mean age of 23 ± 2 years old. The participates were asked to stay in front of the mirror located in front of them; they were instructed not to turn their heads and not to move around during the brushing procedure. In case of movement or head movement, the classification algorithm gave wrong and faulty results [36].

Although several studies and prototypes of commercial smart toothbrushes have been proposed, there is yet no smart toothbrush for people with dementia or older adults with some memory problems.

Most commercial toothbrushes are too complicated to be used by Alzheimer's patients since those toothbrushes do not address the problems that these patients struggle with. Therefore, a new toothbrush system specifically designed for individuals with dementia needs to be designed, implemented and tested.

Design and implementation of a series of hardware which respects the dementia patients' capability during the late stage of the disease and design algorithms for monitoring and guiding users during brushing teeth are the main goals of this research.

Chapter 3

Methods

Having a device to check for proper toothbrushing would be beneficial for individuals, especially for people with cognitive impairment. With this aim, the feasibility and concept of a smart toothbrush for people with dementia has been considered. This toothbrush is capable of guiding users in brushing their teeth using visual and auditory hints.

The smart toothbrush which has been designed has software and hardware for real-time monitoring of the users while brushing their teeth, and assisting them with visual and auditory hints. Alzheimer's patients at moderate or advanced stages of the disease have impaired visual object recognition, while they can still recognize different colors [37]. Thus, we assigned specific colors to different stages of brushing teeth such as picking up the toothbrush, opening the tap, brushing different sides of the teeth, etc. At each stage, the smart toothbrush gives an audio command to the user on what to do next. Using different sensors such as an accelerometer, gyroscope and magnetometer, it also monitors the users' acts; and if the user does not act as instructed, the audio command will be repeated or changed accordingly to user's reaction.

This chapter includes two main parts: hardware (Section 3.1) and software (Section 3.2) which are explained below.

3.1 Hardware

In this section, we will describe a hardware implementation of the smart toothbrush. We will briefly describe what sensors we need to use to monitor the user's acts while brushing teeth.

The hardware of the device includes three main parts: toothbrush (Section 3.1.1), toothpaste holder (Section 3.1.2) and command-board (Section 3.1.3).

3.1.1 Toothbrush

The toothbrush we designed needs some basic components such as a microcontroller, battery charger and wireless communication module. There are several wireless technologies currently available for wireless communication products. The most important ones are listed in Table 3.1. Note that speed and transmission range numbers in Table 3.1 are estimated and can be varied by changing protocol settings and testing environment.

Table 3.1: Comparison between wireless communication technologies.

Technology	Multiple dev	Direct con	Power usage	Speed	Frequency	Range
WiFi	✓	×	High	up to 600 Mbps	2.4GHz	200 m
WiFi Direct	×	✓	High	up to 250 Mbps	2.4GHz	200 m
NFC	×	✓	-	106 to 424 Kbps	13.56 MHz	10 cm
Zigbee	✓	✓	Low	250 Kbps	2.4GHz	30 m
Z-Wave	✓	✓	Low	100 Kbps	1.0GHz	100 m
LoRa	×	✓	Low	27 Kbps	915 MHz	10 km
Bluetooth	×	✓	Low	3 Mbps	2.4GHz	100 m

WiFi communication technology is fast and compatible with mesh network technologies, which allow many devices to be connected to each other [38]. However, WiFi technology needs a router to connect to other devices. The WiFi power consumption is high; thus, WiFi is not recommended if some wireless technologies are used in battery operated devices.

WiFi Direct technology has all of the WiFi properties with the addition that WiFi Direct allows two devices to establish a direct connection without using a router [39]. Devices using WiFi Direct cannot connect to more than one device at the same time.

Near Field Communication (NFC) technology communicates using electromagnetic fields shared between two coils, unlike other wireless technologies that send radio waves. The NFC communication range is less than 10 cm [38]; thus, NFC technology is not a proper choice for the smart toothbrush devices.

Zigbee technology is a short-range, wireless technology [38]. It uses the 2.4 GHz carrier frequency. Its power consumption is very low. Zigbee also offers mesh networking. The Zigbee transmission speed is not fast enough to be used in our design.

Z-Wave technology is another short-range, wireless technology similar in many ways to Zigbee. Unlike Zigbee, which uses the 2.4 GHz band, Z-Wave uses 1 GHz band. The power consumption is low and it offers mesh networking [40]. The Z-Wave transmission speed is not fast enough to be used in our design.

LoRa technology is developed for very long-range data transmission. Compared to other technologies, and its speed is too low. Thus, not a suitable candidate for our proposed device.

One of the best known peer-to-peer wireless technology is Bluetooth. Compared to WiFi, Bluetooth consumes much lesser power. It uses the popular 2.4 GHz band [38]. The advantage of WiFi Direct over Bluetooth is mainly faster transfer speeds.

We require to transfer low amounts of data between three components of the proposed smart toothbrush powered by batteries within a short distance. Therefore, it does not make sense to use any of the long-distance or high-speed wireless technologies. Considering data rate, communication range, power consumption and price, we chose Bluetooth technology for wireless communication of different components of our proposed device.

We used the HC-08 Bluetooth module in the design. The power consumption for this module is approximately 10 mA. The default baud rate is 9600bps, which is enough to send and receive our designed packets, and the communication range is around 80 meters in an open environment.

We used an Arduino Pro Mini board 3.3 V version powered by ATmega328 as our toothbrush processor. A 1000 mAh 3.7V lithium polymer rechargeable battery and a TP4056 lithium battery charging board provide power to the toothbrush, and an HC-08 Bluetooth module takes advantage of Bluetooth 4.0 BLE protocol for wireless communication between the toothbrush and the command-board.

Our toothbrush design should be able to recognize brushing movements, and be able to check whether or not the toothbrush has been picked up. To address these needs, we added an accelerometer, gyroscope and magnetometer to our design. We used the GY-85 module 9-Axis degree of freedom Inertial Measurement Unit (IMU) sensor which has all those three sensors.

We added addressable RGB LEDs on the toothbrush to make visual hints by changing the color of some RGB LEDs, which are located on specific parts of the toothbrush, e.g., on the handle or head of the toothbrush. For example, the command-board changes the color of the toothbrush handle to flashing red at the "picking up the toothbrush" stage, and the command-board changes the color of LEDs located on the head of smart toothbrush to flashing blue to help the user to find the proper location for adding toothpaste at the "rubbing toothpaste on toothbrush" stage. Also, we use these addressable RGB LEDs for other purposes such as debugging, monitoring wireless communication status, showing the progress of brushing each part of the mouth, etc. We used the WS2812B addressable RGB LEDs, which is an intelligent control LED light source.

We designed a water sensor for detecting water on the head of the toothbrush and a toothpaste sensor for checking whether the toothpaste is rubbed on the toothbrush. All of those two sensors are available only for the smart head of the toothbrush but not for the regular head of the toothbrush. We will discuss these sensors in more detail in the following section describing the toothbrush handle (Section 3.1.1).

Also, we added a buzzer, push-button switches and a Liquid Crystal Display (LCD) for debugging purposes on our design. We used a 0.91-inch Organic Light Emitting Diode (OLED) display 128x32 module.

The block diagram of the smart toothbrush is shown in Fig 3.1 which depicts the important components and how the different components of the toothbrush circuit connect to each other.

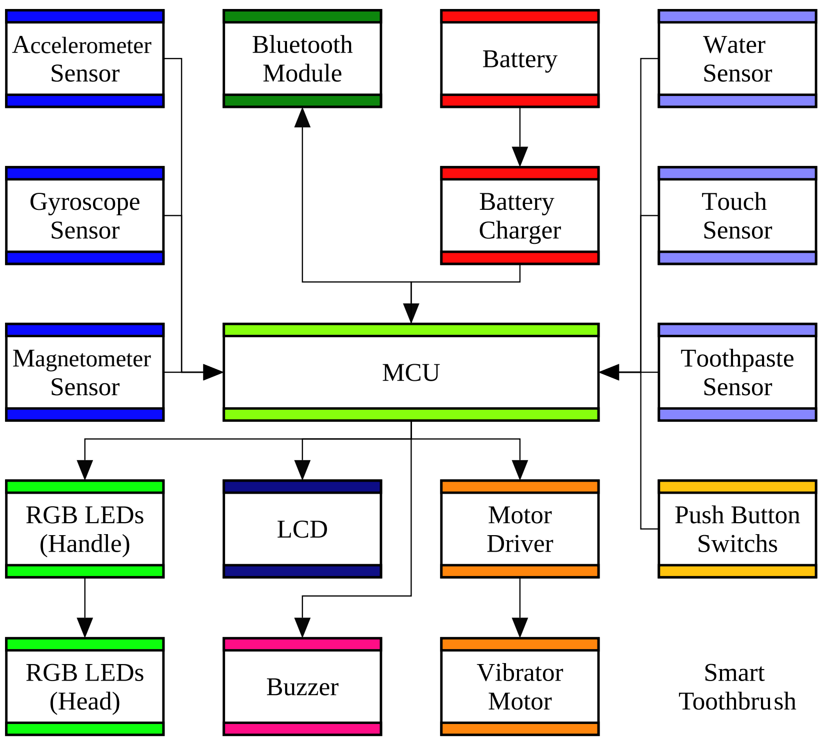

Figure 3.1: Block diagram of the smart toothbrush

The breadboard diagram of the smart toothbrush is shown in Fig 3.2, which depicts the components wiring using breadboard.

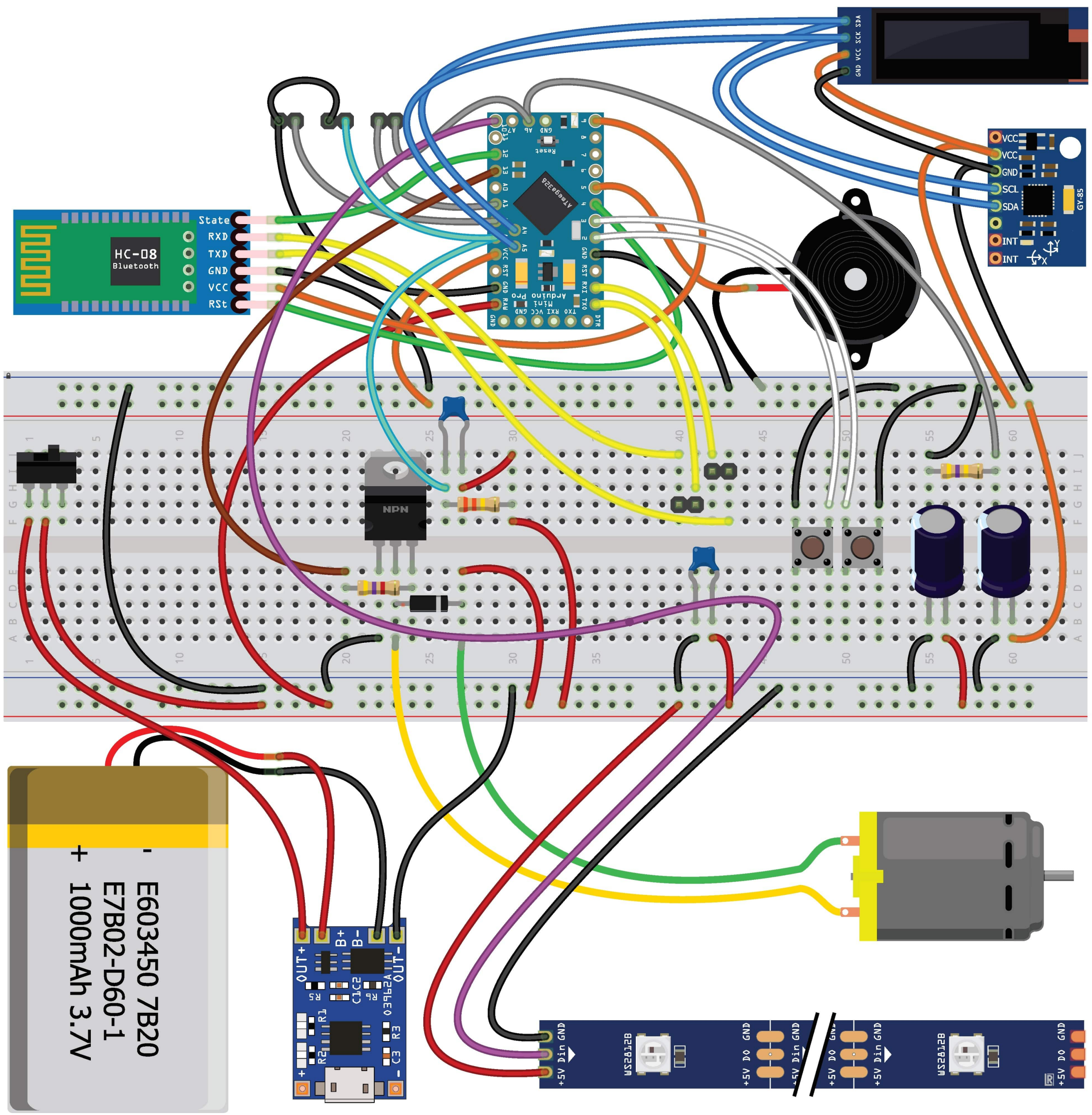

Figure 3.2: Breadboard diagram of the smart toothbrush

The toothbrush includes two main parts, the toothbrush handle and toothbrush head; they are described in the following subsections.

Toothbrush Handle

Since there was not enough space for all components to fit on one single PCB, the toothbrush handle is designed in two separate boards. The battery and vibration motors are placed between the two boards so that the users can hold the toothbrush easier. Figures 3.3 and 3.4 show the two PCBs schematically.

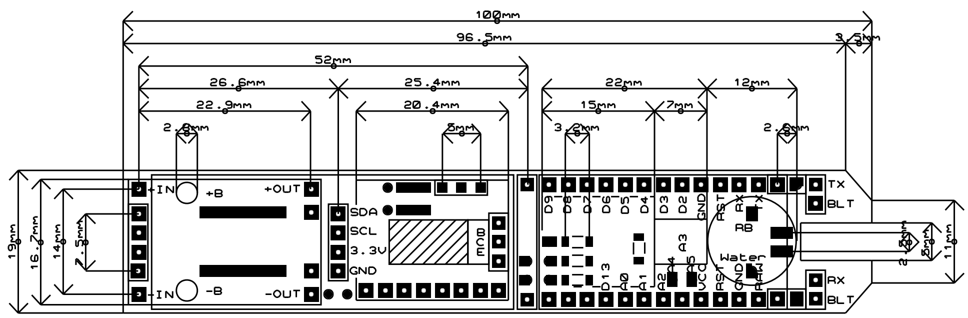

Figure 3.3: Board 1 of the toothbrush handle

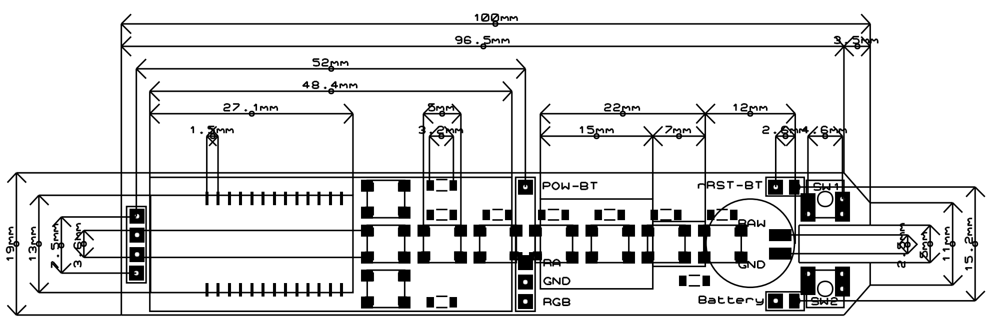

Figure 3.4: Board 2 of the toothbrush handle

The size of both boards is 100mm x 19mm x 1.6mm, and they are connected to each other using a male and female pin header.

The top and bottom view of the PCB prototype for the board 1 of the toothbrush handle is shown in Fig 3.5. The lithium battery charging board, IMU sensor, motor driver, Arduino Pro Mini board, buzzer and some other parts are installed on this board.

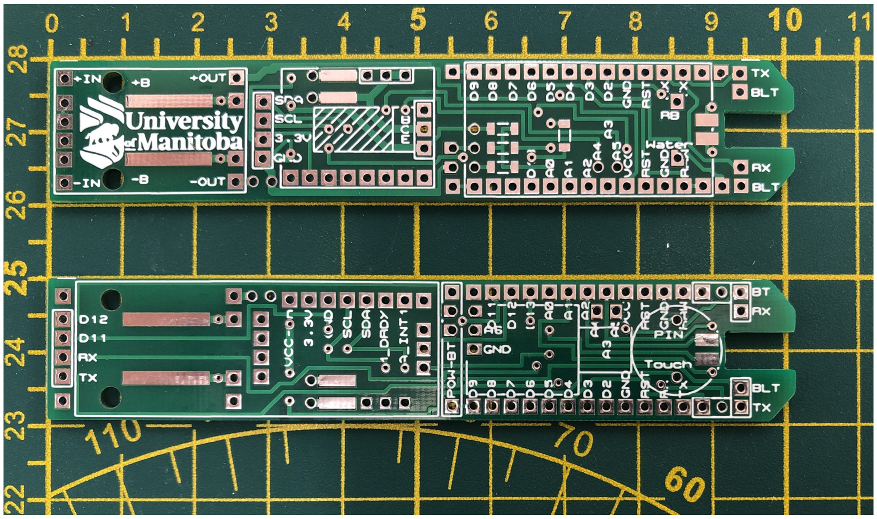

Figure 3.5: Top and bottom layer of the toothbrush handle board 1

The top and bottom view of the PCB prototype of the board 2 of the toothbrush handle is shown in Fig 3.6. The Bluetooth module, addressable RGB LEDs, push-button switches and some other parts are installed on this board.

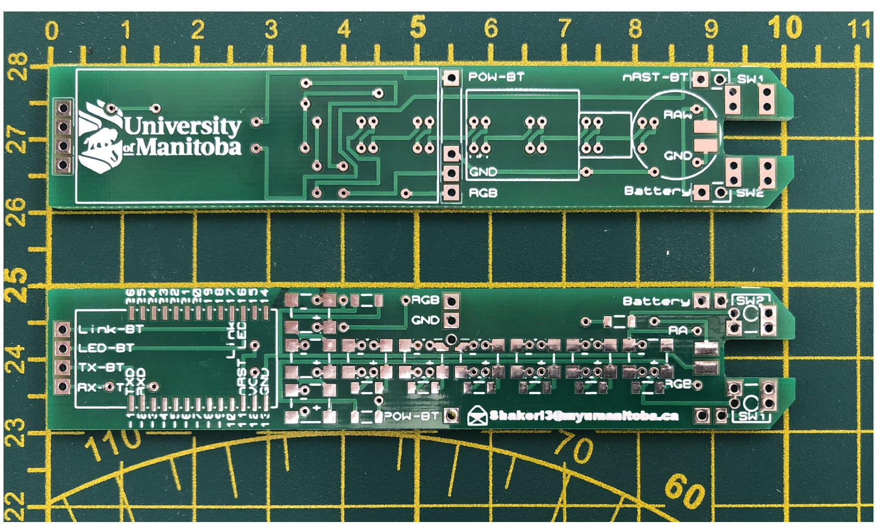

Figure 3.6: Top and bottom layer of the toothbrush handle board 2

The 3D model of the handle of the toothbrush is illustrated in Fig 3.7. A 1000 mAh

3.7V lithium polymer rechargeable battery and a vibrator motor are placed between the two PCBs of the toothbrush handle. The vibrator motor diameter, motor length and total length including vibrating head are 7mm, 16.5mm and 21.6mm respectively. The motor weight is 4g and the motor current at 3.7 V is 42 mA.

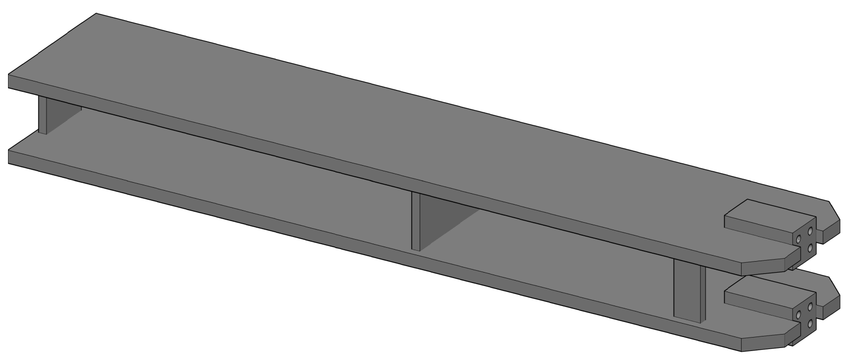

Figure 3.7: 3D model of toothbrush handle

The toothbrush handle is covered with a layer of epoxy resin. This epoxy resin is waterproof and transparent. Therefore, it does not blocks the color of the addressable RGB LEDs located on the handle of the toothbrush.

Toothbrush Head

We designed the smart toothbrush with two different heads. In one design, we used a commercial toothbrush head for the lab tests on some individuals (Oral-B Dual Clean replacement brush head). A small PCB is attached to the end of the commercial toothbrush head, which enables the commercial brush head to connect to the toothbrush handle. The second head, that is supposed to be used only by one individual (the customer), was designed using the regular toothbrush brush with four small PCBs attached with more sensors and options to increase the accuracy of monitoring the users' activities during brushing. This second one is called the smart toothbrush head in this text. The smart toothbrush head includes four boards. The schematic designs of the PCBs are illustrated in Figures 3.8 to 3.11.

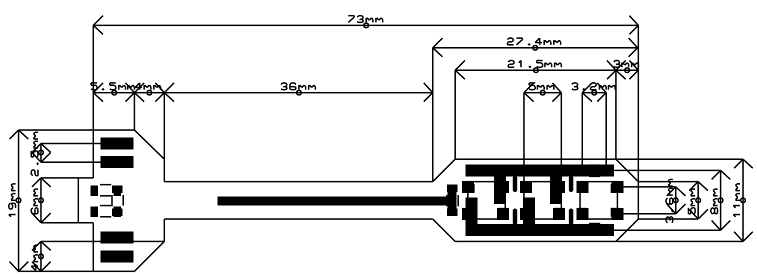

Figure 3.8: Board 1 of the toothbrush smart head

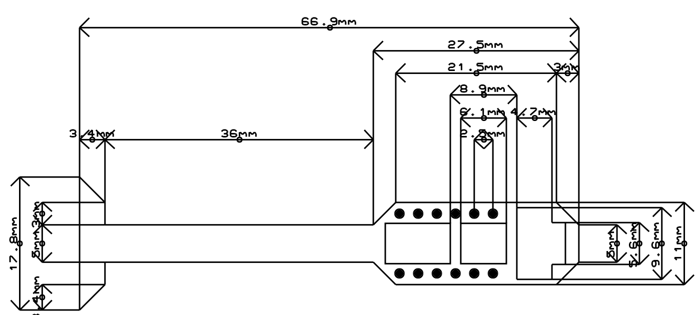

Figure 3.9: Board 2 of the toothbrush smart head

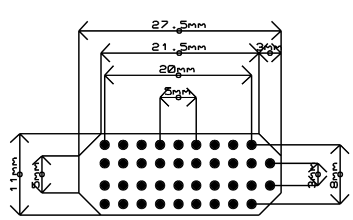

Figure 3.10: Board 3 of the toothbrush smart head

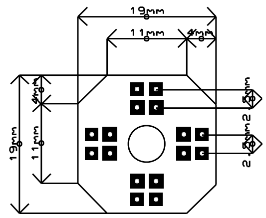

Figure 3.11: Board 4 of the toothbrush smart head

The first board of the smart toothbrush head PCB has a length of 73 mm. The first three boards are assembled on top of each other and connect to the toothbrush handle through board 4.

The top and bottom view of the PCB prototype of the board 1 of the smart toothbrush head is shown in Fig 3.12. The toothpaste detector pads, the water sensor pads, touch-sensor pad, WS2812B addressable RGB LEDs and some other parts are installed on this board.

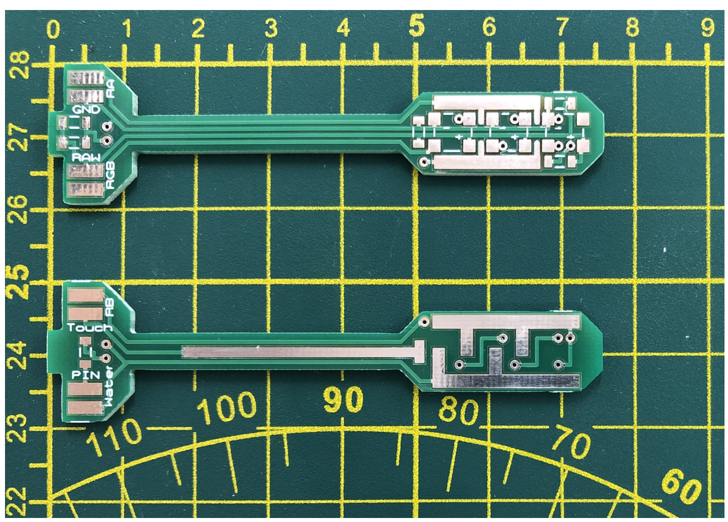

Figure 3.12: Top and bottom layer of the toothbrush smart head board 1

Contact pads are used as input for some sensors and components in this design such as the water sensor, toothpaste sensor, battery input, etc. The toothpaste detector contact pads are placed on the top layer of board 1, which is connected to the brushes using board 2 and 3. Board 2 provides three empty spaces for RGB LEDs located on the smart toothbrush head. Board 2 also has twelve holes to connect toothpaste detector contact pads to conductive brushes (the first six holes on the two sides of the smart toothbrush head). During the tooth brushing procedure, toothpaste will be placed on the surface of the toothbrush head. Thus, the toothpaste sensor has access to the surface of the toothbrush head to detect toothpaste using conductive brushes and contact pads as the input. The other twenty-six brushes that are located in the middle of the brush head are made of nylon fibres like a normal commercial brush head.

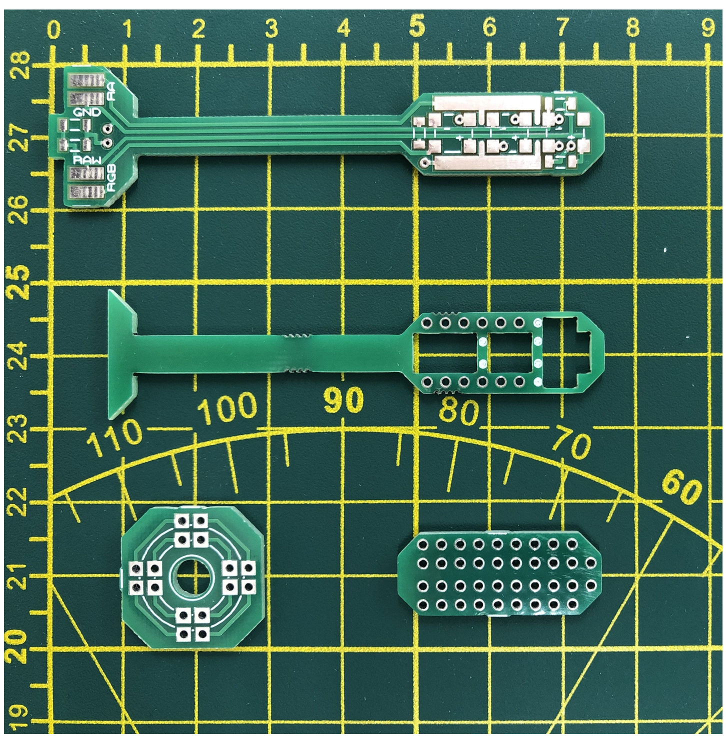

Figure 3.13: PCB design of the toothbrush smart head board 1,2,3 and 4

The 3D model of the smart toothbrush head is illustrated in Figures 3.14 and

3.15. As mentioned before, the brushes for the first six holes on the two sides of the smart toothbrush head are made of conductive materials and other brushes are made of non-conductor materials such as nylon fibers.

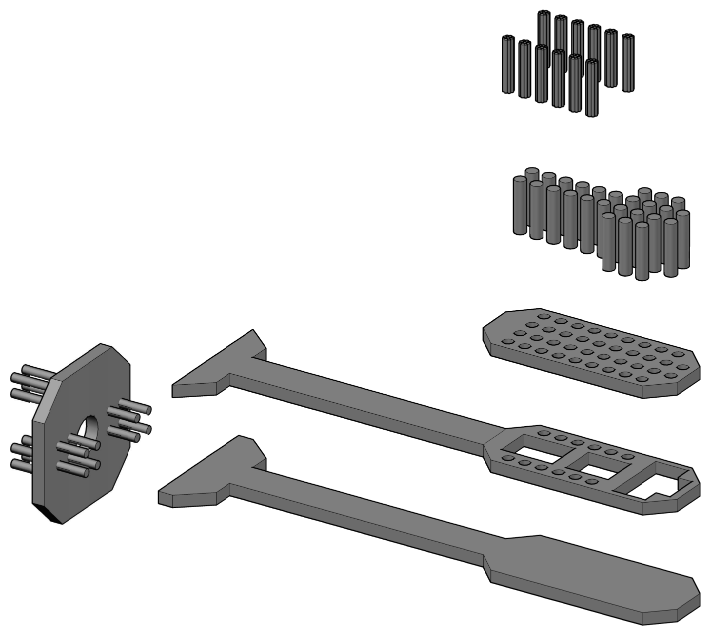

Figure 3.14: Exploded 3D model of toothbrush smart head

We used a 1000 mAh 3.7V lithium polymer rechargeable battery in our designed toothbrush handle. If the head of a smart toothbrush is dropped or damaged, it is possible to have a leaked current that may pose a safety concern. To provide a market prototype of the device, the electrical standards which deal with oral hygiene products, such as the electrical safety standard for oral devices IEC 60335-2-52, should be considered.

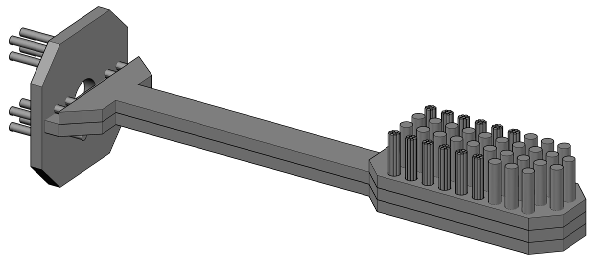

Figure 3.15: 3D model of toothbrush smart head

The toothbrush handle and the toothbrush smart head are connected using male and female pin headers. The connection between the male and female pin headers are shown in Fig 3.16.

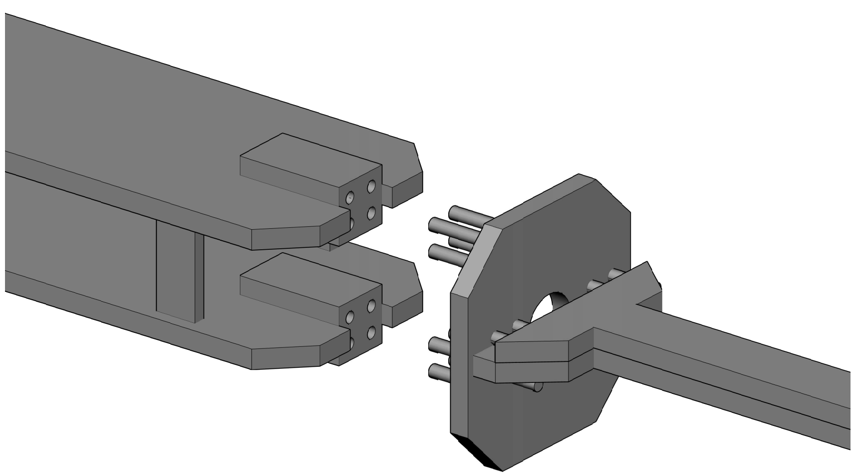

Figure 3.16: 3D model of smart head and handle pin headers

3.1.2 Toothpaste Holder

The designed toothpaste holder includes basic components such as a microcontroller, a battery charger and wireless communication modules. The toothpaste holder communicates with the command-board (described in the next section) using Bluetooth.

We used an Arduino Pro Mini board 3.3 V version powered by ATmega328 as the toothpaste holder processor, a 500 mAh 3.7V lithium polymer rechargeable battery and a TP4056 lithium battery are used to charge the board and the HC-08 Bluetooth module provides wireless communication between toothpaste holder and command-board.

Our toothpaste holder design should be able to detect if the toothbrush is picked up or not so we added an accelerometer and gyroscope to our design. We used the GY-521 module 6-Axis degree of freedom IMU sensor which has an accelerometer and gyroscope in one small IC called MPU6050.

Also, we added push-button switches and LEDs for debugging purposes on our design. We used LEDs to monitor the status of wireless communication as well.

The block diagram of the toothpaste holder is shown in Fig 3.17 which shows the important components and how the different components of the toothpaste holder circuit are connected.

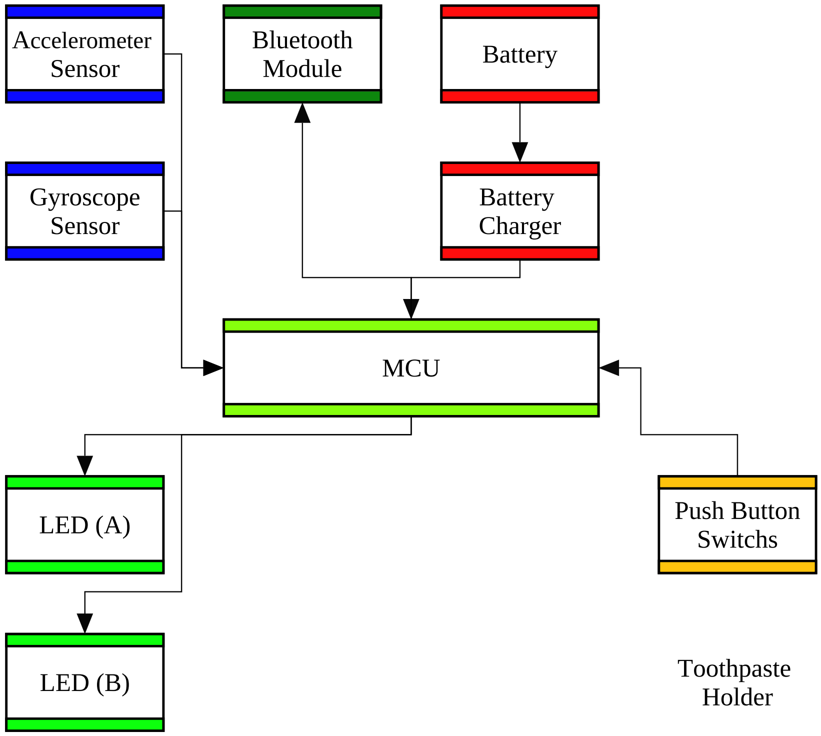

Figure 3.17: Block diagram of the toothpaste holder

The breadboard diagram of the toothpaste holder is shown in Fig 3.18, which depicts the components wiring using breadboard.

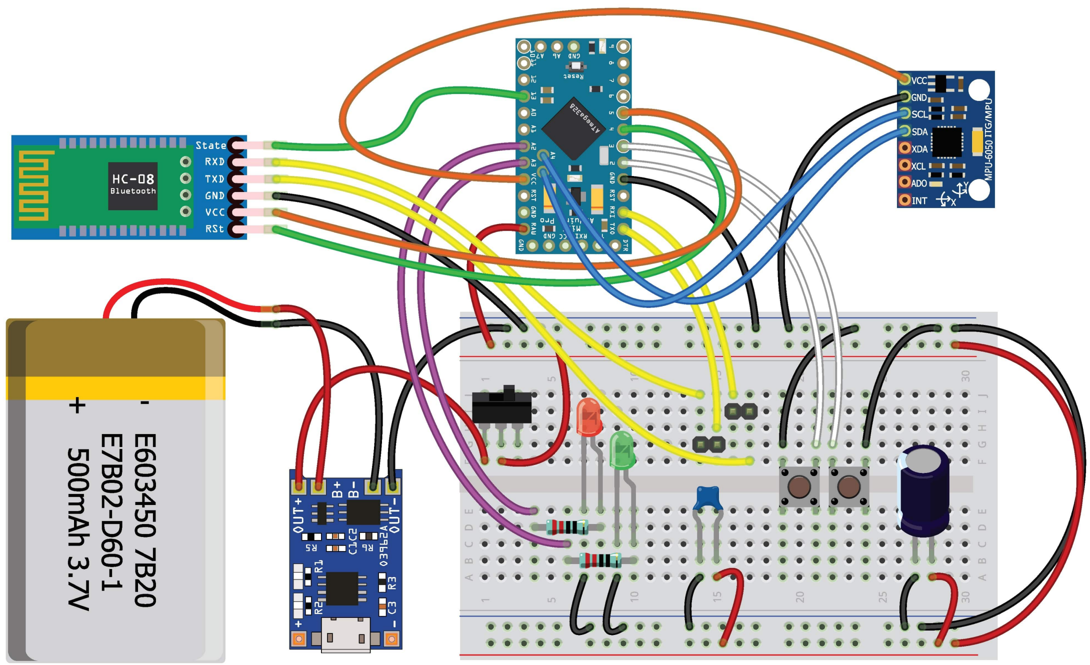

Figure 3.18: Breadboard diagram of the toothpaste holder

The toothpaste holder includes two boards. The outline drawing for toothpaste holder board 1 is illustrated in Fig 3.19 and the outline drawing for toothpaste holder board 2 is illustrated in Fig 3.20.

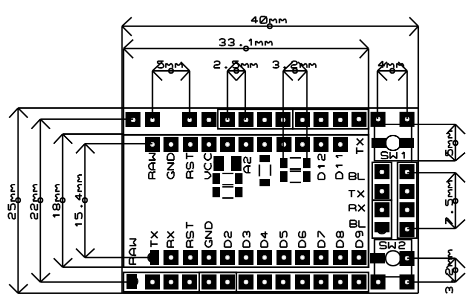

Figure 3.19: Board 1 of the toothpaste holder

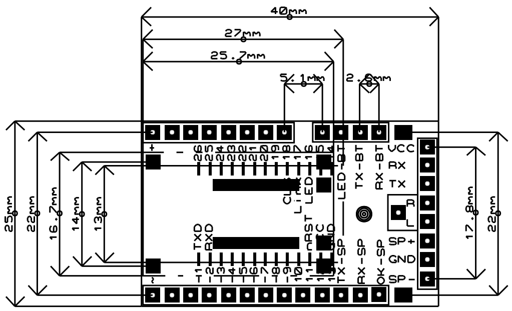

Figure 3.20: Board 2 of the toothpaste holder

Note that in Fig 3.19 and Fig 3.20, the PCB size for both of the boards is 40mm x 25mm x 1.6mm. These two PCBs are connected to each other using male and female pin headers.

The top and bottom view of the PCB prototype of the toothpaste holder board 1 is shown in Fig 3.21. The Arduino Pro Mini board, push-button switches and some other parts will be installed on toothpaste holder board 1.

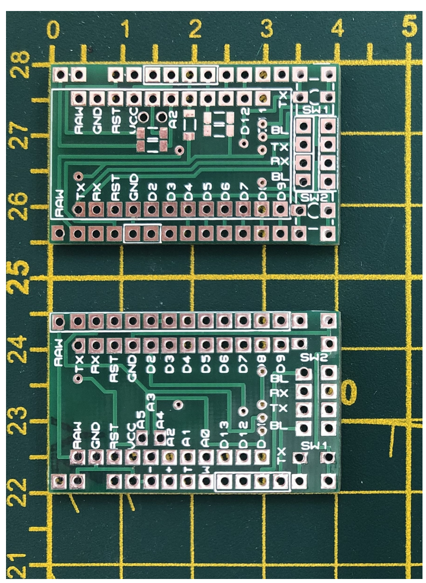

Figure 3.21: Top and bottom layer of the toothpaste holder board 1

The top and bottom view of the PCB prototype of the toothpaste holder board 2 is shown in Fig 3.22. The lithium battery charging board, Bluetooth module, GY-521 module and some other parts will be installed on the toothpaste holder board 2.

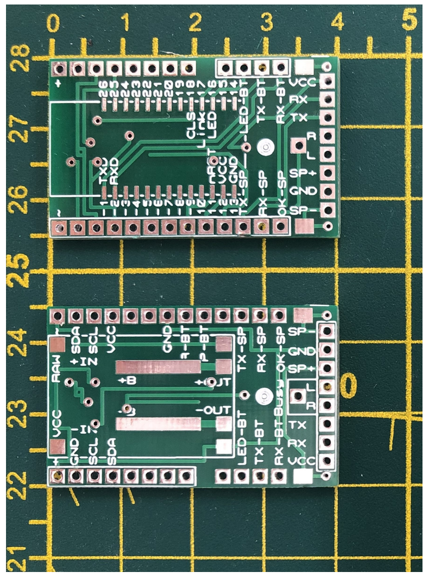

Figure 3.22: Top and bottom layer of the toothpaste holder board 2

The 3D model of the toothpaste holder is illustrated in Fig 3.23. A 500 mAh 3.7V lithium polymer rechargeable battery will be placed between PCBs one and two of the toothpaste holder.

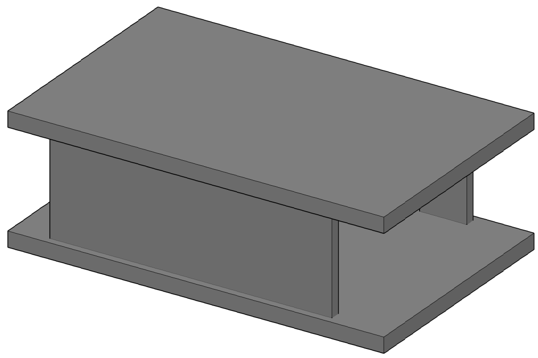

Figure 3.23: 3D model of toothpaste holder

The toothpaste holder is covered with a layer of transparent epoxy resin for waterproofing. The toothpaste holder is a soft elastic sleeve with an embedded miniature circuit including sensors, and it holds any common type and size of toothpaste tube.

3.1.3 Command-board

Similar to the toothpaste holder, our command-board design has all the basic components like a microcontroller, battery charger and wireless communication module.

We used a Teensy 3.2 board powered by Cortex-M4 MK20DX256VLH7 as our command-board processor, a 500 mAh 3.7V lithium polymer rechargeable battery and a TP4056 lithium battery charging board to provide power and an HC-08 Bluetooth module for wireless communication between the command-board, toothbrush and toothpaste holder.

A water sensor was also considered in the design to check whether or not the water tap is opened. A temperature sensor was also used to check whether the water temperature is within the proper range. We considered a temperature between 32C and 42C as comfortable. An analog temperature sensor, LM35, was used to monitor the tap water temperature.

The method for detecting water from the tap is the same as that used to detect water on the toothbrush smart head (described in Section 3.2.3).

We need to be able to assist the user using auditory hints. One option is to use an integrated MP3, WMV or other audio format hardware decoding. We chose a small serial MP3 module called DFPLayer Mini because reading audio files and playing them directly from the microcontroller increases the CPU usage dramatically. This module can be used as a stand-alone MP3 module and release the main microcontroller from the burden of decoding sounds files.

Also, we added push-button switches, LEDs and a LCD for debugging purposes on our design. We used a 0.96-inch OLED display 128x64 module.

The block diagram of the command-board is shown in Fig 3.24, which shows the important components and how they are connected.

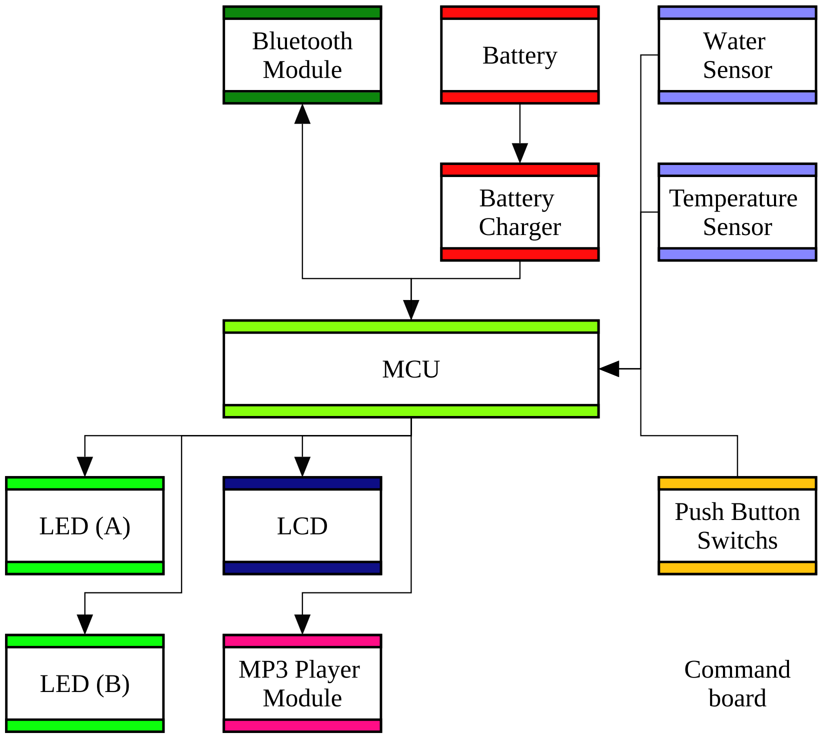

Figure 3.24: Block diagram of the command-board

The breadboard diagram of the command-board is shown in Fig 3.25, which depicts the components wiring using breadboard.

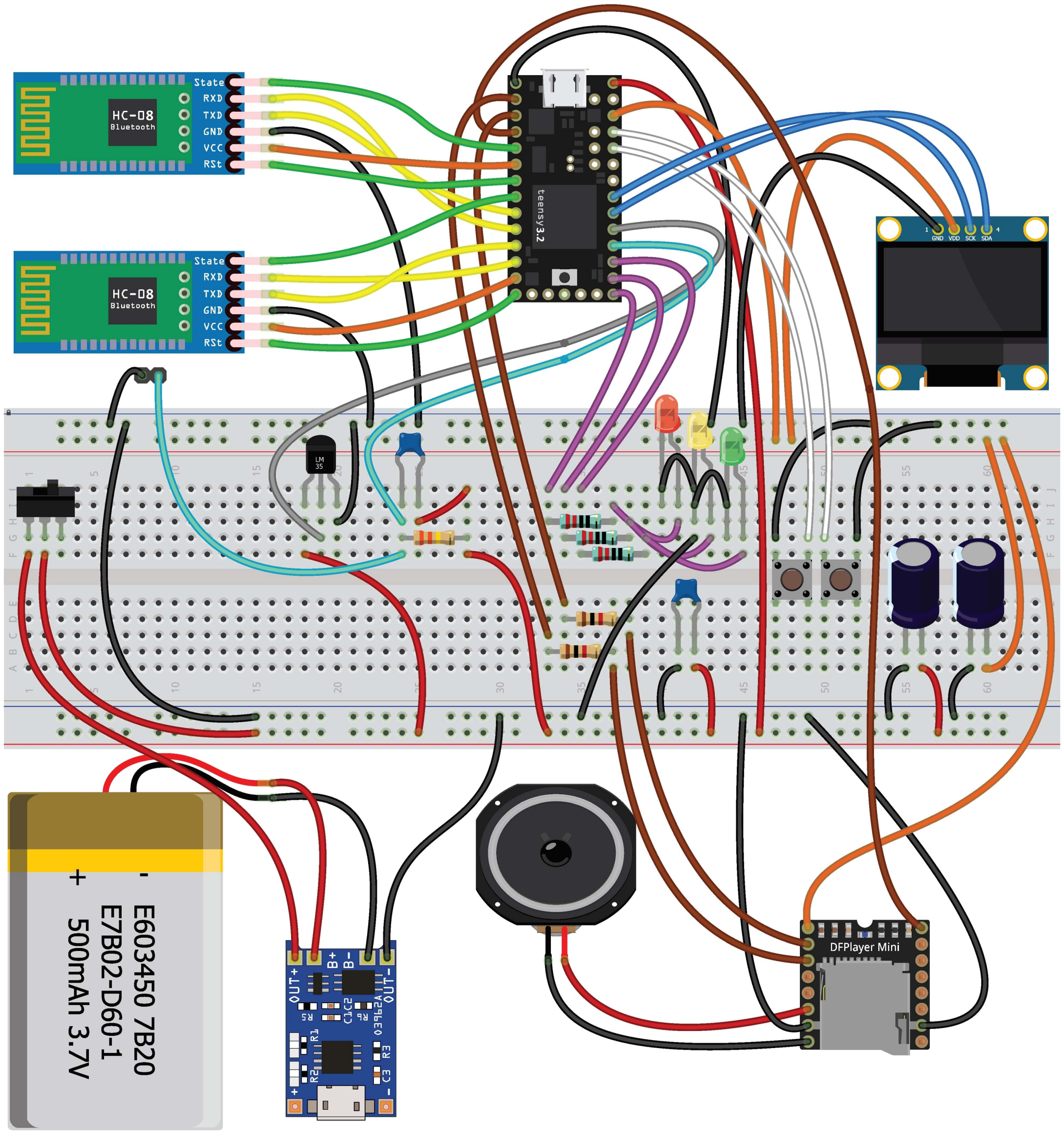

Figure 3.25: Breadboard diagram of the command-board

Note that we designed the command-board and toothpaste holder to use completely identical PCBs. This means that we can make a command-board or toothpaste holder by changing the software and some hardware components. If we wish to build a command-board we just need to remove the 6-Axis degree of freedom IMU sensor from the PCB prototype of the toothpaste holder board 2 and add a serial MP3 module and Bluetooth module to that board and change the microcontroller.

The command-board is covered with a layer of epoxy resin that is waterproof and transparent.

3.1.4 Experimental Hardware

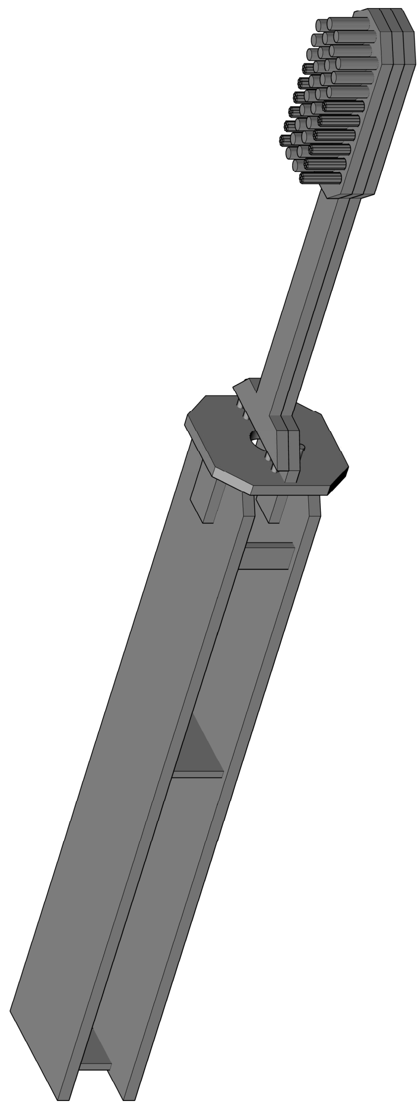

Figure 3.26: 3D model of smart toothbrush view 1

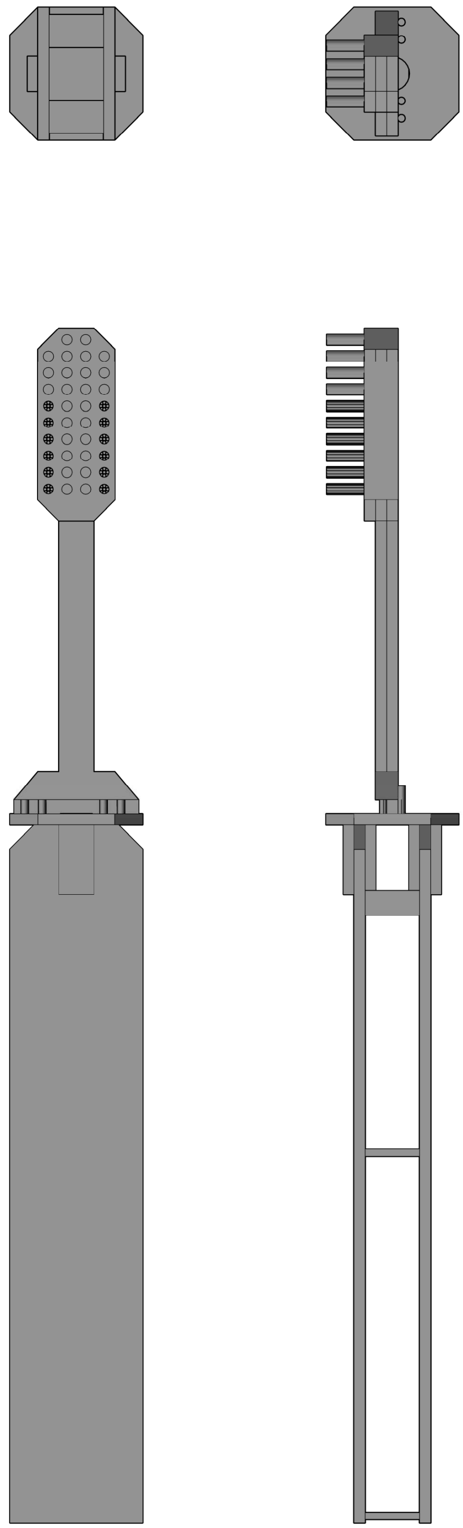

Figure 3.27: 3D model of smart toothbrush view 2

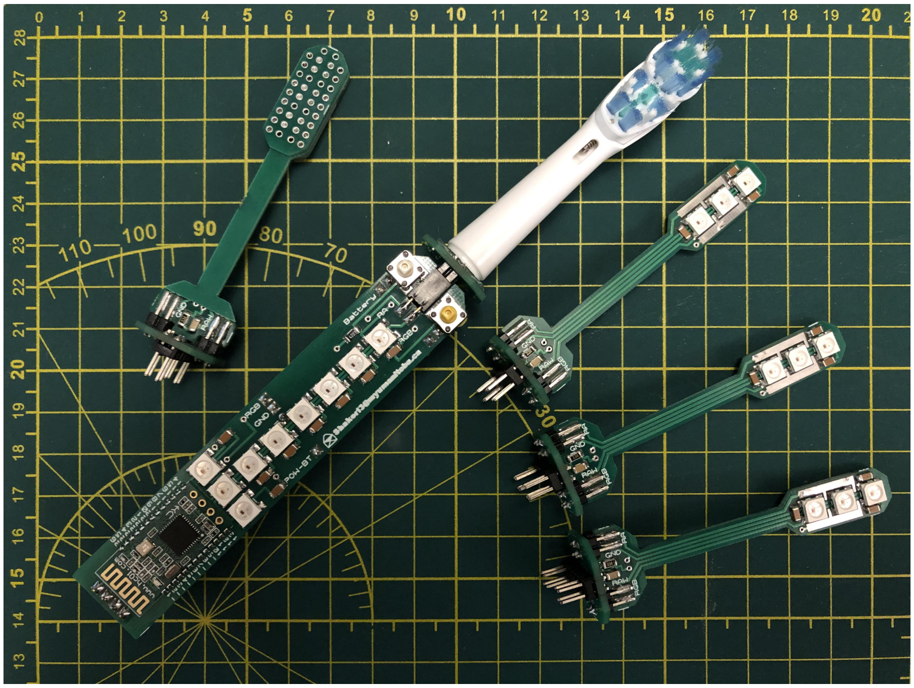

Figure 3.28: Toothbrush view 1

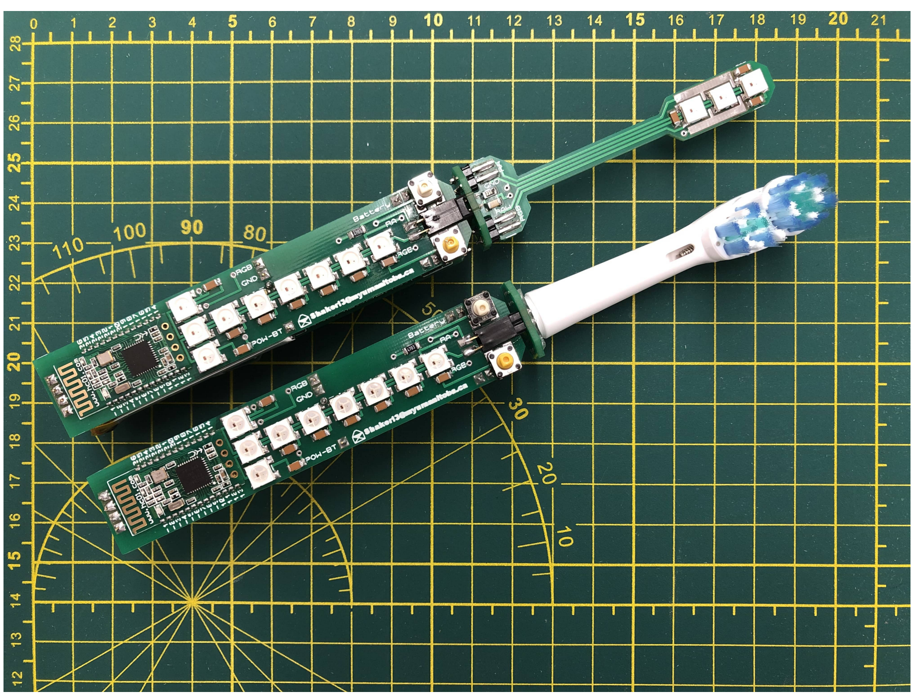

Figure 3.29: Toothbrush view 2

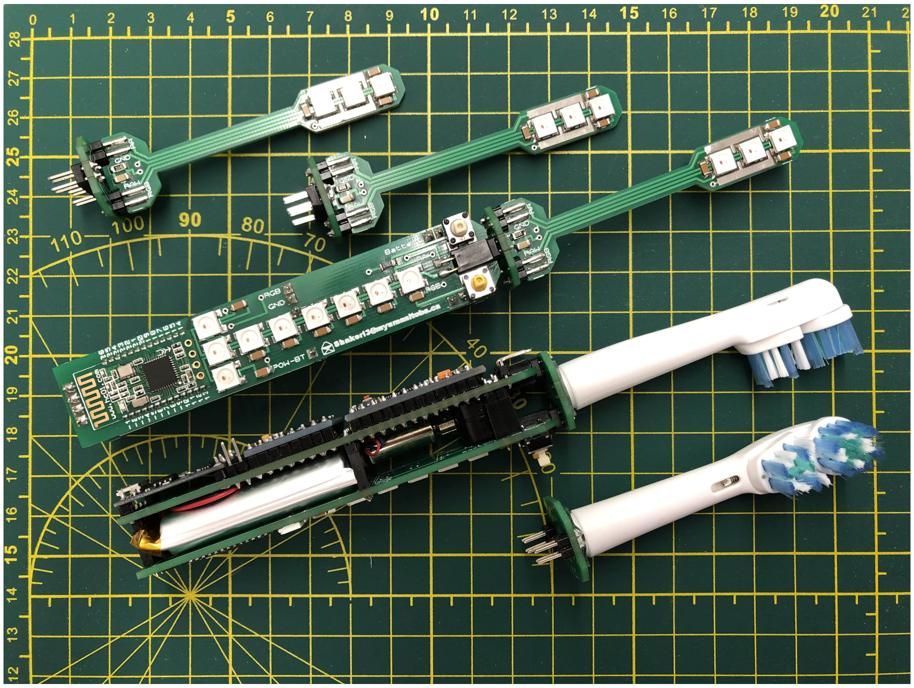

Figure 3.30: Toothbrush view 3

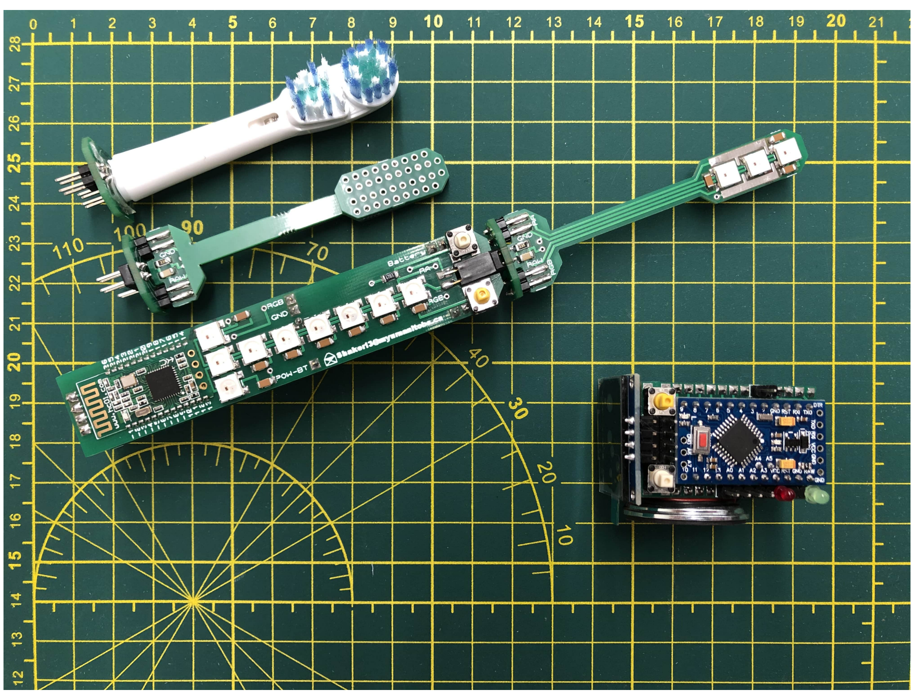

Figure 3.31: Toothbrush and command-board

Figure 3.32: Installed prototype on a normal sink

3.2 Software

In this section, we will describe a software implementation of the smart toothbrush. We will briefly describe how we divided the overall process of brushing teeth into several sub-tasks. We will also describe how we process data that the device receives from sensors to check and verify each step of the brushing process.

Our design monitors the user's hand movement using an accelerometer, gyroscope and magnetometer and assists the user with visual hints using RGB LEDs. The color of LEDs change at different stages of brushing teeth. For example, before the user picks up the toothbrush, the LEDs flash red, and after the toothbrush is picked up, the LEDs flash green. When the command-board asks the user to put toothpaste on the toothbrush the color of the head of the toothbrush changes to blue. The smart toothbrush communicates with the command-board using Bluetooth.

The command-board checks if the water tap is opened or closed using a water sensor. It also checks the water temperature in real-time using an analog temperature sensor (LM35). If the water temperature is not within a proper range for brushing teeth, the command-board asks the user to change the water temperature by closing or opening hot or cold water.

In addition, the command-board gives an audio command to the user and assists the user by suggesting what to do next. It monitors all the data received from the smart toothbrush and toothpaste holder and assists the user based on this data, the current stage of brushing teeth and the user's action. For example, if the user does not follow the audio command and if that command is for one of the mandatory tasks, the command-board changes the LEDs to a unique color and directs the user by mentioning the color instead of name of the action or object. Each step of the toothbrushing process is assigned a unique color. For example, instead of saying "pick up the toothbrush", the command-board makes the LEDs located on the handle of toothbrush flash red and plays the phrase "pick up the red flashing object".

The toothpaste holder communicates with the command-board. If the toothpaste is picked up or placed down, the command-board will receive a digital packet from the toothpaste holder. This allows the system to assist the user based on the status of the toothpaste holder and the current stage of brushing teeth.

3.2.1 Tooth Brushing Stages

We divided the tooth brushing procedure into 16 different stages as illustrated in Fig 3.33, in which different sensors are used to ensure each task is done correctly. Each stage needs to be monitored by a specific hardware device. For example, the command-board is responsible for checking if the water tap is opened or closed and for measuring the water temperature (blue) and the smart toothbrush is in charge of verifying brushing different sides of teeth, etc. (green).

Some of these stages are mandatory for completing the entire procedure of brushing teeth such as picking up the toothbrush and brushing the right, front and left sides of the teeth. However, some other parts, such as gargling water and spitting in the sink, are not mandatory. If a user does not act as instructed on mandatory stages, the audio command will be repeated or changed accordingly but for the optional tasks the system will remind the user only once. This is because our intended target users are those with dementia and we wish to make the entire procedure as easy as possible to complete.

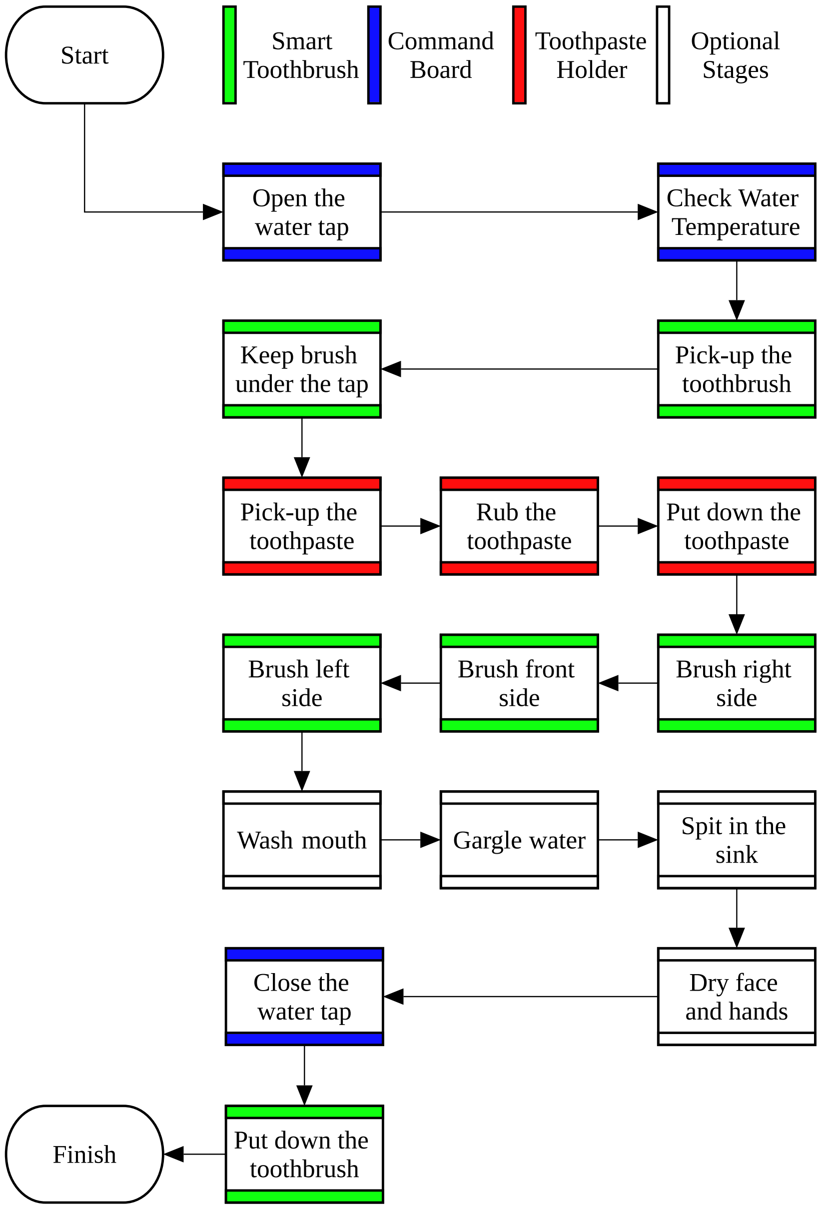

Figure 3.33: Main algorithm/flowchart

People in general have various approaches for brushing teeth. For example, some people may not wet the toothbrush before they apply the toothpaste on the brush head. We tried to consider some variation in the brushing process. For example, after the water tap is opened for the first time, one may prefer to turn the water off and then on during brushing his/her teeth. However, we did not consider all plausible variations for brushing different sides of the teeth in the current version of the software. The step by step procedure of the brushing process could be designed more flexibly to cover more variations.

The designed algorithm works based on the input signals and the information from the previous step. The algorithm collects data from three main sources: the smart toothbrush, command-board and toothpaste holder, which have six, two and two input signals, respectively. The input signals and the routine of generating the next commands are shown in Fig 3.34.

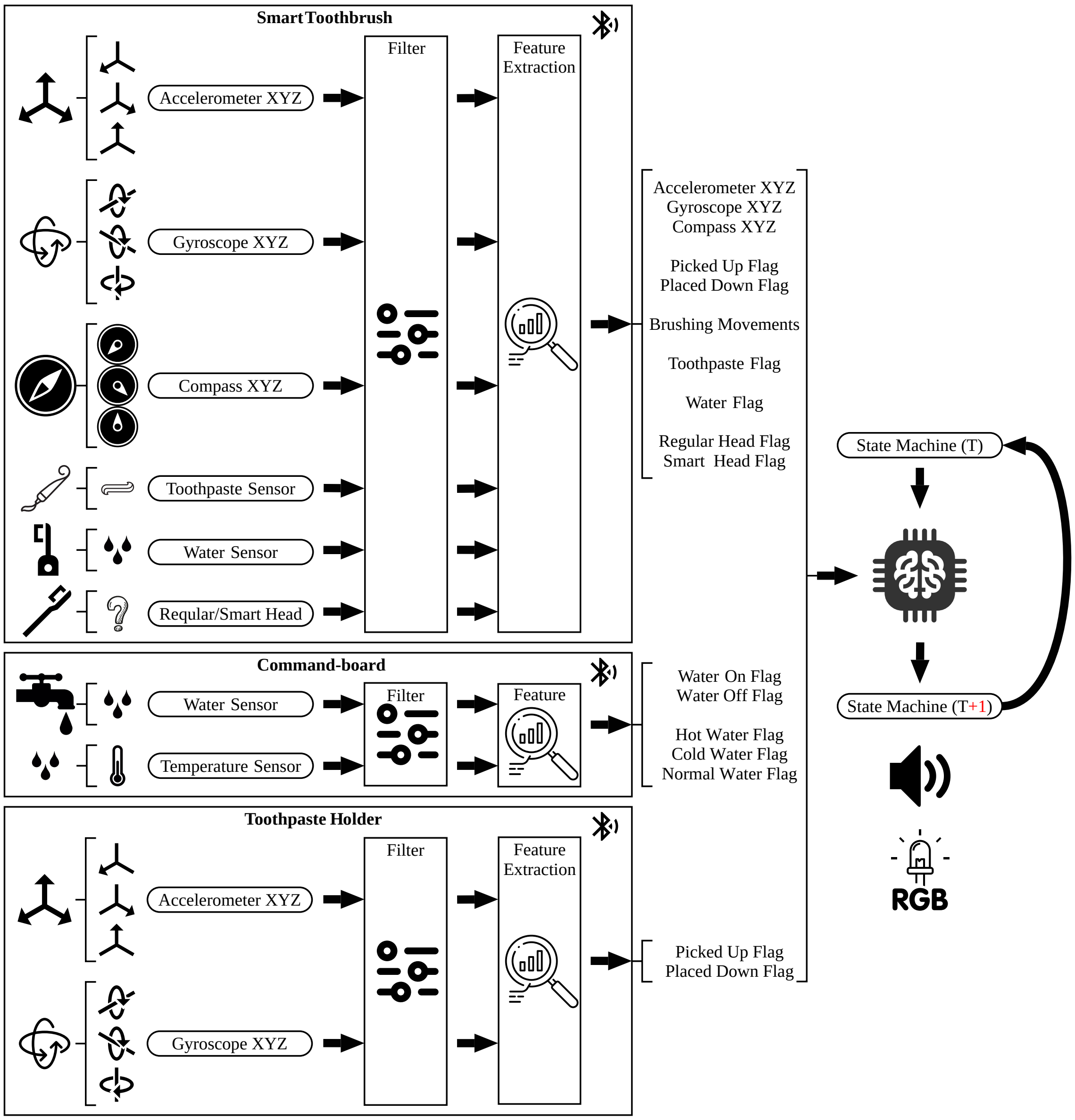

Figure 3.34: Main inputs and outputs

The designed algorithm generates the next step's visual and auditory commands by analyzing the input signals of these three devices. The input signals are first filtered to reduce any existing noise signals. The filtered signals are then sent to the feature extraction units to look for specific data and conditions. These data provide the required information to the main algorithm on what the next step should be. Consequently, the output of the feature extraction units generates the next commands based on the previous steps until the brushing procedure is finished.

Toothbrushing procedure includes the predetermined sequence of actions depending on a sequence of events with which they are presented. The state machine can change from one state to another in response to inputs. Therefore we used the state machine in our design to implement the making decision unit.

3.2.2 Detect the Type of Attached Toothbrush Head

There are two models of detachable brush heads for our smart toothbrush, the commercial brush head and the proposed prototype brush head. Some parts of the brushing procedure will change depending on which brush head is attached. For example, toothpaste detection is not available with the commercial brush head.

We detect the type of attached head by observing the analog voltage received from the head of the toothbrush named $AttachmentPin_{value}$. When no brush head is connected to the handle of the toothbrush, the received analog voltage is at 3.3V. For the commercial brush head and smart brush head, this voltage is at 0V and 1.65V, respectively.

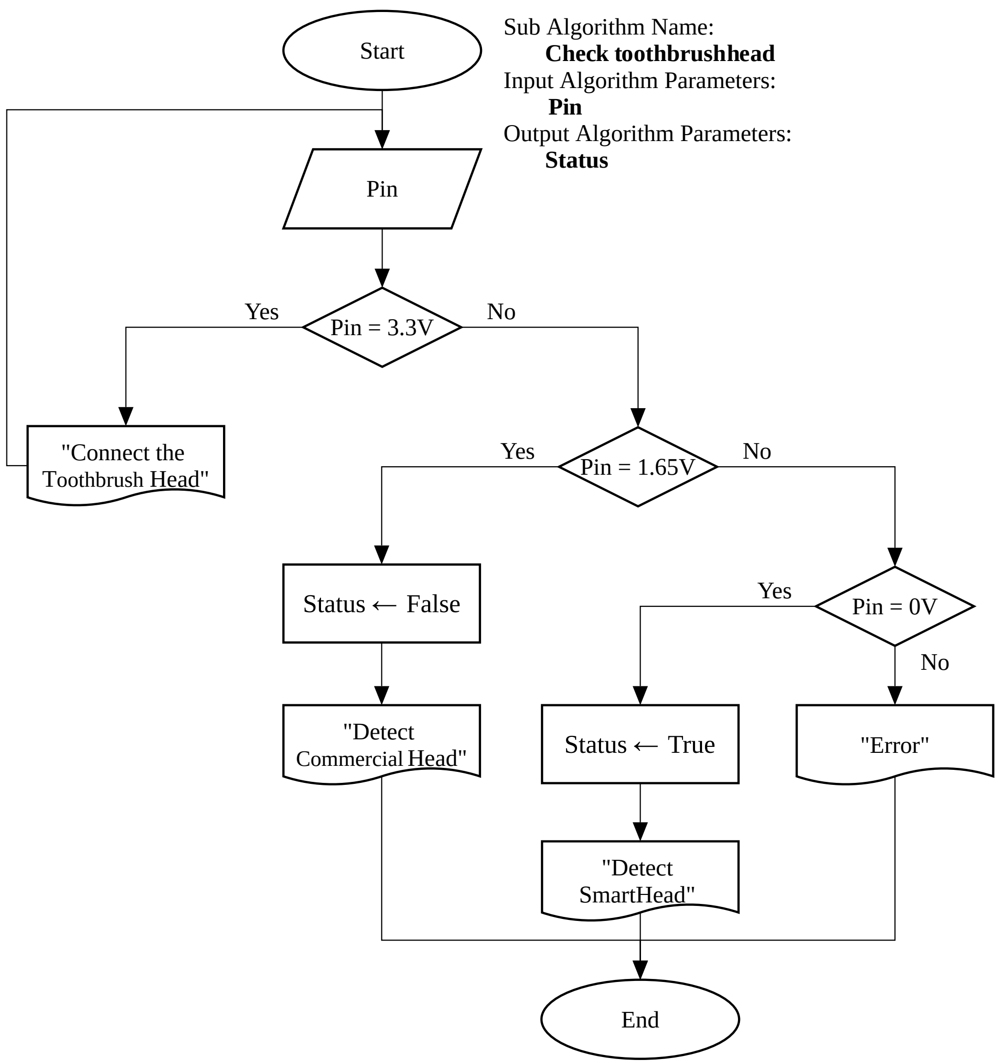

Figure 3.35: Check the toothbrush head algorithm/flowchart

The algorithm monitors this voltage to determine whether the brush head is connected to the handle or not. Moreover, it can determine whether the connected head is the commercial brush or the smart head.

3.2.3 Check Water Sensor Located on the Head of Toothbrush

The output of the water sensor located on the head of the toothbrush and water tap is analog. Our algorithm continuously reads the analog output of the water sensor using a microcontroller's internal analog to digital converter. This value is then compared to the predefined threshold for the water sensor. If the measured value is more than the threshold, then the existence of water is presumed.

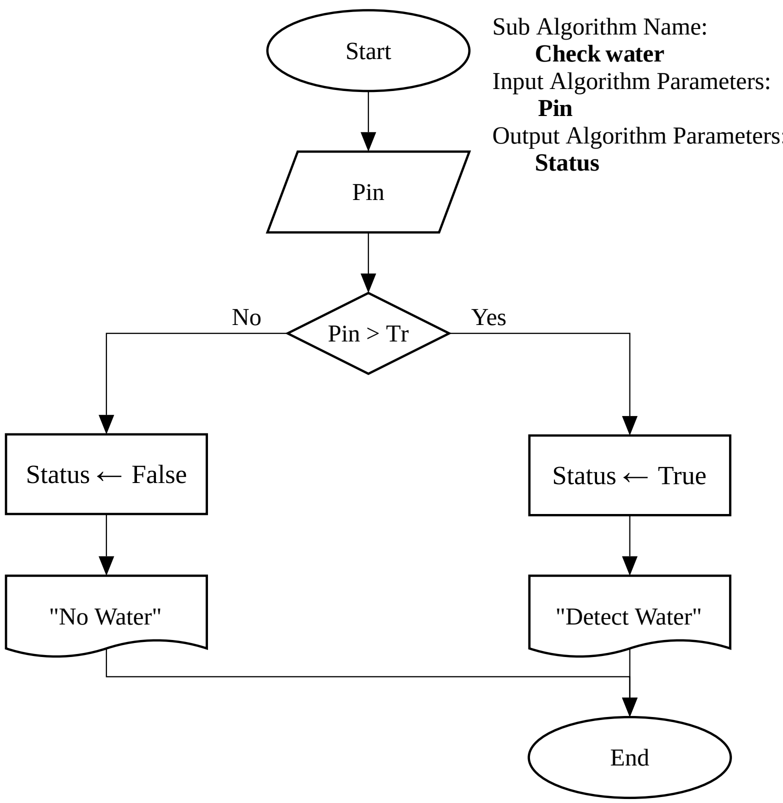

Figure 3.36: Check the water sensor algorithm/flowchart

3.2.4 Detect Toothpaste on the Smart Toothbrush Head

We used a novel and simple idea for detecting toothpaste on our smart toothbrush head using Kirchhoff's laws. We assume that the smart head of the toothbrush will be in contact with limited materials while brushing teeth, such as water, saliva, the user's skin, the user's mouth, air and toothpaste. All of those materials have a specific range of resistance. For example, the resistance of tap water and saliva is low and resistance of the user's skin is high. Because of the consistency of the toothpaste, the range of resistance of toothpaste is completely different from water and air. Therefore, we check the resistance of the smart head of the toothbrush to detect if there is toothpaste on it. The following section describes a basic voltage divider which is used to calculate the resistance between the toothpaste detector pads.

The voltage divider divides the input voltage into two parts using two resistors in series, R1 and R2. R1 is connected to an input voltage, and R2 is connected to ground, as shown in Fig 3.37.

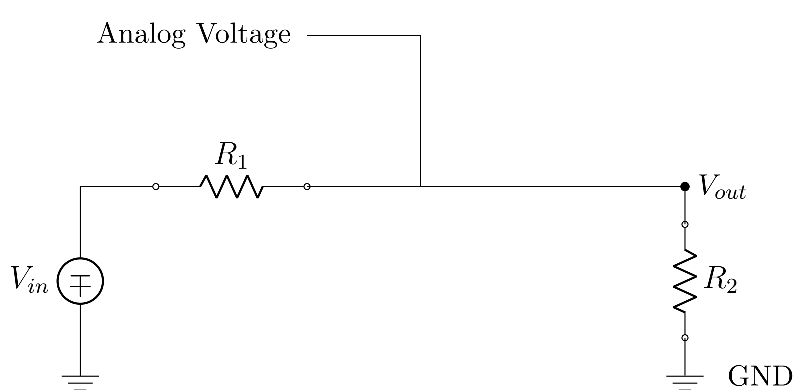

Figure 3.37: Voltage divider circuit

The equation for the output voltage of the voltage divider is given in Equ 3.1, where the magnitude of each part depends on the resistor values.

$$V_{out} = \frac{V_{in} \times R_2}{R_1 + R_2} \tag{3.1}$$

In our case,

i. The input voltage will be set to 3.3 V from the Arduino during this measurement.

ii. The output voltage is measured using one of the Arduino analog-to-digital converters (ADCs).

iii. R2 has a predefined value.

iv. The head of the toothbrush represents R1, which varies when different materials come into contact with it. Therefore, in our case, the value of R1 is unknown.

All we need to do now is measure the output voltage using one of the Arduino ADCs. The analog to digital conversion equation is shown in Equ 3.2.

$$AnalogVoltageMeasured = \frac{ADCReading \times SystemVoltage}{ResolutionOfTheADC} \tag{3.2}$$

The microcontroller that we used has a 10-bit resolution for the ADC and the system voltage is 3.3 V. We can obtain the value of the Toothpaste Detector Pads Resistance (R1) in terms of R2 as shown below in Equ 3.3.

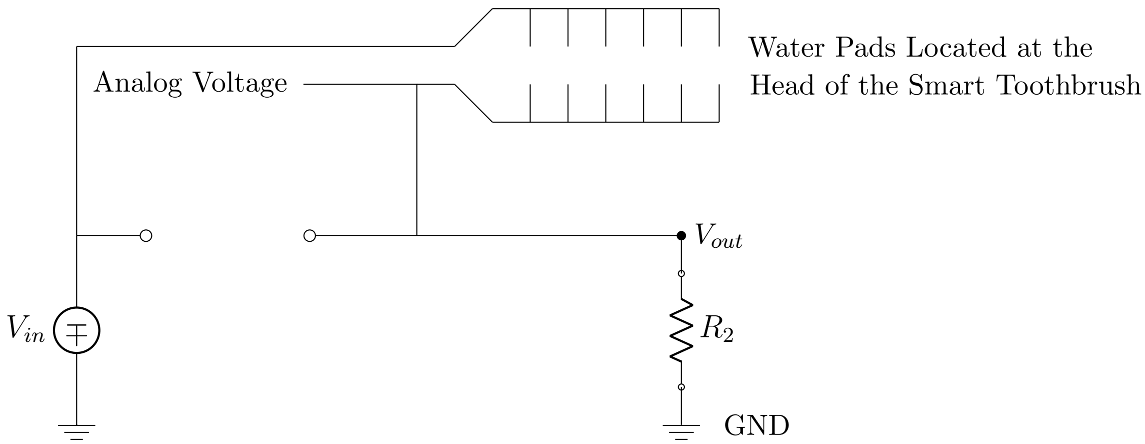

Figure 3.38: Toothpaste sensor circuit

$$
\begin{aligned}
ToothpasteDetectorPadsResistance &= R_2 \times \left(\frac{V_{in}}{\frac{ADCReading \times SystemVoltage}{ResolutionOfTheADC}} - 1\right) \\
&= R_2 \times \left(\frac{1023}{ADCReading} - 1\right)
\end{aligned}
\tag{3.3}
$$

The range of resistance that we can measure accurately is limited to the resolution of the microcontroller's ADC and the range of R2. Therefore, we choose R2 to be in the range of toothpaste resistance otherwise the analog read would be inaccurate. The range of toothpaste resistance is $500K\Omega \pm 300K\Omega$. The resistance comparison between different materials have been shown in Table 3.2. These numbers are estimated. For example, the skin resistance depending on contact area, moisture, condition of the skin, and other factors. The resistance of water depends on several factors, such as the number of particles in the water. For example, pure water is not a good conductor of electricity, but rainwater and tap water are good conductors.

Table 3.2: Resistance comparison between different materials.

Material	Resistance
Tap Water	$100K\Omega$
Toothpaste	$500K\Omega$
Skin	$10M\Omega$
Air	$10000M\Omega$

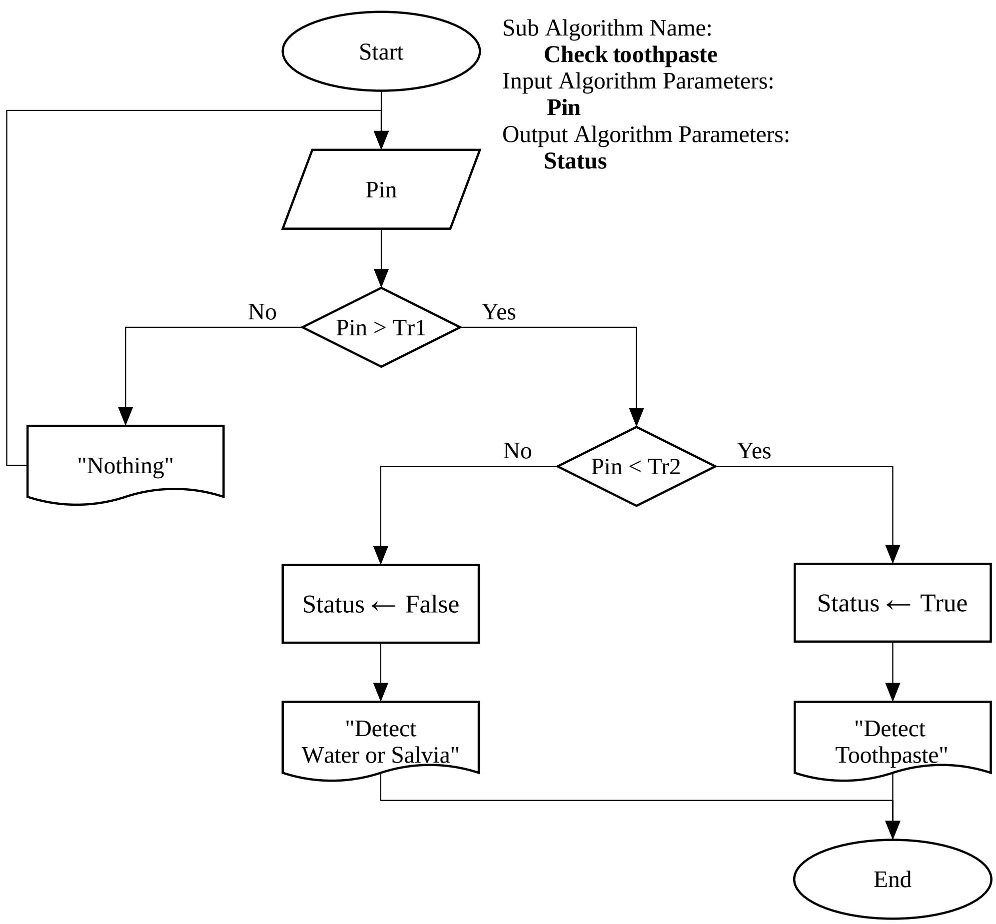

Figure 3.39: Check the toothpaste sensor algorithm/flowchart

3.2.5 Accelerometer Filter

The accelerometer input sensors need to be filtered before any further analysis. We used a data buffer for each accelerometer signal to temporarily store data while a low pass filter is applied to the signals. After receiving a new value, the previous elements on the buffer are shifted one position to the left to make room for the new value. It means that the oldest element in the buffer drops out in each iteration.

$$FilteredAccX_{Currentvalue} = \frac{1}{n} \times \sum_{i=0}^{n} AccBufferX(i_t) \tag{3.4}$$

We used a moving average filter as our low pass filter. For example, to filter the X axis of the accelerometer, a buffer named $AccBufferX$ with a length of n can be used as input to the filter.

Before calculating the $FilteredAccX_{Currentvalue}$, the previous result of the filter is stored in a variable named $FilteredAccX_{Previousvalue}$ for the future analysis.

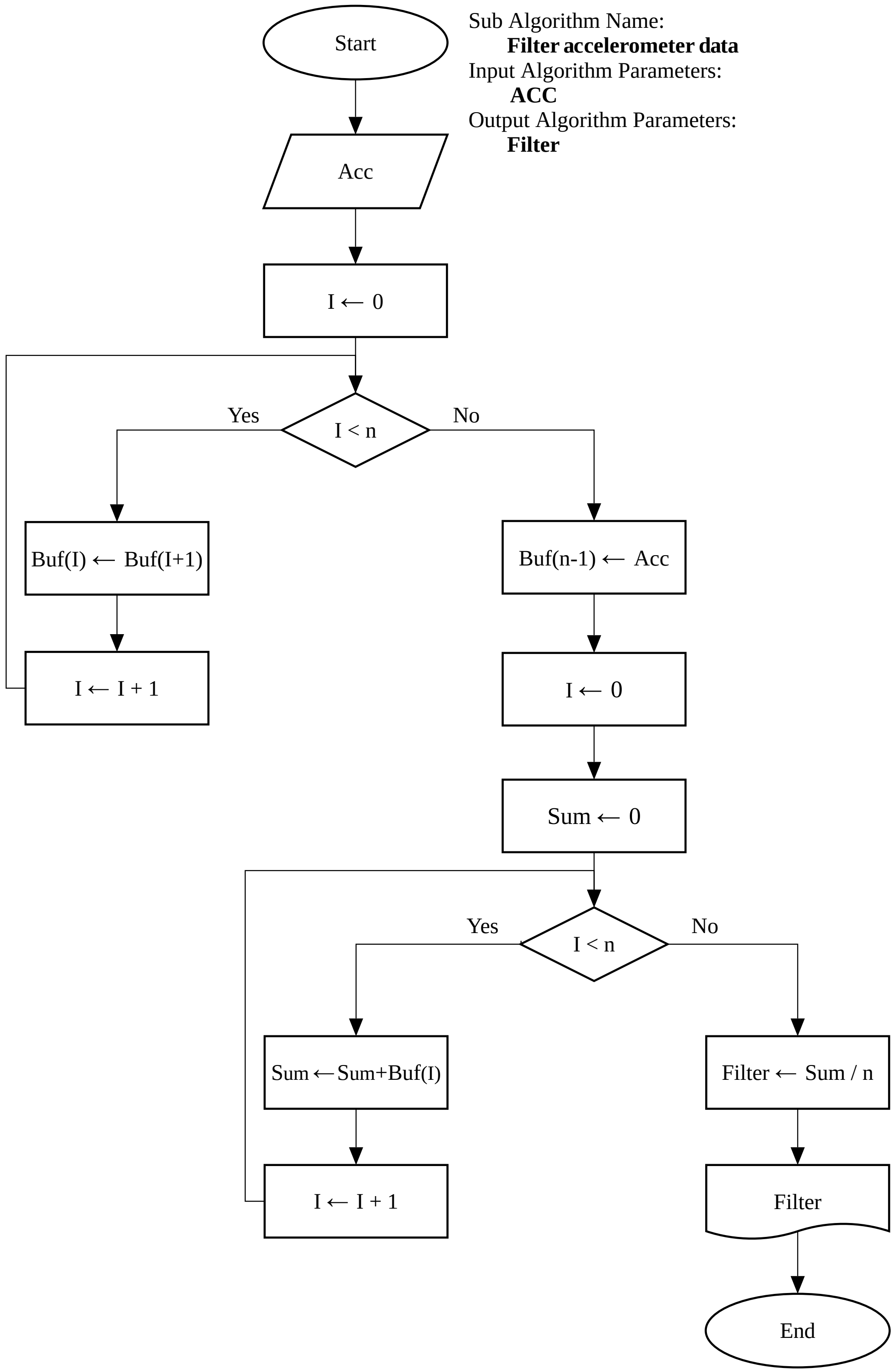

Figure 3.40: Filter the accelerometer data algorithm/flowchart

3.2.6 Check Toothbrush Position

The algorithm continuously monitors the accelerometer data for all three axes.

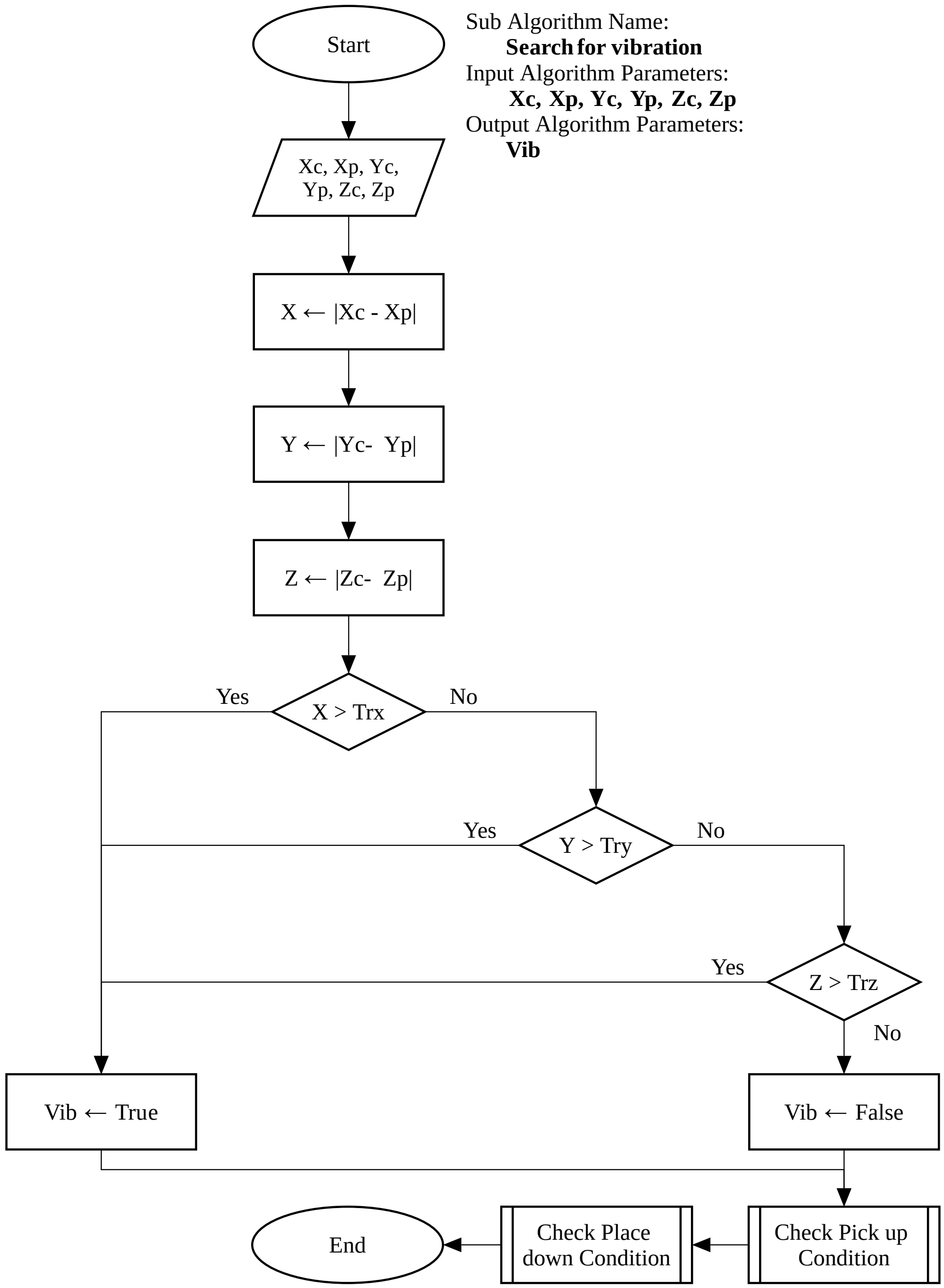

Figure 3.41: Search for the vibration algorithm/flowchart

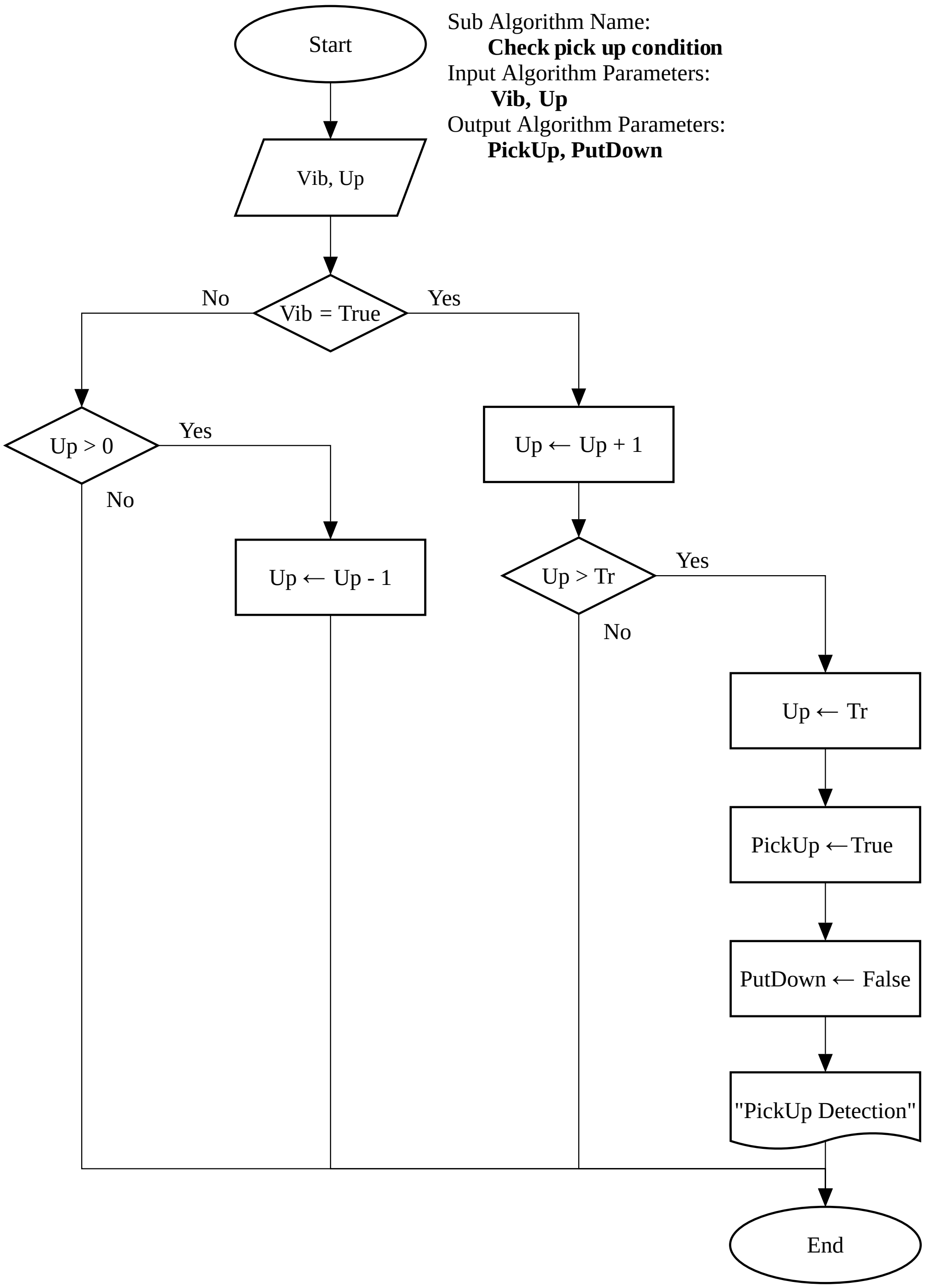

Figure 3.42: Check the pick up condition algorithm/flowchart

If the absolute distance between $FilteredAccX_C$ and $FilteredAccX_P$ (named

$\Delta AccX$) remains higher than the defined threshold for picking up the toothbrush for more than 650 milliseconds the picking up action is presumed.

$$\Delta AccX = |FilteredAccX_{Currentvalue} - FilteredAccX_{Previousvalue}| \tag{3.5}$$

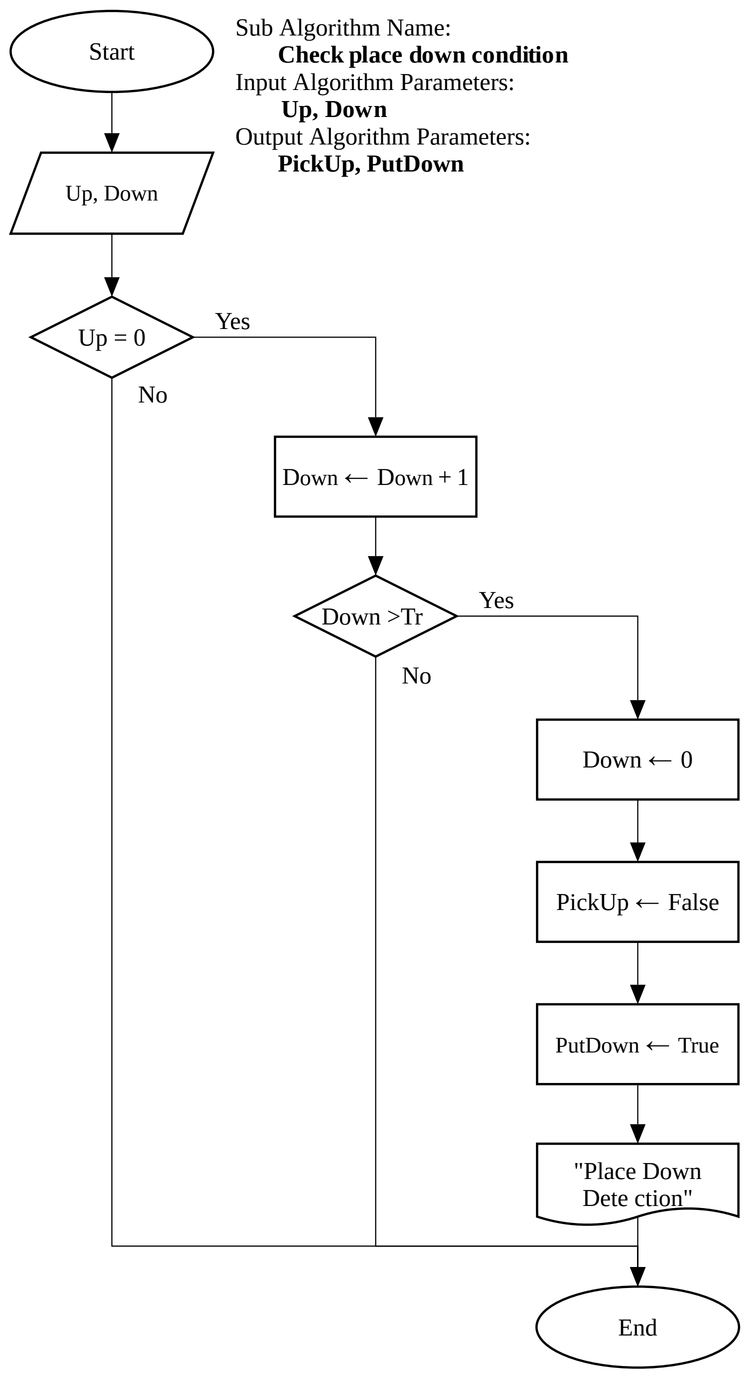

Figure 3.43: Check the place down condition algorithm/flowchart

If there is not any $\Delta AccX$ higher than the defined threshold for more than 20 seconds the placing down action is detected.

3.2.7 Monitor Brushing Movements

We divided the mouth into three areas named "right side", "front side" and "left side". The toothbrush is set to count forty up and down movements within a predefined range of acceleration to verify the brushing procedure is completed for each area.

The defined range of acceleration ignores unwanted up and down, such as movements related to shaking hands and movements with low domain range (signals with low amplitude). The Y-axis of the accelerometer sensor is aligned with the up and down movements of the brush. The algorithm continuously monitors the Y-axis of accelerometer data in order to detect the local maximum and the local minimum.

If the absolute distance between $AccY_{LocalMaximum}$ and $AccY_{LocalMinimum}$, (named $\Delta BrushingMovements$) is higher than the defined threshold for brushing movements, the value of $BrushingMovements_{Counter}$ will increment by one. This indicates that one correct movement is detected.

$$\Delta BrushingMovements = |AccY_{LocalMaximum} - AccY_{LocalMinimum}| \tag{3.6}$$

When forty increments for $BrushingMovements_{Counter}$ have been achieved for a part of the mouth (right, front, or left), the brushing for that part is completed.

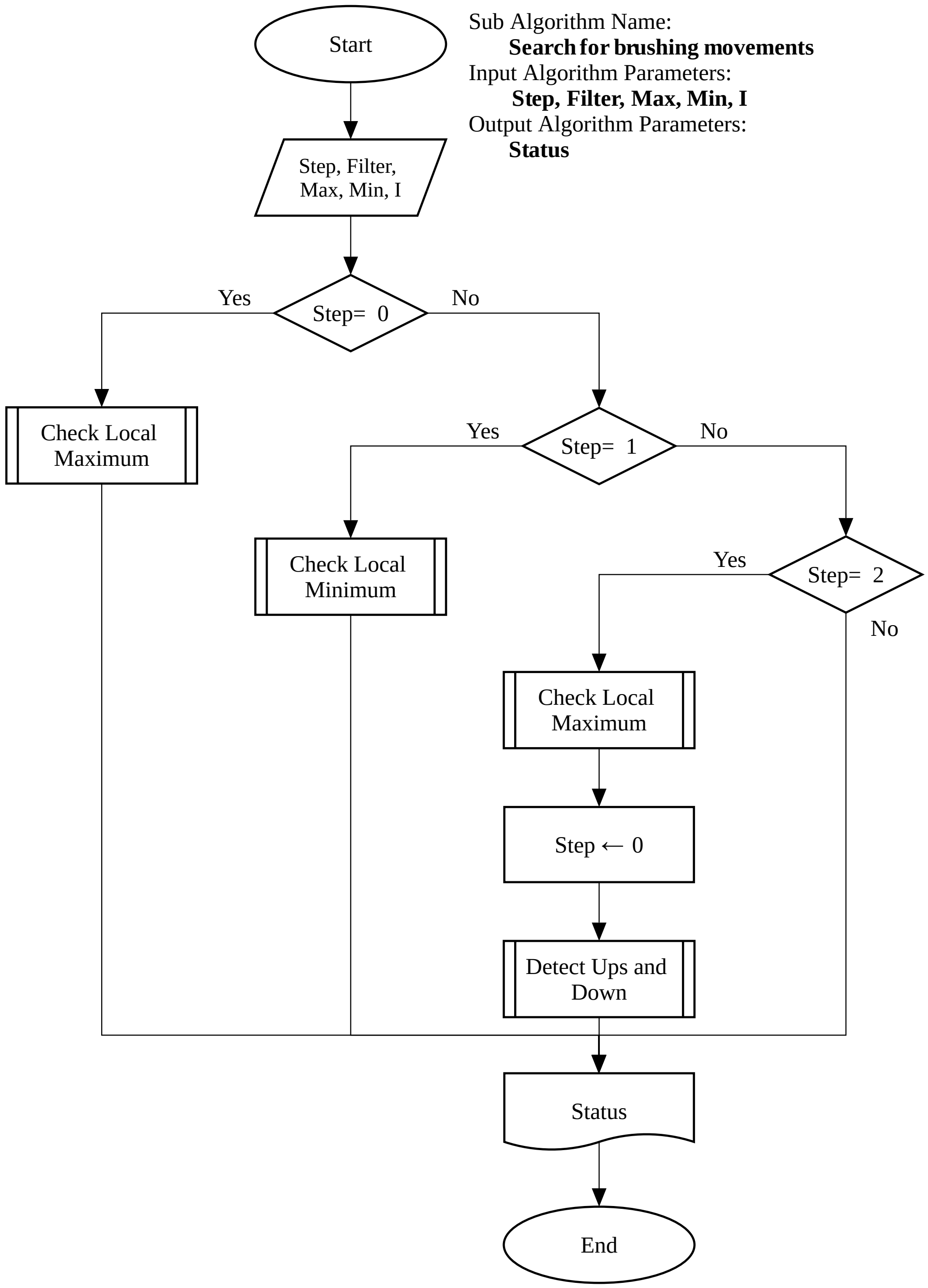

Figure 3.44: Search for the brushing movements algorithm/flowchart

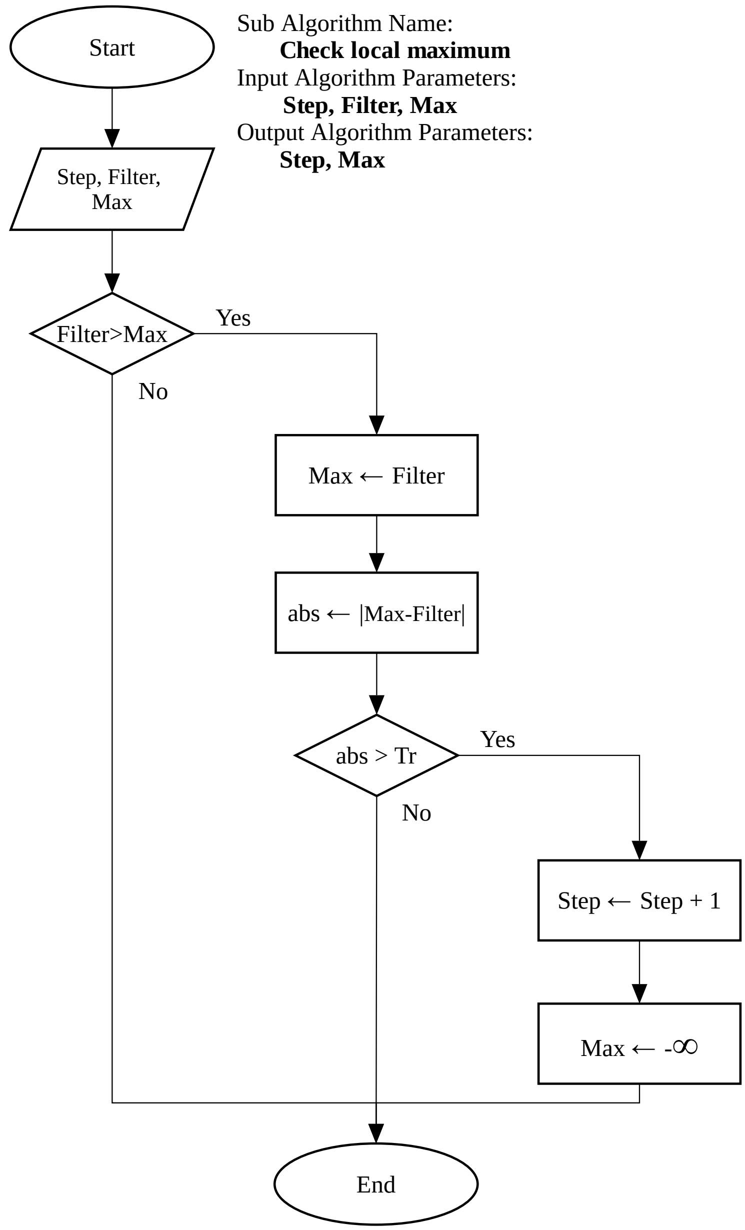

Figure 3.45: Check for local maximum algorithm/flowchart

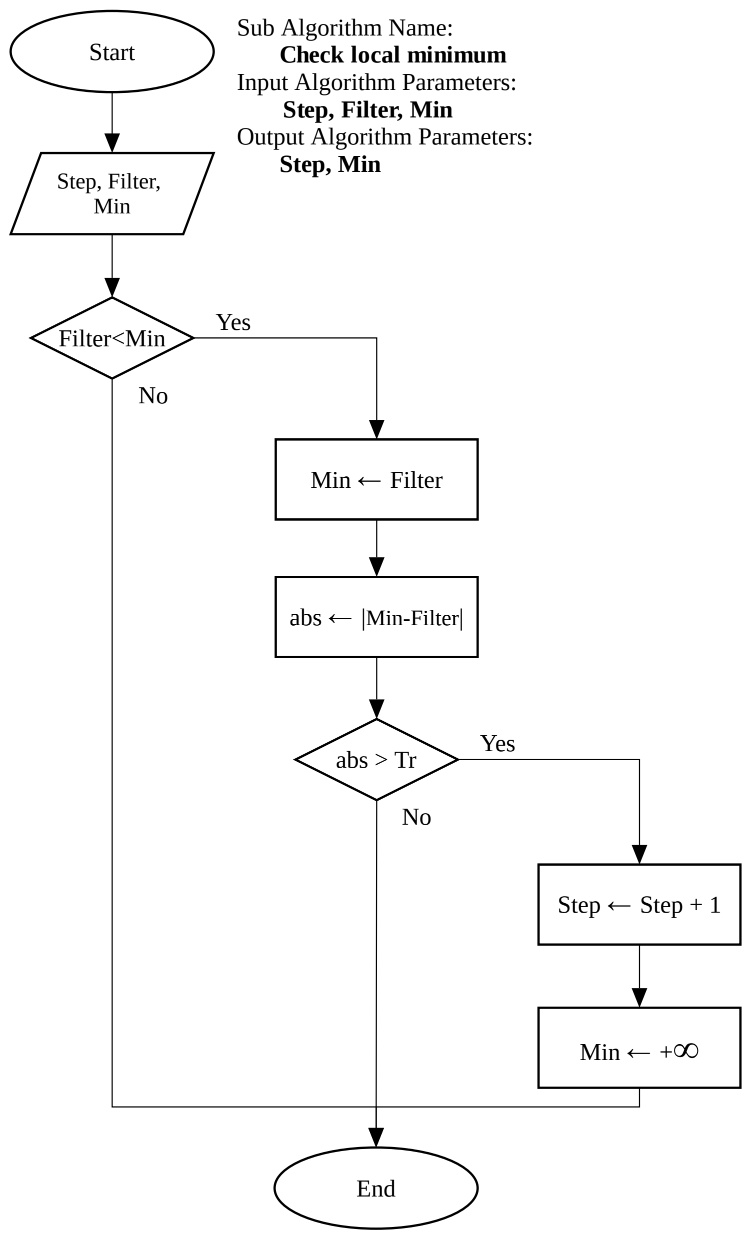

Figure 3.46: Check for local minimum algorithm/flowchart

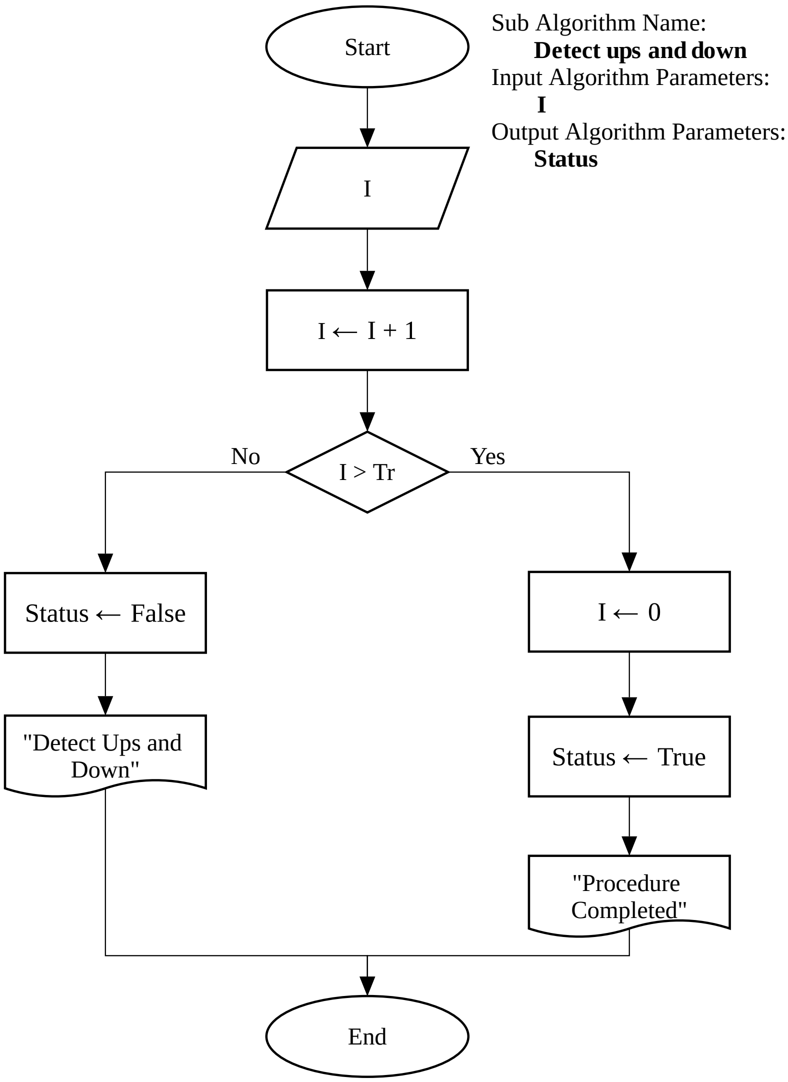

Figure 3.47: Detect up and down movement algorithm/flowchart

3.2.8 Smart Wireless Communication Protocol

The communication method is one of the most important parts of a wireless project. Imagine that we have two devices, after powering on Device A, it will send a packet to Device B to update and inform Device B that Device A is ready. If that packet is lost Device B never finds out that Device A is ready and Device B will be locked and never start the rest of the program. Therefore, we need a solution to make sure that Device B receives the packet from Device A.

For example, if the toothbrush wants to let the command-board know that the toothbrush is picked up it will send a "T=>M-PickupDevice(A)\n" string to the command-board. This allows the command-board to resume the rest of brushing teeth processes.

We are using Bluetooth communication in our prototype. There is always a chance of getting faulty data during transmission because of environmental noise or other reasons such as baud rate error.

There is a baud rate error in the RS232 communication based on the microcontroller frequency and how fast the data is sent over a serial line. For example, there is a 0.2% error with RS232 communication with a bit rate of 9600 and CPU frequency of 8 MHZ. We need to define some additional rules in our communication algorithm to be robust to noisy data.

We propose a communication protocol algorithm to make sure that communications between the toothbrush, command-board and toothpaste holder are safe and reliable.

Before sending a new command, system needs to make sure that Bluetooth connection is paired, the previous outgoing command was successfully sent, the previous incoming command from the device that Bluetooth is paired to was successfully executed, and the requested delay by other subroutines was finished. For sending a new command, the system requests a delay, places the packet on sending buffer (BufOut) and sets Send flag to True to let the other sub-algorithm named "Outgoing packet handler” know that a packet needs to be sent.

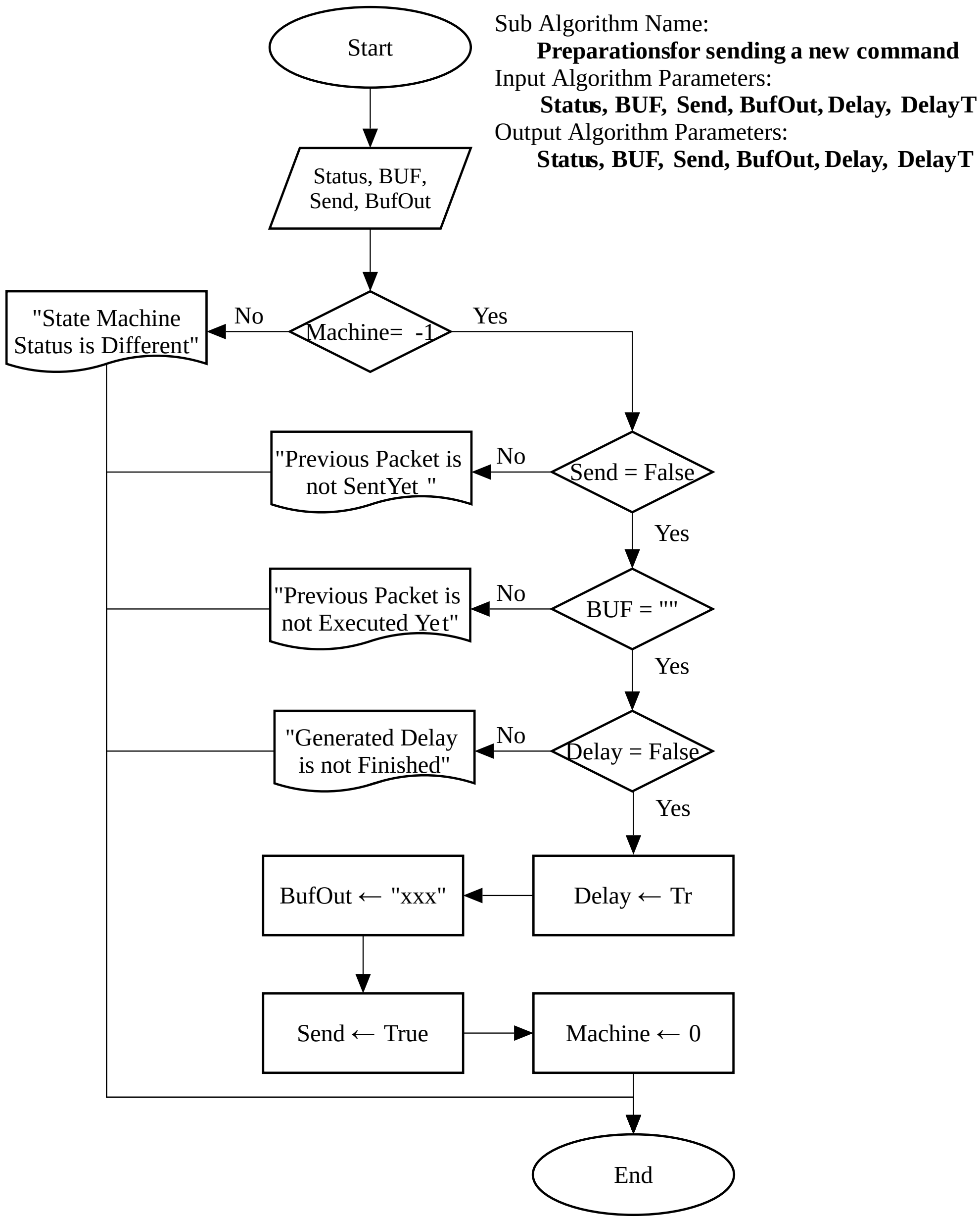

Figure 3.48: Preparations for sending new command algorithm/flowchart

The serialEvent() function constantly checks for the incoming data in the buffer. Each byte (character) found in the buffer, is added to a string called “inputString-RealTime” until the ’\n’ character is received which indicates the end of the packet.

Next, the input string real-time buffer named Buf in flowchart will be copied to another string called BUF to protect the input string against any unwanted changes. The input string real-time buffer (Buf) is shared between several sub-routines, and it may be changed while the system is executing the packet. After locking the string, the Status flag will change from false to true to verify that the packet is completely received and is ready for further analysis.

Note that in our design, the receiver waits for the '\n' to acknowledge the end of the packet. In case of a loss of '\n' character in the sub-algorithm "Check for the incoming packet", due to noise in the environment, the receiver continues to add the data to the buffer until the next '\n' is received. Also, in our designed communication protocol, if the sent packet is not received by the sender after 200ms, the sender resends the same packet. Consequently, the second packet will be exactly like the first packet. Because of the missing '\n' in the first packet, the first and second packets will be considered as one packet. This faulty long packet will be ignored by the "Execute incoming packet" sub-algorithm and, this noisy packet will be dismissed and, the sender will not receive the faulty packet back. As a result, the sender will send the packet again after 200ms, and the above procedure will be repeated. If the receiver receives the packet correctly, it will send the packet back to the sender as an acknowledgement. If the packet becomes noisy again, the above procedure will be repeated until a correct packet is transferred successfully.

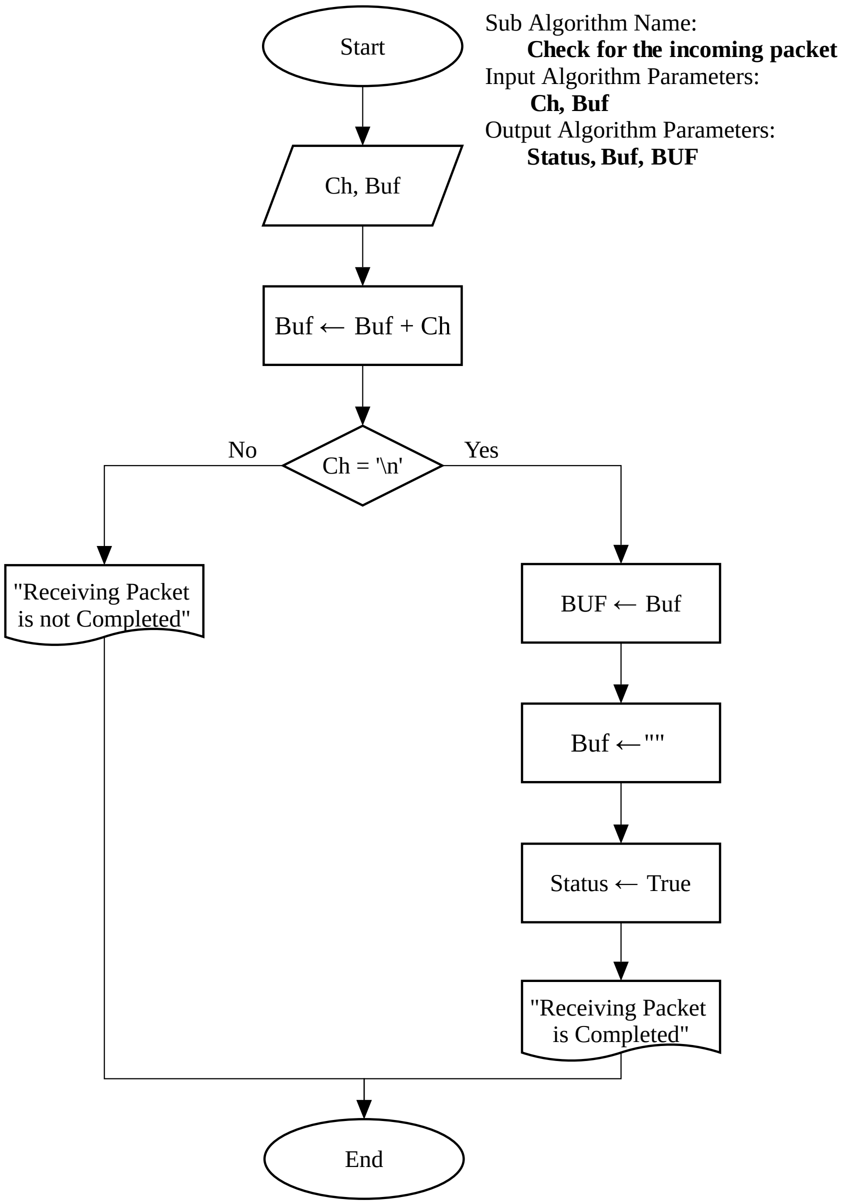

Figure 3.49: Check for the incoming packet algorithm/flowchart

“Send and receive handler” subroutine run every 50 milliseconds to manage the proposed communication protocol.

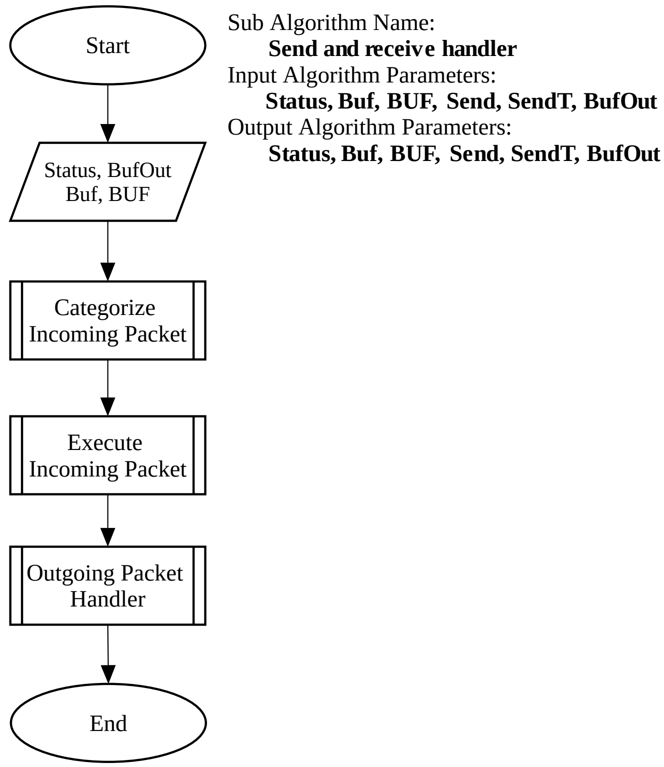

Figure 3.50: Sending and receiving handler algorithm/flowchart

If the received packet equal to the packet that the device sent previously, the system verifies that the previous packet is received successfully and clears the outgoing buffer (BuffOut) and sets the send flag to false to finish the sub-algorithm called "Outgoing packet handler".

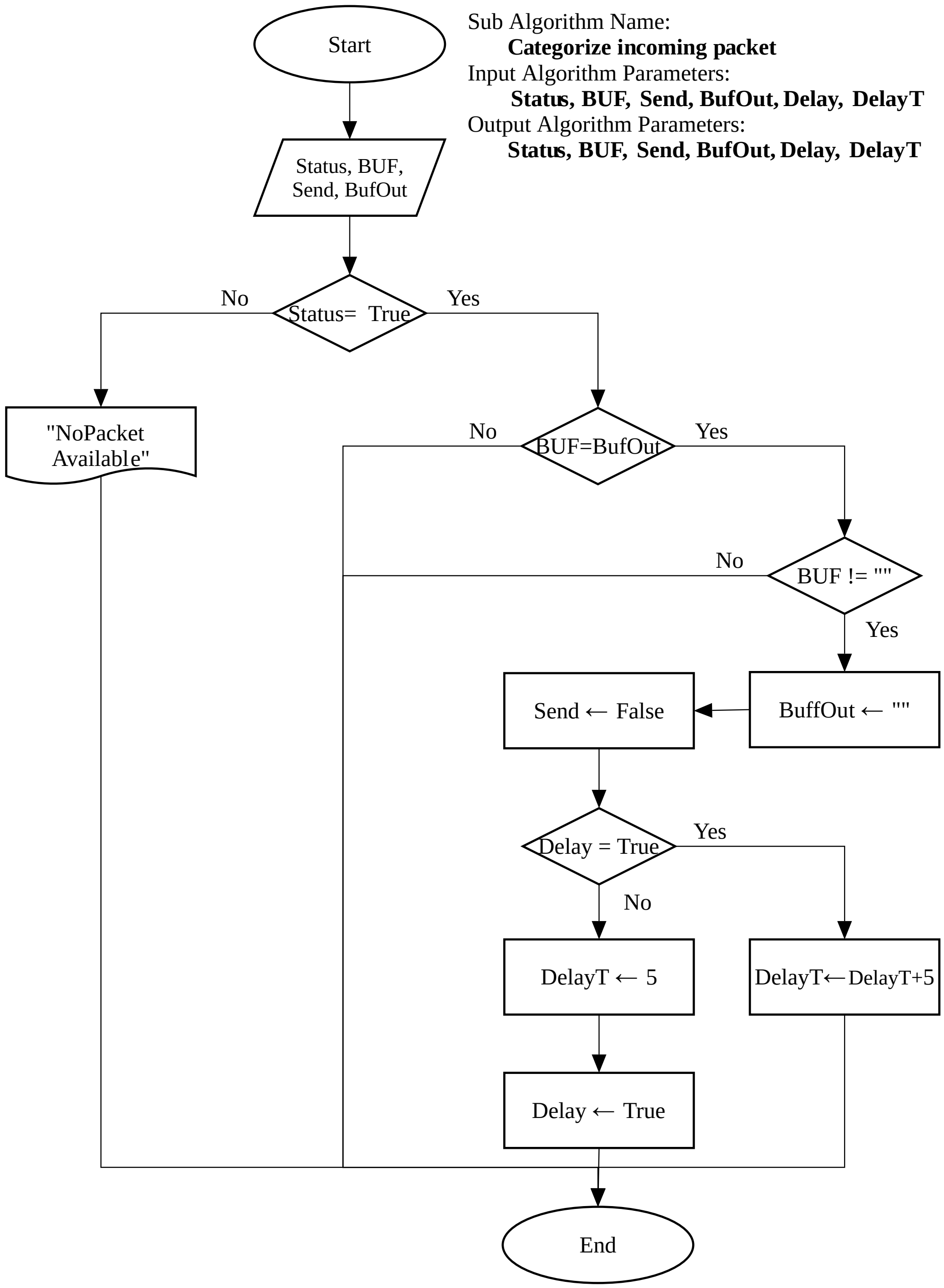

Figure 3.51: Categorize incoming packet algorithm/flowchart

"Execute incoming packet" subroutine sends back the received packet which is in the list of the valid sender or receiver command and executes incoming packet if the packet destination is the receiver. Next, it clear the input string protected buffer named BUF and set the incoming status flag to False to let the next packet to be processed by the system. If the received packet equal to the packet that the device sent previously, the system does not send it back to the sender to avoid making dead-end send and receive feedback loop.

Note that, when the receiver receives a packet completely and without any noise, that packet will be executed. After that, an acknowledgement packet will be sent back to the sender to verify that the packet was successfully received and executed.

In the case of any damage or loss in the returning packet (acknowledgement packet), the sender cannot verify if the packet was received and executed. As a result, the sender will send the packet again until it receives the acknowledgement packet back from the receiver. Consequently, the receiver might receive some packets more than once. Meaning that some commands may be executed more than one time. In such circumstances, the system never halts or locks because of the communication error.

For example, if the receiver receives the command for "picking up the toothbrush", and an error has happened in returning the acknowledgment packet, the sender will send the "picking up the toothbrush" again. Consequently, the "picking up the toothbrush" command will be executed more than one time, and the user will hear this command more than once and consecutively.

Note that, the chance of getting these errors is very low, and it will be handled by the designed error handler algorithm, as explained above.

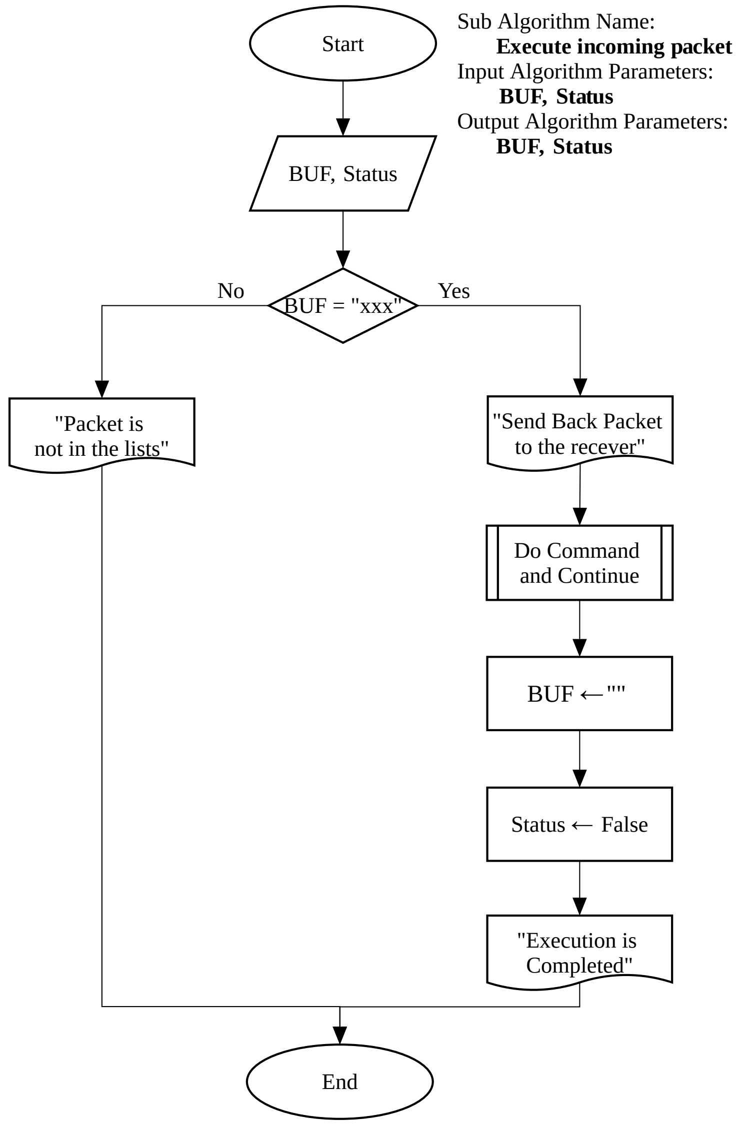

Figure 3.52: Execute incoming packet algorithm/flowchart

After sending each packet, the sender waits for 200ms to receive the packet back from the receiver. If the sender does not receive the packet, that means that the packet is damaged or lost. Therefore, the sender will send the packet again until it receives the same packet back from the receiver.

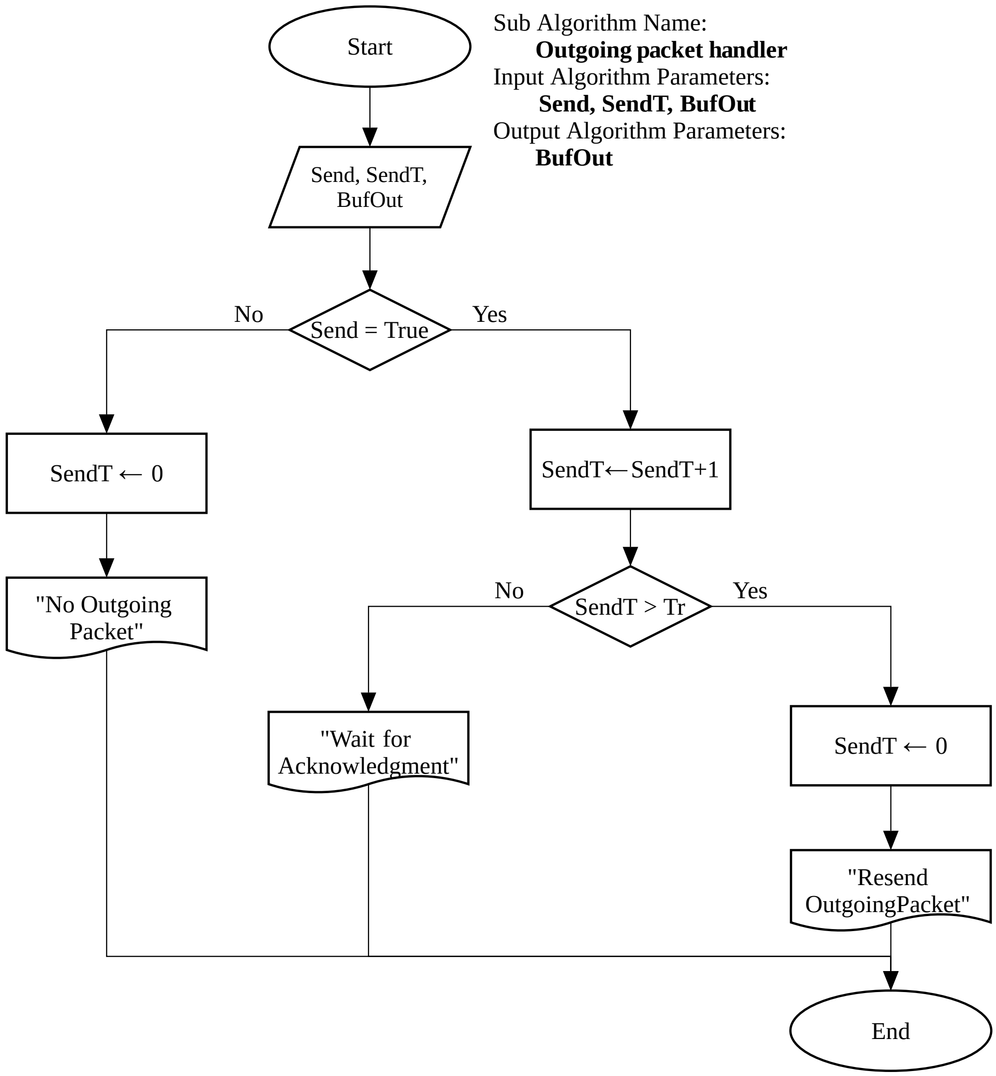

Figure 3.53: Outgoing packet handler algorithm/flowchart

Chapter 4

Results and Discussion

In this thesis, a smart toothbrush has been designed and implemented with the purpose of being used by people with moderate to advance stage of dementia or for educational purposes. This toothbrush is capable of guiding users in brushing their teeth using visual and auditory hints.

4.1 Design Criteria

The device was evaluated to check if its components individually and also collectively achieve the design's criteria.

The water sensor is responsible for detecting the water on the water tap or the smart toothbrush head. During the test, the water sensor was able to detect running water correctly. It is important to note that after a while, the water sensor pads can be covered by the water impurities. These impurities may decrease the sensitivity of the sensor in the long term, and finally disable the sensor. Cleaning the water sensor pads are recommended to keep the device fully functional.

The temperature sensor is used to monitor the water tap temperature and inform the user whether the water tap is too hot, too cold or ready to use. We added this part to the device because some central heating systems make the water too hot, and this may burn people with a cognitive problem. During the test, the water temperature sensor was able to assist the user by audio commands to keep the water temperature within the proper range. As mentioned before, we considered a temperature between 32C and 42C as comfortable.

The motion sensors of the device are used to monitor the device's movements to detect whether the device is picked up or placed down. The motion sensors are also responsible for measuring the brushing movements during brushing the right, left or the front sides of the teeth. During the test, the motion sensors were able to generate the picking up and placing down signals properly. We tested the device in a noisy environment, and the system was able to generate correct signals and filter the noise. We made the noisy environment by placing the device close to a source of vibration, such as a small mixer, to ensure the generated signals are reliable. Moreover, the motion sensors were able to measure the brushing movements properly. If the brushing domain is too small or the speed of brushing is too fast, the system ignores the up and down movements and considers them as noise, and will subsequently gives an audio command.

4.2 Testing

Since the designer was familiar with the device, the device was tested on three participants who were not familiar with the project. These people did not have a cognitive impairment.

We asked the participants to use the smart toothbrush for brushing their teeth. They did not have any information about what was supposed to happen in each brushing stage. We used the Oral-B Dual Clean replacement brush head as the commercial toothbrush head for the lab tests on individuals who tested the device.

The participants did not have any difficulty locating the smart toothbrush and the toothpaste holder. They did not have any problem in detecting the RGB LEDs colors and understanding and following the voice commands generated by the command-board. They were able to open the water tap and keep the water temperature within the proper range by following the command-board voice commands. The participants successfully finished all of the tasks.

The main criticism was about the long delay between the sequential tasks and the frequency of the voice commands when they did not want to follow the instructions. However, we should consider that our participants did not have any cognitive impairment. This delay is determined by the user's pace and may vary between individuals. Therefore, more tests on individuals with dementia need to be performed to investigate an optimum delay.

The average power consumption for the command-board, the smart toothbrush and the toothpaste holder is 100 mA, 40 mA and 10 mA, respectively. We used a rechargeable battery in the design. The battery capacity for the command-board, the smart toothbrush and the toothpaste holder is 500 mA, 1000 mA and 500 mA, respectively.

By considering the battery capacity of the smart toothbrush, the device needs to be recharged after 25 hours of usage. If we consider 7 minutes as the maximum time to finish brushing by an individual with dementia and assuming it is repeated twice per day, the smart toothbrush battery life will be 107 days.

Chapter 5

Concluding Remarks

5.1 Conclusion

Our literature review on assistive technology showed that although many prototypes of a smart toothbrush have been proposed and implemented, there is yet no smart toothbrush for individuals with dementia in the market. As a result, further research needs to be conducted to develop a smart toothbrush that can address the needs of those individuals.

This thesis takes the first step to make a smart toothbrush for individuals at moderate to advance stage of dementia. The main objective of our prototype is to assist the patients in advanced stages of dementia to brush their teeth independently and maintain their oral hygiene. The presented prototype assists the patient through the stages of brushing their teeth via auditory and visual commands. Different sensors and algorithms were implemented to monitor the user's actions and to verify whether the user has completed the requested tasks. The developed prototype has been tested in the lab setting and passed all the required designed aspects.

The proposed smart toothbrush may be useful for young children or individuals born with cognitive impairments as an educational tool to teach them how to brush their teeth properly.

5.2 Discussion and Suggestions for Future Work

In this work we explored various avenues to design and implement a compatible smart toothbrush for individuals with dementia. It was validated by testing the device on three healthy participants.

We suggest adding more flexibility to cover various approaches for brushing the teeth. For example, instead of having three fixed stages like brushing the right, front and left sides of the teeth, it might be better to ask the user to brush one side of their teeth and then brush the other side. The device can recognize the chosen side for brushing, and based on that can ask the user to brush the other side to finish the brushing procedure.

The device is designed for people with cognitive problems, and it tries to assist the user by auditory hints. When a step is not completed, there is no way to check whether the user has forgotten to follow the audio commands, or the user wants to do something else during brushing teeth such as washing the face, washing hands, etc. Therefore, the user may find auditory hints too frequent and distracting. For example, if a healthy user wants to answer his or her phone during brushing teeth, the device assumes that he or she cannot continue the task and tries to assist the user by auditory hints, which may be inconvenient. In the future works, multiple levels of auditory hints and levels may be added to the device to adjust the device to the patients' level of cognitive impairment.

At severe stage of dementia, people who have a different mother tongue language, may forget the English language. Thus, we suggest adding several languages with male and female voices. The caregiver can set the language and male/female voice of auditory commands based on the patients' needs and the level of the cognitive impairment.

We used an LCD in the command-board and smart toothbrush handle. We suggest assisting the user by giving some text messages and some graphical emojis to inform the user about what the task is and also update the user about his or her progression and performance.

The validation method for monitoring if the user is brushing the left, front and right sides of the teeth in the proper way, as described in Section 3.2.7, is based on periodic toothbrush movement. In this case, the signal of interest is the accelerometer sensor values. Due to different habits of brushing teeth, there is room for improvement in this part. This modification could improve the validation method, and can improve the accuracy of the monitoring system. Another extension to the smart toothbrush would be to design several circuits to detect toothpaste on the toothbrush. If a user places a small amount of toothpaste on the toothbrush, the toothpaste may not connect to the toothpaste sensor pads and result in a faulty signal. This addition would be beneficial to more accurately track the whole procedure of brushing teeth. Also, we can replace the USB charger with an induction coil to make the device completely water-resistant.

Due to the additional noise affecting the accelerometer and gyroscope sensor values, the prototype device works without any vibration motor. However, the vibration motor may help improving the quality of brushing teeth. One method is to design a special low pass filter to remove the additional noise generated by the vibration motor.

Some of the used sensors are sensitive to moisture such as the water detecting sensor. The output of this type of sensors may easily become noisy, while the user keeps the toothbrush in their mouth, while it is touching saliva, or when it is under the water tap. The level of noise due to the moisture contacts can potentially be further attenuated by changing the toothbrush cover material. Currently, the smart toothbrush is covered with a layer of epoxy resin. We believe if a water-resistant plastic is used instead, the level of noise will potentially be further reduced.

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