

JOÃO DUARTE PEREIRA SARDO

**PORTABLE DEVICE FOR AUGMENTED REALITY
FIVE-SENSE EXPERIENCES**

Master Thesis in Electrical and Electronics Engineering
Specialisation in Energy Systems and Control

Developed under the orientation of:
Prof. Doutor Jorge Semião



UNIVERSIDADE DO ALGARVE

Instituto Superior de Engenharia

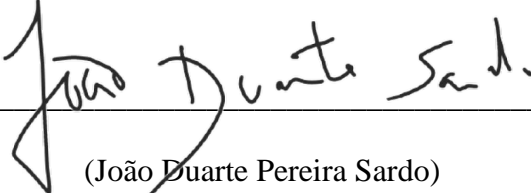
2017

PORTABLE DEVICE FOR AUGMENTED REALITY FIVE-SENSE EXPERIENCES

Declaration of Originality

I hereby declare to be the author of this original and unique work. Authors and references in use are properly cited in the text and are all listed in the included reference section.

Declaro ser o autor deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluída.



(João Duarte Pereira Sardo)

©2017, JOÃO DUARTE PEREIRA SARDO

The University of the Algarve owns the right, in accordance with the terms of the Copyright and Related Rights Code, to archive and publicize this work, regardless of the media format used, as well as to promote it through scientific repositories and to admit its copy and distribution for educational, research and non-commercial purposes, as long as credit is given to the author and publisher.

A Universidade do Algarve reserva para si o direito, em conformidade com o disposto no Código do Direito de Autor e dos Direitos Conexos, de arquivar, reproduzir e publicar a obra, independentemente do meio utilizado, bem como de a divulgar através de repositórios científicos e de admitir a sua cópia e distribuição para fins meramente educacionais ou de investigação e não comerciais, conquanto seja dado o devido crédito ao autor e editor respetivos.

To everyone who cares.

Acknowledgements

First, I would like to thank everyone that one way or another, helped me during the development of this thesis.

In particular my parents, for always supporting me and providing the necessary environment and motivation for me to follow academic studies, starting as early as when I was a kid, by offering me scientific and engineering toys. They also thought me to establish my objectives and to fight for them. To the rest of my family, a big thank you as well.

I would also like to thank all my closer friends and my lab colleagues for their support these last few months, for their words of encouragement, shared knowledge, long hours of study and patience.

Last but not least, I would like thank my advisor Professor Doutor Jorge Semião for all the help, knowledge, orientation and availability he provided, for me to be able to finish this thesis.

Resumo

O objectivo deste trabalho é apresentar um dispositivo portátil capaz de proporcionar sensações de tacto, paladar e olfacto a uma experiência de realidade aumentada.

Hoje em dia, muitas experiências culturais e pessoais são construídas com base em aplicações móveis, incluindo aqueles que usam Realidade Aumentada (AR). Estas aplicações têm crescido em utilização, devido à enorme popularidade dos dispositivos móveis, com câmaras existentes, com sistemas de posicionamento global (GPS) e também com uma enorme disponibilidade de conexões de internet. Por outro lado, a maior parte das interfaces de utilizador (UI – *User Interface*) actuais seguiu tradicionalmente um modelo de tamanho único, geralmente ignorando as necessidades, habilidades e preferências dos utilizadores individuais. No entanto, estudos recentes indicam que o desempenho da visualização dos dispositivos poderia ser melhorado se fossem adaptados aspectos de visualização especificamente para cada utilizador individual.

Tendo este contexto em mente, o projeto *Mobile Five Senses Augmented Reality System for Museums* (M5SAR) visa desenvolver um sistema de AR para ser um guia em eventos culturais, históricos e em museus, complementando ou substituindo a orientação tradicional dada pelos guias, sinais direccionais ou mapas. O trabalho descrito na presente tese faz parte deste projeto M5SAR. O sistema completo consiste numa aplicação para *smartphone* (fora do âmbito desta tese) e num dispositivo físico (o presente trabalho), às vezes referido como "*gadget*", "dispositivo portátil", "AMtop" (*Aplicação Móvel + tacto olfacto e paladar*) ou "PDTTSS" (*Portable Device for Touch Taste and Smell Sensations*), para ser integrado no *smartphone* de forma a explorar os 5 sentidos humanos: visão, audição, tacto, olfacto e paladar.

Os sistemas tradicionais de AR dão *feedback* sensorial a apenas dois dos nossos sentidos, a visão e a audição. Ao contrário desses, a multimídia multissensorial concentra-se em fornecer comunicações imersivas e melhorar a qualidade de experiência dos utilizadores. Com isto em mente, é um dos objetivos do projeto M5SAR, a implementação de um dispositivo de *hardware* para se integrar ao *smartphone*, que permita ao utilizador sentir toque, cheiro e sabor, expandindo a experiência digital típica para todos os cinco sentidos. Portanto, é o objetivo deste trabalho, construir e desenvolver esse mesmo dispositivo de realidade aumentada.

As soluções actuais relacionadas com o aumento de experiências sensoriais consistem em grandes sistemas de *hardware* e estão longe de ser portáteis. Nesta tese, é apresentado um novo dispositivo pequeno e portátil, para integrar com o *smartphone* do utilizador, para reproduzir uma experiência completa com todos os cinco sentidos. O dispositivo implementado embora pequeno e, adiciona ao sistema de realidade aumentada as experiências do toque, cheiro e sabor. Além disso, o dispositivo é suficientemente flexível para se adaptar aos diferentes tamanhos dos *tablets* e *smartphones* dos utilizadores. É alimentado por uma bateria recarregável, o que dá ao módulo a capacidade de manter o sistema a funcionar durante toda a visita ao museu. O núcleo principal é um microcontrolador que recebe as instruções da aplicação móvel a correr no *smartphone* e reage de acordo com essas instruções, activando o restante *hardware* necessário para disponibilizar a experiência multissensorial ao utilizador. A comunicação entre a aplicação e o dispositivo é feita sem fios, através de um interface *Bluetooth*. A comunicação com o resto do módulo, denotados aqui como interfaces físicos, é cablada. Estas interfaces serão responsáveis por criar os estímulos que reproduzem os três sentidos: tacto, paladar e olfacto. O restantes sentidos, a visão e a audição, já são reproduzidos pelo próprio *smartphone* ou *tablet* do utilizador.

Neste relatório, depois de explicados os objectivos e o enquadramento do trabalho, são explicados alguns conceitos necessários para compreender o conteúdo e alcance desta tese, que inclui a compreensão dos sentidos humanos e a forma como são estimulados. São analisadas algumas das tecnologias existentes para reproduzir o estímulo sensorial para os três sentidos humanos menos explorados, toque, sabor e cheiro, quer sejam projetos académicos, ideias em desenvolvimento ou produtos de consumo comercialmente disponíveis, independentemente do tamanho, eficiência ou praticidade.

Pela análise dos objetivos e dos requisitos do projeto, e considerando a aplicação final, é apresentado o estudo do modo de desenvolver o dispositivo portátil, desde o seu

aspecto físico, até os sistemas sensoriais mais intrincados. São apresentadas diferentes possibilidades de recriar o estímulo para cada sensação e que tecnologias existem e como podem ser aplicadas. Pela sua comparação e análise, são determinadas quais são as melhores e mais apropriados para usar neste projecto, tendo em consideração o tamanho, a portabilidade e as limitações de energia existentes num dispositivo portátil, também não esquecendo a comodidade e segurança para o usuário.

São apresentados ainda neste relatório todos os detalhes importantes para a construção do protótipo do dispositivo portátil. Foi desenvolvido um protótipo que serve para fazer a “prova de conceito”, e neste relatório são detalhados os componentes usados, como eles foram ligados e explicadas as mudanças necessárias efectuadas em relação ao conceito projetado anteriormente. São ainda apresentadas as especificações técnicas de cada componente e do próprio PDTTSS, assim como a estrutura da caixa que suporta o dispositivo, mostrando a evolução que a estrutura teve ao longo do projecto, com os seus modelos 3D e a estrutura real impressa em 3D para a construção do protótipo. Desde a posição para cada componente na estrutura, a sua montagem, passando pela electrónica necessária, com a especificação da placa do microcontrolador, o firmware e a interface de comunicação, tudo é apresentado e detalhado neste relatório.

Sob o protótipo do dispositivo desenvolvido, foram executados diversos testes. Devido à natureza de algumas interfaces usadas, alguns testes não foram possíveis de quantificar, por isso esses testes foram conduzidos com pessoas para obter seus comentários sobre sua experiência real como usuário da unidade portátil. Os resultados são apresentados e resumidos por interface sensorial. Além do estímulo sensorial, alguns resultados sobre a compatibilidade do uso, em relação ao tamanho e ao peso, também são representados aqui, assim como Uma discussão sobre os múltiplos resultados, analisando-os em termos de relevância e interesse para este aplicativo, bem como possíveis problemas e sua causa provável.

Em termos gerais, os resultados são coerentes com uma primeira versão de um protótipo realizado com o objectivo de ser uma prova de conceito. Assim, os resultados mostram que há interfaces que necessitam de ser melhorados, para serem mais perceptíveis pelo utilizador final, nomeadamente a sensação de frio. Outros interfaces são ainda passíveis de melhorias, embora o resultado já obtido seja satisfatório, nomeadamente a sensação de vento. Outros interfaces apresentam já resultados aceitáveis para uma solução final, como a sensação de quente. Em suma, para um protótipo desenvolvido como prova de conceito, este cumpriu exemplarmente as suas funções, pois

permitiu validar a ideia, permitindo ainda ter uma noção real da utilização e implementação dos interfaces pelos utilizadores finais. Neste âmbito, a análise dos problemas encontrados nos resultados dos testes permitiu encontrar soluções possíveis para corrigir esses problemas, e soluções de como melhorar o dispositivo portátil para o desenvolvimento de um novo protótipo.

Palavras chave: Realidade aumentada, display multissensorial, dispositivo portátil, experiência de cinco sentidos, museus.

Abstract

The purpose of this work is to present a portable hardware device that can provide touch, taste and smell sensations to an augmented reality experience.

The proposed hardware is part of a mobile five senses augmented reality system for Museums (M5SAR) project, which aims at developing an augmented reality (AR) system to be a guide in cultural, historical events and museums, complementing or replacing the traditional orientation given by a guide, directional signs or maps. The complete system consists of an App (out of the scope of this thesis) and the hardware portable device (presented in this work), sometimes referred as “gadget”, to be integrated with the user smart device, allowing him to explore all 5 human senses, to improve and augment, as much as possible, the visiting of a museum, for example, see, ear, touch, feel and experience all its interesting objects.

The existing solutions related to the augment of sensing experiences consist of big hardware systems and they are far from being portable. In this work, a new small and portable device is presented, to integrate and connect with the user’s smartphone to provide the complete five-sense experience.

The implemented device is portable and small, but it adds to the complete augmented system, the touch, smell and taste experiences. Moreover, the device is flexible enough to adapt itself to different sizes of the user’s smartphone or tablet. It is powered by a rechargeable battery, which gives the module the ability to keep the system running during the visit of the museum. The core unit is a microcontroller; it receives instructions from the mobile application in the user’s smartphone and acts accordingly, controlling the remaining hardware of the portable device to deliver the five-sense experience to the user.

The communication between the device and the mobile application is possible through wireless communication, using a Bluetooth interface. The communication with the remaining module, denoted here as physical interfaces, will be wired. These physical interfaces are responsible for creating the stimuli that reproduce the three senses: touch, taste and smell. The remaining senses, sight and hearing, are already reproduced through the user's smartphone or tablet.

Keywords: Augmented reality, multisensorial display, portable device, five-sense experience, museums.

Contents

List of Figures.....	xix
List of Tables	xxiii
List of Acronyms	xxv
1 Introduction.....	1
1.1 Scope of the Thesis	2
1.2 Objectives.....	3
1.3 Structure of the Thesis	4
2 State of the Art	5
2.1 Background	6
2.1.1 Touch	6
2.1.2 Smell	11
2.1.3 Taste.....	13
2.2 Multisensorial Systems	14
3 Concept Design.....	17
3.1 General Overview	18
3.2 Touch Stimulus	20
3.2.1 Heat and Cold	21

3.2.2	Vibration	22
3.2.3	Airflow	23
3.3	Taste Stimulus	26
3.4	Smell Stimulus	28
3.4.1	Taste Vaporizers	30
3.4.2	Aromatized Containers	31
3.4.3	Fragrance Spray	32
3.4.4	Pressurized Can.....	33
3.4.5	Ultrasonic Atomization.....	35
3.4.6	Comparison	36
3.5	Mechanical Design.....	37
4	Device Development.....	43
4.1	Introduction	44
4.2	Thermal System.....	44
4.3	Vibration Interface	49
4.4	Air Interface	50
4.5	Taste Interface	52
4.6	Smell Interface	55
4.7	Casing Structure	58
4.8	Assembly.....	61
4.9	Main Board.....	70
4.10	Firmware.....	72
4.11	Communication	82
4.11.1	Bluetooth Interface.....	83
4.11.2	Communication Protocol	85
4.11.3	Sequence Diagram	89
5	Results.....	93

5.1	Tests	94
5.1.1	Thermal System Results	94
5.1.2	Vibration Results	95
5.1.3	Airflow Results	97
5.1.4	Taste Results	98
5.1.5	Smell Results	99
5.1.6	Comfortability Results	100
5.1.7	Battery Durability	101
5.2	Discussion	102
6	Conclusions.....	105
6.1	Conclusions	106
6.2	Future Work	107
6.3	List of Publications	108
	References.....	111

List of Figures

Figure 2.1: Sony’s PlayStation DualShock 3 controller [11].	7
Figure 2.2: Disney Research’s AIREAL [25].	9
Figure 2.3: AxonVR’s HaptX Skeleton [30].	10
Figure 2.4: An olfactometer by Aurora Scientific [40].	12
Figure 2.5: oPhone DUO [43].	13
Figure 2.6: Digital taste interface [48].	14
Figure 2.7: FeelReal Mask [47].	15
Figure 2.8: MOFAD’s The Smell Synthesizer [55].	15
Figure 2.9: MOFAD’s taste pellets [56].	16
Figure 3.1: Concept for the first prototype.	19
Figure 3.2: Block diagram of basic functionalities for the portable device.	19
Figure 3.3: General architecture and spatial distribution of modules in the device.	20
Figure 3.4: Thermoelectric module construction [59].	22
Figure 3.5: Air distribution system based on the Smelling Screen.	24
Figure 3.6: Screen quadrants airflow points of origin.	25
Figure 3.7: Exploded view of a vaporizer [61].	26
Figure 3.8: Taste outputs (left side of the device).	28
Figure 3.9: Fragrance dispersal system through the ventilation channels.	29
Figure 3.10: Smell system with vaporizers option.	30
Figure 3.11: Smell system with aromatized container.	32
Figure 3.12: Smell system with fragrance sprayer.	33
Figure 3.13: Smell system with pressurized fragrance cans.	34
Figure 3.14: Smell system with ultrasonic atomization.	35

Figure 3.15: First design sketch for the portable device.	38
Figure 3.16: Technical sketch of one side of the device (right side of the device).	39
Figure 3.17: Placement of the tablet/smartphone on the portable device.	40
Figure 4.1: Schematic for the thermal system driver.	45
Figure 4.2: Thermoelectric module.	46
Figure 4.3: Thermal sensation system design.	48
Figure 4.4: Schematic for the vibration system driver.	50
Figure 4.5: Selected vibration motor.	50
Figure 4.6: Air flow channel design.	51
Figure 4.7: Schematic of the ventilation system driver.	51
Figure 4.8: Sunon Maglev fan 30x30x10mm.	52
Figure 4.9: Types and parts of vaporizers [64].	53
Figure 4.10: Clearomizer tank (left), clearomizer threaded connector (right).	53
Figure 4.11: Schematic for the taste system driver.	54
Figure 4.12: Fragrance chamber design.	55
Figure 4.13: Air generation design for the smell system.	56
Figure 4.14: Solenoid air valve.	56
Figure 4.15: Schematic for the smell system driver.	57
Figure 4.16: Sunon Maglev micro fan 20x20x10mm.	57
Figure 4.17: Second design sketch for the PDTTSS.	58
Figure 4.18: 3D Model for the portable device.	59
Figure 4.19: Detailed 3D model inner side view.	59
Figure 4.20: Detailed 3D model top view.	60
Figure 4.21: Detailed 3D model backside view.	60
Figure 4.22: Ventilation channel assembly.	61
Figure 4.23: Printed ventilation channel (left) and structure (right).	61
Figure 4.24: Thermal system assembly.	62
Figure 4.25: Thermal parts (left), TEC assembled (centre), handle assembled (right).	62
Figure 4.26: Smell system assembly.	63
Figure 4.27: Smell system parts (upper line), assembled components (bottom line).	63
Figure 4.28: Vibration system and electronic board assembly.	64
Figure 4.29: Vibration motor and electronics inside the structure.	64
Figure 4.30: Taste system assembly.	65
Figure 4.31: Taste vials (left), connectors (centre), vaporizers (right).	65

Figure 4.32: Battery assembly.	66
Figure 4.33: Back covers assembly.	66
Figure 4.34: Front cover assembly.	67
Figure 4.35: Left side of the portable device finished.	67
Figure 4.36: Final assembly of both sides.	68
Figure 4.37: Portable device assembled.	68
Figure 4.38: 3D Model of the portable device with a tablet.	69
Figure 4.39: Portable device assembled with a tablet.	69
Figure 4.40: Schematic for the main board of the left side (master).	70
Figure 4.41: Schematic for the main board of the right side (slave).	71
Figure 4.42: Firmware main loop flowchart.	73
Figure 4.43: Serial command parser process flowchart.	74
Figure 4.44: Cold mode process flowchart.	75
Figure 4.45: Typical thermistor output undergoing a sudden temperature transition. ...	76
Figure 4.46: Heat mode process flowchart.	77
Figure 4.47: Blow mode process flowchart.	78
Figure 4.48: Shake mode process flowchart.	79
Figure 4.49: Taste mode process flowchart.	80
Figure 4.50: Smell mode process flowchart.	81
Figure 4.51: General communication interface diagram.	82
Figure 4.52: HC-05 Bluetooth Serial Module	83
Figure 4.53: Timing diagram request/response example.	90
Figure 5.1: Temperature readings on the handle for a cold request.	94
Figure 5.2: Temperature readings on the handle for a heat request.	95
Figure 5.3: Subjects response to vibration sequence.	96
Figure 5.4: Subjects response to vibration intensity.	96
Figure 5.5: Identification of the airflow point of origin by test subjects.	97
Figure 5.6: Subjects response to airflow intensity.	98
Figure 5.7: Subjects response to flavour intensity.	99
Figure 5.8: Subjects response to smell intensity.	99
Figure 5.9: Subjects response to size and weight comfortability.	100
Figure 5.10: Vapour leak in the taste output.	103

List of Tables

Table 3.1: Comparison of smell generation systems.	36
Table 4.1: Bluetooth HC-05 module configuration AT commands [66].	84
Table 4.2: Protocol commands and respective parameters.	86
Table 4.3: Protocol parameters variables and acceptable values.	87
Table 4.4: BLOW command ID parameters.	87
Table 4.5: SHAKE command ID parameters.	88
Table 4.6: SMELL command ID parameters.	88
Table 4.7: TASTE command ID parameters.	89

List of Acronyms

ACK	<i>Acknowledge</i>
AFH	<i>Adaptive Frequency Hopping</i>
AMtop	<i>Aplicação Móvel + tacto olfacto e paladar (portable device)</i>
APP	<i>Mobile Application</i>
AR	<i>Augmented Reality</i>
CT	<i>Computed Tomography</i>
CLD	<i>Cold Instruction</i>
DC	<i>Direct Current</i>
DOF	<i>Degrees Of Freedom</i>
DPDT	<i>Double Pole Double Throw</i>
DT	<i>Temperature Differential</i>
EDR	<i>Enhanced Data Rate</i>
GPS	<i>Global Positioning System</i>
LED	<i>Light Emmiting Diode</i>
M5SAR	<i>Mobile 5 Senses Augmented Reality</i>
MCU	<i>Microcontroller Unit</i>
MOFAD	<i>Museum Of Food And Drink</i>
MOSFET	<i>Metal Oxide Field Effect Transistor</i>
NTC	<i>Negative Thermal Coefficient</i>
PCB	<i>Printed Circuit Board</i>
PDTTS	<i>Portable Device for Touch Taste and Smell Sensations</i>
PID	<i>Proportional Integral Derivative</i>

PLA	<i>Polylactic Acid</i>
PSK	<i>Phase Shift Keying</i>
PWM	<i>Pulse Width Modulation</i>
RFID	<i>Radio Frequency Identification</i>
SAW	<i>Surface Accoustic Waves</i>
SHK	<i>Shake Instruction</i>
SML	<i>Smell Instruction</i>
TEC	<i>Themoelectric Cooling</i>
THL	<i>Total Heat Load</i>
UART	<i>Universal Assynchronous Receiver Transmitter</i>
UI	<i>User Interface</i>
VR	<i>Virtual Reality</i>

1 Introduction

ABSTRACT

This chapter introduces the present work, and also its context and integration in the M5SAR project. The main objectives of the thesis work are described and an overview of this report is also presented here.

1.1 SCOPE OF THE THESIS

Nowadays, many personal and context-aware tourism and cultural experiences are constructed based on mobile Apps [1], including the ones that use Augmented Reality. Those are increasing due to the popularity of built-in cameras and GPS, also with the massive availability of Internet connections on mobile devices. On the other hand, most of the present User Interface (UI) still traditionally follow a one-size-fits-all model, typically ignoring the needs, abilities and preferences of individual user's. However, research indicated that visualization performance could be improved by adapting aspects of the visualization to the individual user [2].

In [2], authors state very recently that intelligent user-adaptive interfaces and/or visualizations, that can adapt on-the-fly to the specific needs and abilities of each individual user, is a long-term research goal. This is due to two main reasons: (a) the difficulty to extract information about the users' needs and abilities, and (b) the implementation of the UI that can adapt/change "itself" on-the-fly.

In [3] it is referred that a modular UI that allows a flexible composition of various interface elements increases the number of variations of the interface element to the power of the number of adaptable elements. Thus, instead of designing each interface from scratch, a modular user interface approach is a possible good solution, once allows achieving many more versions with less design effort. The requirement, therefore, change to create different designs for all those parts of the interface that are subject to user or cultural preferences. Equal importance should be given to the adaptation of the UI to users with different visual, auditory, or motor impairments. Unfortunately, because of the great variety of individual's incapability's among such users, as expected, manually, and probably modular designing interfaces for each one of them is impractical and not scalable [4][5]. In reality, the number of existing UI than can automatically adapt themselves to users' capabilities is very low, and when existing, it focus in one specific impairment, e.g., motor [4].

Nevertheless, the modular and/or adaptive generation of UI offers the promise of providing personalized interfaces on-the-fly, but this does not mean that the user will be satisfied with his/her personalized App. According to [6], the psychological process behind satisfaction is highly complex and requires a differentiation between transaction-specific satisfaction and cumulative satisfaction. Transaction-specific satisfaction is the judgment of an experienced service encounter at a specific point in time, whereas

cumulative satisfaction is the result of “the overall evaluation of all services encountered over time”. Augmented reality exacerbates some of the challenges mentioned before, because multiple types of augmentation are possible at once, and proactive Apps run the risk of overwhelming users.

Having this context in mind, the M5SAR project aims to develop an AR system to be a guide in cultural, historical and museum events, complementing or replacing the traditional orientation given by tour guides, directional signs, or maps. This thesis work is part of this M5SAR project. The complete system consists of a smartphone application (out of the scope of this thesis) and a physical device (the present work) sometimes referred to as “gadget”, “portable device”, “AMtop” or “PDTTSS” (Portable Device for Touch Taste and Smell Sensations), to be integrated in the smartphone, in order to explore the 5 human senses: sight, hearing, touch, smell and taste.

1.2 OBJECTIVES

The AR traditional systems give sensorial feedbacks to only two of our senses, sight and hearing. Unlike those, multisensory media focuses on providing immersive communications and enhancing user quality of experience [7].

Therefore, the purpose of this work is to build and develop an augmented reality portable device, to provide to the user experiences in his five senses, and enhanced the quality of the visit to the museum, raising it into a different level. The portable hardware device should provide touch, taste and smell sensations to an augmented reality experience, to be part of the M5SAR system for Museums, to improve and augment, as much as possible, the visiting of a museum, i.e., see, ear, touch, feel and experience all the interesting objects that exists.

The existing systems related to the augment of sensing experiences are big hardware systems and they are far from being portable. With this thesis, a new small and portable device should be presented, to integrate and connect with user’s smartphone to provide the complete five-sense experience. The device should be portable and small, but it adds to the complete augmented system the touch, smell and taste experiences.

By developing the new augmented reality device, the first big challenge will be to integrate a visitor’s smart device (tablet or smartphone) in a compact new device that allows the user to have these five sense experiences. The second big challenge will be to

integrate, in a portable and small device, all the hardware needed to allow the five sense experiences. The device should integrate physical interfaces, which will be responsible for creating the stimuli that reproduce the three senses: touch, taste and smell. The remaining senses, sight and hearing, should be reproduced in the user's smart-phone or tablet, connected to the device.

Moreover, the device should be flexible enough to adapt itself to different sizes of user's smartphone or tablet. It should be powered by a rechargeable battery, which gives the module the ability to keep the system running during the visiting of the museum.

1.3 STRUCTURE OF THE THESIS

This thesis is organized as follows.

The current chapter makes an introduction to the scope of the thesis, the project objectives and a summary of what is going to be presented and where.

Chapter 2 focuses on the state of the art for sensorial interfaces, whether they are techniques or technologies, academic projects or commercial products. It presents some of the most important developments done in this area in the past.

Chapter 3 analyses the project's goals and requirements to start designing a concept for the portable device. It goes over the different possibilities of reproducing sensorial stimulus and considers their applicability in such a device.

Chapter 4 details all the steps for the construction of the prototype for the PDTTSS, going interface by interface. It presents all the technical specifications, such as the components that were used, electronics, connections, physical structure, firmware and communication protocol.

Chapter 5 presents the multiple tests that were conducted to the prototype, for all its sensorial interfaces. It also discusses the results in terms of accomplishment of the desired objectives, comfortability for the user, and possible problem causes.

Chapter 6 finalises this work with the general conclusions, mentioning how some problems can be fixed in future work, and also presents some publications which were published during the course of this work.

2 State of the Art

ABSTRACT

This chapter will explain some concepts necessary to understand the content and scope of this thesis, which includes understanding human senses and how they are stimulated. It will analyse some of the existing technologies for reproducing sensorial stimulus for the three less explored human senses: touch, taste and smell. Whether they are academic projects, ideas in development or commercially available consumer products, regardless of their size, efficiency or practicality. It is presented in two main sub sections, Background and Multisensorial Systems. In Background, the technologies and projects are divided by sense and type of stimulus, while the Multisensorial Systems focus on single solutions that mix together two or more senses in the same system, independently of their final application.

2.1 BACKGROUND

In psychology, it is a generally accepted fact that, the more informational channels we use, the better the transmitted information will be perceived [8]. Still, most existing multimedia systems in use today, focus only on two senses (sight and hearing). One reason why is because it is difficult to reproduce compelling sensations for the other senses. Even though there have been a series of attempts in the past, almost none of them seem to be picked up by developers, product designers, manufacturers or consumers.

In this analysis, the focus will be on the three human senses that are not generally stimulated in technological devices and commercial products, which are the touch, taste and smell senses. Some of the following examples are separated into sub categories, and are sometimes considered extra senses or non-traditional senses, however they are presented here categorized under the three traditional human senses for simplification.

2.1.1 Touch

The sense of touch is the perception that results from the activation of neural receptors present in the skin, hair follicles and other parts of our bodies. Among the three studied senses (touch, taste and smell), touch is probably the most technologically advanced and where more examples, commercial products and academic research works, are available. These examples are here presented, but subdivided into different types of stimulus.

2.1.1.1 Vibration

One example which is widely used, although its limitations, is the sense of touch through haptic feedback with vibration motors. This feature has been in use for years and it was mostly introduced in the consumer market thanks to videogames and cellphones. In 1976, the arcade racing game “Fonz”, developed by Sega, was the first videogame to use haptic feedback, which caused the handlebars to vibrate during collisions [9]. Newer generation consoles now include built-in haptic feedback features in their controllers, like Sony’s DualShock technology (Figure 2.1), and Microsoft’s Impulse Trigger technology, which is a standard feature in videogame controllers nowadays [10].



Figure 2.1: Sony's PlayStation DualShock 3 controller [11].

More far-reaching than videogames is probably the mobile phone industry, which has been incorporating the tactile feedback for years, either for notifications or, more recently, as a touch response in touchscreen keyboards, to help mimic a real mechanical button, aiding users to hit their targets faster and more accurately [12]. The vibration haptic technology still has many opportunities to evolve and expand into other areas, and some studies have already been made, exploring some of these possibilities. For example, in medical applications, where CT (Computed Tomography) scan images can be analysed recurring to a haptic vibrotactile display, helping doctors to easily detect lesions without excessively burdening their vision [13].

2.1.1.2 Electrovibration

Another existing way to create sensations of touch is through electrovibration. Although not yet found on the consumer market, this recent invention is probably going to reach out to smartphones and tablets in the next few years. It works by controlling electrostatic charges on the surface of the touchscreen, therefore varying the friction between the surface and the user's finger [14]. This technology, initially called TeslaTouch, has been developed by Disney Research and has, ever since, been subjected to more studies and experiments. One obvious application is aiding the visually impaired to explore the world around them, rendering tactile information about the objects sensed by a camera [15]. More recently this technology has been used to simulate 3D geometric features, through an algorithm able to render the desired texture on a display [16].

2.1.1.3 *Ultrasounds*

Ultrasounds have also been used to reproduce tactile sensations. In [17] authors have developed a prototype that uses ultrasonic air pressure waves to create contactless vibration feedback. Described initially as UltraTV, it is a mid-air multi-point ultrasonic haptic feedback system. This technology has later evolved into rendering volumetric haptic shapes in mid-air [18]. In 2013 the company Ultrahaptics was founded, based on the technology developed at the University of Bristol, UK, where their focus falls mainly in touchless user interfaces [19]. There is not yet a product on the consumer market with this technology, but they do have evaluation and development kits available for pre-order.

Still, the research on this area is just beginning, and the initial steps have been made to start combining ultrasonic haptics with newer display technologies, creating better mid-air interactions and displaying visual elements wherever the user needs them [20]. For example, this technique was already used to add the sense of touch to a holographic display with the help of a hand tracker, where the user could see and touch a virtual ball [21].

2.1.1.4 *Air*

Also in the category of contactless haptic feedback systems is the usage of air as a way to stimulate our sense of touch. One of the earlier usage of this technique was a wind display called the WindCube. A metal structure fitted with a series of fans, where a subject could get inside and experience a virtual scene [22]. Since then, other virtual reality applications have been using similar approaches to enrich their experiences. One example of this is the VR Scooter, that used a fan to simulate the wind blowing over the user, when the scooter is moving [23]. Another technique is the recreation of a force feedback display using air-jet. A prototype grid composed of 100 nozzles, each one controlled individually to generate an overall pressure, where the user could place a paddle to produce the force feedback and feel the sensation of touch [24]. Disney Research, however, introduced a different system called AIREAL, shown in Figure 2.2. Their device uses compressed air to hit the user with an air ring, called a vortex, generating tactile sensations on the skin.

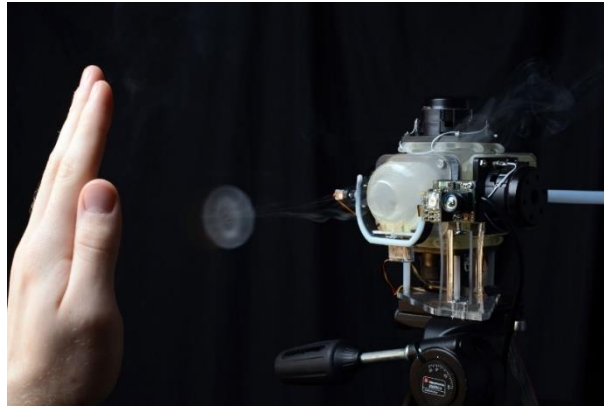


Figure 2.2: Disney Research's AIREAL [25].

It also features a pan and tilt system, a 3D depth camera and a flexible nose to be able to detect and aim at the target, improving its accuracy [25]. Microsoft has a similar device called AirWave [26]. Still, these technologies are not yet distributed on the consumer market.

2.1.1.5 Mechanical

Yet, another way to represent sensations of touch is through mechanical actuators, and several studies and prototypes have been developed in this area. One of the initial works was the Sensor Glove II, a multi degree-of-freedom (DOF) haptic device with 20 DOF. Each joint controlled by wire transmission actuators is able to reproduce force feedback sensation on the fingers, simulating the manipulation of virtual objects [27].

A similar research was later conducted with different prototypes to provide a framework for a multi-fingered exoskeleton master hand with passive force feedback for tele-operation [28]. Many other studies followed, more recently, for example the HEXOTRAC, which is a 3-digit hand exoskeleton with single attachments to the fingertips, through a 6 DOF kinematic chain [29]. Some of these exoskeletons prototypes focus not only on a hand, but on an entire body suit, although almost none of them are commercially available. A company called AxonVR is currently developing full body exoskeleton with force feedback, the HaptX Skeleton, for entertainment, educational and healthcare applications. They also have a gaming platform with microfluidic actuators and thermal feedback, the HaptX [30].



Figure 2.3: AxonVR's HaptX Skeleton [30].

Another approach to the mechanical haptic feedback systems is through pneumatic tactile displays, which use air chambers between special layers of transparent acrylics and latex, to create simple shapes and buttons [31]. A similar setup is being commercially developed by Tactus Technology, which uses fluid instead of air to bring tactile feedback touchscreen keyboards [32]. More recently, another similar system was experimented, using closed loop shape control on a 3x4 cell prototype, with a Kinect depth sensor for feedback [33].

A completely different approach to the mechanical haptic texture feedback was introduced by Microsoft Research, with a device called TouchMover. A robotically actuated display that moves closer or further away from the user, varying the pressure between the surface and the user's finger, therefore able to represent 3D textures on the screen [34].

In terms of tools for development and academic research, there is some interesting hardware available in the market, like the Geomagic's line of haptic interfaces [35]. Other particularly innovative studies are being conducted using shape memory alloy to provide eyes free interaction with devices [36]. Although these technologies are certainly interesting, some of them would be impractical on a mobile device.

2.1.1.6 Thermoreception

To finalize the analysis on the sense of touch haptic feedback systems, there is the thermoreception or perception of temperature. Although sometimes categorized as an

extra sense to the traditional five human senses, it is presented here as included in the tactile category for simplification.

The application of thermal feedback in devices is not exactly new, in [37] authors presented an experimental setup of a temperature display apparatus, used to determine a reliable model for heat transfers occurring between different materials and the user's finger. It was focused on virtual reality applications. With the dissemination of Peltier devices (thermoelectric modules), more and more studies and experiments were conducted. More recently for example, a haptic transmission system for telexistence was developed using the TELESAR V, a telexistence surrogate anthropomorphic robot, that was able to detect pressure, vibrations and temperature on the robot's finger and display that information on the operator's finger [38]. The usage of Peltier devices on mobile applications is, however, problematic from the point of view of efficiency and energy consumption, and that is likely one of the reasons why this technology is not yet present in everyday consumer products.

2.1.2 Smell

The smell or olfaction, is a chemical human sense. There are hundreds of olfactory receptors, each binding to a particular molecular feature. Specific receptors can be more or less strongly excited due to the varieties of odour molecules features. It is the combination of signals from different receptors that makes the brain perceive a particular smell.

For reproducing the sense of smell, there have been quite a lot of academic studies and even a few commercially available products. In terms of techniques, there are also some different options available, like pushing a flow of air through a scent filter or recipient, vaporizing an aromatized solution, pressurized scented cans, heated or evaporative diffusers, ultrasonic scent atomization, among others [39].

In terms of scientific equipment, there is the olfactometer, an instrument used to detect and measure odour dilution, used in conjunction with human subjects to quantify and qualify human olfaction [40]. They generate odour by pushing a flow of air through an odour vial and then mixing it with pure air.



Figure 2.4: An olfactometer by Aurora Scientific [40].

The first combination of smell with video was back in 1906 when a cinema owner, diffused a scent of rose in the audience during a screen of the Rose Bowl [41]. In the late 1950's Hans Laube presented the Smell-O-Vision, a system which released odour during the projection of a film, however some technical problems led to the decline of the invention. After that, few attempts were made to release digital scent technology to the market, but none of them seemed to have gained traction.

In 2001, a company called DigiScents developed the iSmell prototype, a personal scent synthesizer that could be connected to a computer via USB or Serial Port. It was designed to emit a scent when the user visited a website or opened an email. The cartridge contained 128 of what they called, primary odours and could supposedly be mixed together to create other scents. Later, PC World Magazine [42] considered it one of the 25 worst tech products of all time.

One particularly interesting prototype was a wearable olfactory display that used micro DC pumps to force a flow of air through an odour filter, releasing it on the user's face. Using RFID proximity tags, it was able to replicate a virtual environment, releasing a different scent at different locations [44].

Another peculiar prototype is the Smelling Screen, which combines a display with four fans, rotating at low speed so the user won't perceive the flow of air. The fans carry the scent and work together at different settings, to change the odour's point of origin on the screen [45].

David Edwards and Rachel Field recently presented their scent messaging platform, the oPhone DUO, which allows the user to send a photo tagged with a specific odour to another person with the device [43]. Their system later evolved into a company, Vapor Communications, which currently sells a digital scent speaker called Cyrano [46].



Figure 2.5: oPhone DUO [43].

Another interesting wearable olfactory display prototype was developed in 2016, combining micropumps and a surface acoustic wave (SAW). The system works by using the pumps to pull the odour compounds from a reservoir to the surface of the SAW device, where the scent is atomized [47].

2.1.3 Taste

The sense of taste is the capability to detect the taste of substances, such as foods, minerals, poisons, among others. It is somewhat mixed with the sensation of flavour, which is actually a combination of taste and smell. Flavour depends on odour, texture, temperature and taste. There are five widespread accepted basic tastes: sweet, bitter, sour, salty and umami. This is the least explored of all senses and probably the hardest to digitally stimulate. Most studies and projects on this topic, try tricking the brain by using other senses like sight and smell, to recreate thoughts and activate existing memories of food flavours.

Authors in [49] conducted an interesting experiment evaluating pseudo-olfaction and pseudo-gustation, by examining the relationship between scents and visual feedback, as well as colours and flavours. One curious system that makes use of this correlation is the Meta Cookie, a pseudo-gustatory display, which uses plain cookies found on the market, identified with augmented reality markers. Each marker overlays a different visual aspect onto the cookie and emits the respective smell, with the help of a VR headset and a scent emitting device. This way, without changing the chemical composition of the cookie, the user is able to perceive a different taste [50].

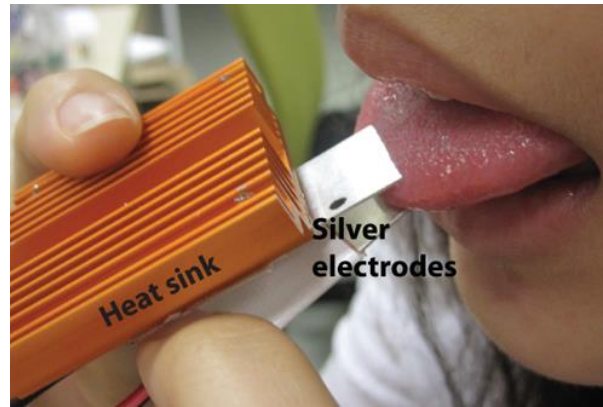


Figure 2.6: Digital taste interface [48].

There is some research, however, on a real digital taste interface that attaches to the user's tongue via two silver electrodes (Figure 2.6). Applying pulses with different electric properties like current, frequency and voltage, seem to produce sour, bitter and salty sensations [51]. Further research demonstrated that by combining other influential factors like temperature, enabled the system to produce a wider variety of results, for example sweet and minty tastes [48]. More recently this technology was used to develop the Digital Lollipop, an experimental instrument to simulate the sensation of taste. A study was conducted in different regions of the human tongue asserting that different tastes occur in different regions. A second study examined the possibility of controlling the artificial sour taste at three different intensity levels [52]. Despite very interesting and promising, this technology still seems impractical to use and incorporate in mobile devices. Not only that but it also raises some comfortability, health and safety questions.

2.2 MULTISENSORIAL SYSTEMS

There are not many examples of systems that combine together multiple senses to offer a more immersive sensorial experience. The most similar devices available are probably the ones used in 4D movie theatres or shows, which besides the 3D films allow you to experience physical effects synchronized with the movie, which can include rain, wind, temperature changes, strobe lights, vibrations, smells, fog and chair movements, among other things [53]. However, these are usually expensive to install and maintain, therefore

are limited to special venues like amusement parks. Still, if classified based on the three uncommon generalized senses touch, taste and smell, these systems only use two of them.



Figure 2.7: FeelReal Mask [47].

In the virtual reality consumer market, there have been also some developments, as the example of the FeelReal VR Mask, presented in 2015 (Figure 2.7). It is a multisensory gaming interface, which enables the user to experience different smells and simulated effects of wind, heat, water mist and vibration. It is also compatible with some existing VR headsets like the Oculus Rift [54].



Figure 2.8: MOFAD's The Smell Synthesizer [55].

The Museum of food and drink (MOFAD), in New York, also developed a very interesting odour interactive display, called The Smell Synthesizer (Figure 2.8). It allows the visitors to press different buttons, that release chemicals associated with the smell of certain elements, and by pressing different buttons at the same time, different odour combinations will be perceived as something else [55], working the same way as primary

odours, in an analogy to primary colours. For example, by releasing both maple and butter odours, the users supposedly associate that to the smell of pancakes.



Figure 2.9: MOFAD's taste pellets [56].

However, their multisensory approach was not exactly integrated into a single system, and the taste aspect of it was recreated separately using gumball machines (Figure 2.9). These dispensers then release to the visitors, candy-like pellets with peculiar flavours such as tomatoes, porcini mushrooms and parmesan cheese.

It is common, for some museums nowadays, to provide some kind of sensorial experience to their visitors. The smell sense has been used for a while now, like for example in the Lindt Chocolate Museum in Cologne, Germany, where people can try the odours of spices and ingredients used in their chocolates [57]. The same happens for taste, which usually is through food samples, or chocolates in this case. As for the touch sense, it is generally present, one way or another in most museums. What is however uncommon, is the mixture of all these stimulus in one single object, product or display.

3 Concept Design

ABSTRACT

This chapter starts by analysing the project objectives and requirements, considering its final application. It studies the way to develop this portable device, from the physical aspect to the more intricate sensorial systems. It presents different possibilities of recreating the stimulus for each sensation module, the technologies that exist, and the techniques that could be applied, comparing and determining which are better or more appropriate to use, considering the device's size, portability and energy limitations, and also not forgetting about practicality, comfortability and safety for the user. It follows the same methodology and line of thought that was used during the project design, as a way to explain why certain decisions were made, until it reached the final actual state of the prototype.

3.1 GENERAL OVERVIEW

Like it was mentioned before, the objective of this thesis is to develop a portable device, capable of providing a complete five sense experience when used in conjunction with a mobile device running an application (out of the scope of this work). The focus falls over the design and construction of that device or gadget, considering that it is meant to be coupled with the user's mobile device. This means that it should be flexible enough to adapt do different mobile devices, light and small enough so that it could be comfortably carried by a person during a typical museum visit, and, obviously, able to reproduce compelling stimulus for the three senses, touch, taste and smell, at the appropriate time, when instructed by the application via wireless commands.

In terms of the initial objectives and design requirements, they can be summarized:

- Be a portable device that can reproduce touch, taste and smell contents;
- Dimension should be small, maximum size 7x7x25 cm for each part (two parts, one on each side of the mobile device);
- Should also be lightweight;
- Must be capable of adapting easily to multiple sizes of mobile devices;
- Able of reproducing touch sensations such as: wind, heat, cold and vibration;
- Able of generating 3 to 5 different odours;
- Able of recreating taste sensations with 3 to 5 different flavours;
- Wireless communication between the device and the application;
- Simple communication protocol to activate sensorial interfaces;
- Battery powered operation to allow portability.

Figure 3.1 presents a sketch of the proposed portable device. The system consists of two similar hardware parts, placed on each side of user's device where the mobile application is running, and connected in the bottom through the adjustable supports.

As depicted in Figure 3.2, a microcontroller is the core unit of the device. It receives instructions from the mobile application and acts accordingly, controlling the remaining hardware of the portable device to allow the five-sense experience to the user. The communication between the device and the mobile application is possible through a wireless communication, in this case, using a Bluetooth interface. The communication

with the remaining interfaces will be wired. The physical output interfaces will be responsible for reproducing the multiple sensorial stimulus for the three senses.

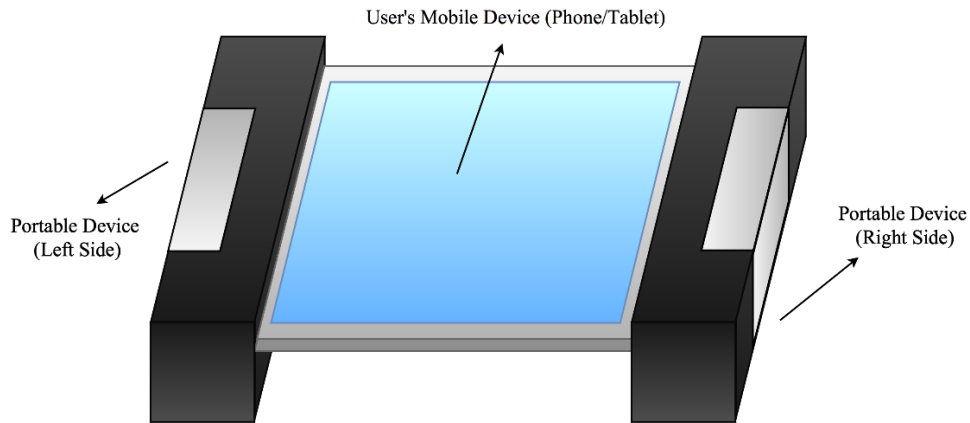


Figure 3.1: Concept for the first prototype.

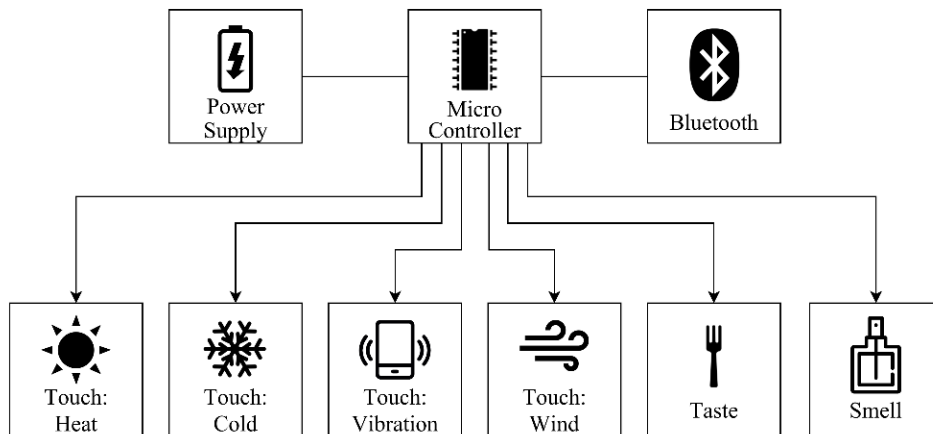


Figure 3.2: Block diagram of basic functionalities for the portable device.

The general architecture of the prototype and an initial spatial distribution of the modules is represented in Figure 3.3. The image does not portrait scale but merely an identification of the individual systems that need to be integrated, and their possible positions inside both sides. The left and right hardware parts are very similar to each other, as they should take exactly the same modules, components and connections. However, there is one main difference: only one of them has a Bluetooth communication interface. It does not make sense for the user to have to connect with two different Bluetooth devices through the

application on his smartphone or tablet, therefore only one Bluetooth address should exist per prototype.

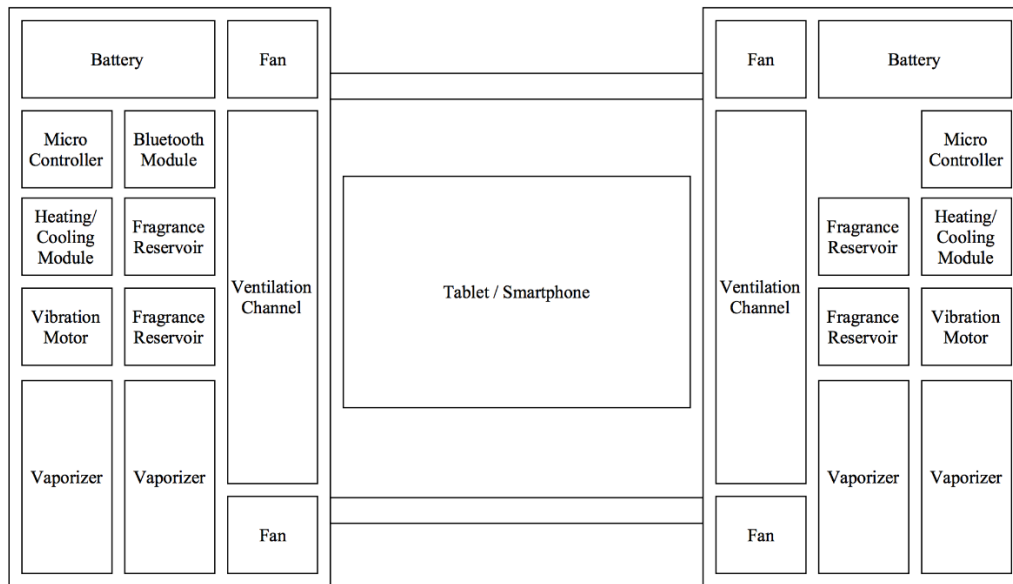


Figure 3.3: General architecture and spatial distribution of modules in the device.

The idea is to have a master microcontroller, the one on the side that has the Bluetooth module (left), and a slave microcontroller on the other side (right). In terms of software and hardware, they are similar, and the firmware running on both microcontrollers can even be mostly the same code. The difference between them is how they receive their instructions and how they replicate them. The master microcontroller receives the activation commands through Bluetooth and resends the same instruction to the slave microcontroller, via a wired serial communication. If the activation command refers to interfaces on the left, or on the right side, the respective microcontroller will know it and do its job.

3.2 TOUCH STIMULUS

For the touch sense reproduction, different types of possible touch stimulus were analysed. However, considering the state of the art, availability, complexity, dimensions and price of all these technologies, only three were selected for this device. For example, electrovibration technology would be incredible to represent textures of museum objects

that people are not allowed to touch, however it is not yet disseminated in the consumer market and appears to exist only in a research and development stage, so it is not feasible. Therefore, it must be dropped from this work (at least for now). The three selected types of touch stimulus are thermal touch, vibration and air flow. In order to adapt these modules into the portable device, we must put some thought into these features first, about how they can be faithfully reproduced and implemented, considering the device's limitations and requirements.

3.2.1 Heat and Cold

The idea here is to be able to make the user somehow experience sensations of heat and cold through the portable device. People can feel temperature in different ways, depending on the heat transfer method, as for example direct contact, which is thermal conduction, or at distance through radiation.

With that in mind, the direct contact seems to be the ideal approach for a portable device, but even so there are different possibilities. One way could be through a system similar to a fan heater, or an air conditioner. Another way, and probably easier and more efficient, could be by changing the temperature on the device's handles, so that the users could immediately feel it in their hands. This second option seems more feasible for this project requirement, so that was the selected approach.

In order to change the temperature in the device's handles, there are three things needed: a heating module, a cooling module and thermal conductive handles. Regarding the handles, that can be easily solved with some metallic part like aluminium or a similar material, as long as it is a good heat conductor. As for the heating module, a simple heating resistor could be used for this purpose.

It is however the cooling module that presents the more challenging problem: generating cold on a small scale. Luckily, nowadays, thermoelectric cooling modules (TEC), also known as Peltier devices, are easily available at accessible prices. A Peltier module uses the Seebeck effect to create a solid-state active heat pump. It has two sides, a hot side and a cold side, and it transfers heat from one side to the other, through the consumption of electrical energy, depending on the direction of the current (represented in Figure 3.4). This means that, by applying a DC electrical current through the device, one side will get hot, while the other side will become cold, creating a temperature

differential (DT) [58]. Therefore, by using and tuning heatsinks on one or both sides of the device, it is possible to generate a desired temperature on a specific side. For example, by using a Peltier device with a maximum DT of 50°C, with the hot side “attached” to the ambient temperature of 30°C, in ideal conditions it would be possible for the cold side to reach -20°C (30°C-50°C).

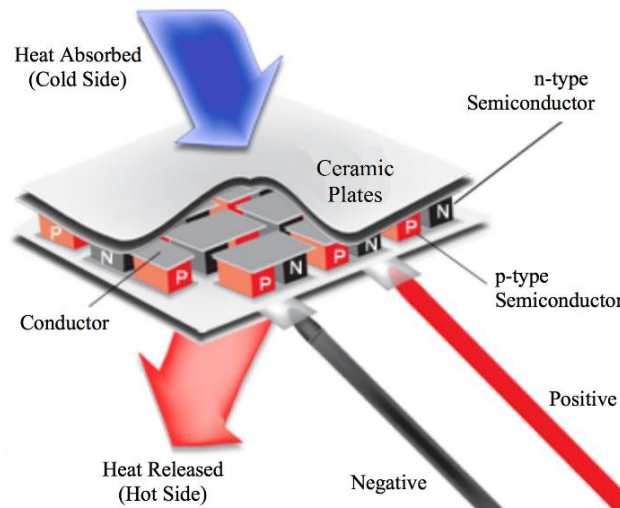


Figure 3.4: Thermoelectric module construction [59].

Of course, there are other parameters that must be considered, but in a general approximation, this is how Peltiers work. Since they can be used both for cooling and heating, just by reversing the electrical current, it seems practical to do that, in order to save space and money. Therefore, the heating and cooling modules will be fused together with a Peltier device. So, the thermal touch module should be able to recreate ideal heat and cold sensations, using thermoelectric modules. In terms of desirable temperatures for the touch sense, the range between 0°C and 40°C seems like a good selection, which is safe for the user, yet still sufficiently noticeable to convey the intended sensations.

3.2.2 Vibration

Vibration is another way to simply represent another stimulus related to the sense of touch. Like it was referred in the State of the Art chapter, it has been in use in electronic devices for years, and it is mostly found on videogame controllers, smartphones and

tablets. Since this type of stimulus is relatively easy to implement, it was decided that it should be used in our portable device. Sure, the gadget is supposed to be used together with the user's mobile device, which most likely already has vibration features. However, implementing it on our system will make it definitely available to be used, not depending on the user's device, and obviously, it will make possible the designing of a few new extra features that wouldn't be possible through the user's smartphone. One example would be aiding the user to navigate through the museum using vibration pulses, since we have a left and right side of the portable device. If following a predetermined path or route, the system can subtly indicate which way the user should go, without the need for a visual representation, but instead using a vibration signal, either on the left or on right side of the device. Other possible features include generating the feeling of shock, trepidation or certain vibration patterns that can be designed to better represent a specific object, action or scenario.

The vibrations can be easily obtained through vibration motors, with one on each side of the device, independent and as close as possible to the handles, to increase the noticeability of vibrations. Vibration motors are also quite common and cheap, with a lot of different sizes and shapes available. Still the working principle is usually the same, a rotating motor with a counter weight on the axis.

3.2.3 Airflow

Still for the sense of touch, there is also the possibility of using air to represent haptic sensations. The usage of an airflow can be used to recreate the idea of wind or a small breeze, in a certain given scenario. Some VR games are already making use of this technique. Besides, fans are found everywhere and are, basically, inexpensive, so it makes sense to adapt it onto the portable device. Size is also not a problem, since there are fans as small as 15x15 mm, and they are quite easy to use, and to control the flow, if necessary (via PWM).

The purpose here is to make the user feel a breeze in certain situations, so there are a couple of ways this can be done. The most obvious one is merely to place the fans in such a way that the air flow goes directly into the user face. However, another possibility is doing something similar to the Smelling Screen [45]. Although the latter is more complex, it allows for some peculiar features like making the airflow originate from

a particular area of the mobile device's screen, and if already thinking about the smell sense stimulus, it could have some very interesting uses by making a specific smell appear in only one part of the screen. Certain applications or games could make use of this feature to create something really immersive and unique.

With this under consideration, that was the chosen option for the wind/air flow touch sense stimulus. The basic idea is to replicate the Smelling Screen on a smaller scale adapting it to a portable device and to our project requirements.

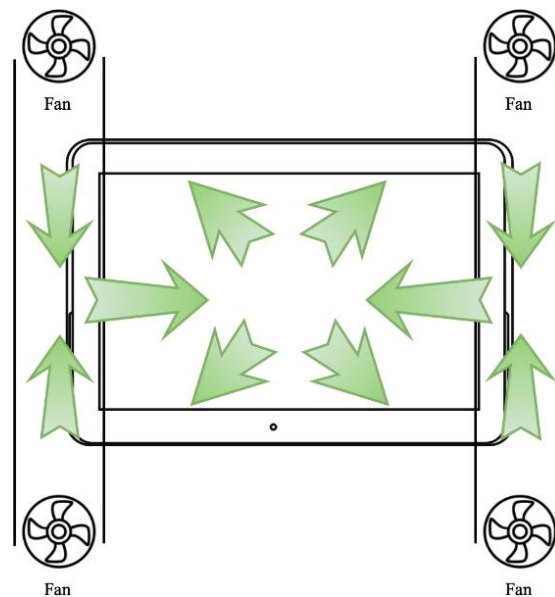


Figure 3.5: Air distribution system based on the Smelling Screen.

The airflow or wind sensation is obtained using a ventilation system with four fans and two air channels, two fans and a channel on each side of the device. As proposed in [45], the cooperative work of these four fans can cause a sense of wind directed to the user's face, and by varying the speed of each one individually, it can generate an airflow coming from different points of origin. Since the screen area will be substantially smaller than a desktop monitor, the allowed points of origin will be reduced to five: one on the centre of the screen, and the other four for on each quadrant of the screen (Figure 3.6).

The ventilation channels consist on a tube with a fan on each ending blowing air inside, with a longitudinal opening on the side of the tube. This way, the air that is forced inside will collide at a certain point in the channel and be forced to exit the side opening on that location. If, for example, both equal fans are working at 100% speed, the air collision should happen exactly in the middle of the channel. By varying the speed of the

fans and their relations between each other, different points of origin and flow rate are possible. By using a channel on each side of the device, with the side openings facing each other, the air that exited one channel will also collide with the air that exited the other channel, somewhere in the middle of the screen. In this last collision, some air will escape to the top and bottom of the screen, but a decent amount will flow perpendicular to the screen, directly to the user.

In terms of the total amount of airflow to reach the user and its perceivability, this solution is weaker than the option of using the fans directly, however this option was selected because of the possible features, and because of the possible integration with smell sensation.

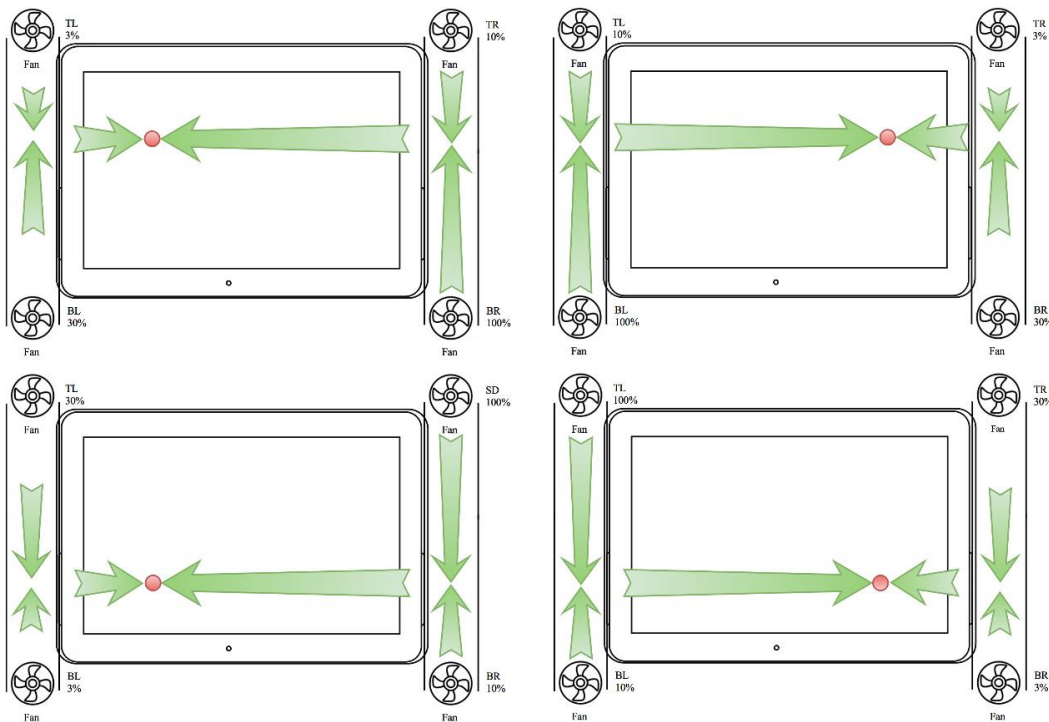


Figure 3.6: Screen quadrants airflow points of origin.

It was also considered the possibility of heating and cooling the air flow, in an attempt to fuse both thermal and air touch senses, because it is easier to sense, since a person's face is more sensible to thermal variations. However, since the system is portable, it should run on batteries and this idea is heavier on energy consumption. Besides, the air flow might have a counter effect on the thermal element and nullify the heating or cooling of the haptic handles, since they should be low-power as well, this would act like a heatsink airflow.

3.3 TASTE STIMULUS

For the sense of taste, there are not many solutions available. As analysed in the state of the art, only now researchers are starting to get results on how to electrically stimulate the tongue in order for the user to perceive different tastes and flavours. Since it is still a new born technology, it would be difficult and time consuming to create a similar system for our portable device, therefore other simpler solutions were studied.

One possible way would be to use individually wrapped candy like foods, inside a secret compartment of the gadget, being unlocked and opened for the user to eat, when desired by the application via wireless commands. Another similar possibility would be using certain special vending machines inside the museum, that would only release the desired food when the user approach them, being the portable device responsible for giving the machines the instruction to release the snack. Both these options require an external process of producing or getting unusual flavoured snacks for the museum system, and the second even needs an actual vending machine which either would be time consuming to develop or expensive to buy and maintain, making the system complex and dependent on external entities.

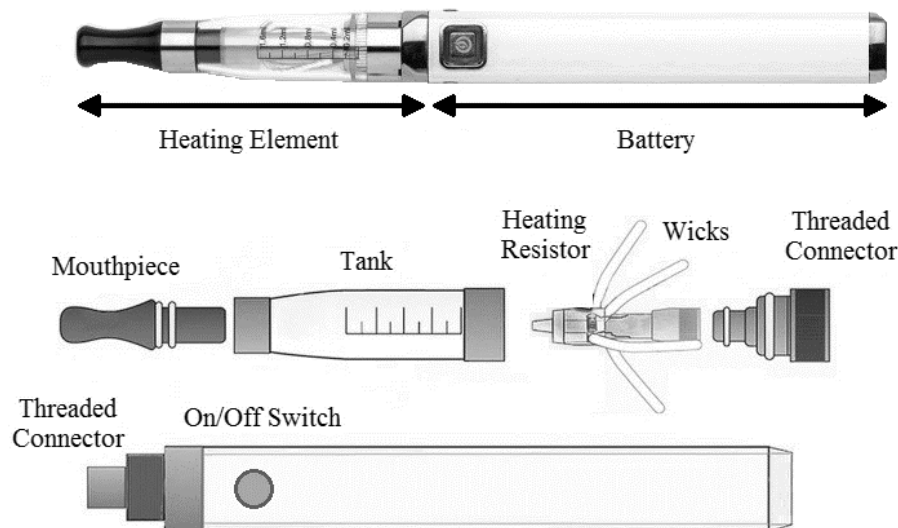


Figure 3.7: Exploded view of a vaporizer [61].

With that considered, another option comes to the top: the usage of electronic vaporizers, also known by electronic cigarettes. They can be divided in two main parts: the heating

element and the battery. The working principle is always the same. The tank, which also includes the heater, takes a special liquid called “e-liquid”, which contains a mixture of propylene glycol, glycerol, water, flavourings and nicotine, among other chemicals [60]. The heater, then, heats the liquid to the point of vapour or aerosol that the user inhales. The battery also includes the electronic controller and user interface to power the heating element, which usually is a single button or a more complex display.

Obviously, for the museum application, the liquid would be nicotine free, which is also easily available in every vaping stores and with a wide variety of flavours. This solves the problem of developing certain more uncommon flavours, and even if that becomes a necessity, “e-liquid” is relatively easy and cheap to produce with custom properties. Another advantage of this solution is that it is an already developed system by itself, and it could be adapted to integrate the portable device with a certain ease. For instance, the potential problem of spilling the liquid is reduced, because the vaporizer system is already well closed and protected against it. Another example, the threaded connectors between the tank/heater and the battery/controller, are usually a standard size, which means that could be used to integrate it on the system. Since it only really needs the tank and heater, the portable device has its own battery and circuit.

That said, the chosen solution was to incorporate the electronic vaporizers to give the visitor the sensation of savouring some food and tasting different flavours. Initially the design contemplated a single output for both vaporizers on each side; however, that would require valves, and since the space limitation is very demanding, a direct approach to each vaporizer was later adopted (Figure 3.8). This means that there will be two taste outputs per side of the device, and in order for the user to know which one to use, they shall have an output indicator like a small LED nearby.

If the same output connects to both vaporizers, the flavours ends up mixing with each other, even though one of them might be turned off. Besides, the suction pressure gets divided between two different vaporizers and, therefore, more pressure required to release the same amount of flavoured vapour.

The device should then be developed with four vaporizers, two on each side, thus providing a total of four different flavours per visit. In order to guarantee the hygiene of the system, each visitor should receive with the device, a disposable tube that will serve to connect to the outlet of the flavour, and at the other end will have the respective mouthpiece to prove and ideally a one-way valve, to avoid people from blowing inside the device.

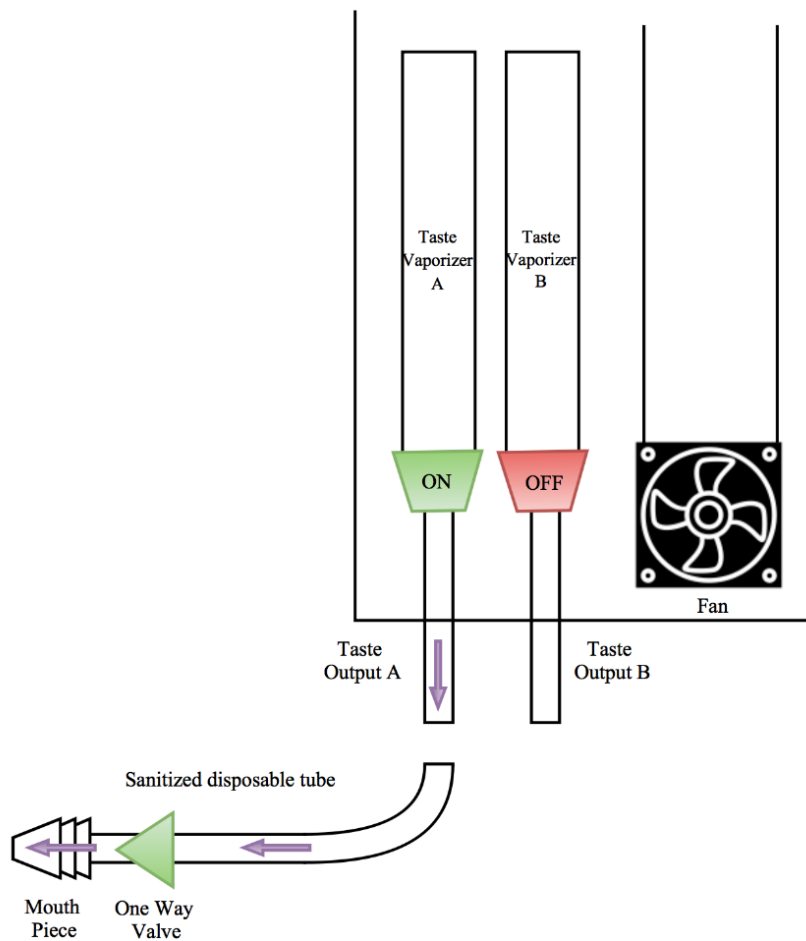


Figure 3.8: Taste outputs (left side of the device).

Taste outputs can also eventually have small cover to protect the tubing inside the device. This system also has the advantages of being easy to replace flavours and not being completely necessary to develop the flavours themselves, since food grade aromatizers are easily found and commercially available.

3.4 SMELL STIMULUS

For the smell sensation, there are some different possibilities as well. In terms of usability, there are some aspects that must be considered. First of all, the final purpose is to develop a portable device, so once again size, weight and energy efficiency are primary factors. Another specific aspect is the danger of spilling liquids inside the gadget, not only

potentially damaging the electronics inside, as well as the user's mobile device and clothes. Other consideration should be the ambient contamination with a certain smell. If the odours are too strong or released for a long time, the device unit or even certain areas of the museum could become aromatized undesirably.

Considering those conditions, the possible solutions were analysed to compare advantages and disadvantages. Most of them require an airflow to help carry and release the fragrance into the environment, and this is usually done with micro air pumps, or a compressed air reservoir, like in the case of olfactometers. However, this presents a problem, because micro pumps can be quite noisy and that is not desirable for any museums. The pressurized container is also a problem, because of the necessary space required for it.

So, to generate the necessary air flow, once again the design choice will fall on fans, micro fans in this case, which are smaller and less noisy. Initially the idea would be to use the same fans used for the wind/breeze sensation, redirecting a part of that flow for the smell system, but after a few tests, this proved ineffective.

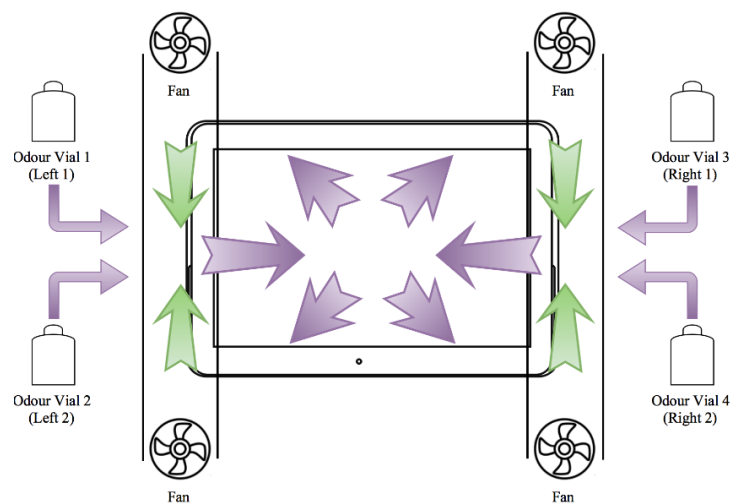


Figure 3.9: Fragrance dispersal system through the ventilation channels.

Therefore, the resulting option is to use extra fans, specifically just for the smell module, pushing the air through some sort of odour reservoir and then releasing it to the ventilation channels of the wind stimulus system, but with the wind fans rotating at slow speeds to not over dissipate the fragrance (Figure 3.9).

Regarding odour releasing techniques, there are a few different options and a big industry of air fresheners behind it. The most common include pushing a flow of air

through a scent filter or fragrance recipient, vaporizing an aromatized solution, pressurized scented cans, heated or evaporative diffusers, ultrasonic scent atomization, among others. The following presents an overview of these techniques and determines whether or not they could be a good choice for this work.

3.4.1 Taste Vaporizers

One of the most obvious solutions would be to take advantage of the taste module and reuse the vaporizers to release the vapour into the ventilation channels. It makes sense, since the vapour also has smell and it seems to save space, money and complexity. After all, it would be reusing something that is already there. However, this implies certain changes in the taste system and it is not as simple as it seems. First, it needs control valves to interrupt and select between taste and smell module as represented in Figure 3.10.

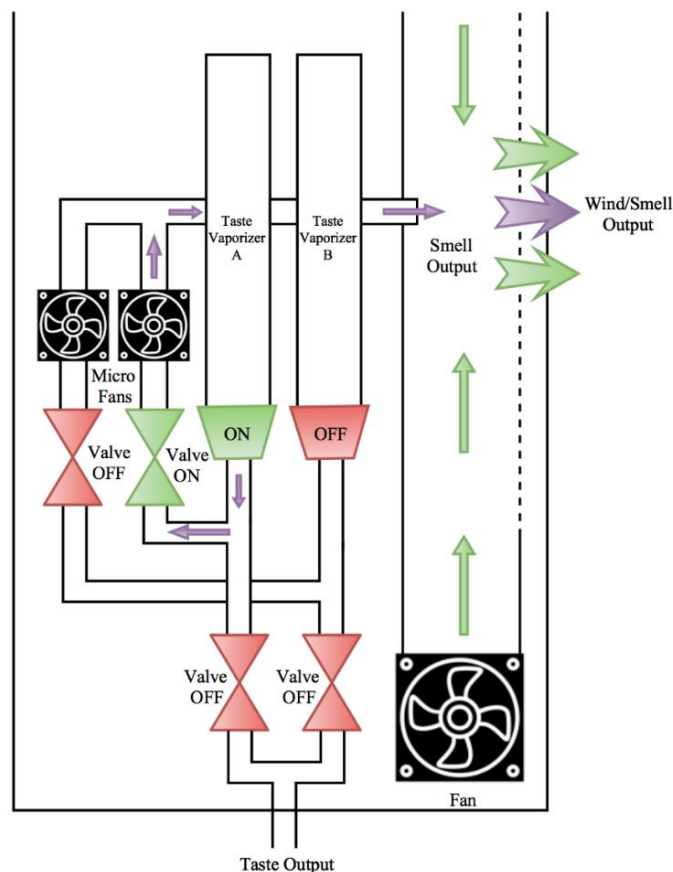


Figure 3.10: Smell system with vaporizers option.

If using flow control electro valves, then a single taste output would be possible and a single smell output as well but that would require four valves, which is quite an inconvenient considering the size requirements. Another limitation inherent to this solution would be the fact that both the flavours and the odours would be the same, making the device unit lack in diversity. In some scenarios, that could actually be useful, but not in general cases.

This solution is represented in Figure 3.10, showing the left side of the device unit and how the connections between different modules and components would be done. The air suction necessary to pull the vapour from the vaporizers would be done with micro fans. However, after some initial tests, it proved that it did not create enough pressure to release sufficient odour on the ventilation channel. The other solution would be using micro air pumps, which was also briefly tested, with smaller and quieter pumps. Still, the results were again unsatisfying. Not only this time the system was using a heavy and noisy component, but the own nature of the pump construction seemed to affect the odour present in the vapour, rendering unnoticeable or completely altering its fragrance.

In summary, this option has the advantage of reusing some components, it is relatively simple and avoids spilling. On the other hand, it has the disadvantages of needing too much space for the four valves, which are also heavy, the variety of flavour and fragrances is the same and it requires micro pumps, which are also heavy and noisy.

3.4.2 Aromatized Containers

A second solution implies using an airflow to travel on a separate circuit and go through a small vial or reservoir, with a concentrated aroma inside, being that air then released in the existent ventilation channel. Like mentioned before, this solution is often used in olfactometers, where the air flow is generated by air pump or a pressurized air canister. Still, the application of this project would give preference to quieter devices, and considering the space limitations once again, the fans become an appropriate alternative. This option also implies the use of valves for two basic reasons: first to prevent against spilling, and second to completely isolate the source of the odour when it is deactivated, therefore avoiding ambient contamination (Figure 3.11). The fact that this solution makes use of a separate container for fragrances, allows for the use of commercially available

concentrated odours. Depending on the type of liquid used, it might be necessary to heat the container to help volatilize the chemical solution.

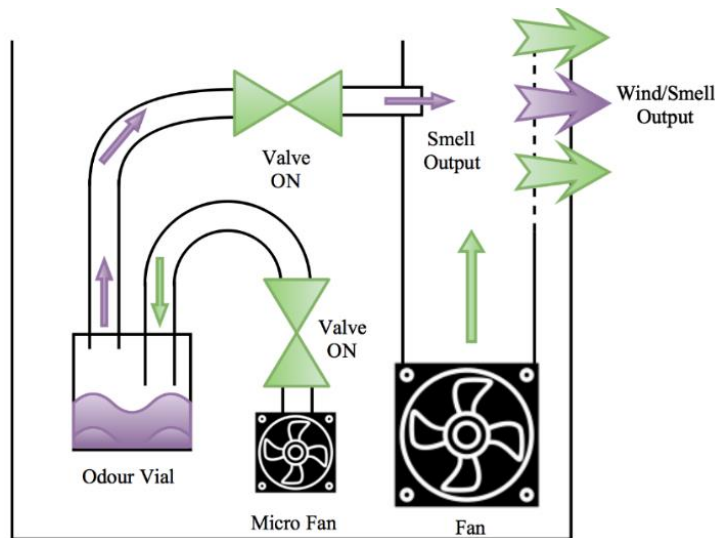


Figure 3.11: Smell system with aromatized container.

Nevertheless, this increases complexity of the system, and it is easier to use naturally evaporating ambient fragrances that are easily accessible in most stores. Again, having a liquid solution in a portable device is always at risk of spilling. However, that can be avoided by using a textile material soaked in the desired fragrance, such as cotton for example.

In summary, this solution has the disadvantages of using two valves per odour and a potential risk of spilling. On the bright side, it seems simple, it allows for commercially available aromas, it is easy to activate and turn off, and finally it can have odours different from the flavours used in the taste module.

3.4.3 Fragrance Spray

The third option would be using a regular perfume atomizer, with the odour inside a flask or vial, with an atomizer on top, activated mechanically with a motor, spraying the aroma in the ventilation channel (Figure 3.12). This solution, however, immediately rises a few concerns. The fact that it needs a mechanical system with gears to activate the sprayer, the fragrance vial needed to be in a vertical position in the moment of spray, and since this is an atomizer, in practicality it means the output is not a gas but an aerosol, a group

of suspended tiny particles of liquid. This is potentially negative because some particles might accumulate as drops on the user's mobile device, raising concern that it could damage their device. There was the possibility of using some sort of filter to protect against that, but it was concluded that the filter would accumulate the odour contaminating the environment, therefore would need frequent replacement.

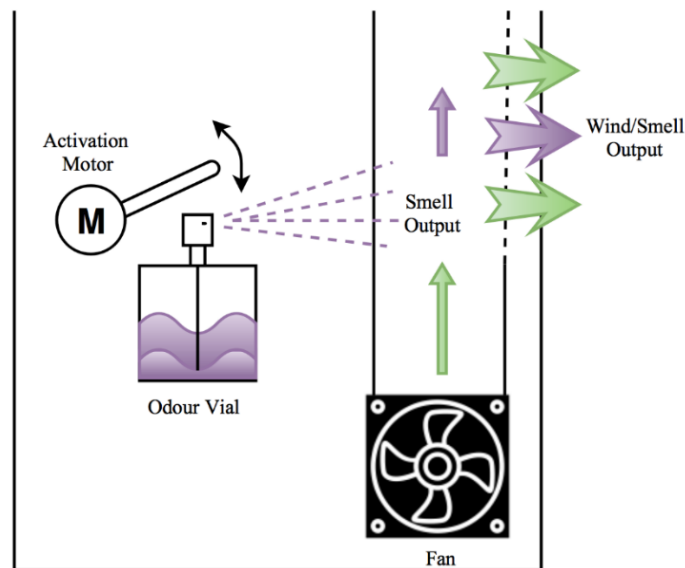


Figure 3.12: Smell system with fragrance sprayer.

Like the previous solution, the random reservoir with a sprayer cap allows any commercial available liquid fragrance to be used, though not all products are not ideal to be sprayed. In summary, it has the advantages of allowing any liquid fragrance to be used, and again the odours can be different from the flavours, besides a reduced risk of spilling. On the negative side, it is a much more complex system, and requires the development of a mechanical release system with motors, which takes space and is heavy, and therefore has moving parts. It also has the requirement of having the flask on a vertical position in the moment of activation, and finally it can release some tiny liquid particles onto the mobile device.

3.4.4 Pressurized Can

The fourth option relies on the usage of pressurized fragrance containers, like many of the commercially available air fresheners are supplied nowadays. In terms of functioning,

it is quite similar to the previous solution, and it also requires a mechanical system to push on the can and activate the release of the odour (Figure 3.13). In the same way, it also shares a few of the same problems, as the case of the suspended liquid particles accumulating on the user's mobile device, and the necessity of a mechanism with a motor and possibly gears as well. The verticality issue is not as severe as in the last case, but still exists. Regarding a spilling risk, that does not pose a problem, since these containers are well made and watertight. On the other side, having a pressurized can in a portable unit in the user's hand and next to his mobile device, can raise some safety questions.

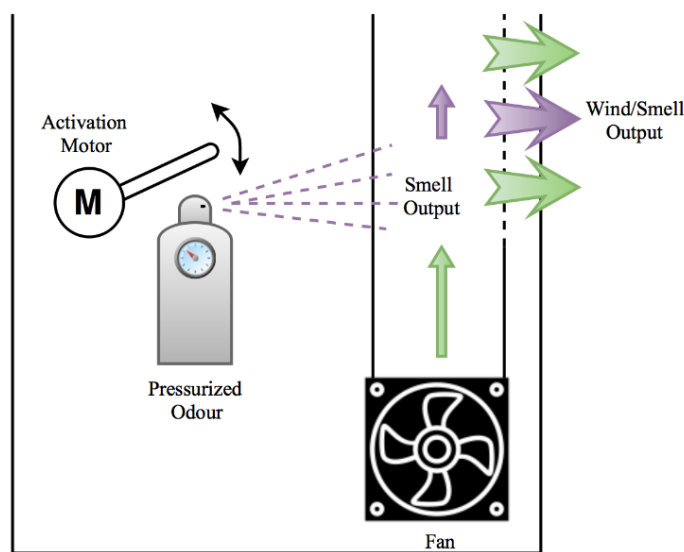


Figure 3.13: Smell system with pressurized fragrance cans.

The selection of odours in pressurized cans is wide and are easily found, although it is probably more limited than the liquid alternatives. In addition, it probably requires more space available in the device as well, since the smaller size pressure cans are still relatively large for a portable design, and might not have standard shapes or sizes, which can be a problem if switching suppliers.

In summary, it has the advantages of having different smells and flavours in the device and being spill risk free. On the disadvantages side, it requires a mechanical system, it might accumulate liquid particles on the mobile device, it might occupy too much space and be heavy, and if custom odours want to be used, those need to be pressurized into cans, which might imply additional costs.

3.4.5 Ultrasonic Atomization

The final option explores the possibility of using ultrasonic atomization to release the odour into the ventilation channels (Figure 3.14). This technique is often used in aromatherapy diffusers, where a mixture of water and essential oils are dispersed into the air. They work by using a piezoelectric element that generates ultrasonic vibrations, i.e., sound waves that will separate the mixture into micro particles, similar to atomization, which then disperses through the environment. However, for this to work the fragrance should be mixed with water and then make direct contact with the ultrasonic transducer, otherwise it will not work, although it is possible to use a soaked textile material to make contact with the transducer.

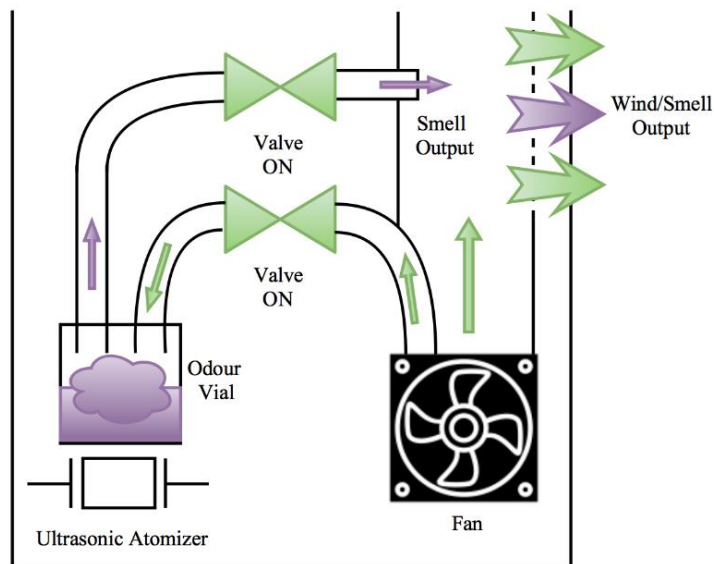


Figure 3.14: Smell system with ultrasonic atomization.

It has, however, a few problems. Since the result is a moisture cloud like the previous solutions, it will also present the accumulation of micro drops in the mobile device. In addition to that, the fact that it is a liquid mixture, it presents a serious spilling risk and therefore would require valves. Even so, when the system is active it would not be possible to guarantee that there would not occur a spill, since at that moment the valves would be open and the user could be moving or carrying the portable unit at any possible position.

In summary, this solution has the advantage of using any available fragrances and be different from the flavours on the taste system, however it has a high risk of spill, it generates tiny liquid particles on the mobile device and requires an ultrasonic transducer and flow valves.

3.4.6 Comparison

Having analysed all the different options, it is time to compare and decide which one is a better solution for this project characteristics and requirements. In Table 3.1 a comparison of the multiple smell generation methods, and their respective vantages and disadvantages is presented.

Solution	Advantages	Disadvantages
(a) Taste Vaporizer	<ul style="list-style-type: none"> - Reuse components; - Simple; - Spill free; 	<ul style="list-style-type: none"> - Large footprint; - Requires valves; - Heavy; - Odours are the same as flavours; - Requires pumps; - Noisy;
(b) Aromatized Container	<ul style="list-style-type: none"> - Simple; - Availability of aromas; 	<ul style="list-style-type: none"> - Requires valves; - Spill risk; - Needs forced airflow;
(c) Fragrance Spray	<ul style="list-style-type: none"> - Availability of aromas; - Spill free; 	<ul style="list-style-type: none"> - Mechanical system; - Large footprint; - Heavy; - Vertical position needed; - Moist on the user device;
(d) Pressurized Can	<ul style="list-style-type: none"> - Availability of aromas; - Spill free; 	<ul style="list-style-type: none"> - Mechanical system; - Large footprint; - Heavy; - Moist on the user device; - Additional custom odour costs;
(e) Ultrasonic Atomization	<ul style="list-style-type: none"> - Availability of aromas; 	<ul style="list-style-type: none"> - Requires ultrasonic transducer; - High risk of spill; - Requires valves; - Needs forced airflow; - Moist on the user device;

Table 3.1: Comparison of smell generation systems.

After analysing all five solutions, we can almost immediately discard the last three (c, d and e), as they present too much complexity or an uneven balance between their disadvantages compared to the advantages that they offer. For example, they all generate that moist effect that accumulates on the mobile device, which users will not appreciate, and require either large and heavy mechanical parts or additional electromechanical components. Yet they only give in return the availability of multiple aromas that could be used.

That said, the first two options remain as possibilities (a and b). At first sight, the taste vaporizer solution seems to be the ideal one (a), for it gave more advantages compared to negative side. But, as it was mentioned before, this solution was briefly tested and did not perform well. The fans and micro pumps, were not able to pull sufficient odour to be noticed from the vaporizers, and therefore it required more powerful and noisy pumps, which is not an option for a portable device to be used in museums.

With that considered, there is only one option left, the aromatized container (b). It is relatively simple and does not present as many disadvantages as the other solutions, besides the risk of spill can be reduced, for example with cotton soaked on the desired fragrance. It does, however, require valves which can be a problem. For the sense of smell, the idea is to incorporate four different fragrances on the portable unit, two different odours on each side of the device, then releasing the aroma to the ventilation channel of the wind/breeze module, to disperse it to the ambient. It is also important for the fragrance to be contained in a reduced area and not to spread to the entire environment, which would overwhelm users and saturate the entire room, and that can be controlled through the duration of the release.

3.5 MECHANICAL DESIGN

With the sensorial interfaces studied and selected, it comes the moment to start thinking on the structure of the portable unit itself. Once again, the project requirements are rigorous and limited in terms of size, adaptability to multiple mobile devices, weight and comfortability. The first factor to consider is the adaptability to a wide variety of smartphones and tablets in the market. Most of these devices vary between three to ten inches diagonal, but it is relatively difficult to design something that will attach as well

to three inches as on a ten inches device and still be comfortably used. Ideally, the smaller the better, and if it couples well on a small device, it should have no problem on a larger device. The opposite, however, is not exactly true, as a bigger prototype attached to a small mobile device is not very practical, neither it looks pleasing. However, in terms of prototyping, it is easier to start with a bigger design and then gradually, start reducing modules, components and finally the structure. Following the same line of thought, it was decided to start with the maximum allowed dimensions of 25x7x7 cm and then, if possible start reducing the prototype to an optimal size.

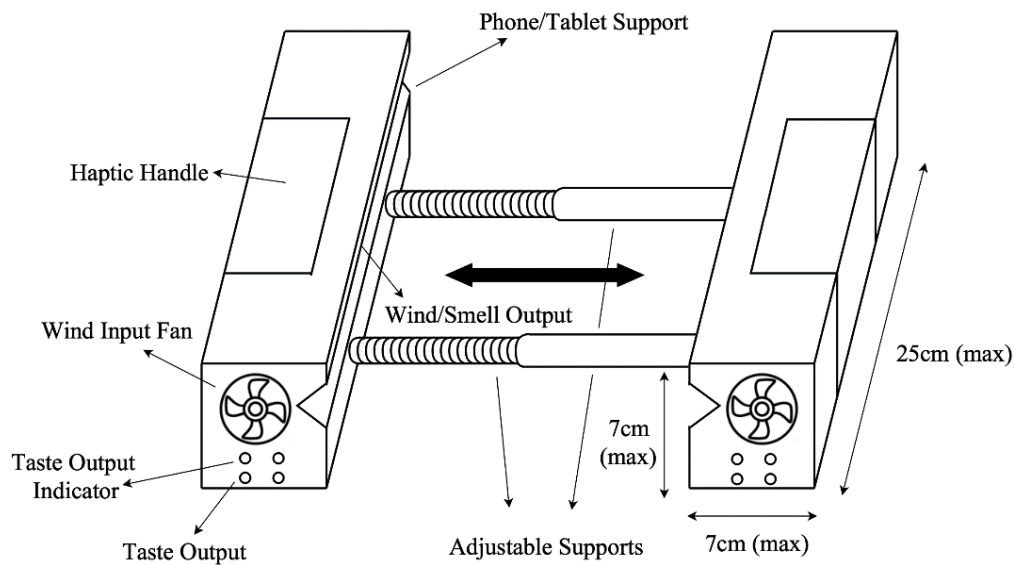


Figure 3.15: First design sketch for the portable device.

The system should be light, practical and intuitive. As depicted in Figure 3.15, the prototype will consist of two almost independent and identical, but symmetrical, hardware parts, one on each side of the user's mobile device. They are designed to be used with both hands, one on each side, locking the smartphone or tablet in between. Both parts are connected on the bottom through adjustable supports that can increase or decrease distance between both sides. They serve three main functions: first, it is a mechanical connection between both sides to make the device a robust single unit; second, they serve as cabling conduit for the electric cables between each side (possibly for communication or interface connection); and third, they provide a mechanical tightness to keep the mobile device in place via springs or a manual adjustable screw.

Each side will start with the maximum dimensions and should contemplate the incorporation of the previous referred systems, which are the thermal haptic handles

(temperature and vibration), the air/wind ventilation channels, two electronic vaporizers for tasting and two odour reservoirs for the smell sensation. Giving the prototype a total of two haptic handles, four flavours and four fragrances. Besides the components necessary to the reproduction of compelling sensorial experiences, it must also be considered the electronic parts, such as the microcontroller and main circuit board, the communication interface, which will be a Bluetooth module, and finally the battery, to power the entire system. Initially there was also a design requirement for both sides of the device to be exactly symmetrical, so they could be interchanged and used either for the left or right side, with the goal of saving money later on a production phase, for only requiring one casting mould.

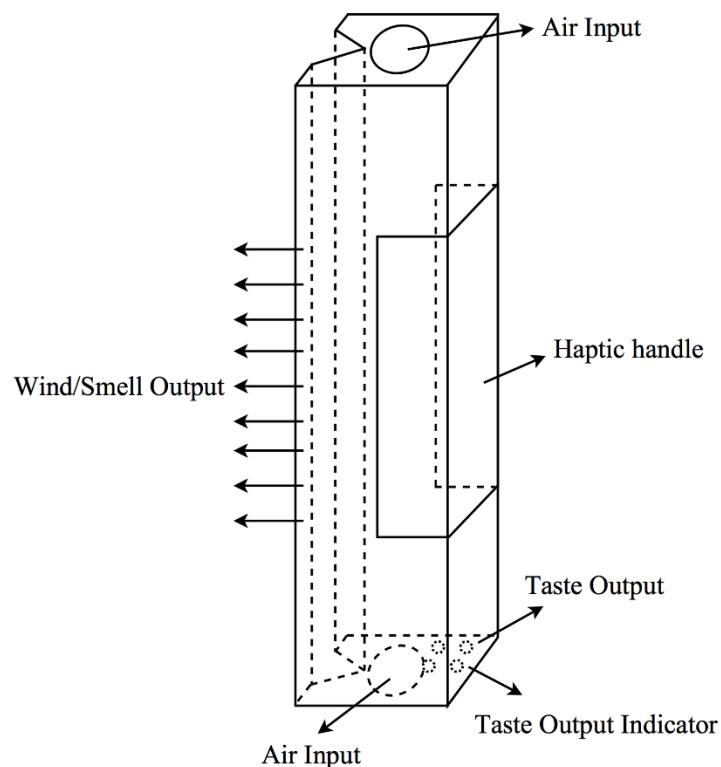


Figure 3.16: Technical sketch of one side of the device (right side of the device).

However, this idea was quickly dropped, because it would mean that the device would need to work upside down, and considering the taste outputs are usually on the bottom, it would mean there would have to be outputs also on top, and therefore more valves. Also, the adjustable supports are difficult to design in way that are exactly the same and yet fit inside each other to lock the parts in place. The fixation support to attach the user's device to the prototype was designed as an inside cut, triangular or curved, in a way that

could fit multiple device thickness, and the thinner it is, the closer together both sides are, as represented in Figure 3.15 and Figure 3.16. This guarantees that the device stays safely locked in place and centred. This cut can also be covered by a rubber layer to increase friction between the prototype and the mobile device, to avoid it slipping out of place. One of the tops of this cut could be closed, maybe the one is the bottom, to prevent the device from falling of the supports and crashing into the ground. This means that the mobile device would have a very specific way to be inserted into the prototype, which would be from above, like represented in Figure 3.17. Besides, if this is designed that way, that is another feature that is incompatible with the interchangeability between right and left sides for production saving costs. However, since it was concluded interchangeability would not be done, it is unlikely that these bottom cuts would be closed, unless proven essential.

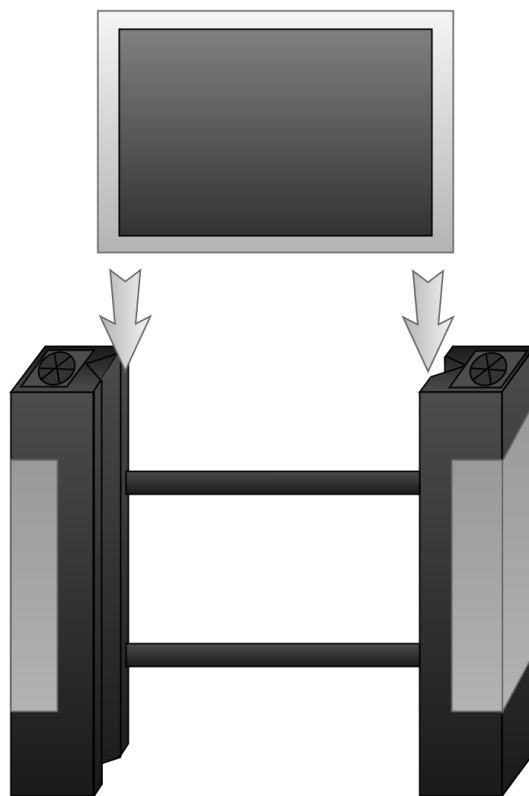


Figure 3.17: Placement of the tablet/smartphone on the portable device.

Those are all the design considerations for now, and the portable device should follow these lines which some will probably need to change during the construction stage, for reasons that are yet to appear. One feature that is very like to need alteration is the own

structure design of the prototype. Both side are considered rectangular now, for prototyping reasons, to see what does and does not fit inside, starting with the maximum allowed size. However, if the handles follow that design, it probably won't be very comfortable to hold a 7cm rectangular object in your hand. Something more ergonomic should probably be considered in the next step. Still, some things are certain, the device construction must always consider the fact that this is meant to be a portable device to be used by visitors in a museum, therefore aspects such as usability, practicality and comfortability are of the uppermost importance.

4 Device Development

ABSTRACT

The chapter explains all the important details for the construction of the portable device's prototype. It starts by offering a general view over the structure and the following steps, going through sensorial interface by interface. Inside each section, it details which components were used, how they were connected and explains eventual changes to the previously designed concept. It also gives the technical specifications of each component and of the PDTTSS itself. The physical casing structure is also detailed in this chapter, evolving a bit from the initial sketch, adapting to the project requires and user comfortability. Its 3D model is presented here, as well as the 3D printed version for the prototype. The position for each component on the structure and assembly is also presented. The microcontroller board, the electronics, the firmware and communication interface are all present in this chapter. The communication protocol is explained as well.

4.1 INTRODUCTION

With the design considerations analysed, it is time to start putting together all the pieces and developing the portable unit, module by module. Although it is somewhat difficult to talk about these systems individually, since they are all interconnected, and were after all somewhat developed in parallel, they will be presented separately in this chapter. The individual analysis of these modules will focus mostly on how the previous mentioned solutions in Chapter 3 were implemented, what particular components were used and why, if possible design changes were made and what problems might have been encountered along the way. In terms of space requirements and arrangements, that will be presented after the individual modules are designed and it is known exactly what is needed, when getting to the part of designing the portable device's structure and casing. The schematics and design representations on this chapter will refer to the hardware present of the left side of the gadget, considered the master side, since it will have the Bluetooth module and the master microcontroller. The right side or slave side, can be somewhat neglectable for now, since it is basically a hardware copy of the master side with some minor modifications. That said, all information, images, diagrams are representing the hardware of the master side, unless specified otherwise.

4.2 THERMAL SYSTEM

As mentioned before, the solution here is to use a Peltier thermoelectric module or TEC, to serve as both a heating and cooling source. These modules are solid-state heat pumps, and they absorb heat from one side and release it on the opposite side, when an electrical current is applied, resulting on a hot and a cold surface. Even though they can produce heat and cold, they are generally used for cooling applications. Peltier devices have many benefits over traditional refrigeration systems, the inexistence of moving parts, their long life and small and flexible shapes are some of them, but they come at the expense of their poor power efficiency and elevated costs. The heat transfer direction can be controlled by the direction of the electrical current applied, therefore it is possible to reproduce heat and cold, on the same side, simply by inverting the supply voltage, which is very useful for the desired application. This way the thermal sensation module only really needs one critical component, the TEC module that generates both heat and cool.

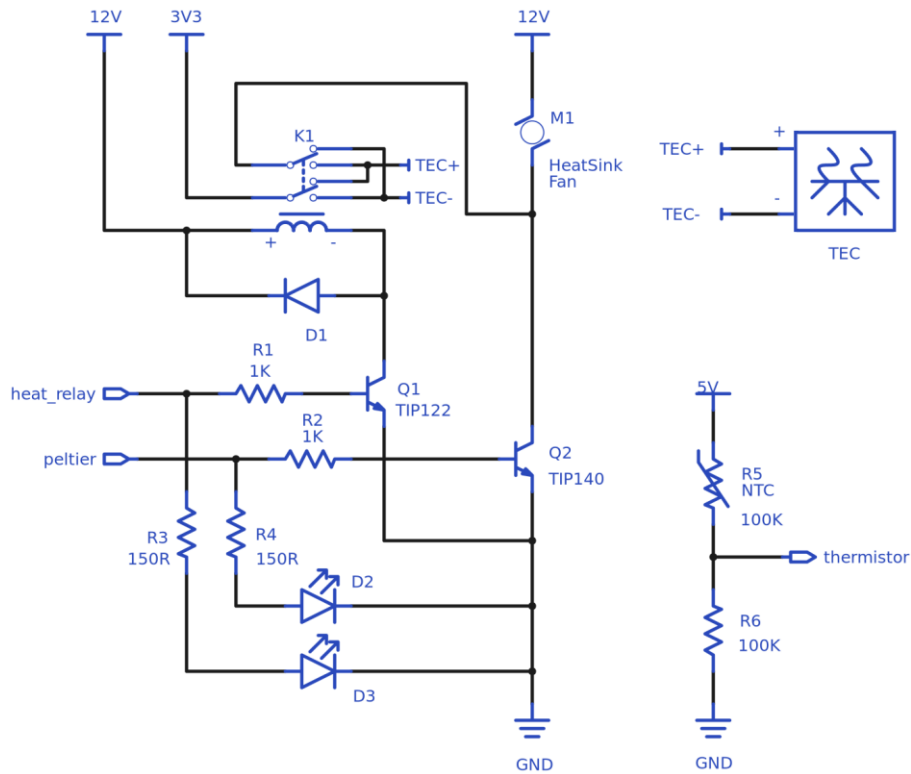


Figure 4.1: Schematic for the thermal system driver.

One way to do that power inversion is by using a transistor bridge using MOSFET's, however this will add more heating losses, need for heat dissipation, and decrease the overall efficiency of the system, which might be already too much for a battery powered device.

Another solution is using a DPDT (Double Pole Double Throw) relay wired in a polarity reversal configuration, as shown in Figure 4.1. This alternative seems ideal for a portable device application, since it has minimal power losses and requires no heat dissipation. Not only that, but since physical space is a project limitation, a single relay solution is going to need less space than a MOSFET bridge with a heatsink. It's also a cheaper a simpler solution, since the transistor bridge requires additional electronic complexity. This will require two outputs from the microcontroller, one for the relay which selects between cooling and heating, and another one to activate the Peltier itself. The relay only inverts the wires, it does not have an off position, that is why a second output for the TEC module is needed. The heat/cool switch is done by a 12V, 75mA coil DPDT 10A relay (K1), which has a flyback diode in parallel, providing a path for the current to flow when the coil is turned off, preventing voltage spikes from arcing on contacts or destroying the switching transistor.



Figure 4.2: Thermoelectric module.

The diode used (D1) is a 1N4001, low voltage drop, high surge current capability, 50V peak repetitive reverse voltage, with an average no repetitive peak forward surge current of 30A. The selected Peltier is a TES1-3104 module, it has a 3.8V nominal voltage, 4A rating, a maximum temperature difference of 68°C (DT_{max}), a maximum refrigerating power of 12.5W (Q_{max}) and its size is 20x20mm. The TEC module has a heatsink fan (M1) that turns on at the same time as the Peltier, to help the interior side stay close to the ambient temperature, so that the exterior handle can reach higher or lower temperatures. This fan is a Sunon Maglev, 12V operating voltage, with 0.44W power and 30x30x10mm size. Both the relay and the Peltier device and fan, are powered by switching transistors since they require a lot more current than the microcontroller could give. The relay's transistor (Q1) is a TIP122 which is a 5A NPN Darlington transistor with V_{CEO} of 100V. An over dimensioned transistor like many other components but with a good margin for prototyping errors. The TEC's transistor (Q2), on the other hand, is a TIP140, a 10A NPN Darlington transistor as well, but with more current capability, since the thermoelectric module has a power rating of 4A and the TIP122 with 5A would be near the limit. In parallel with these transistors are also LEDs, which are meant as physical indicators that those outputs are activated. The first one (D2) is associated with the Peltier, and the second (D3) is attached to the heat relay.

Now all it is missing is a way to read the temperature of the handle so that the microcontroller can decide if it needs to turn the system on or off. This is done via a 100k NTC thermistor (R5), which is placed between the outer side of the Peltier and the haptic handle, configured with a pull-down resistor (R6) also 100k, and the middle node later

connected to an analogue input of the microcontroller. A resting human can put out on average 100W of power [62], considering that the thermal handles will have most of the user's hand on them and considering that each palm of a hand is approximately 1% of total body surface [63], it is relatively safe to estimate that the hand will have a thermal output of 1W. Of course, there are many contributing factors for the heat generation in the human body, like the proximity of internal organs. Still, this is considered a close enough approximation, to allow the following calculations. Now in terms of thermodynamics, Q_{max} is the max amount of heat load the Peltier can transfer from the cold side to the hot side, if running at 100% efficiency, which is never the case, since they have very low efficiency, in this case is 12.5W. The V_{max} and I_{max} are the values for both voltage and current, respectively, that get the better performance out of the thermoelectric module. Finally, the DT_{max} is the temperature difference between the hot and the cold side, that provides better efficiency under no load, 68°C for this module. A simple way to determine whether the Peltier specifications are good for the desired application is by calculating the actual temperature difference between the hot and cold side, which is represented by ΔT (eq. 1).

$$\Delta T = \left(1 - \left(\frac{Q}{Q_{max}} \right) \right) \times DT_{max} \quad (1)$$

Considering Q as the thermal load on the cooling side, in this case the user's hand, then $Q = 1W$, and the equation becomes:

$$\Delta T = \left(1 - \left(\frac{1}{12.5} \right) \right) \times 68 = 62.56 \text{ } ^\circ C \quad (2)$$

This means there will be a real temperature difference of 62.56°C between the hot side and the cold side for this TEC module, using the nominal values of current and voltage, plus proper heat dissipation on the hot side. Therefore, if the cold side should be able to get to 10°C to stimulate the sense of cold in the user's hands, that means the hot side cannot be over 72.56°C. The total heat load of the thermoelectric module (THL) will be the sum between the maximum heat load and the electric power (eq. 3).

$$THL = Q_{max} + P = Q_{max} + (V_{max} \times I_{max}) \quad (3)$$

Replacing the values on the equation:

$$THL = 12.5 + (3.8 \times 4) = 27.7 W \quad (4)$$

That value should be considered when choosing a heatsink for the hot side. Another important factor to have in mind is the fact that Peltier devices should not work for temperatures higher than 80°C, because they will degrade quickly. That said, the heatsink should be able to dissipate 27.7W in a worst-case scenario, and keep temperatures below 80°C for conservation of the module, however it shouldn't get higher than 72.56°C, or the cold temperature will rise above 10°C. If possible, the hot side temperature should be as close as possible to the ambient temperature, reaching cold temperatures faster, which the microcontroller will then turn off and on the device to maintain the desired value.

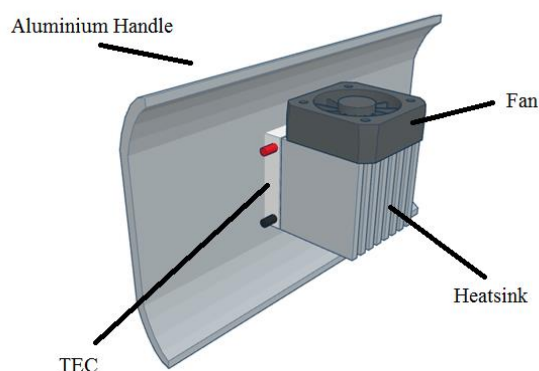


Figure 4.3: Thermal sensation system design.

These calculations are important to check if the thermoelectric module is able to generate enough cold for the application. When activated in heat mode, this becomes kind of irrelevant since its own wasted energy is heat, like any other electric component, which is the desired output in that case. Therefore, the only real concern is about cold generation, if it works well that way, the other way around will work for sure. Figure 4.3 shows the design of the thermal touch handle. The construction consists on the 20x20mm Peltier module for thermal generation, an aluminium plate on the left side of the Peltier to convey the thermal sensation to the user's hand, and an internal heatsink with ventilation on the other side of the Peltier module. The main challenge here is the portability of the system,

therefore power and dimension requirements are quite important. Getting the proportions of the heatsinks right is also critical. Since the space inside will be limited it will be very hard to get a heatsink with the desired specifications.

Another situation is the fact that the aluminium handle outside also serves a heatsink. For that reason, it should be as small as possible, or that will be the one to get closer to the ambient temperature and, instead of cold side getting cold, the hot side will get even hotter, possibly overcoming the maximum allowed 80°C and damaging the thermoelectric module. The contact among the module, the handle and the heatsink must be done with thermal paste to improve thermal conductivity. More details about spatial disposition or placement on the overall portable device structure, along with dimensions, materials and heatsinks will be specified later, on the subchapter dedicated to the casing structure.

4.3 VIBRATION INTERFACE

The vibration system is quite basic, like it was considered in the previous chapter. It simply consists of a small vibration motor fixed to the structure next to handles of the device, one on each side in order to allow for all those previously mentioned navigation functionalities. By sending different vibration patterns it will be possible to create different sensation scenarios, similar to video games.

Figure 4.4 presents the schematic for the vibration system driver. Just like the thermal system, the motor (M2) will be activated from a switching transistor (Q3), to allow it to pull the necessary current and in a way to isolate higher power components from the microcontroller unit. For this, the selected transistor was again a TIP122, a 5A NPN Darlington transistor, which should be more than enough for a little vibration motor, considering prototyping purposes. In the same way as the other outputs, there is a LED (D4) connected in parallel with the transistor base, to provide visual feedback on the physical board, to check if the output was really activated or not. In order to transmit the most compelling sensations to the user, the motor needs to be powerful, which also means it will be large, noisy and inappropriate for portable and museum applications. The other solution would be using a smaller and low powered device really close to the haptic handles that, not only solves the noise issue, but also helps with energy efficiency of the

overall system, allowing the portable device to last longer, during an average museum visit. Therefore, the second option seems more appropriate for this particular application.

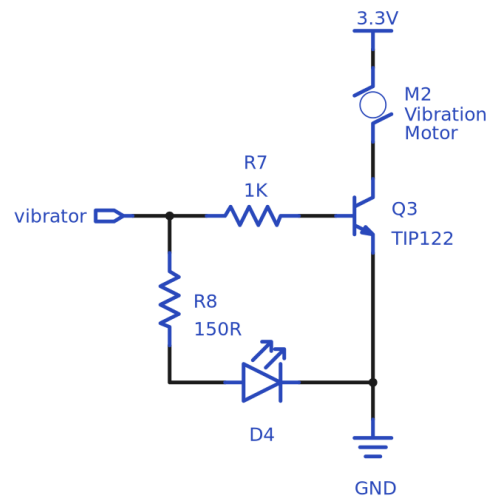


Figure 4.4: Schematic for the vibration system driver.

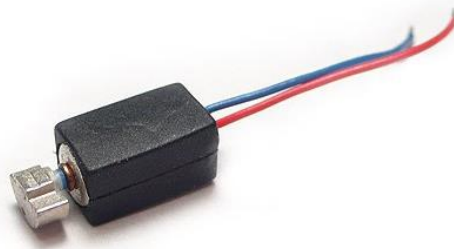


Figure 4.5: Selected vibration motor.

The selected motor has a 3.3V operating voltage and 90mA rated current, with the dimensions of 12x6x3.6mm (Figure 4.5). Since it is so small, it should be relatively easy to place near the handles of the portable device. Although if more intense vibrations are necessary to convey stronger sensations, another motor must be considered.

4.4 AIR INTERFACE

The airflow or wind sensation, as mentioned before, is based on the Smelling Screen prototype [49], using a ventilation system with four fans, two in each side of the device.

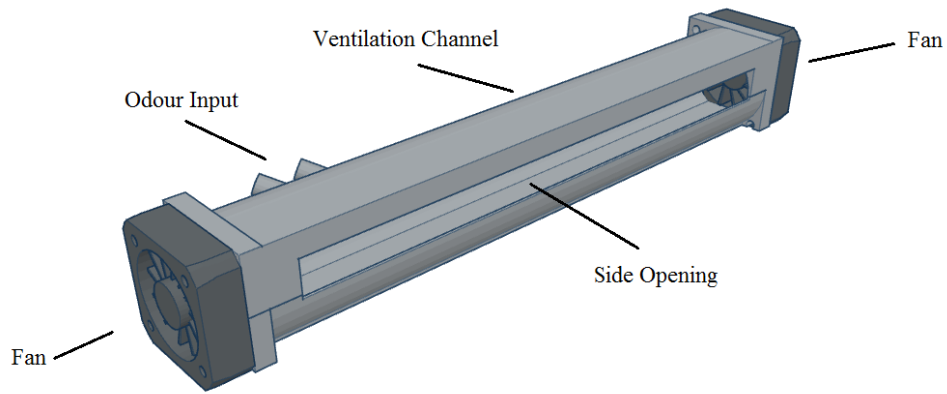


Figure 4.6: Air flow channel design.

Varying the speed of each individual fan allows for control over the air flow point of origin on the screen of the user's device. As depicted in Figure 4.6, the ventilation channel is basically a pipe with a fan on each top and a small opening across the side of the tube. The pipe also has two odour inputs, to insert the fragrances in the ventilation system. The air flow generated by each fan collides inside the pipe and is forced to leave through the side opening. If the fans are rotating at the same speed, considering they are similar, both air flows should also be equal, therefore the collision should happen exactly in the middle of the pipe, and the air will exit in the middle of the screen, as represented in Figure 3.5.

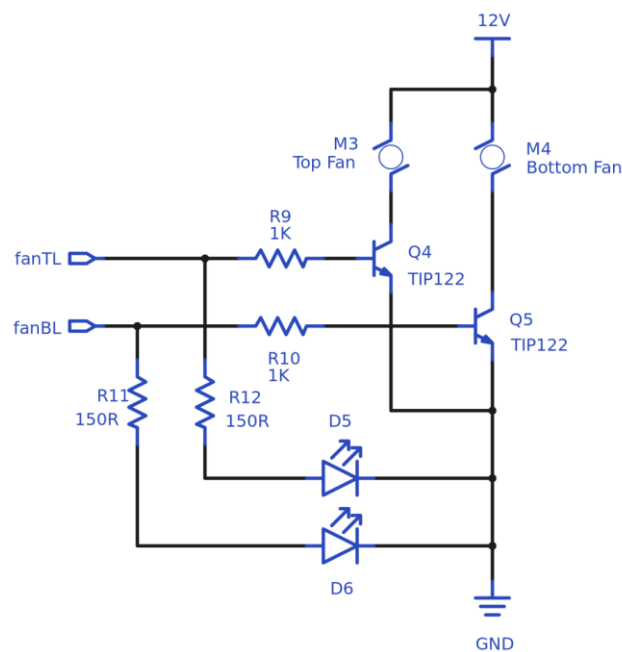


Figure 4.7: Schematic of the ventilation system driver.

The electronic circuit for the fans driver is straightforward, as shown in Figure 4.7, two fans (M3 and M4) activated by two switching transistors (Q4 and Q5 respectively), which are both TIP122 5A NPN Darlington transistors, again overengineered but chosen for prototyping reasons, which can later be replaced by a more suitable transistor. Like all previous outputs, these transistors also have LEDs in parallel with their bases (D5 and D6), to represent whether the respective output is activated or not.



Figure 4.8: Sunon Maglev fan 30x30x10mm.

The fans (M3 and M4) in use are Sunon Maglev with 12V operating voltage, 0.44W consumption power, a 30x30x10mm size, a rotational speed of 7000rpm and a static pressure of 2.033mmH₂O (Figure 4.8). Details on the placement of the ventilation channel inside the portable unit will be presented in the casing section.

4.5 TASTE INTERFACE

Taste is probably the most difficult sense to stimulate digitally, so the chosen solution is to use an electronic vaporizer to recreate different flavours. There are a few different types of vaporizers, although they all work on the same principle of heating the flavour or “e-liquid” to a temperature of vaporization. As it was studied before, they have two main components, the heating element and the battery. The heating element is where the liquid is stored and vaporized, while the battery has the power source and the electronic controller board. For this prototype, only the heating element is required, since the battery and controller will be part of the design. The atomizer is a generic term referring to the heating part of the vaporizer, but there are a few different types with different designations as represented in Figure 4.9, the atomizer itself, the cartomizer and the clearomizer are three of the most common ones.



Figure 4.9: Types and parts of vaporizers [64].

The atomizers are one of the original devices, they have a small liquid capacity and usually have a heating coil on the bottom with a metal mesh above the coil. The cartomizer has a similar design but instead of a mesh, it has polyfill wrapped around the heating coil which soaks the liquid and allows for longer usage. Finally, the clearomizer, it is the most common one, they consist of a clear polycarbonate plastic or Pyrex glass tank, which allows you to see the level of the liquid inside, the liquid is absorbed by silica wick and delivered to the heating coil.



Figure 4.10: Clearomizer tank (left), clearomizer threaded connector (right).

The selected one for this prototype is a clearomizer, shown in Figure 4.10, although slightly more expensive, they have a larger liquid capacity, typically around 1.6 and 3ml, have longer life cycles and are easy to check the level of liquid in the reservoir. The electronic driver is represented in Figure 4.11, and it is quite similar to the wind system circuit, the vaporizers, which are basically just resistors (R17 and R18), are connected through switching transistors (Q6 and Q7). These vaporizer resistors are typically very low, which means that currents will be high.

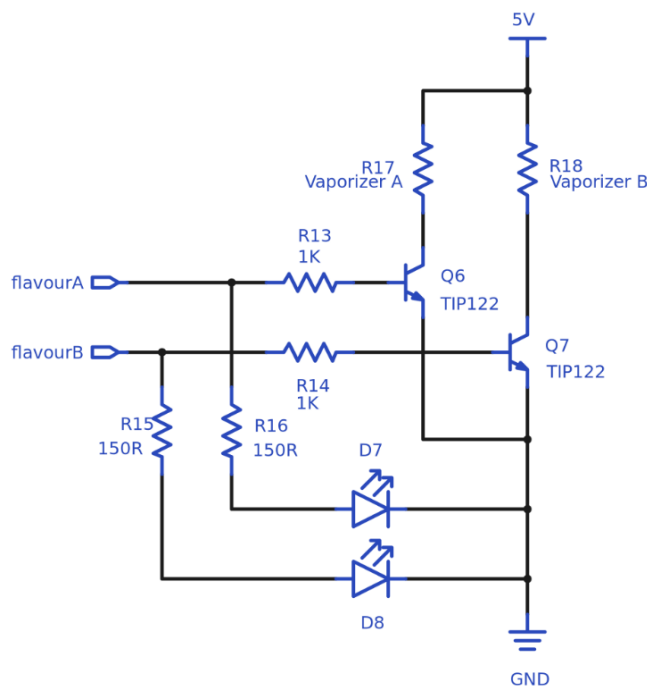


Figure 4.11: Schematic for the taste system driver.

The clearomizers usually have a heating resistor of around 0.75 to 2.4Ω and a power of 8 to 25W , with an operating voltage of typically around 3V to 5V . Since energy consumption is important for portability reasons, the selected clearomizer has a 1.8Ω heating resistor, 5V nominal voltage, which translates to a power of 13.89W and current of 2.77A . That means that the switching transistors can still be the same TIP122 5A NPN Darlington transistors, although they will require a heatsink. Once again, the operating status outputs are physically signalled by LEDs (D7 and D8). As for the clearomizers, since they have a threaded pattern connector on their base, that will be system to plug them in and out of the prototype, which also allows for simple and quick replacement of the tank or flavour if desired. More details on that in the casing section.

4.6 SMELL INTERFACE

The selected system here was using a forced flow of air through an aromatized container, which is then inserted into the fan ventilation channels. Following a similar approach to the olfactometer, but using a small fan to generate the airflow instead of pressurized air. It basically consists of an oil wick air freshener, where the oil fragrance in a small bottle is absorbed by the wick which transports the oil from the bottle to the collar in a closed chamber.

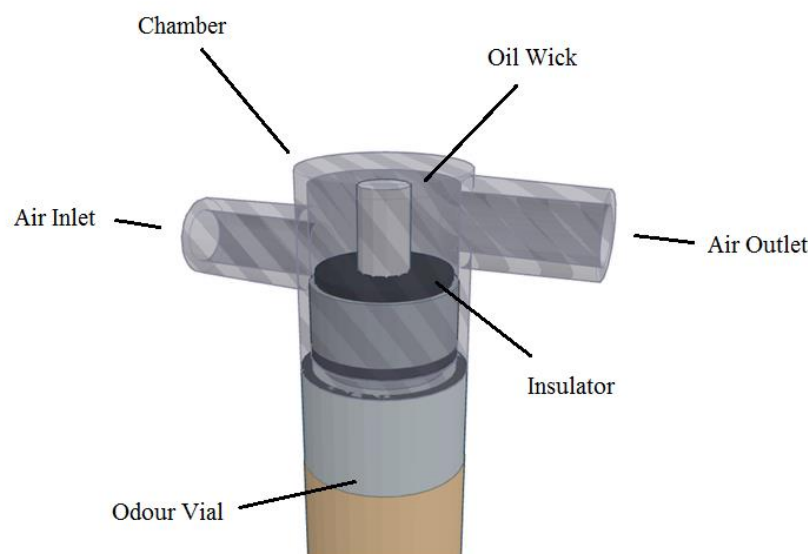


Figure 4.12: Fragrance chamber design.

This chamber, depicted in Figure 4.12, has an air inlet and outlet, when the smell system is activated, a small fan will push the air through the chamber inlet, which forces the oil to mix and slightly evaporate into the air, and exit through the outlet, directly into the ventilation channel. There are two fragrance bottles, two chambers and two inlet fans in each side of the device, therefore creating a total of four different smells in the portable device. In between the odour vial and the oil wick, there should be a rubber insulator to serve as a cover, to protect against spilling, since this is a portable unit in the user's hands, and there is no way to guarantee in which position the user will move it. The forced airflow for the smell system will be generated by a small fan, for each odour. The fan is attached to an air funnel, which concentrates the flow into one single outlet, represented in Figure 4.13, which is later connected to the air inlet of the fragrance chamber.

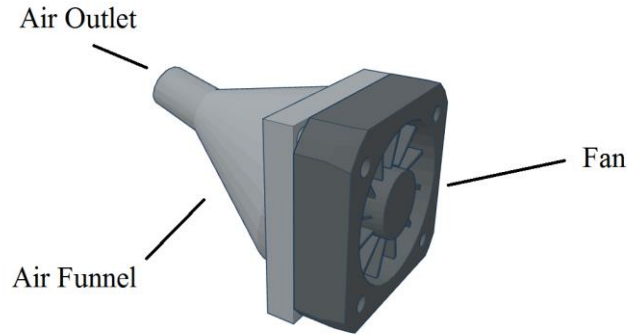


Figure 4.13: Air generation design for the smell system.

This solution is preferred in terms of noise and size, since air pumps or pressurized air canisters would require more space and/or produce more noise, even though this alternative might produce a weaker flow. This fan can be as small as 20x20mm and still generate a sufficient airflow to carry and disperse the odour. Regarding the flow valves, for now they are being ignored, since the insulator guarantees there is no fluid leaks, and the available space might not be sufficient for them.

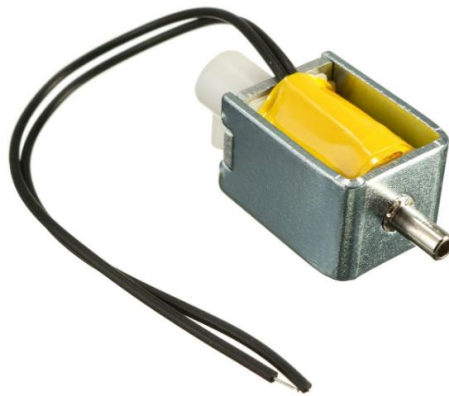


Figure 4.14: Solenoid air valve.

However, if later they are needed to avoid ambient contamination, one option would be using small solenoid air valves as the one represented in Figure 4.14, which is a 3V, 60mA air valve, capable of withstanding a maximum pressure of 350mmHg with a size of 20x15x13mm. They exist with the possibility of a simple normally open or normally closed valve or a three-way position with a common end, one normally closed and a normally closed position.

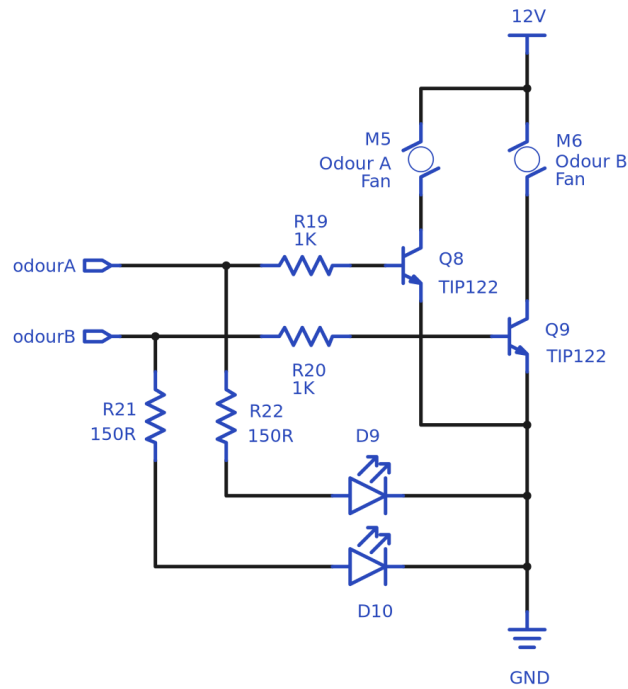


Figure 4.15: Schematic for the smell system driver.

The electronic driver is exactly the same used for the taste system, the only difference being the use of two micro fans (M5 and M6) instead of the vaporizers (see Figure 4.15). They both are activated by TIP122 5A NPN Darlington switching transistors (Q8 and Q9). They are also both signalled by two LEDs (D9 and D10). If valves need to be added, they can be connected in parallel with the fans. The fragrance vial being used is a small glass flask, similar to those used in perfume samples, the chamber is 3D printed in flexible material.



Figure 4.16: Sunon Maglev micro fan 20x20x10mm.

The fans are Sunon Maglev GM0501PFB3-8, with 5V operating voltage, 0.2W consumption power, a 20x20x10mm size, a rotational speed of 7000rpm and an air flow of 0.86CFM (Figure 4.16).

4.7 CASING STRUCTURE

With all the physical outputs decided, it is time to start designing the actual structure of the portable device. Considering the concept requirements for this project in terms of size, sensorial interfaces and practicality, a new sketch was designed with round edges, a lower height of 52mm and also a reduced width of 57mm, to improve comfort while holding the device, as represented in Figure 4.17. The length is kept at 250mm.

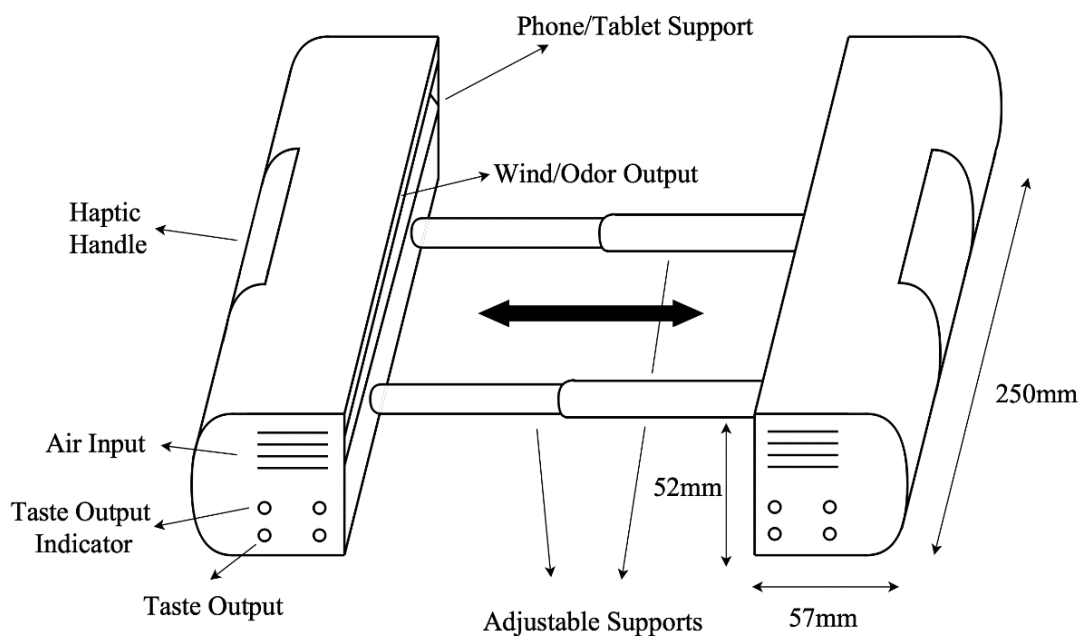


Figure 4.17: Second design sketch for the PDTTSS.

The idea is to design the 3D model of the entire structure, considering all components and interfaces to be used, their dimensions and positions. Then, respecting their requirements, such as having the thermal system and vibration motors near the handles, the wind/airflow output to the inner side of the module, over the user's mobile device, the taste output on the bottom part of the portable unit, a place for the electronic board, a space for the battery and an easy way to access and replace the odours and flavours. Not forgetting about comfort, usability and flexibility to adapt to multiple mobile devices. The 3D model design was an iterative process, almost like putting together a big three-dimensional puzzle. The software used was the online, browser based, Autodesk's Tinkercad. Figure 4.18 shows the final 3D model, without covers, for the portable device. It consists of two sides attached together via the adjustable supports.

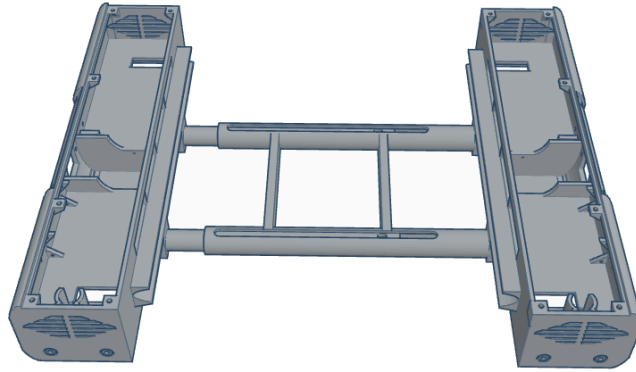


Figure 4.18: 3D Model for the portable device.

Another design consideration is the fact that the prototype will be 3D printed, therefore the 3D model has to be carefully designed to avoid certain problems. The mobile support had to be designed outward, beyond the 52mm limit in order to save space. If the cut was done inwards, it would just steal available space inside the PDTTSS, limiting even more the components placements. To optimize the usage of space, the volume inside was separated into two floors.

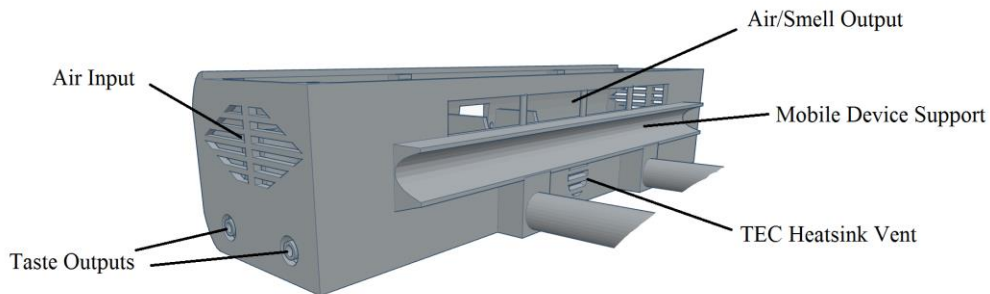


Figure 4.19: Detailed 3D model inner side view.

Figure 4.19 represents the side view of the 3D model, as it is observable on the left of the image, which is actually the bottom side of the device, there is the air input and the two taste outputs. Note that there is also another air input on the opposite side of the device. On the central part of the structure there is the mobile device support, which is meant to hold the user's smartphone or tablet, it should be coated with rubber to increase friction and keep the device from sliding in the rail. Right above that, there is the air/smell output, to make sure they are dispersed just on top of the user's device. Finally, there is the TEC heatsink vent, which serves as an output for the airflow used to cool the Peltier heatsink.

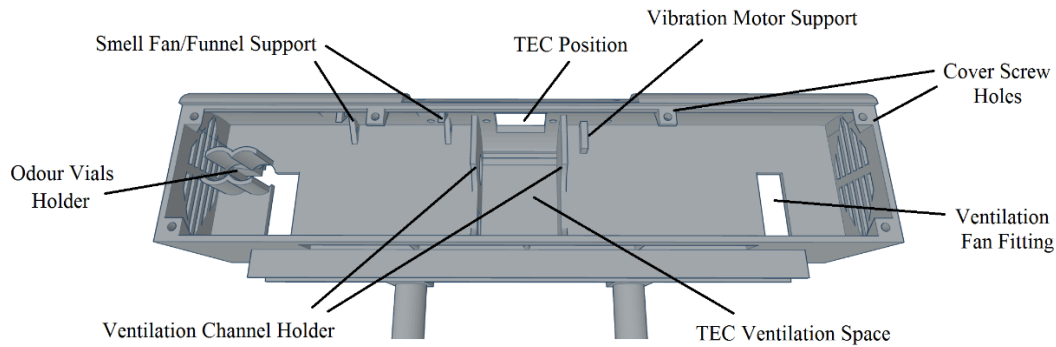


Figure 4.20: Detailed 3D model top view.

The top floor of the portable device is represented in Figure 4.20. There, it is possible to observe some essential parts of the structure, like the square hole for the thermoelectric module, the odour vials holder that will keep the fragrance chambers in place, the supports for the smell micro fans, among others. The middle section is an empty area that will serve as an air duct for the Peltier heatsink forced airflow.

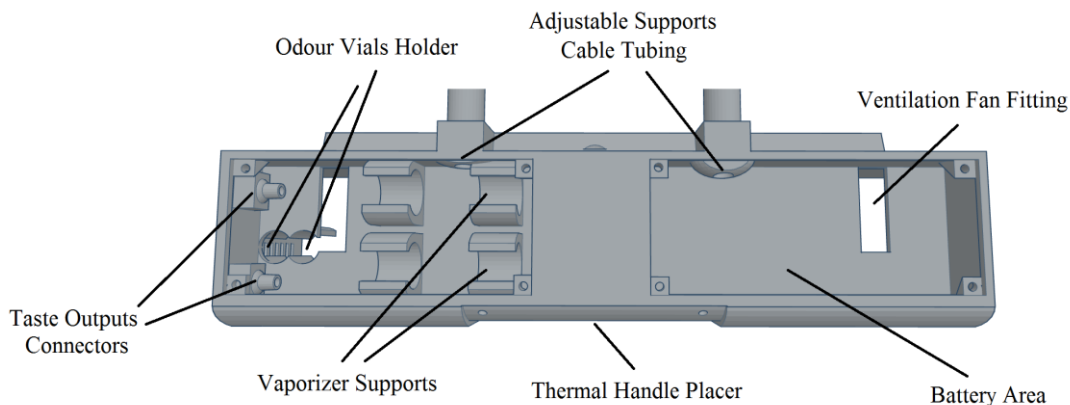


Figure 4.21: Detailed 3D model backside view.

On the other side, Figure 4.21 represents the backside of the structure. This floor will be composed of two compartments, the one on the right side of the image is an area reserved for the battery, even though it is not yet decided which one to use, and the available space can hold a battery size up to 100x30x13mm. The area on the left is meant to be an easy access to the odour and flavour reservoirs, by opening the cover of this area, fragrance vials or taste vaporizers can be easily replaced. The adjustable supports are hollow inside to allow the passing of cables from the left to the right side of the portable device, the serial communication between the master and slave microcontrollers.

4.8 ASSEMBLY

With the interfaces all ready, and the structure designed, it is finally possible to start integrating all modules into one. Figure 4.22 shows how the ventilation channel attaches to the portable device. With the fans fixated to the ventilation channel, the module is simply place down from the top. The fans are placed close to the air inputs. The side opening will match the air/smell output from the casing, the curvature of the channel also fits the curvature on the structure base which together with the fan fitting holes, keeps the channel in place.

The structure of the portable device was 3D printed in PLA to start the assembly of the modules. The ventilation channel and the left side of the structure are presented in Figure 4.23. The image on the left represents the ventilation duct, which was also 3D printed. The 30x30mm fans were screwed to the channel. The image on the right shows channel placed inside the gadget's base structure.

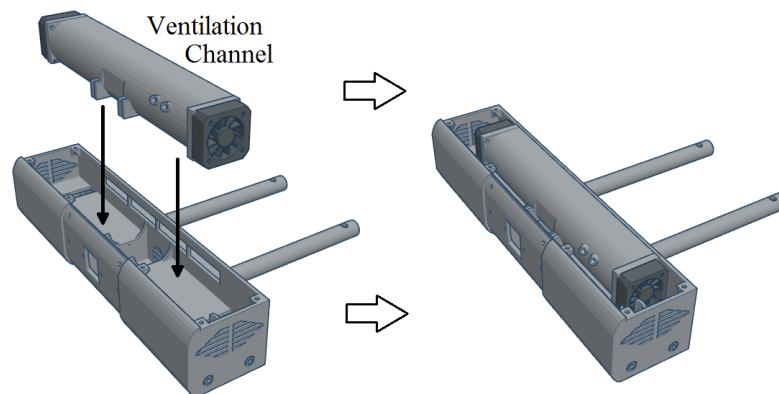


Figure 4.22: Ventilation channel assembly.

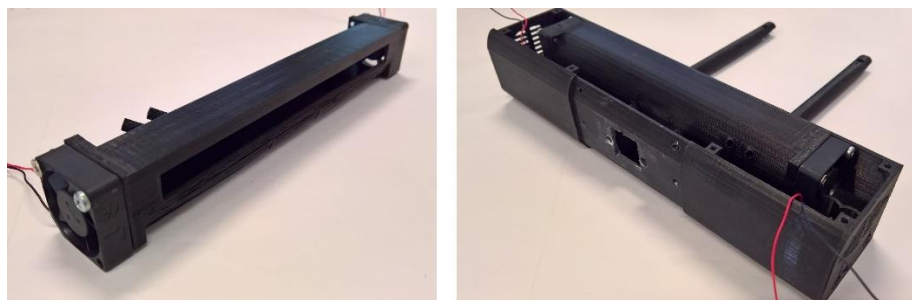


Figure 4.23: Printed ventilation channel (left) and structure (right).

Next to fit the structure is the thermal system, as represented in Figure 4.24. The Peltier is placed on its square lateral hole, locked from the inside with the heatsink, and on the outside with the aluminium handle. In between the TEC module and the handle there is the thermistor, to allow a temperature reading as close as possible to the user's hand. The heatsink on the hot side of the Peltier is cooled down with the micro fan on top.

The images of Figure 4.25, represent the physical assembly of the thermal system onto the portable structure. In the image on the left, it is possible to see the aluminium handle and the Peltier module attached to a small heatsink with the thermistor on the other side. Because of the already occupied space, the maximum size of the heatsink that it was possible to fit inside was 20x20x20mm. The ventilation channel on the front does not allow the use of a larger heatsink. Which might be problematic if this heatsink does not prove to be enough to cool down the hot side of the Peltier even with a forced airflow. The micro fan on the heatsink is not represented on the image; however, it was added on a later occasion.

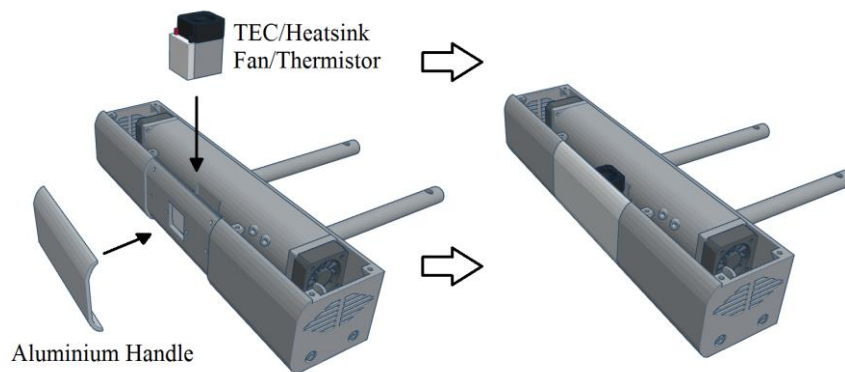


Figure 4.24: Thermal system assembly.



Figure 4.25: Thermal parts (left), TEC assembled (centre), handle assembled (right).

The smell module assembly follows, as shown in Figure 4.26. The micro fans that generate the forced airflow necessary to the smell system, are attached to the 3D printed funnels and locked in place in their respective structure support. The fragrance chambers were fused into just one piece, 3D printed in flexible material, that holds the two vials and has the two air inputs and two outputs. The outputs from the funnels connect to the inputs of the chambers, then the chambers outputs connect with the inputs on the side of the ventilation channel, where the aromatized air is mixed with the wind system. These airflow connections are made with silicone flexible tube. Figure 4.27 represents the smell system components, on the upper line it is visible the odour vials, fragrance chamber, micro fans and funnels. The bottom line images show these parts assembled in the device structure.

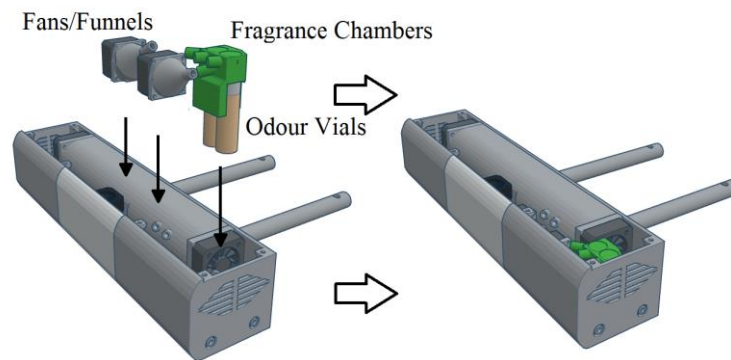


Figure 4.26: Smell system assembly.

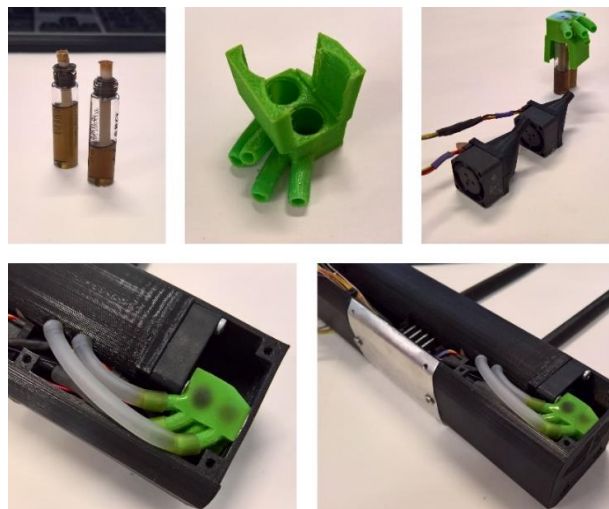


Figure 4.27: Smell system parts (upper line), assembled components (bottom line).

The vibration motor is placed near to the thermal module and locked in place in its correspondent structure support. The available space on the top floor is reserved for the circuit board, as represented in Figure 4.28. In the same way as the battery, it is not yet designed a final version, however the available volume can hold a multi layered PCB up to 18x96x19mm. It is a small space, but it is possible to design a PCB that fits that area.

The vibration motor and the electronics are shown in Figure 4.29 placed in their locations inside the portable structure. The motor is visibly close to the thermal system, therefore close to the centre of the handle to help convey vibrations better to the user. The electronics board was not yet developed, however for now the space is occupied by two Arduino Nano boards to represent the available space inside the structure of the top floor. Each Arduino Nano board has an area of 17.78x43.18mm. And there is still space available vertically.

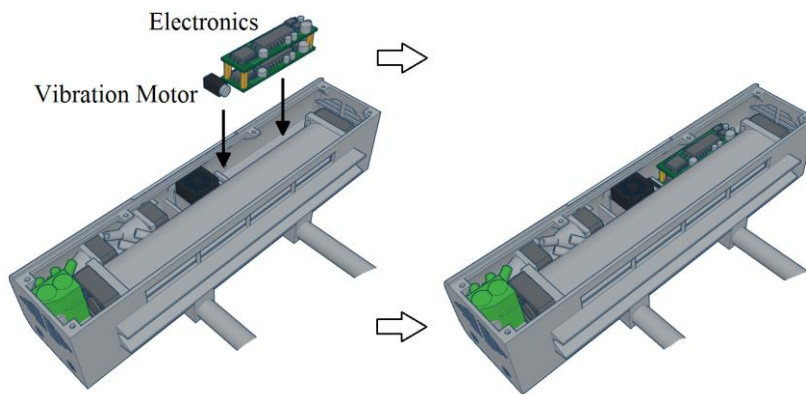


Figure 4.28: Vibration system and electronic board assembly.

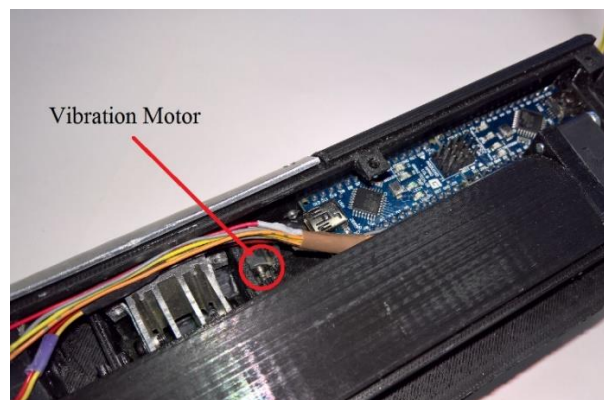


Figure 4.29: Vibration motor and electronics inside the structure.

After finishing with the top floor, it is time to turn to the bottom floor, Figure 4.30. The vaporizer holder has the threaded connector attached to the portable device's structure, so the vaporizers can just be screwed in placed and they will guarantee a good electrical connection. The mouthpiece of the clearomizers is connected to the taste outputs via a flexible silicon tube, like the one used in the smell module. A flexible 3D printed part was necessary to attach the mouthpiece to the silicon tube, and to make sure the connection would not have pressure leaks. This opening on the back also allows to reach and replace the odour vials when necessary.

The taste system is shown in Figure 4.31. The left image shows the clearomizers with different flavoured liquids, the centre image shows the threaded connectors on the portable device and the image on the right shows the vaporizers screwed in their place. It is also visible the 3D printed flexible cap, that makes the connection between the mouthpiece of the clearomizers and the taste outputs on the bottom of the structure. Although not visible in the figure, behind the taste vaporizers there is also the LEDs that work as taste output indicators. They tell the user when to suck on the pipe.

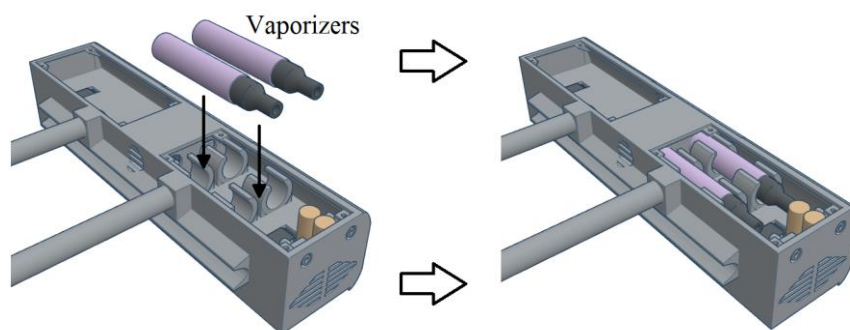


Figure 4.30: Taste system assembly.



Figure 4.31: Taste vials (left), connectors (centre), vaporizers (right).

Once the vaporizers are in place, the only thing left to do in the bottom floor is to insert the battery in its respective place, Figure 4.32. However, like it was mentioned before, since the interfaces of the prototype are not yet guaranteed to work, the energy consumption and durability calculations to choose a battery have not yet been done.

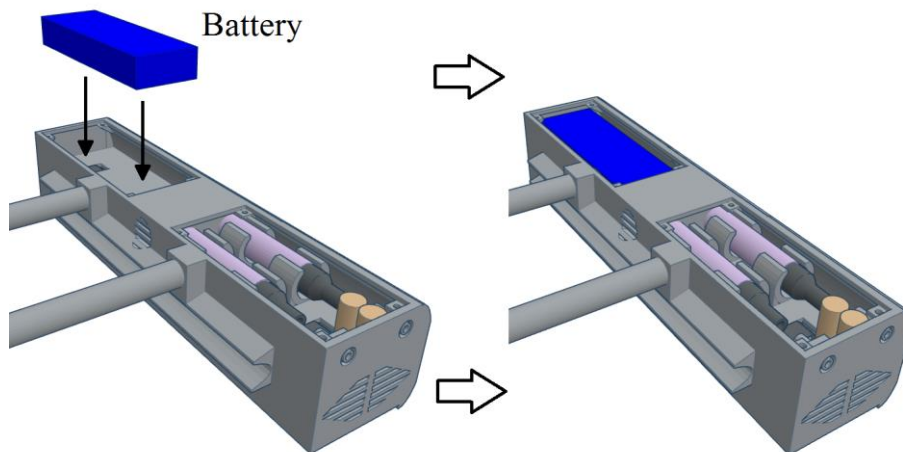


Figure 4.32: Battery assembly.

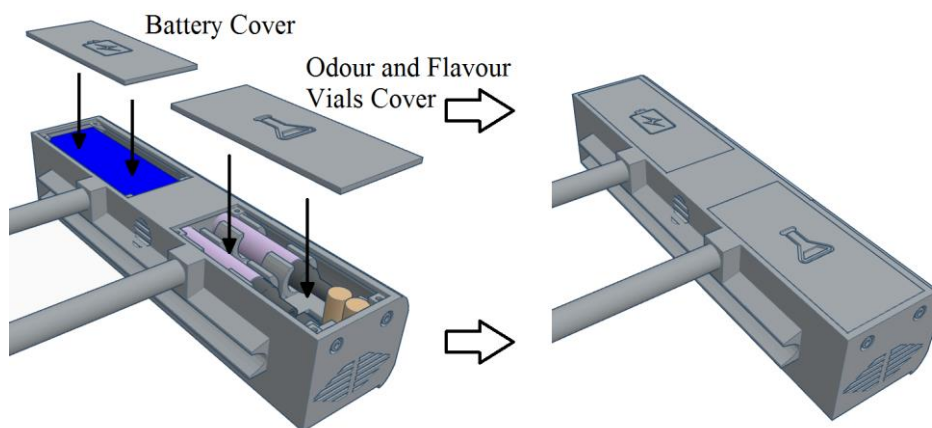


Figure 4.33: Back covers assembly.

Having set up the vaporizers and battery in their respective places, the backside of the portable device can be closed with its covers. There are two separate covers, one for the battery and one for the smell and taste reservoirs as represented in Figure 4.33. This way, only one cover has to be opened in order to refill or replace the odours and flavours of the device. Each cover is correctly identified to allow easy understand of which is which.

With the backside all done, it is time to return to the frontside. Unlike the backside, the frontside only has one single cover as its shown in Figure 4.34. It protects all the physical interfaces on the upper floor, as well as the electronics board. The cover also has an air vent in the middle, next to the thermoelectric module. It serves as an air input for the micro fan that cools down the Peltier heatsink, that air flows through the middle section of the portable device and exits through heatsink vent on the inner side, right under the user's mobile device, as is represented in Figure 4.19.

The gadget's left side is now concluded, as represented in Figure 4.35. The front cover was the last element to be added, which was also 3D printed. This part is ready to be attached to the one on the right side.

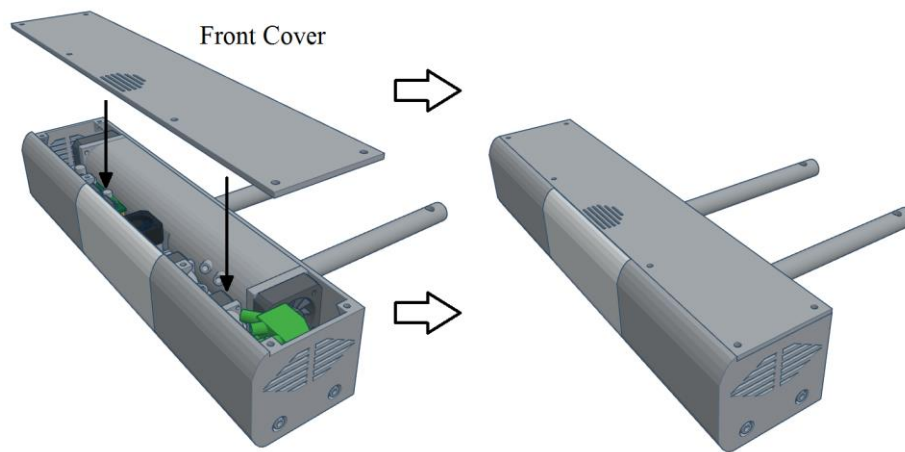


Figure 4.34: Front cover assembly.



Figure 4.35: Left side of the portable device finished.

The left side is now assembled. The procedures on the right side are exactly the same however symmetric. Having the two parts ready, the final step is putting them together, represented in Figure 4.36. The adjustable supports on the left are smaller than the ones on the right, so one fits inside the other. The left supports have holes on the tips, while the supports on the right have a side opening, this way the can move closer or further to each other, to adapt to multiple devices widths. The minimum possible width is 170mm while the maximum is 305mm. The holes and openings serve as places for the manual mechanical screws that locks the supports into one position. These supports are hollow so that wires can go from one side to the other, for the serial communication line between microcontrollers.

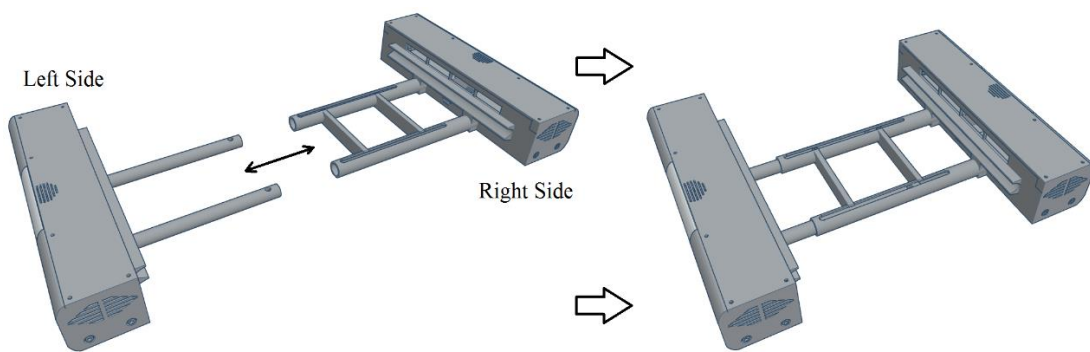


Figure 4.36: Final assembly of both sides.



Figure 4.37: Portable device assembled.

Figure 4.37 shows the finished PDTTSS, mostly 3D printed and fully assembled with all the previously designed sensorial interfaces. Now all it is missing is a mobile device, such as a smartphone or a tablet.

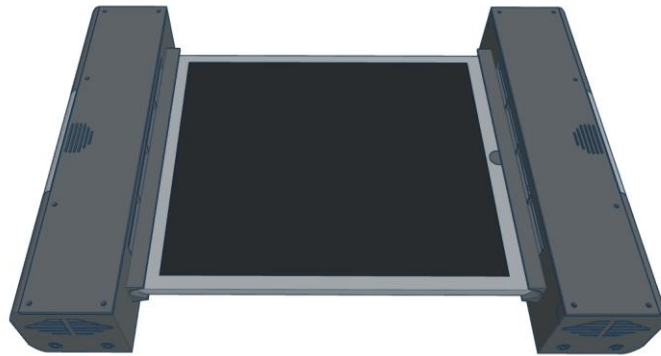


Figure 4.38: 3D Model of the portable device with a tablet.

Figure 4.38 represents the finished 3D model for this project. It also represents a mobile device attached to it, in this case a tablet with the dimensions of 240x170mm, as a way of representing scale.



Figure 4.39: Portable device assembled with a tablet.

The real prototype is shown in Figure 4.39, also with a tablet, an Asus Zenpad 3S 10, which has a size of 240.5x163.7mm. On the frontal bottom side, the air inputs and the taste outputs are visible. The curved shaped of the mobile device support proved to be effective for holding the device, however depending on the position of the camera on the tablet and its thickness, it is possible for some devices to have the camera obstructed by the 3D printed structure, which should not happen.

4.9 MAIN BOARD

In terms of electronics, most of the electrical schematics have already been presented individually by sensorial stimulus. However, besides those there is still the main board diagram, both for the master device (left side) and slave device (right side). The chosen microcontroller for this is an ATmega328P, since both Arduino Uno and Nano were used for tests and while developing the prototype.

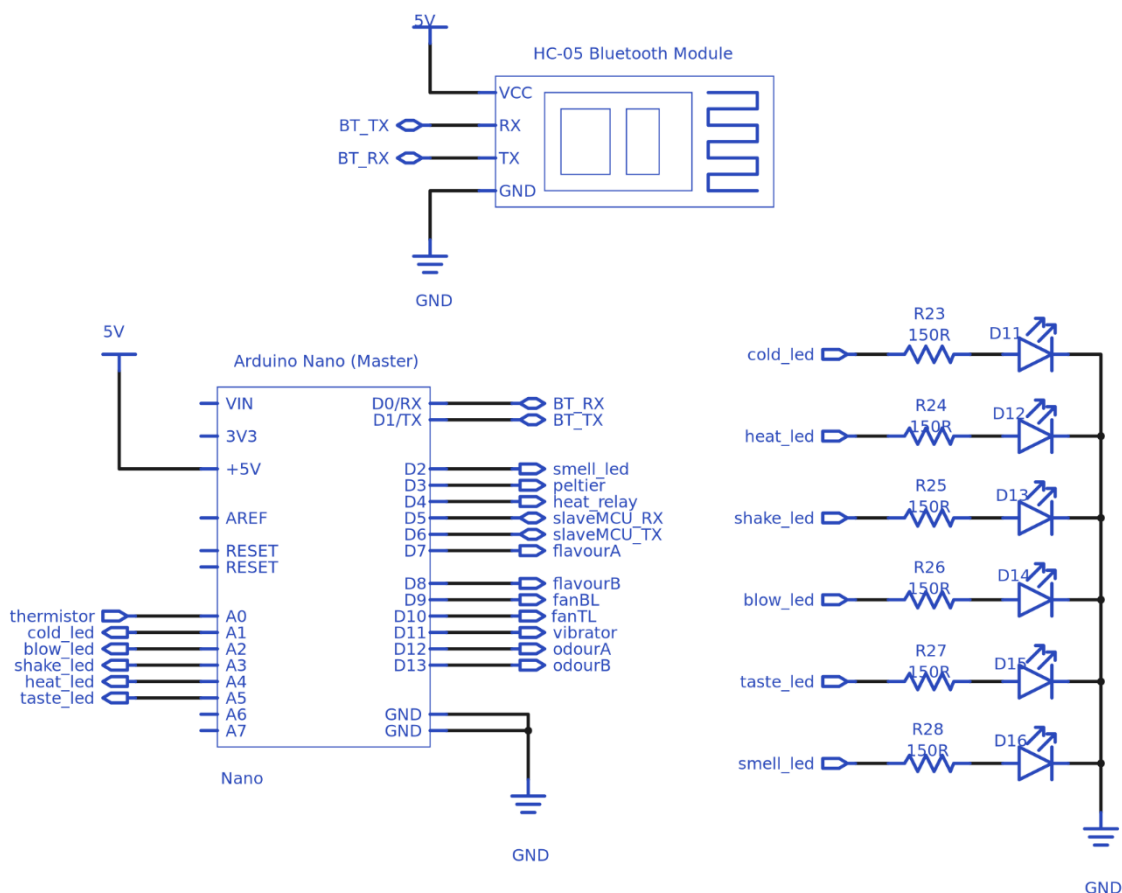


Figure 4.40: Schematic for the main board of the left side (master).

The master microcontroller represented in Figure 4.40, will be responsible for all devices on the left side of the portable device. Also, as was mentioned before, it will be the one that connects to the application via Bluetooth, receiving sensorial reproduction instructions. In case it needs to activate interfaces on the right side, it will resend the instruction to the slave microcontroller via serial communication. Since the microcontroller only has one serial port and it is already in use by the Bluetooth module,

this communication between master and slave is done with a software serial function on pins D5 and D6 of the master Arduino Nano. On the side of the slave microcontroller, since there is no Bluetooth module, the normal serial port of the ATmega328P, which correspond to pins D0 and D1, can be used. The output pins on both microcontrollers will activate the switching transistors of the respected interfaced, and represented in previous diagrams.

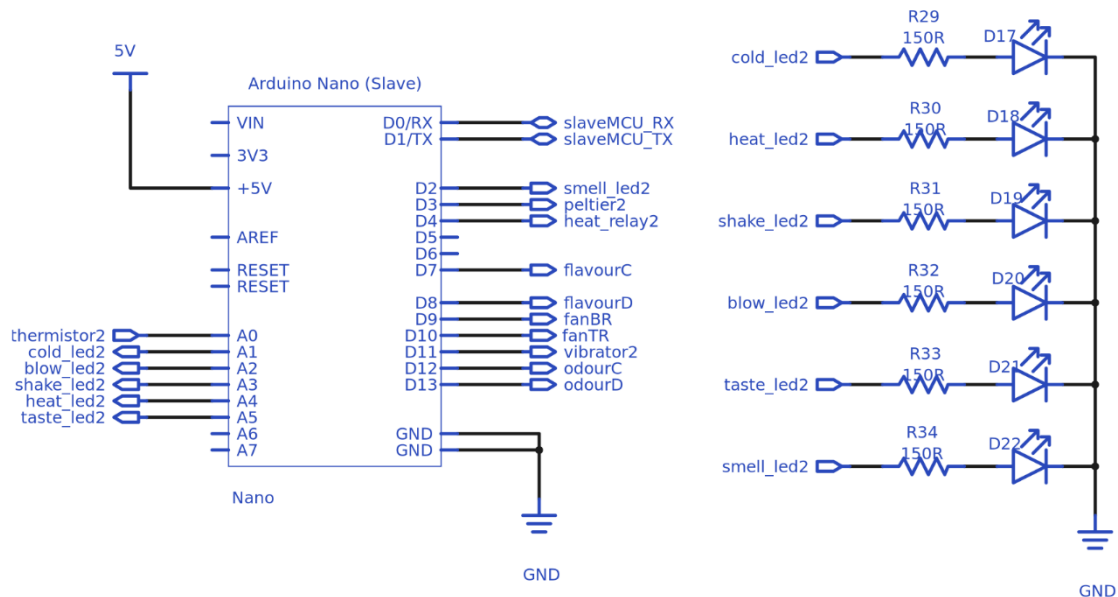


Figure 4.41: Schematic for the main board of the right side (slave).

Regarding those switching transistors, it is important to mention that some of them will require heat dissipation, therefore the circuit board must consider the required space for heatsinks. The LEDs on both these diagrams should not be confused with the LEDs used in the previous sensorial specific schematics, those represented a physical way to tell if the outputs were being activated, while these shown on Figure 4.40 and Figure 4.41, are directly associated with the working modes in the firmware. Each time a different system is activated, that respective mode turns on a flag, which will then activate the appropriate outputs when the firmware decides. That means that for example the shake led on the left side (D13) on Figure 4.40 and the LED in parallel with the switching transistor for the vibration motor on the left side (D4) on Figure 4.4, might not always turn on at the same time. One particular situation when this happens is the example when the vibration is activated for ten seconds in intermittent pattern. Even though the mode LED (D13) will

be turned on for ten seconds, the motor LED (D4), will blink with the interval period defined by the intermittent pattern. That's the main difference between those LEDs. The other ones are directly attached to the outputs, while these ones to a mode requested by an instruction. The circuit of the main board is powered by 5V however some of the interfaces require a 12V or 3.3V power supply. During prototyping tests, a single voltage power supply was used, but the 12V and 3.3V lines were created with DCDC converters.

4.10 FIRMWARE

The pretended portable device is supposed to be capable of reproducing multiple sensorial stimulus at any desirable moment, sometimes it might be just a single sensation, but other times it might be all at once. For this reason, an asynchronous firmware had to be developed. Instead of having a particular function or sensorial interface occupying the processor until it finishes, everything was designed based on timings. This way the microcontroller can activate multiple stimulus at the same time and still be able to communicate without getting stuck. The idea is that every action has to be temporized, any reproduction request must indicate the duration for that particular task.

The microcontroller starts by getting the time in every loop, when a new instruction arrives, that instruction mentions what interface should be activated, which settings it should have and how long it will last. The microcontroller then calculates the timer for when it should deactivate that interface, by adding the desired duration to the current time. Then, a flag for that interface is activated, which is the mode flag, the same that is connected to the mode LEDs. When the loop is confirming if it should process a certain sensorial module, it checks if its respective flag is activated or not, if so, it enters that process and activates the outputs. Each loop that runs with an active flag, the firmware also checks if the timer for that interface has expired, if that is the case then the flag is reset. The firmware was designed to never depend on a delay function, so it would never freeze while executing a request.

Figure 4.42 represents that main loop of the firmware, where it starts by getting the current time and also the temperature read by the thermistor. The sensorial interfaces were given short names to simplify the protocol, making it lighter and faster. They are here presented as cold, heat, blow (air/wind), shake (vibration), taste and smell.

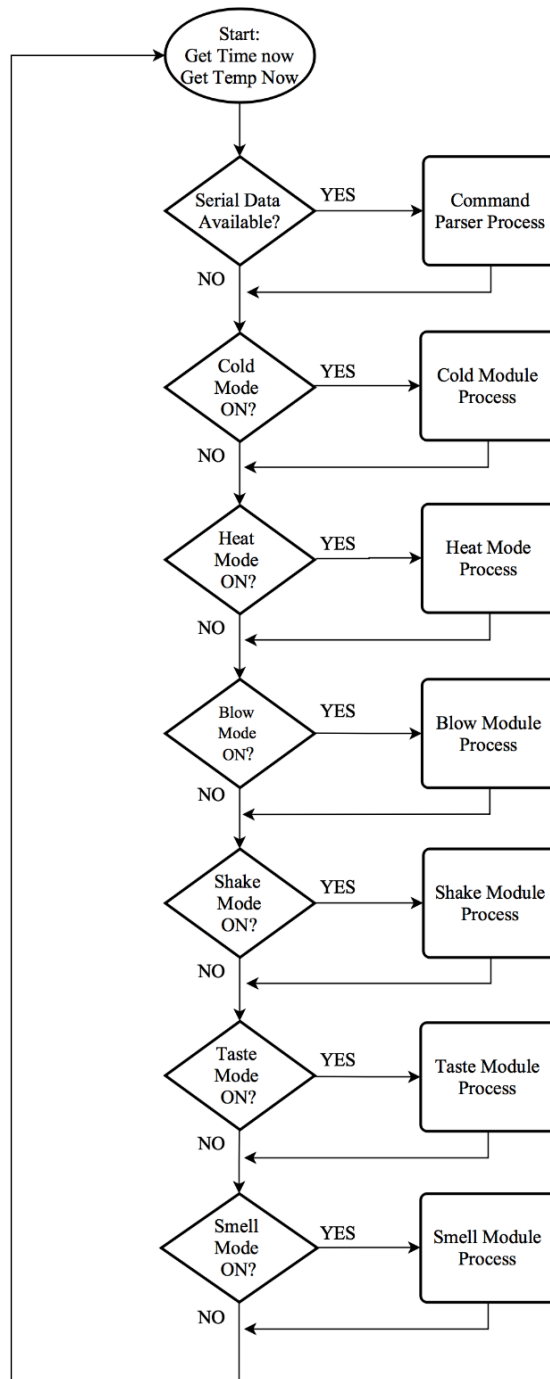


Figure 4.42: Firmware main loop flowchart.

After getting the time and temperature reading, it checks whether there is data available of the serial buffer or not. If there is data on the serial buffer, then there is a new instruction awaiting to be read, therefore the firmware enters the command parser process, where it reads the new command, checks if it is a valid instruction, and either activates the respective flag and outputs or delivers an error message through the serial port. This is represented in Figure 4.43.

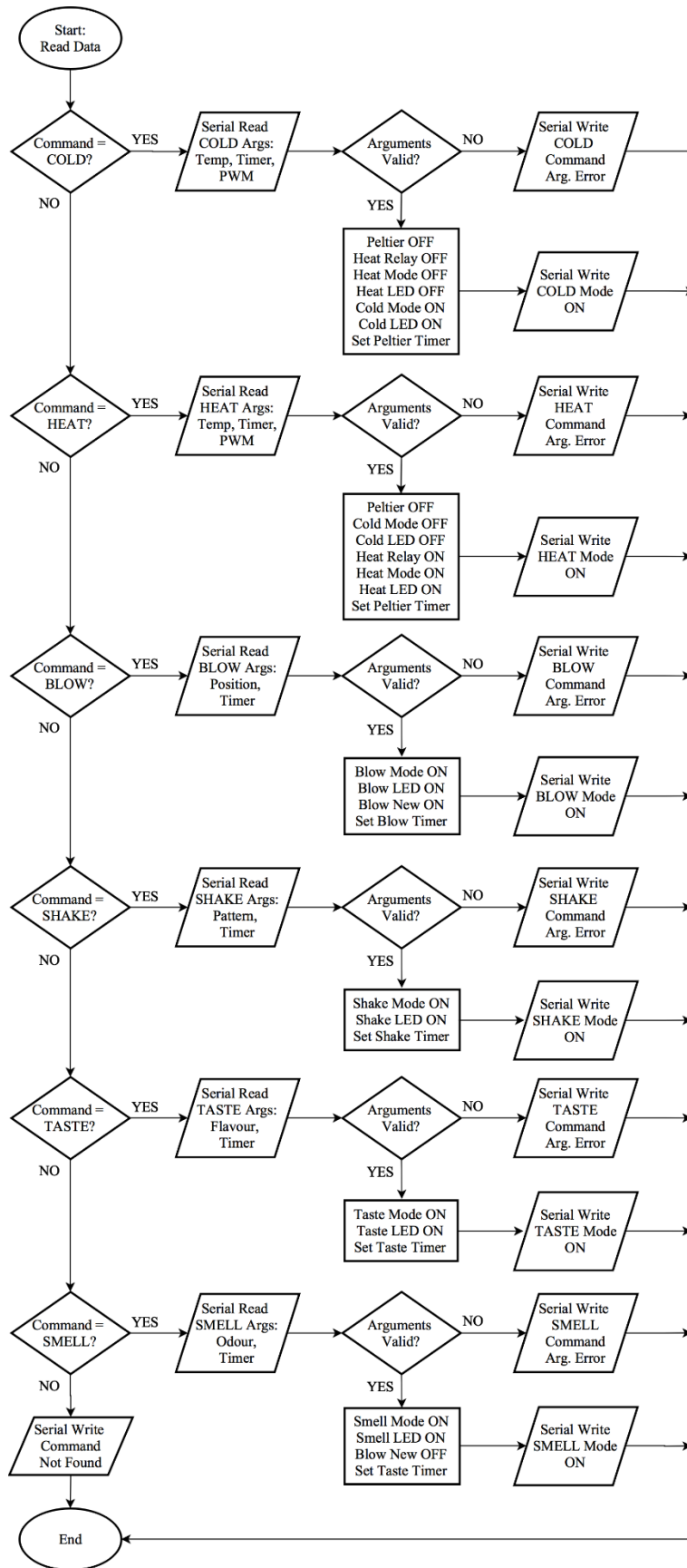


Figure 4.43: Serial command parser process flowchart.

The program starts by identifying the sensorial interface based on the short name that was attributed to them, next it reads the desired parameters or settings for that command, then it checks if they are valid. The command parser process is followed by the different sensorial modules or processes, the firmware only enters these processes if the respective mode flag was activated.

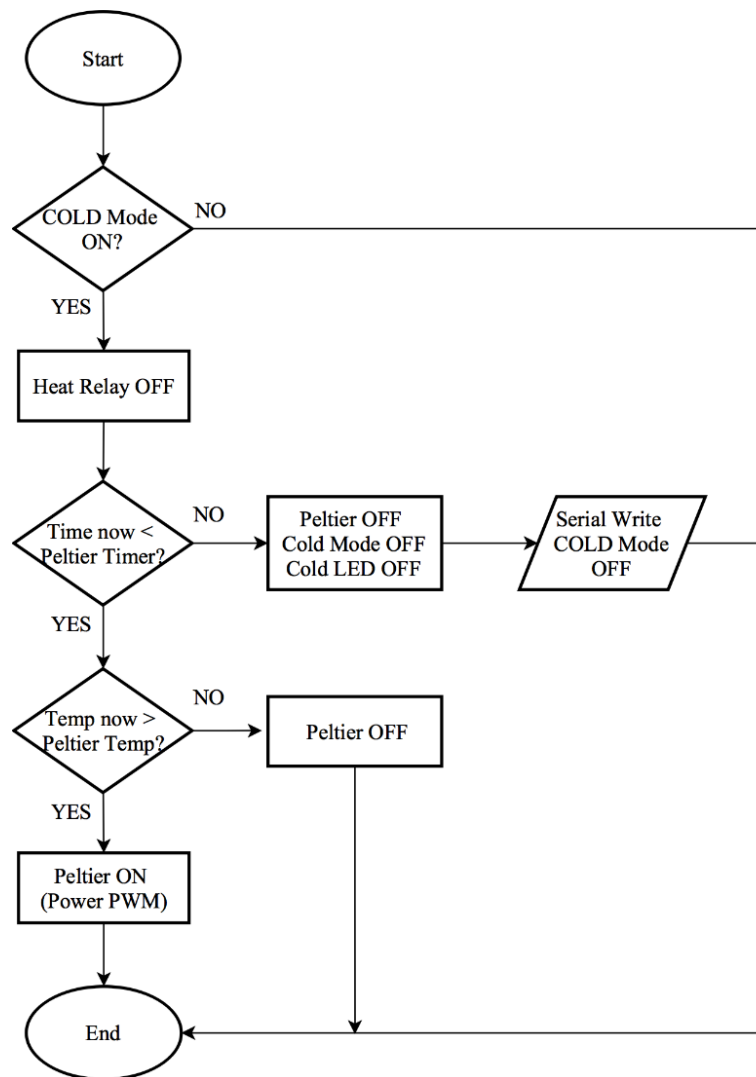


Figure 4.44: Cold mode process flowchart.

The cold process is relatively simple, when the cold mode is activated, the processor activates the Peltier module for cold generation, while constantly checking if it has reached the desired temperature. When the temperature is lower than requested, the thermoelectric module is deactivated but the cold mode keeps active until the timer expires. If the temperature rises above the setpoint while the cold mode is on, the Peltier

is turned back on. This process is represented in Figure 4.44. A PID controller was idealized in the beginning for this control, however, there was some difficulty adjusting the parameters, therefore a direct approach was selected. Some of this difficulty came from a value called the thermistor time constant, which is characterized as the response time of a thermistor to a temperature change by 63.2%.

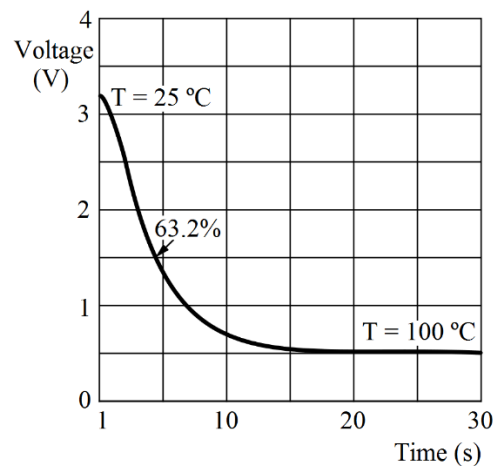


Figure 4.45: Typical thermistor output undergoing a sudden temperature transition.

The graph represented in Figure 4.45 shows the typical voltage drop on the thermistor and the time it takes, when it experiences a change from air at 25°C to a container of boiling water. It shows a response time of about 4s. The 100K NTC thermistor used for the thermal handles has a five to ten second time constant, which means it can take up to ten seconds for the voltage output to change 63.2%. This creates a problem, when cooling (or heating) the thermal handles, it can take a few seconds for the thermistor output to represent the real temperature value, therefore the microcontroller is working in real time with wrong temperature readings. This can cause the temperatures to largely exceed the predetermined setpoint, which might be a safety hazard for the user. This was one of the reasons why the PID parameters were hard to determine. However, with the direct approach on the temperature control, this problem still exists. The solution here was to create a new parameter on the cold and heat commands, called power. Since the thermistor takes a while to update the temperature reading, then we simply activate it with a fraction of its total power, via PWM, therefore taking it longer to reach the setpoint. This makes the curve of the real temperature change created by the Peltier become more similar to the curve of the thermistor time constant. It takes more time to cool or heat the

thermal handles, but it also gives the thermistor time to catch up to the real temperature, avoiding temperature extremes. This parameter is basically a percentage.

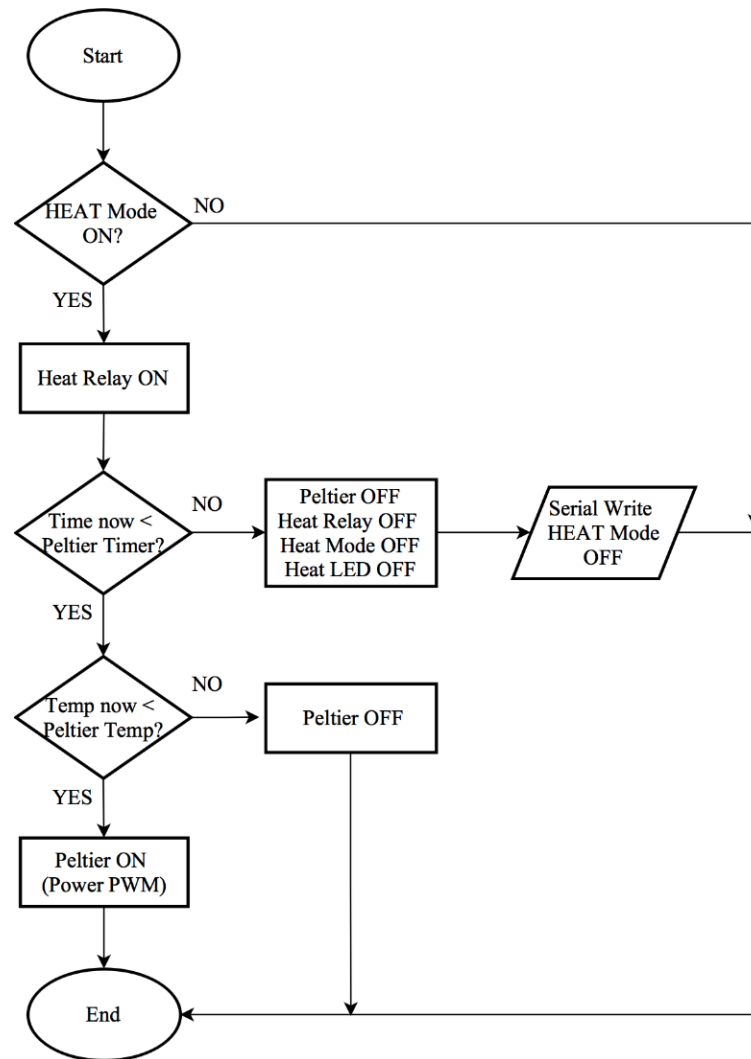


Figure 4.46: Heat mode process flowchart.

The heat generation process, represented in Figure 4.46, is very similar to the cold process, the main difference being the activation of the heat power supply inversion relay. Like the previous module, it also has a direct temperature control while in heating mode, which creates the same problem with the thermistor time constant. And, since the heating of thermoelectric modules is easier and faster than cooling, it becomes more severe here. Because the temperature of the handles could easily reach very high values, enough to cause burns to the user's hands. Therefore, the power parameter must be always considered when the heat mode is activated. Values of around 30% seem to generate a good balance between temperature and time.

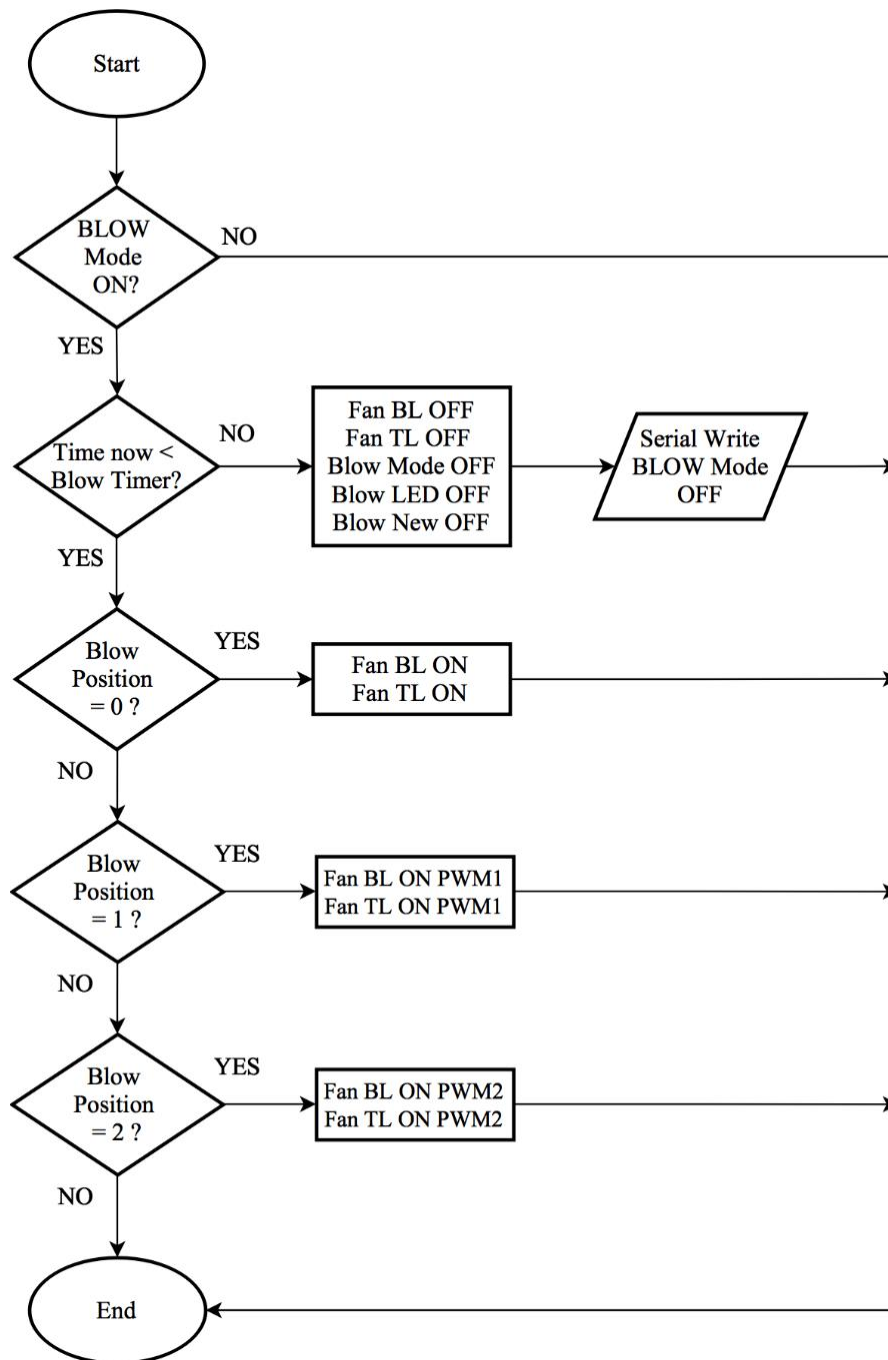


Figure 4.47: Blow mode process flowchart.

The blow process corresponds to the air/wind module. It basically checks the air flow origin position ID, and it activates the respective fans at the respective speeds conformingly, as represented in Figure 4.47. For example, if the ID is '0' that means the point of origin is the centre, therefore both fans will turn on at 100% speed. All fans are connected to PWM outputs in order to allow the firmware to generate different origin locations for the air flow stimulus.

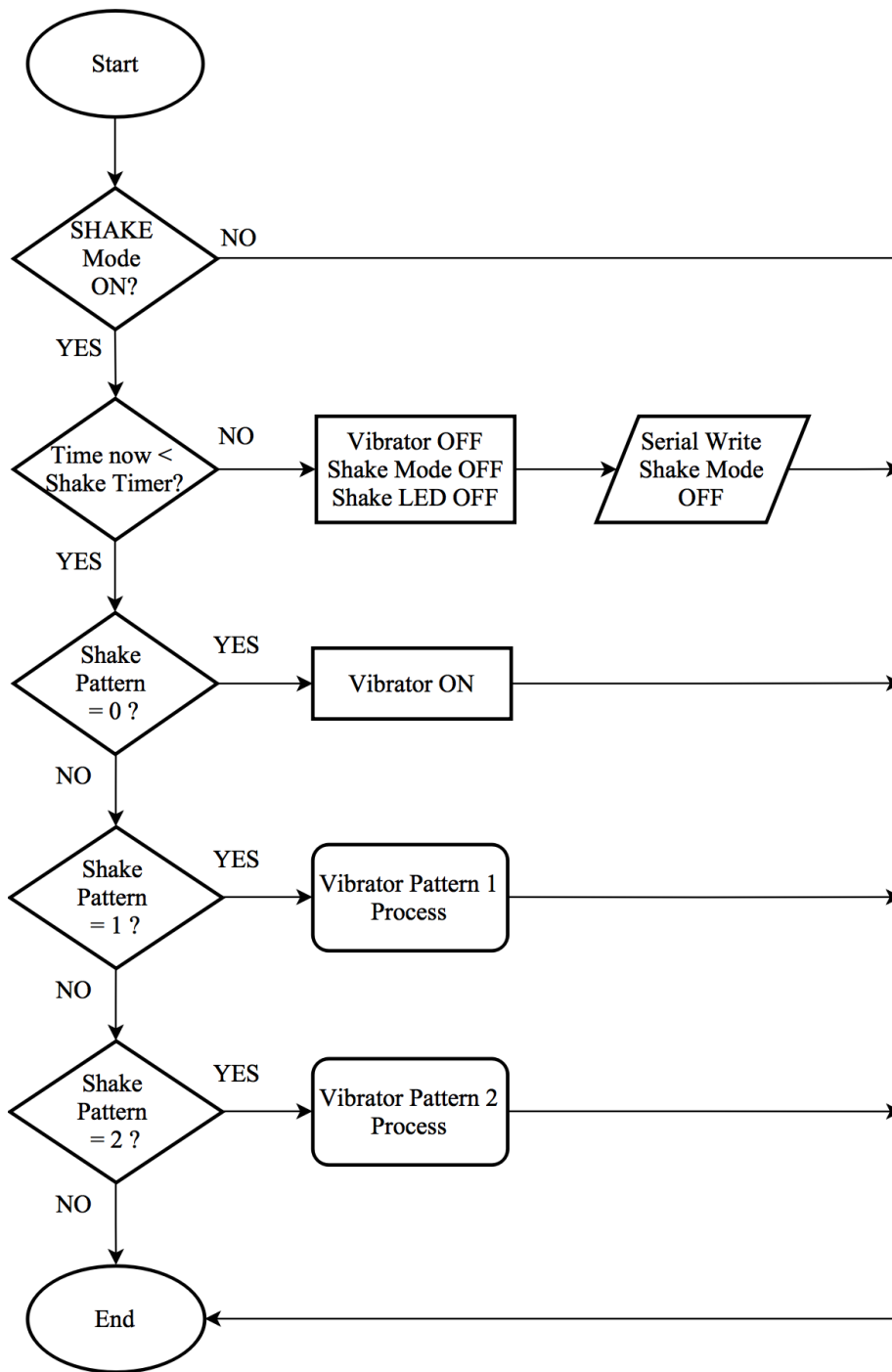


Figure 4.48: Shake mode process flowchart.

The shake mode corresponds to the vibration module. Similarly, to the blow process, it basically just checks the ID of the desired pattern, shown in Figure 4.48. Then it either activates the motor at 100% via PWM or it can enter sub processes that are designed to represent different vibration patterns.

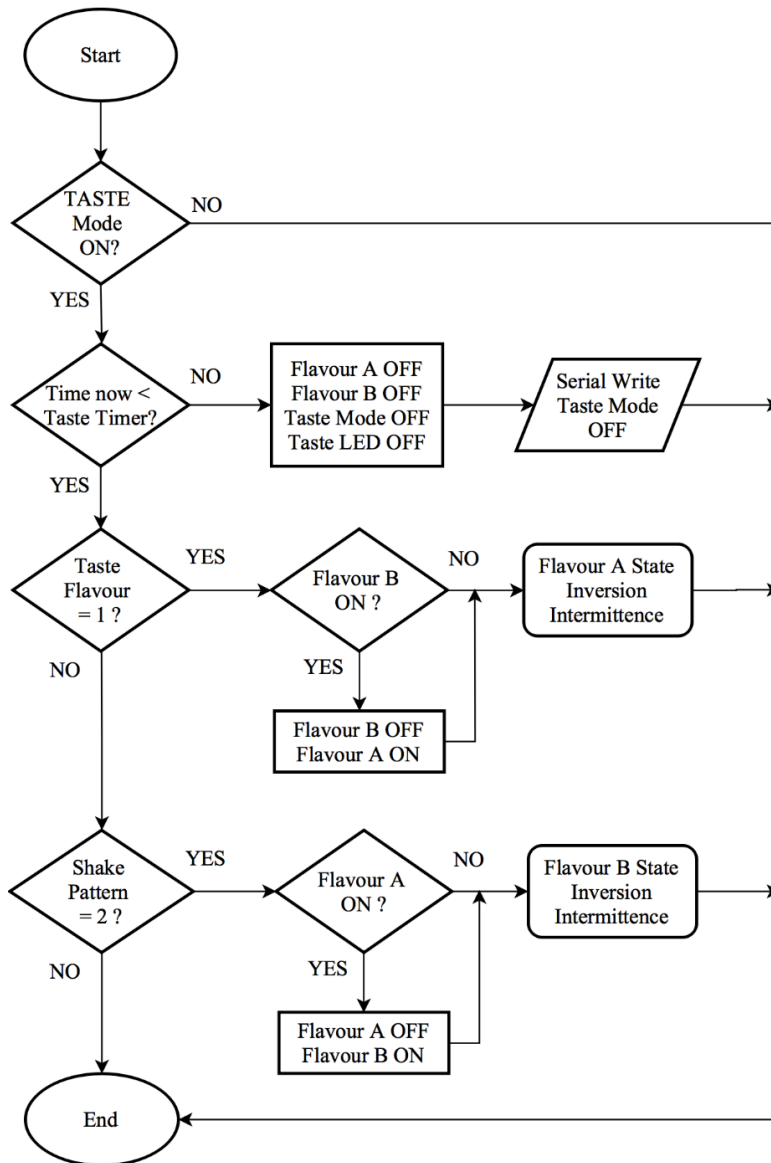


Figure 4.49: Taste mode process flowchart.

The taste process is a bit different than the rest, as shown in Figure 4.49. When a specific flavour is activated, the system must check if the other flavour is active as well. Since there are individual taste outputs, it is pointless to have both vaporizers turned on at the same time, it would just waste power. Another particularity of this module is the vaporizers intermittence. An electronic vaporizer cannot be turned on indefinitely, otherwise it might get damaged or destroyed. For that reason, it should have pauses in between uses. To accomplish this, an intermittence between buffs was added, which means the vaporizers turn on 5 seconds for the user to taste the vapour, and then turn off for another 5 seconds. This is indicated to the user via the taste output indicator, which are the same LEDs that are connected in parallel with the transistor outputs.

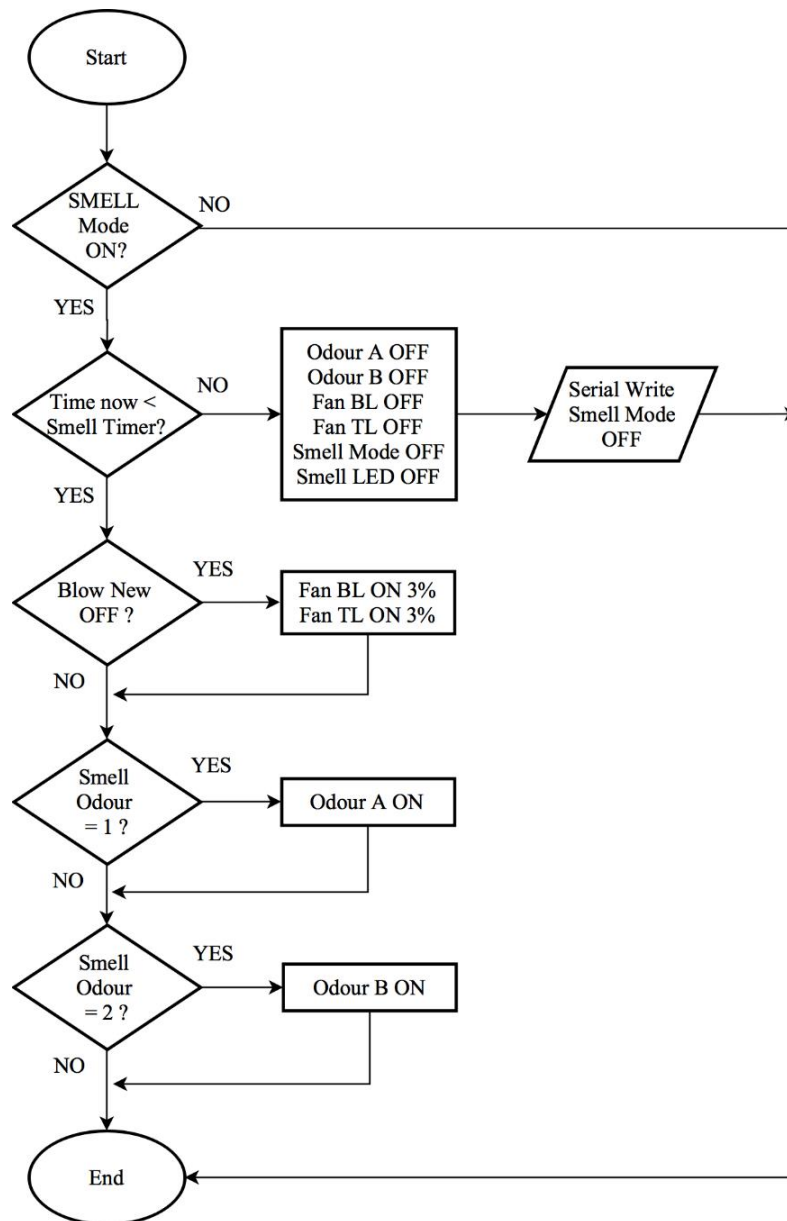


Figure 4.50: Smell mode process flowchart.

The smell process is represented in Figure 4.50 and has a few peculiarities. It starts by checking for the flag blow new, this flag indicates the system if the air/wind module is already working, since it is necessary to disperse the fragrances. If it is not active, the smell process will activate the fans at 3% of their usual speed, which is better for scent delivery. However, when the smell timer expires, it resets the fan to their previous state. Then it simply checks which odour is requested to be released. That is all for the firmware of the portable device. Regarding the firmware of the slave microcontroller, it is basically the same, but instead receives commands from the master device, and has more odours and flavours available.

4.11 COMMUNICATION

The communication between the user's device, either a smartphone or a tablet, and the portable multisensorial device is done via Bluetooth. This makes sense since most devices already have integrated Bluetooth, besides the distance range is more than enough for devices that will be as close together as in this case. The Bluetooth interface for the portable gadget is a HC-05 Bluetooth Serial Module, which creates a simple wireless serial bridge between the devices. The app running on the user's device, or a simple serial console, will be the master device, sending commands through its own Bluetooth interface, via the wireless bridge, to the HC-05 Bluetooth module, which then redirects those serial instructions to the master microcontroller through a wired UART link. The HC-05 module and the microcontroller work as a slave device. The representation of the communication link is shown in Figure 4.51.

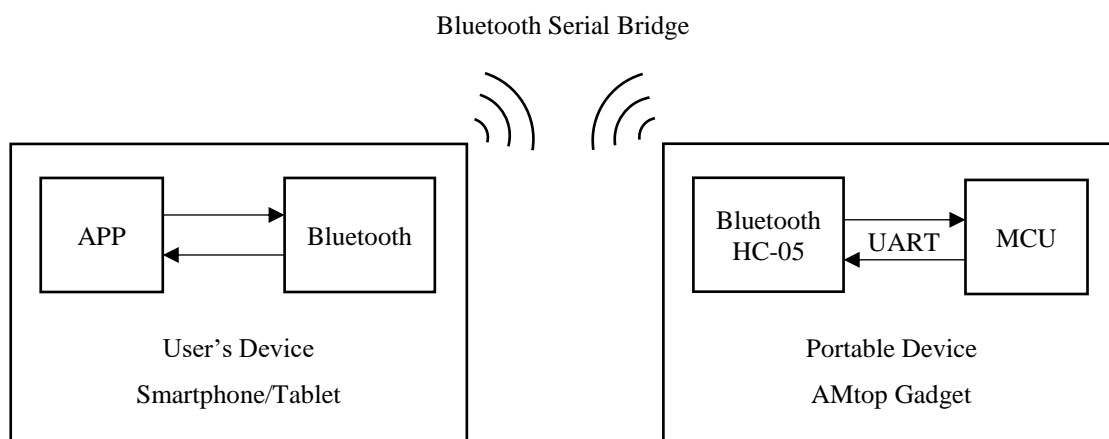


Figure 4.51: General communication interface diagram.

Once the serial communication is made transparent between the device and the application, the focus falls on the communication protocol to activate the reproduction of the desired sensations. For this, a simple protocol was designed that works as a word parser, where a determined sensorial module is activated by its respective command instruction, together with its own set of parameters. Depending on the desired sensation, so it depends the parameters that the command instruction will need as inputs. More information about the protocol on the following sections.

4.11.1 Bluetooth Interface

For the wireless physical interface, as mentioned before, the chosen hardware is the HC-05 Bluetooth Serial Port Protocol module, pictured in Figure 4.52, it is ideal for transparent wireless serial connection setups. It has a Bluetooth V2.0 specification with EDR (Enhanced Data Rate), 3Mbps Modulation [65] with a complete 2.4GHz radio transceiver. It has a PSK modulation capable of transmitting data two or three times faster than the previous versions, it is safer against “man-in-the-middle” attacks, it is easier to pair with devices and allows for multiple connections. It uses a Cambridge Silicon Radio BC417 Bluetooth single chip with AFH (Adaptive Frequency Hopping) feature. This module has a low power operation of 1.8V to 3.6V, average consumption of 50mA, a UART interface with programmable baud rate, an integrated antenna and can be configured to work as either Master or Slave device.

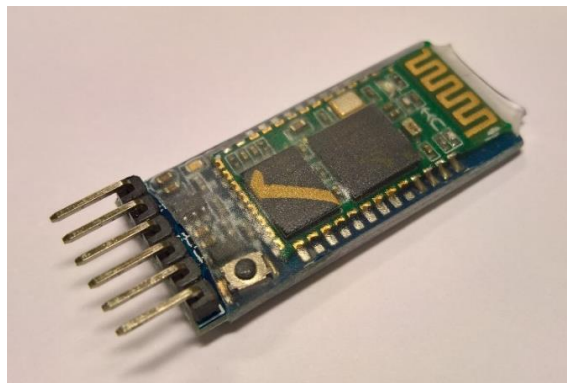


Figure 4.52: HC-05 Bluetooth Serial Module

It has two modes of operation, Data Mode where it receives and transmits data to other Bluetooth devices, and Command Mode where it can be configured through AT commands. The module in use has a breakout board to simplify the circuit, which has a level shifting adapter to allow the Tx and Rx pins to work with 5V as well, a 5V-3.3V voltage regulator, and a press switch to select the operation mode. To enter Command Mode with this specific breakout board, the circuit must be connected to a Serial console and the press switch should be held for two seconds during the power up. The Serial console settings for Command Mode operation should be 38400 bps for the baud rate, 8 data bits, no parity and 1 stop bit, the AT commands should be sent with CR+LF at the end. The AT commands shown in Table 4.1 are some of the most important ones.

Name	Command	Response	Parameter	Example
Test	AT	OK	None	AT OK
Reset	AT+RESET	OK	None	AT+RESET OK
Get Software Version	AT+VERSION?	+VERSION:<Param> OK	Param: Version Number	AT+VERSION? +VERSION:2.0-20100601 OK
Get Device Name	AT+NAME?	1. +NAME:<Param> OK 2. FAIL	Param: Bluetooth device name	AT+NAME? +NAME: HC-05 OK
Set Device Name	AT+NAME=<Param>	OK	Default: "HC-05"	AT+NAME=HC-05 OK
Get Module Role	AT+ROLE?	+ROLE:<Param> OK	Param: 0.Slave 1.master	AT+ROLE? +ROLE:0 OK
Set Module Role	AT+ROLE=<Param>	OK	2.Slave Loop Default: 0	AT+ROLE=0 OK
Get Passkey	AT+PSWD?	+PSWD:<Param> OK	Param: passkey	AT+PSWD? +PDWD: 1234 OK
Set Passkey	AT+PSWD=<Param>	OK	Default: 1234	AT+PSWD=1234 OK
Get Serial Settings	AT+UART?	+UART: <Param1>, <Param2>, <Param3> OK	Param1: baud rate (bps): 4800 9600 19200 38400 57600 115200 Param2: stop bit: 0. 1 bit 1. 2 bits Param3: parity bit: 0. None 1. Odd 2. Even Default: 9600,0,0	AT+UART? +UART:115200,1,2 OK
Set Serial Settings	AT+UART=<Param1>, <Param2>, <Param3>	OK		AT+UART=9600,0,0 OK
Get Connect. Mode	AT+CMODE?	+CMODE: <Param> OK	Param: 0. Connect to the specified address.	AT+CMODE? +CMODE:0 OK
Set Connect. Mode	AT+CMODE=<Param>	OK	1. Connect to any address. 2. Slave Loop. Default: 0	AT+CMODE=0 OK

Table 4.1: Bluetooth HC-05 module configuration AT commands [66].

For example, to configure the module in order to meet the project specifications, the name of the Bluetooth interface should be changed to “AMtop” and the pairing password changed to “1”.

4.11.2 Communication Protocol

With the physical interface ready and the wireless serial bridge made transparent, the communication protocol becomes the next priority. In order to activate a specific stimulus system a simple communication protocol was conceived. It consists of a basic word parser that receives the desired command instruction and its respective parameters. The protocol was created with the following command syntax:

<Command> <Space> <Parameter1> <Space> <Parameter2> <Space> <Parameter3>

The first word determines which sensorial system is to be activated, the options vary among heat, cold, blow, shake, smell and taste. Following that comes the first parameter, then a space character, followed by the second parameter, and so on. These parameters depend on the command, some commands can take up to three parameters and all the words must be separated by spaces. The full list of commands and their respective parameters is presented in Table 4.2. The order of the parameters is important and cannot be changed, the syntax itself is not case sensitive, which means it is irrelevant to use heat or HEAT for example, they both will activate the heat system, if the parameters that follow are considered valid. In terms of programming, the duration parameter variables are all unsigned long, storing 32 bits of data and are not firmware limited, which means acceptable values vary between 0 and 4294967295 seconds. The value 0 for the duration parameter will immediately turn off that specified sensorial module. All the other command parameters, temperature, power, position, pattern, odour and flavour, have integer variables, which store 16 bits and therefore accept values between -32768 and 32767. However, depending on the parameter, the firmware limits the valid values for each one. The acceptable values for each parameter are presented on Table 4.3. Most parameters are quite straightforward, like temperature setpoint or the duration of a desired sensorial reproduction, one receives directly the value in Celsius degrees and the other in seconds, both integer numbers, no unit symbol allowed.

Command	Parameters	Description	Example
HEAT	1: Temperature (°C) 2: Power (%) 3: Duration (s)	Activates the thermal system in heating mode for the duration requested. It will reach or try to reach the desired setpoint. It is deactivated after the duration expires, either if it reached the setpoint or not.	“HEAT 30 40 60” It will heat up the handles up to 30°C, with a power output of 40% for 60 seconds.
COLD	1: Temperature (°C) 2: Power (%) 3: Duration (s)	Activates the thermal system in cooling mode for the duration requested. It will reach or try to reach the desired setpoint. It is deactivated after the duration expires, either if it reached the setpoint or not.	“COLD 10 100 120” It will cold down the handles down to 10°C, with a power output of 100% for 2 minutes.
BLOW	1: Position (ID) 2: Duration (s)	Turns on the air flow module for the duration specified. The ID is a code that corresponds to a different air flow point of origin on the screen. Technically it represents different combinations of fan rotation speeds. See Table 4.4.	“BLOW 0 300” It generates an air flow coming from the centre of the device, for 5 minutes.
SHAKE	1: Pattern (ID) 2: Duration (s)	It activates the vibration system in a specified pattern, referenced as ID, for the duration requested. See Table 4.5.	“SHAKE 0 15” Vibrates the device uninterruptedly for 15 seconds.
SMELL	1: Odour (ID) 2: Duration (s)	Activates the smelling module for the duration specified, releasing the fragrance correspondent with the odour vial selected by the parameter ID. See Table 4.6.	“SMELL 1 10” Releases the fragrance in vial number 1 for 10 seconds.
TASTE	1: Flavour (ID) 2: Duration (s)	Activates the tasting module with the selected flavour identified by parameter ID for the duration requested. See Table 4.7.	“TASTE 4 25” Activates flavour vaporizer number 4 for 25 seconds.

Table 4.2: Protocol commands and respective parameters.

The thermal module is separated between cold and heat instructions and each command has its own range of allowed temperature values. In short, the full range of temperature values varies from 0 to 40 °C, considering the interval from 0 to 25°C as valid values for the cold module, and from 25 to 40°C for the heat module, with the value 25°C being acceptable for both thermal modules. It is important to mention that the thermal sensation will be done via direct contact and through our hands, which means the “feeling” of hot and cold on our bodies is different than a usual sensation as for example, from an air-conditioned system.

Parameter	Variable Size	Min	Max
Temperature (HEAT)	int	25	40
Temperature (COLD)	int	0	25
Power	int	0	100
Position	int	0	5 (Table 4.4)
Pattern	int	0	5 (Table 4.5)
Odour	int	1	4 (Table 4.6)
Flavour	int	1	4 (Table 4.7)
Duration	unsigned long	0	--

Table 4.3: Protocol parameters variables and acceptable values.

Other parameters however are a little more complex and require some knowledge of the entire system to be used. This is the case for the position, pattern, odour and flavour parameters, which are all basically an identification code for their respective sensorial module. The position parameter belongs to the blow system and it identifies the desired point of origin on the device's screen for the air flow to appear from. According to Table 4.4 there are 5 valid values for this parameter, from 0 to 4. The id 0 represents the centre of screen as the point of origin, and id 1 to 4, the four quadrants previously defined.

ID	Air Flow Point of Origin	BL Fan Power	TL Fan Power	BR Fan Power	TR Fan Power
0	Centre	100%	100%	100%	100%
1	Top Right Quadrant	100%	10%	30%	3%
2	Top Left Quadrant	30%	3%	100%	10%
3	Bottom Left Quadrant	3%	30%	10%	100%
4	Bottom Right Quadrant	10%	100%	3%	30%

Table 4.4: BLOW command ID parameters.

The pattern parameter for the shake command works in a similar way, each id number is associated to a different vibration pattern, shown in Table 4.5. By now six patterns were developed, id 0 to 5, but new patterns can be added later if needed. The id 0 represents that the vibration motors from both sides will be always turned on, id 3 for example will

turn on both motors intermittently with a 5Hz frequency. Other id patterns can turn on just one side of the device, left or right, either intermittently or not, which might be particularly useful aiding people with special needs navigating through the museum or following a predetermined path.

ID	Vibration Pattern
0	Both handles ON
1	Left handle ON
2	Right handle ON
3	Both intermittent at 5Hz
4	Left handle Intermittent at 5Hz
5	Right handle Intermittent at 5Hz

Table 4.5: SHAKE command ID parameters.

The odour and flavour parameters are also identifiable by id numbers, and they are both quite similar between each other. Both smell and taste modules have 4 different identification numbers, corresponding to 4 different fragrances or flavours, respectively. There are 2 odour vials and 2 flavour vaporizers on each side of the device. Odour vials and fragrance vaporizers on the left side are represented by id 1 and 2, while the ones on the right side have the id 3 and 4. Following this logic, a particular odour can be associated with a specific vial, as represented in Table 4.6.

ID	Odour Vial	Fragrance
1	Left 1	Forest
2	Left 2	Pine
3	Right 1	Lemon
4	Right 2	Ocean

Table 4.6: SMELL command ID parameters.

It is exactly the same way for the taste module, where a desired flavour will be associated with a determined taste vaporizer, as shown in Table 4.7.

ID	Taste Vaporizer	Flavour
1	Left 1	Cappucino
2	Left 2	Red Fruits
3	Right 1	Almond
4	Right 2	Lemon

Table 4.7: TASTE command ID parameters.

Now, there is one final parameter that must be mentioned, which is the power on both the heat and cold thermal modules. This parameter represents a percentage of power to be applied to the Peltier element, either in heating or cooling mode, via PWM. Although it makes the communication protocol a bit more confusing and complex, this parameter had to be created by necessity because of the thermistor time response. The thermal time constant of the current thermistor can be up to 15 seconds, which means the difference between the real applied temperature and the measured temperature by the thermistor can be delayed for 15 seconds or more. What this causes is a temporary unreal temperature measurement which can make the cooling or heating of the conductive handle plates, reach over the set point, undesired or dangerous temperatures for the user. This is particularly noticeable and worse in heating mode, since it is easier and faster for the Peltier to generate heat than cold.

Therefore, to avoid this problem without making changes in the circuit, a power PWM parameter was created to control the Peltier element. This way, a more controlled and reduced power output can be applied to the Peltier, therefore making the plates take more time to cool or heat, giving the thermistor time to catch up to the real temperature. Eventually this value could be tested to find an ideal setting, and hidden from the protocol, however, depending on ambient temperature, changes might be needed on this parameter, in order to get an effective thermal module sensation. The ideal solution would be to replace the current thermistor for one with a faster response time.

4.11.3 Sequence Diagram

In terms of timing the algorithm was developed in an asynchronous way, so that the microcontroller can be executing multiple tasks “at the same time” and not get stuck waiting for certain processes to finish. To do that, everything was designed based on time

and schedules. One particular useful feature is being able to activate multiples outputs and communicate without any delays. As an example, Figure 4.53 represents the timing diagram of a pre-designed narrative scene with multiple sensorial stimulus, for a museum painting representing the “legend of the almond trees in blossom”.

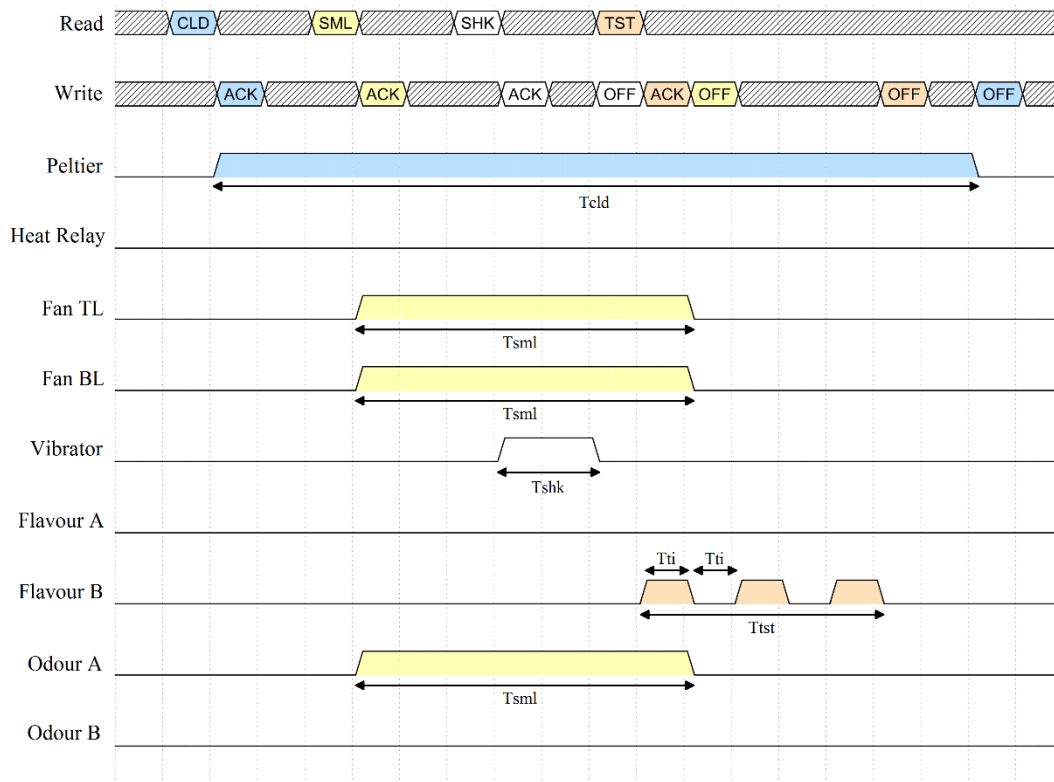


Figure 4.53: Timing diagram request/response example.

The Read signal represents the commands sent by the mobile application and received by the PDTTSS. Oppositely, the Write signal represents the responses sent by the portable device to the mobile application. The commands duration of these two communication lines is not represented to scale in the diagram, they are only there to represent the moment when they were sent. For explanatory reasons in the diagram, the blue elements are associated with the cold system, the yellow elements with the smell system, the white elements with the shake system, and the orange elements with the taste system, and each time step represents 5 seconds. It can be observed that just after the first 5 seconds have passed, the first instruction arrives (CLD or cold, considering a duration of 80 seconds). Immediately after the instruction was received, the portable device sends an acknowledge response (blue ACK), indicating that the command was received, validated and initiated,

and at the same time the Peltier element was activated as well. This will recreate the part of the legend, where the white colour of almond tree blossoms represents the snow and the cold.

Approximately 15 seconds after the Peltier was activated, a new instruction is received (SML or smell, considering the fragrance A for 35 seconds), followed by the smell acknowledge response (yellow ACK). At the same time, the odour A starts being released, however, since the blow system was not active before, the microcontroller also turns on the fans (TL and BL) in slow speed, to help spread the fragrance around. In terms of narrative, the fragrance A represents the smell of almond blossoms that would come from trees in the painting.

Another 15 seconds later, a new instruction is received (white SHK or shake, for 10 seconds), followed by a shake acknowledge response (white ACK), and at the same time the vibration motor is activated. This can be used as a notification for the user to be ready for what is to come next.

After the 10 second shake timer expires (Tshk) the vibration motor is stopped and the PDDTSS notifies the mobile application with a shake shutdown acknowledge (white OFF). At the same time, the mobile application sends a new instruction (orange TST or taste, considering flavour B for 25 seconds), followed by the acknowledge response (orange ACK). At the same time, the vaporizer B is activated, allowing the user to taste the specified flavour. As mentioned before, the vaporizers are intermittent to avoid overheating, therefore turning on and off every 5 seconds (Tti), for the required duration of 25 seconds (Ttst), which corresponds to 3 tasting periods. As for the story sake, the flavour can be used to give the user a sense of the almond taste.

After the first tasting period (Tti), the smelling timer of 35 seconds expired (Tsm), the odour A stops being released and the fans are returned to their previous state, which in this case is off, this is followed by a smell module shutdown message sent to the mobile application (yellow OFF). When the taste timer of 25 seconds is over (Ttst) the portable device sends a taste shutdown notification (orange OFF). And finally, after the cold 80 second timer expired, a cold shutdown notification is also sent to the mobile application (blue OFF). The device then returns to its initial state.

5 Results

ABSTRACT

This chapter presents the multiples tests that were conducted with the portable device in its current state. Because of the nature of some used interfaces, some tests were not possible to quantify, for that reason those tests were conducted with people in order to obtain their feedback on their actual experience as a user of the portable unit. The results are also presented here, summarized by sensorial interface. Besides the sensorial stimulus, some results on comfortability of use, regarding size and weight, are also represented in here. The end of this chapter presents a discussion over the multiple results, analysing them in terms of relevance and interest to this application, as well as possible problems and their probable cause.

5.1 TESTS

To check the sensorial interface perceivability of the portable device prototype, several different tests were performed to the individual interface systems. Since these are sensorial stimulus, some can be difficult to quantify, for that reason some tests were executed with people, where they classify the intensity of the stimulus they felt.

5.1.1 Thermal System Results

Following the same interface order that was presented in the constructions chapter, the first one is the thermal system. Temperature is something quantifiably; therefore, this interface was tested with an external thermometer. The first test was executed with an external thermometer on the haptic handle, when a cold instruction for 10°C was requested for 60 seconds, with an 100% power PWM. The initial ambient temperature was 24°C. The results are presented in Figure 5.1.

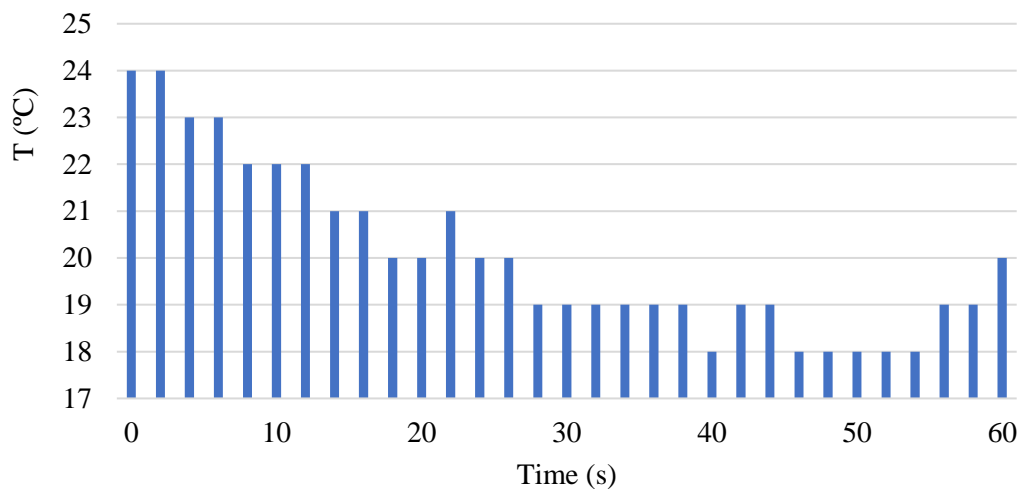


Figure 5.1: Temperature readings on the handle for a cold request.

The results presented in the graph show that the temperature never reached the desired set point of 10°C during the 60 second test. In fact, it probably never would, since the lowest temperature achieved was 18°C and near the end of the graph, the temperature starts rising again. Another noticeable issue is the fact that the temperature decreases very slowly, taking the system 40 seconds to reach the lowest point of 18°C.

The second test follows the same settings with an external thermometer on the haptic handle, but with a heat instruction instead, for 35°C during for 60 seconds, with an 30% power PWM. The handle was resting for a few minutes until it reached the initial ambient temperature of 24°C as before. The results are presented in Figure 5.2.

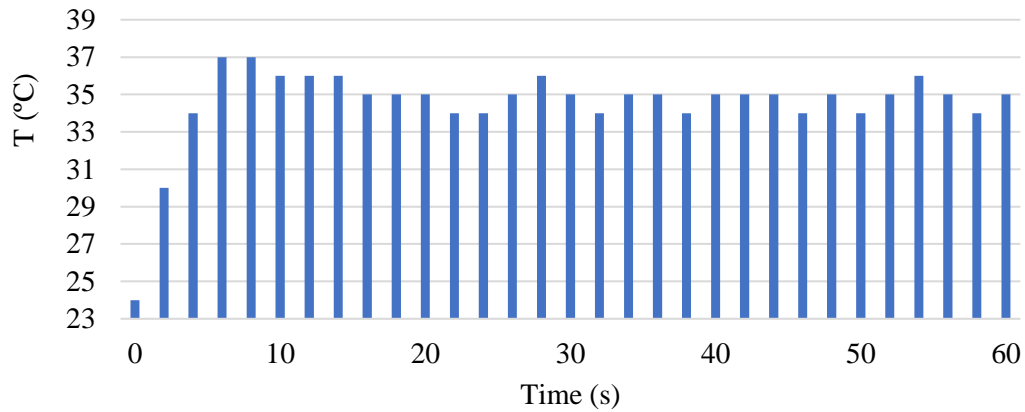


Figure 5.2: Temperature readings on the handle for a heat request.

The results in the graph show that the behaviour of the thermal system in heating mode is quite different than the cooling mode. It is possible to see that the system has no problem at all, reaching the desired temperature of 35°C, not only that but it is also relatively faster at achieving a determined temperature, it took less than 6 seconds to reach 37°C. However, there are two small issues. The first is the fact that for a few seconds the temperature set point is exceeded. While the second is the small $\pm 1^\circ\text{C}$ variation that the temperature has after stabilizing around the set point. In fact, it never really stabilizes completely on the 35°C mark, it is always slightly varying between 34°C and 36°C.

5.1.2 Vibration Results

The vibration system is one of the cases where it is slightly complicated to quantify the results, for that reason a real test with people was designed, so that they could evaluate the intensity of the vibration. For this, the portable device was handled to a group of ten people and the vibration instruction was sent, with the pattern ID 4 (left handle 5Hz intermittence vibration) for 5 seconds, then a 2 second rest, followed by a new instruction

with the pattern ID 5 (right handle 5Hz intermittence vibration) for 5 seconds again. Then, each person was asked to identify in which side did the vibration occur and the correct sequence. The subject's response is presented in Figure 5.3.

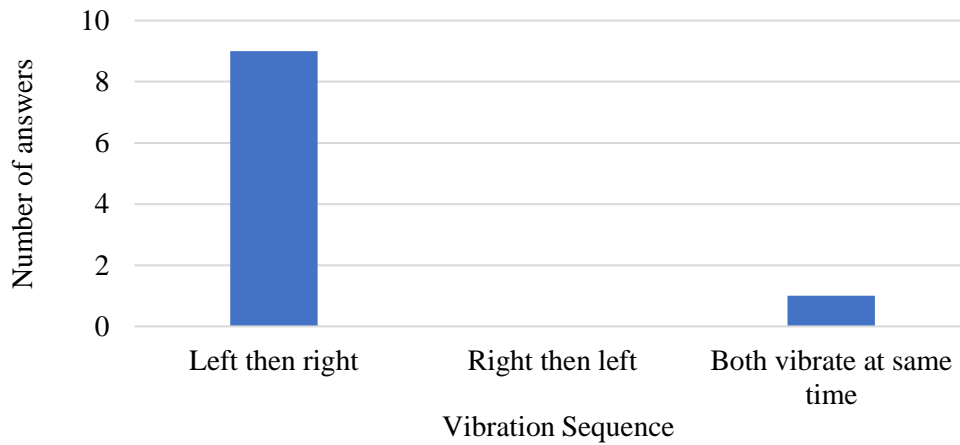


Figure 5.3: Subjects response to vibration sequence.

According to the results, most people correctly identified where the vibrations originated and their right sequence. Only one out of ten responded an incorrect answer, in this case the subject said the vibrations occurred in both sides at the same time. In terms of percentage this corresponds to a 10% error margin, however the size of the sampling group was relatively small and that must be considered as well. The subjects were also asked to rate the level of intensity they felt, from 1 to 5, 1 being “no vibration” and 5 being “strong vibration”. These results are represented in Figure 5.4.

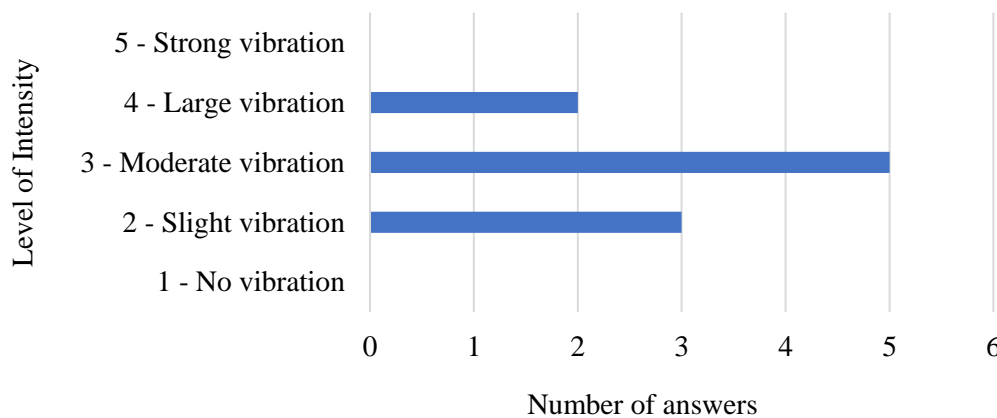


Figure 5.4: Subjects response to vibration intensity.

Regarding the vibration intensity, five out of ten subjects answered “moderate vibration” which is considered the average level of intensity, while three answered “slight vibration” and two “large vibration”. No one said that the vibration was not perceivable but on the other hand, no one also said it was very strong. This shows that the vibration level is enough to be noticeable, however there seems to be a small tendency for users to consider it weaker than stronger.

5.1.3 Airflow Results

This interface presented another challenge to quantify the results. One possibly way could be designing a matrix of anemometers above the portable device and getting the different readings from different positions, however this option was discarded for the lack of resources and added complexity. Therefore, the alternative is again relying on people’s feedback. The same sample group of ten people was used, this time with a blow instruction in the PDTTSS, for 10 seconds with the origin of airflow ID 1 (top right quadrant). The subjects were informed to keep their faces 20 to 30cm away from the gadget’s tablet, to simulate a normal usage. Then, they were asked to pinpoint what they thought the point of origin for the airflow was. The results are presented in Figure 5.5.

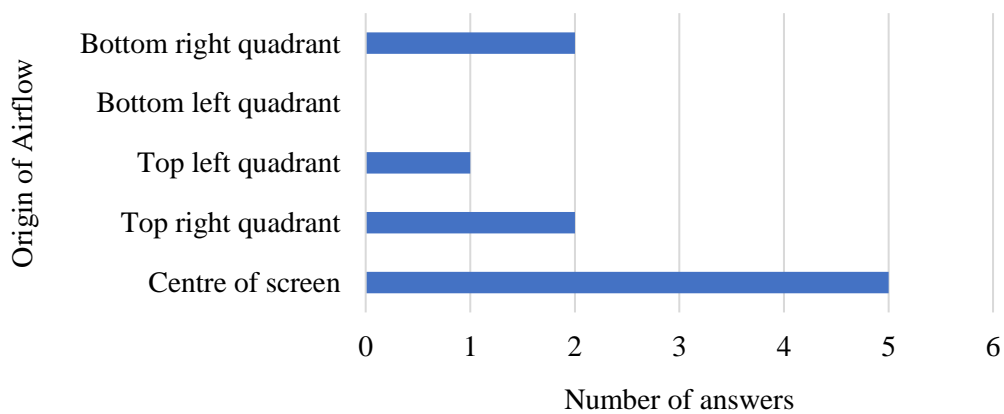


Figure 5.5: Identification of the airflow point of origin by test subjects.

The graph shows that most people get confused about this feature. Even though the point of origin was the top right quadrant, only two out of ten people identified it correctly. Most people actually replied the centre of the screen, which can either mean that they

couldn't pinpoint the exact location and selected a general location, or the airflow origin was irrelevant to them. The second question to the subjects was for them to qualify the intensity of the airflow they felt, from 1 to 5, 1 being "no air" and 5 being "strong airflow". These results are represented in Figure 5.6.

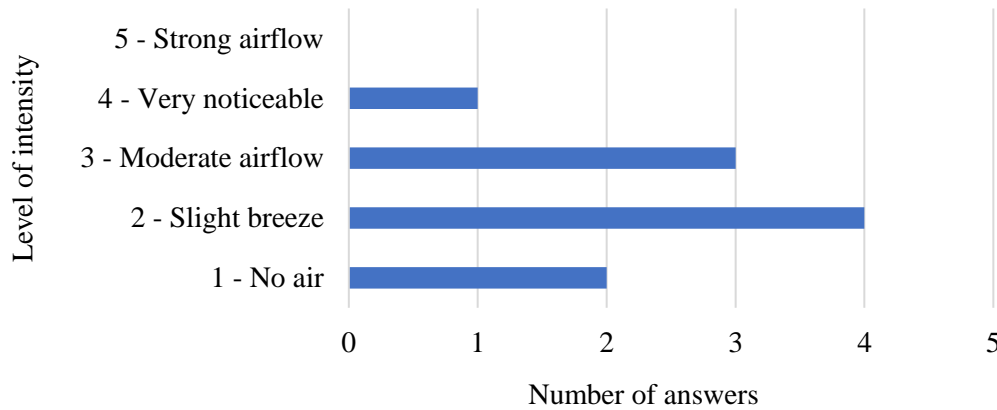


Figure 5.6: Subjects response to airflow intensity.

These results show that the airflow generated by the system is not very noticeable. Most people (four out of ten), responded that they only felt a slight breeze, followed by three people who claimed it to be a moderate airflow, and then by two people who didn't feel any airflow at all. Only one person out of ten said the flow was very noticeable, but no one said it was strong.

5.1.4 Taste Results

This is yet another interface that cannot be quantified, therefore is purely relying on people's feedback. The test was done with the same sample group of ten people and consisted of simply sending a taste instruction of the flavour ID 2 (red fruits) for 25 seconds, which consists of three tasting periods, considering the five second on/off intermittence. The subjects were asked to suck on the disposable tubes whenever they saw the LED of the taste output indicator light up. Then they were asked to qualify the intensity of flavour they perceived, again 1 to 5, from "no flavour" to "too intense". The results are presented in Figure 5.7.

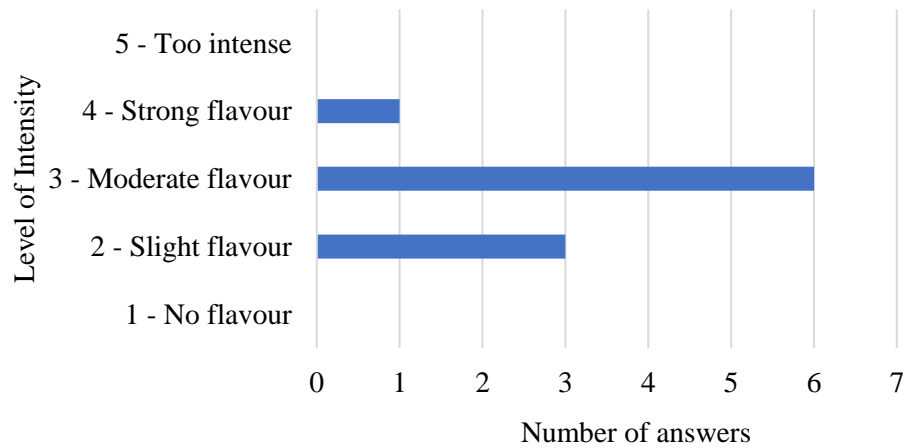


Figure 5.7: Subjects response to flavour intensity.

The results in the graph show that people get the flavour sensation relatively well. Most of them (60%) claimed it was a moderate flavour, while 30% considered it a slight flavour and 10% a strong intensity. No one replied about having no flavour at all or the flavour being too excessive.

5.1.5 Smell Results

Finally, the last interface, the smell system. This one is also quite complicated to quantify, unless some kind of chemical gas sensors were used in a matrix above the screen. But again, the lack of resources led to a people’s feedback test once more.

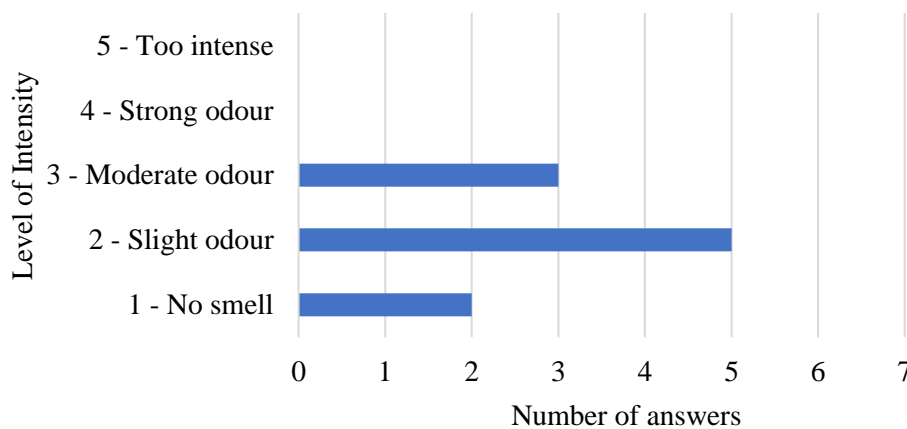


Figure 5.8: Subjects response to smell intensity.

The same sample group of ten people was used, this time with a smell instruction in the portable device, for 10 seconds with the odour ID 2 (pine tree smell). The subjects were informed to keep their faces 20 to 30cm away from the gadget’s tablet, to simulate a normal usage, as it was done in the airflow test. Next, they were asked to qualify the intensity of the fragrance from 1 to 5, from “no smell” to “too intense”. The results are shown in Figure 5.8. The results in the graph show that most people (50%) only felt a slight odour in the air. Followed by 30% answers on a moderate odour and 20% reporting feeling no smell at all. This represents a tendency for the smell system to be relatively weak, since no one reported feeling a strong odour or an excessive smell.

5.1.6 Comfortability Results

Regarding the portability and comfortability of the device and its structure, people were also inquired about these features. The same sampling group was asked to rate size and weight comfortability, both from 1 to 5, 1 being “uncomfortable” and 5 being “comfortable”. The results are presented in Figure 5.9.

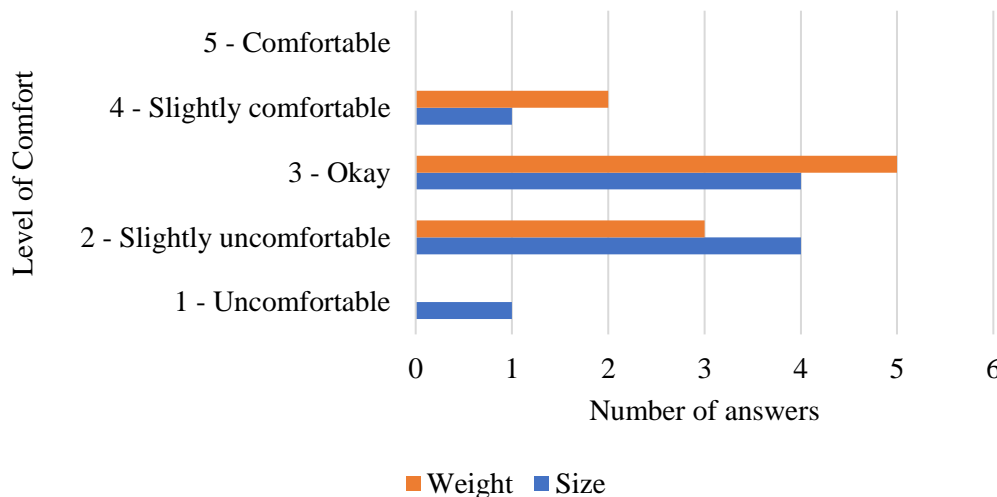


Figure 5.9: Subjects response to size and weight comfortability.

The results represented in the graph show that the portable device is slightly uncomfortable in terms of size, since that response was reported by 40% of the subjects, however, 40% also claimed it was okay. Regarding weight, 50% of the subjects reported the weight was ok, though 30% said it was slightly uncomfortable.

5.1.7 Battery Durability

Regarding the power supply, since the sensorial interfaces are not yet completely tested and finalized, it was not possible yet to have a real museum visit, to check what would be considered normal consumptions, in order to select an appropriate battery. However, an estimation can be calculated based on the interfaces nominal values and a given museum visit scenario. For this, it was considered a visit of one hour, where the thermal handles were used for 3 minutes, the vibration for 2 minutes, the airflow for 5 minutes, the taste for 2 minutes and the smell for 3 minutes. To facilitate calculations, since most components have different nominal voltages, all values are represented in Wh. And since each portable device's side has its own battery, only one side needs to be calculated, the one with the Bluetooth module.

Starting with the microcontroller, the Arduino Nano has an average consumption of 19mA at 5V, therefore corresponds to a power of 95mW. The microcontroller is always working during the entire visit therefore it requires an energy of 0.095Wh. The Bluetooth interface is also always on, although it might consume more or less depending on the amount of communications, but considering its average of 50mA at 3.3V, corresponds to 0.165W, which for one hour translates to 0.165Wh.

Next, the thermal handles, they require the usage of 3 components, the TEC module which at 3.3V and 4A will waste 13.2W, the switching relay with the coil consumption of 75mA at 12V which translates to 0.9W and finally the heatsink fan which uses 0.44W. Considering all these together, it means a total power of 14.54W, which for working during 3 minutes (0.05h), means an energy consumption of 0.727Wh.

The vibration module only requires the motor which works at 3.3V with 90mA, which means 0.297W. For the entire duration of 2 minutes during the whole visit (0.033h), translates to an energy consumption of 0.01Wh.

The wind system uses two fans, each working at 0.44W, therefore a total power of 0.88W, which for 5 minutes (0.083h). This means the airflow interface will consume 0.073Wh.

The taste interface, although having two vaporizers, they won't work at the same time, therefore only one can be considered. Each clearomizer had a resistor with 13.85W, which working for 2 minutes (0.033h), corresponding to an energy of 0.457Wh.

Finally, the smell module, considering it will only activate one smell at a time, there is the scented air fan which uses 0.2W and the smell module will also activate the wind

system, therefore more 0.88W. Which gives a total of 1.08W, for 3 minutes (0.05h), corresponding to a total energy of 0.054Wh.

Now with an estimation of all the interfaces added together, excluding drivers and LEDs for simplification, it results in a total energy of 1.581Wh for a visit with this interface usage pattern. Considering that the battery would have a nominal voltage of 3.3V, this would correspond to a required capacity of 479mAh, which is relatively low for the wide range of batteries available commercially.

5.2 DISCUSSION

Analysing the results, it is possible to observe that the cold temperatures were not enough for this application, not even close to the desired values. The probable cause for this is the heatsink size being too small. Because of the limited available space only allowing a 20x20x20mm heatsink with forced ventilation, this seems to be under the required specifications and critical to proper operation of the Peltier. This is also the probable cause for the long time cooling the thermal handle. Another possible cause is the aluminium handle being too large in comparison to the heatsink, since it also functions as heatsink as well.

On the other hand, the thermal system in heat mode works quite well, which was expected since it is easier for a Peltier or any electric component for that matter, to generate heat instead of cold, since most power losses are reflected that way. The small issues with exceeding the set point temperature and the slight variation when it should be supposedly stable, arise from the two considerations mentioned in the firmware section, which are the thermistor time constant and the inexistence of a PID temperature controller.

The vibration system proved to be sufficient but is arguably weak according with the results. This might be enough to send the user notifications or left or right indications when following a specific route, however it is possibly too weak to convey convincing stimulus of shock or trepidation in a given storyline scenario. The incorrect assessment on the vibration origin and sequence might be because the portable device, although composed of two independent parts, is a singular object, mechanically connected, that said, physical vibrations would travel from one side to the other. If these vibrations are

weak or too faint, it might be possible to confuse where they originated or where they are stronger.

The first results on the airflow system show that the point of origin is a relatively meaningless feature when just conveying a wind or breeze sensation, since the users fail to perceive where it originates. However, it could be useful for smelling odours near the screen, like in the project it was based on, but still, in this breeze application it just does not make sense. Besides that, results also showed that the airflow is slightly weak and this may be a consequence of this design, since the fans are already small, and there are multiple air collisions, with lost flows along the way, before reaching the user. This means the air sensation will be too weak for some users to perceive it.



Figure 5.10: Vapour leak in the taste output

The taste system seems to work relatively well, based on the test results, since all test subjects reported tasting the flavour, despite existing a small tendency for the intensity to be weaker than stronger. However, that does not represent an issue and appears to be a good result for this sensorial interface. Although the fact that the vapour travels through the disposable tube before reaching the user, the flavours still proved to be enough to be noticeable. One minor issue that appeared was a minor vapour leak in the structure taste output, as shown in Figure 5.10. Though, this is due to the fact that the 3D printed structure is not exactly watertight and creates small openings between the layers of plastic.

The smell interface seems to be too weak to be noticed by some users. Despite the majority of subjects reported feeling the odour, still 20% reported not feeling anything, which is negative. This might be related to the airflow system design, since each time there is an air collision, there is also an aroma dilution between the scented air and ambient odourless air. There are some air collisions before the odour reaches the user's

face, therefore it becomes less noticeable, at least with higher fan speeds. Although, since the distance between the device's screen and the user is relatively large, lower speeds might prove ineffective as well, the same way the air breeze had difficulties in being perceptible, despite the high fan speeds. On the other way, the aromatized container together with the oil wick chamber, seemed to be a good choice, activating the scent release immediately, only the air distribution method seems inappropriate for this use.

The battery estimation results were quite positive. Of course, there are few losses that are not being considered here, like the voltage conversion for the multiple interfaces through DCDC step-up or step-down modules, or the losses of the circuit itself. And the use pattern for this museum visit scenario might be too optimistic, but still, these result shows a relatively low power consumption, which provides some margin for more interfaces if required. Another important detail about the battery is that it should have a high current discharge rate, since some components require relatively high currents, such as the TEC module (4A) and the vaporizers (2.77A).

Regarding the rest, the device still needs more testing and optimization. The first prototype was mostly a proof of concept, but now it can evolve to something better.

6 Conclusions

ABSTRACT

This chapter finalizes the thesis by presenting the final general conclusions on the overall accomplished work. It provides a brief analysis of the previously encountered problems on the test results, and provides some possible solutions to fix these issues and to generally improve the portable device, on the future work section. It also presents some publications which were published during the course of this work.

6.1 CONCLUSIONS

The objective of this thesis was to design and develop a new augmented reality, portable device, capable of providing compelling five sense experiences to the visitor of a museum. The device is part of the M5SAR project, and was meant to be integrated with the user's smart device, that together with the application (out of this thesis's scope), would improve and augment as much as possible, the experience of visiting a museum, by allowing the user to feel touch, taste and smell sensations from the museum objects.

This thesis studied most of the different existing techniques and technologies to create multisensory electronic interfaces and used that knowledge as a base to design a portable device with some of those systems, considering some portability limitations like size, weight and power. It presents all the design process that occurred during the development, selection of techniques, components and materials, as well as the necessary steps to physically implement them on a real, functional prototype.

The tests conducted to the prototype are also presented in this work, some of them were done by measuring certain properties, while others relied on actual people that experimented the device and reported the feedback of their experience under certain specific situations.

The results of these tests revealed that some of the interfaces still need improvement, as was the case of the cold module that was not able to reach the desired temperatures. Insufficient heat dissipation seemed to be the probable cause, which renders the module incapable of reaching cold temperatures. The airflow module also seemed to have some design problems that made this sensorial stimulus not noticeable by some users. This design issue also appeared to negatively affect the dispersal of the smell module fragrances.

On the bright side, the heating module, the vibration system and the taste interface all demonstrated positive results, although they could receive some improvements. For example, the heat control could be faster and more accurate, the vibration could be stronger and the taste connections in the casing structure could be better insulated.

Regarding other finishing details, since the sensorial interfaces still needed change, designing a final PCB is still to be done, and the selection of the appropriate battery as well. The ergonomic design aspect might also be improved through user experience feedback.

To conclude, the results in general are coherent with a first version of a prototype, implemented with the aim of being a proof-of-concept. Therefore, in general the results show that there are interfaces that need to be improved, in order to be perceptible by the end-user, namely the cold sensation. There are also some interfaces that can be improved, although their results are satisfactory, namely the wind sensation. And there are interfaces that show results already very acceptable as a final solution, namely the heat sensation. In resume, for a prototype developed as a proof-of-concept, this has accomplished fully its purpose, because it allowed to validate the main idea, allowing also to have a feedback from the end-users about the use and implementation of the real device. In this regard, the analysis of the problems found, allow to find possible solutions to correct those problems, and solutions on how to improve the portable device when designing a future prototype version. These future work perspectives are detailed in the next section.

6.2 FUTURE WORK

As it was demonstrated by the test results, the portable device still has a long way to go, until it is considered ready for application with the sensorial outputs that were initially required.

The first necessary improvement is related with the cold generation module. A bigger heatsink for the hot side of the thermoelectric module is essential, however this creates another problem, there is not enough space inside the prototype to accommodate a bigger heatsink. A full structure design alteration is probably necessary. Fortunately, other sensorial interfaces also need improvement and they are all somewhat related to each other. Since the airflow design proved to be inefficient too, the alternative approach would be to use the fans to send the air directly to the user face, which reduces airflow losses, therefore improving noticeability. This change will likely also improve the dispersal of the fragrances in the smell system, since less air collisions correspond to less scented air dilution and a more direct route from odour reservoirs to the user's face. Another advantage of this fundamental change is the removal of the air channels inside the gadget's structure, which create a relatively large new available space. This new change can allow a new design to be made, which might facilitate the usage of a larger heatsink on the Peltier device. This simple change will likely have a big influence on these three systems, cooling, airflow and smell.

Regarding the other sensorial interfaces, their results were positive, although some minor changes can be accomplished as well. The vibration system could take an upgrade on the vibration motor, replacing the actual one by a stronger and heavier to generate more noticeable vibration waves. The heating module could also be upgraded by changing the current NTC thermistor by another with faster response, a lower time constant. The taste interface does not need much change, the only reported problem was a minor vapour leak, which would occur in a production device, since the casing would not be 3D printed in that situation.

A critical aspect that is in urgent need of development is designing the final PCB with an energy management circuit with battery level indication. This can be done as soon as the interface design is finished and tested with positive results. This way it is guaranteed that the system won't need any more changes.

Regarding other finishing details, based on the comfortability results, the portable device could have a more ergonomic design to reduce as much size and weight as possible, improving the comfort for the users.

In terms of safety and security systems, it would be a good idea to incorporate an independent thermal shutdown on the power supply of the thermoelectric modules. This way, if for some reason the microcontroller or the firmware suffer a problem and stop controlling the temperature on the handles, the independent thermal shutdown will prevent them from reaching dangerous values for the user.

Another interesting feature for the PDTTSS would be incorporating sensors in the essential sensorial interfaces that would be able to detect whether the modules are working correctly or if they are damaged or broken. This way, the microcontroller could detect these faults and report the errors to the mobile application if necessary, indicating the user that the portable device needs technical assistance.

6.3 LIST OF PUBLICATIONS

Five manuscripts were published and/or accepted for publication, during the time of the master's degree: four conference papers and one book chapter. The following list enumerates the published works, the first one focused on this thesis, and the others present complementary information or work not directly related to this thesis, but on the scope of the M5SAR Project:

Sardo, J.D.P., Semião, J., Monteiro, J.M., Esteves, E., Pereira, J.A.R., Freitas, M.A.G., Rodrigues, J.M.F. (2017) *Portable Device for Touch, Taste and Smell Sensations in Augmented Reality Experiences*, accepted for Int. Congress on Engineering and Sustainability in the XXI Century, 11 - 13 October, Faro, Portugal.

Rodrigues, J.M.F, Cardoso, P.J.S., Lessa, J., Pereira, J.A.R., **Sardo, J.D.P.**, Freitas, M., Semião, J., Monteiro, J., Ramos, C.M.Q., Lam, R., Esteves, E., Figueiredo. M., Gonçalves, A., Gomes, M., Bica, P. (2017) *An Initial Framework to Develop a Mobile 5 Sense Museum System*, accepted Chapter 5 in Technological Developments for Cultural Heritage and eTourism Applications, IGI Global. ISBN: 978-1-5225-2927-9.

Rodrigues, J.M.F., Pereira, J.A.R., **Sardo, J.D.P.**, Freitas, M.A.G., Cardoso, P.J.S., Gomes, M., Bica, P. (2017) *Adaptive Card Design UI Implementation for an Augmented Reality Museum Application*, In M. Antona and C. Stephanidis (Eds.): Universal Access in Human-Computer Interaction 2017, Part I, LNCS 10277, pp. 1–11, 2017. DOI: 10.1007/978-3-319-58706-6 35.

Cardoso, P.J.S., Rodrigues, J.M.F., Pereira, J.A.R., **Sardo, J.D.P.** (2017) *An Object Visit Recommender Supported in Multiple Visitors and Museums*, In M. Antona and C. Stephanidis (Eds.): Universal Access in Human-Computer Interaction 2017, Part I, LNCS 10277, pp. 1–12, 2017. DOI: 10.1007/978-3-319-58706-6 24.

Pereira, J.A.R., **Sardo, J.D.P.**, Freitas, M.A.G., Veiga R., Cardoso, P.J.S., Rodrigues, J.M.F. (2017) *MIRAR: Mobile Image Recognition based Augmented Reality Framework*, accepted for Int. Congress on Engineering and Sustainability in the XXI Century, 11 - 13 October, Faro, Portugal.

References

1. Jung, T., Chung, N., & Leue, M. C. (2015). The determinants of recommendations to use augmented reality technologies: The case of a Korean theme park. *Tourism Management*, 49, 75-86.
2. Steichen, B., Conati, C., & Carenini, G. (2014). Inferring Visualization Task Properties, User Performance, and User Cognitive Abilities from Eye Gaze Data. *ACM Transactions on Interactive Intelligent Systems (TiiS)*, 4(2), 11.
3. Reinecke, K., & Bernstein, A. (2013). Knowing What a User Likes: A Design Science Approach to Interfaces that Automatically Adapt to Culture. *Mis Quarterly*, 37(2), 427-453.
4. Gajos, K. Z., Wobbrock, J. O., & Weld, D. S. (2008). Improving the performance of motor-impaired users with automatically-generated, ability-based interfaces. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (pp. 1257-1266). ACM.
5. Rodrigues, J.M.F., Lessa, J., Gregório, M., Ramos, C. & Cardoso, P.J.S. (2017a) An Initial Framework for a Museum Application for Senior Citizens, *Proceedings Software Development and Technologies for Enhancing Accessibility and Fighting Info-exclusion*. doi: <http://dx.doi.org/10.1145/3019943.3020002>
6. Zhao, L., Lu, Y., Zhang, L., & Chau, P. Y. (2012). Assessing the effects of service quality and justice on customer satisfaction and the continuance intention of mobile value-added servic Zhao, L., Lu, Y., Zhang, L., & Chau, P. Y. (2012). Assessing the

effects of service quality and justice on customer satisfaction and the continuance intention of mobile value-added services: An empirical test of a multidimensional model. *Decision Support Systems*, 52(3), 645-656. es: An empirical test of a multidimensional model. *Decision Support Systems*, 52(3), 645-656.

7. Yuan, Z., Bi, T., Muntean, G. M. & Ghinea, G. (2015). Perceived synchronization of multisemedia services. *IEEE Transactions on Multimedia*, 17(7), 957-966.
8. Kovács, P. T., Rozinaj, G., Murray, N., Sulema, Y. & Rybárová, R. (2015). Application of immersive technologies for education: state of the art. Paper presented at the 2015 International Conference on Interactive Mobile Communication Technologies and Learning (IMCL), Thessaloniki, Greece.
9. Wolf, M. J. (2008). The video game explosion: a history from PONG to Playstation and beyond. ABC-CLIO.
10. Shirali-Shahreza, M., & Shirali-Shahreza, S. (2009). Examining the usage of feedback vibration in Nintendo DS handheld game console. In *Advanced Communication Technology, 2009. ICACT 2009. 11th International Conference on* (Vol. 3, pp. 1997-2000). IEEE.
11. PlayStation Universe (2008) Forum Thread: dualshock 3 uneven vibration. Retrieved Sep. 2017 from <https://www.psu.com/forums/showthread.php/119156-dualshock-3-uneven-vibration>
12. Brewster, S., Chohan, F., & Brown, L. (2007). Tactile feedback for mobile interactions. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 159-162). San Jose, CA: ACM.
13. Lin, J., Nishino, H., Kagawa, T., & Utsumiya, K. (2012). A Handy Image Explorer with Tactile Feedback for Diagnostic Imaging. In *Broadband, Wireless Computing, Communication and Applications (BWCCA), 2012 Seventh International Conference on* (pp. 316-321). IEEE.
14. Bau, O., Poupyrev, I., Israr, A., & Harrison, C. (2010). TeslaTouch: electrovibration for touch surfaces. In *Proceedings of the 23rd annual ACM symposium on User interface software and technology* (pp. 283-292). ACM.

15. Israr, A., Bau, O., Kim, S. C., & Poupyrev, I. (2012). Tactile feedback on flat surfaces for the visually impaired. In *CHI'12 Extended Abstracts on Human Factors in Computing Systems* (pp. 1571-1576). ACM.
16. Kim, S. C., Israr, A., & Poupyrev, I. (2013). Tactile rendering of 3D features on touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (pp. 531-538). ACM.
17. Alexander, J., Marshall, M. T., & Subramanian, S. (2011). Adding haptic feedback to mobile tv. In *CHI'11 Extended Abstracts on Human Factors in Computing Systems* (pp. 1975-1980). ACM.
18. Long, B., Seah, S. A., Carter, T., & Subramanian, S. (2014). Rendering volumetric haptic shapes in mid-air using ultrasound. *ACM Transactions on Graphics (TOG)*, 33(6), 181.
19. Ultrahaptics (2016) Ultrahaptics. Retrieved: Dec. 2, 2016 from <http://www.ultrahaptics.com>.
20. Subramanian, S., Seah, S. A., Shinoda, H., Hoggan, E., & Corenthy, L. (2016). Mid-Air Haptics and Displays: Systems for Un-instrumented Mid-air Interactions. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (pp. 3446-3452). ACM.
21. Hoshi, T., Abe, D., & Shinoda, H. (2009). Adding tactile reaction to hologram. In *RO-MAN* (pp. 7-11).
22. Moon, T., & Kim, G. J. (2004). Design and evaluation of a wind display for virtual reality. In *Proceedings of the ACM symposium on Virtual reality software and technology* (pp. 122-128). ACM.
23. Deligiannidis, L., & Jacob, R. J. (2006). The vr scooter: Wind and tactile feedback improve user performance. In *3D User Interfaces (3DUI'06)* (pp. 143-150). IEEE.
24. Suzuki, Y., & Kobayashi, M. (2005). Air jet driven force feedback in virtual reality. *IEEE computer graphics and applications*, 25(1), 44-47.

25. Sodhi, R., Poupyrev, I., Glisson, M., & Israr, A. (2013). AIREAL: interactive tactile experiences in free air. *ACM Transactions on Graphics (TOG)*, 32(4), 134.
26. Gupta, S., Morris, D., Patel, S. N., & Tan, D. (2013). AirWave: non-contact haptic feedback using air vortex rings. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing* (pp. 419-428). ACM.
27. Kitada, T., Kunii, Y., & Hashimoto, H. (1997). 20 dof five fingered glove type haptic interface-sensor glove ii. *Journal of Robotics and Mechatronics*, 9, 171-176.
28. Koyama, T., Yamano, I., Takemura, K., & Maeno, T. (2002). Multi-fingered exoskeleton haptic device using passive force feedback for dexterous teleoperation. In *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on* (Vol. 3, pp. 2905-2910). IEEE.
29. Sarakoglou, I., Brygo, A., Mazzanti, D., Hernandez, N. G., Caldwell, D. G., & Tsagarakis, N. G. (2016). HEXOTRAC: A highly under-actuated hand exoskeleton for finger tracking and force feedback. In *Intelligent Robots and Systems (IROS), 2016 IEEE/RSJ International Conference on* (pp. 1033-1040). IEEE.
30. AxonVR (2016) AxonVR. Retrieved: Dec. 6, 2016 from <http://axonvr.com>
31. Harrison, C., & Hudson, S. E. (2009). Providing dynamically changeable physical buttons on a visual display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 299-308). ACM.
32. Tactus Technology (2016) Tactus Technology. Retrieved: Dec. 2, 2016 from <http://tactustechnology.com/>.
33. Stanley, A. A., Hata, K., & Okamura, A. M. (2016). Closed-loop shape control of a haptic jamming deformable surface. In *Robotics and Automation (ICRA), 2016 IEEE International Conference on* (pp. 2718-2724). IEEE.
34. Sinclair, M., Pahud, M., & Benko, H. (2014). TouchMover 2.0-3D touchscreen with force feedback and haptic texture. In *2014 IEEE Haptics Symposium (HAPTICS)* (pp. 1-6). IEEE.

35. Geomagic (2016) Geomagic. Retrieved: Dec. 6, 2016 from <http://www.geomagic.com>.
36. Wang, H., Kaleas, D., Ruuspaakka, R., & Tartz, R. (2012). Haptics using a smart material for eyes free interaction in mobile devices. In SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring (pp. 83410I-83410I). International Society for Optics and Photonics.
37. Benali-Khoudja, M., Hafez, M., Alexandre, J. M., Benachour, J., & Kheddar, A. (2003). Thermal feedback model for virtual reality. In International Symposium on Micromechatronics and Human Science (Vol. 1, pp. 153-158).
38. Kurogi, T., Nakayama, M., Sato, K., Kamuro, S., Fernando, C. L., Furukawa, M., ... & Tachi, S. (2013). Haptic transmission system to recognize differences in surface textures of objects for telepresence. In 2013 IEEE Virtual Reality (VR) (pp. 137-138). IEEE.
39. Yanagida, Y. (2012). A survey of olfactory displays: Making and delivering scents. In Sensors, 2012 IEEE (pp. 1-4). IEEE.
40. Aurora Scientific (2016) 206A; Olfactometer. Retrieved: Sep. 2017 from <http://aurorascientific.com/products/neuroscience/olfactometer/>
41. Kaye, J. N. (2001). Symbolic olfactory display (Doctoral dissertation, Massachusetts Institute of Technology).
42. PC World (2006) The 25 Worst Tech Products of All Time. Retrieved: Dec. 6, 2016 from http://www.pcworld.com/article/125772/worst_products_ever.html.
43. Engadget (2014) The iPhone Duo lets you send aromas when pictures aren't enough. Retrieved: Dec. 6, 2016 from <https://www.engadget.com/2014/06/18/iphone-duo/>.
44. Yamada, T., Yokoyama, S., Tanikawa, T., Hirota, K., & Hirose, M. (2006). Wearable olfactory display: Using odor in outdoor environment. In IEEE Virtual Reality Conference (VR 2006) (pp. 199-206). IEEE.

45. Matsukura, H., Yoneda, T., & Ishida, H. (2013). Smelling screen: development and evaluation of an olfactory display system for presenting a virtual odor source. *IEEE transactions on visualization and computer graphics*, 19(4), 606-615.
46. Onotes (2016) Onotes. Retrieved: Dec. 6, 2016 from <http://www.onotes.com/>.
47. Hashimoto, K., & Nakamoto, T. (2016). Tiny olfactory display using surface acoustic wave device and micropumps for wearable applications. *IEEE Sensors Journal*, 16(12), 4974-4980.
48. Ranasinghe, N., Nakatsu, R., Nii, H., & Gopalakrishnakone, P. (2012). Tongue mounted interface for digitally actuating the sense of taste. In *Wearable Computers (ISWC), 2012 16th International Symposium on* (pp. 80-87). IEEE.
49. Tanikawa, T., & Hirose, M. (2008). A study of multi-modal display system with visual feedback. In *Universal Communication, 2008. ISUC'08. Second International Symposium on* (pp. 285-292). IEEE.
50. Narumi, T., Kajinami, T., Nishizaka, S., Tanikawa, T., & Hirose, M. (2011). Pseudo-gustatory display system based on cross-modal integration of vision, olfaction and gustation. In *Virtual Reality Conference (VR), 2011 IEEE* (pp. 127-130). IEEE.
51. Ranasinghe, N., Cheok, A. D., Fernando, O. N. N., Nii, H., & Ponnampalam, G. (2011). Electronic taste stimulation. In *Proceedings of the 13th international conference on Ubiquitous computing* (pp. 561-562). ACM.
52. Ranasinghe, N., & Do, E. Y. L. (2016). Digital Lollipop: Studying Electrical Stimulation on the Human Tongue to Simulate Taste Sensations. *ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM)*, 13(1), 5.
53. CJ 4Dplex (2016) CJ 4Dplex. Retrieved: Dec. 2, 2016 from <http://www.cj4dx.com>
54. FeelReal (2016) FeelReal. Retrieved: Dec. 6, 2016 from <http://feelreal.com/>.
55. Museum of Food and Drink (2016) Flavour. Retrieved: Sep. 2017 from <http://www.mofad.org/flavor/>

56. Mashable (2015) Inside NYC's first museum dedicated to food. Retrieved: Sep. 2017 from <http://mashable.com/2015/10/27/museum-of-food-and-drink/>
57. World Traveling Military Family (2015) Chocolate Museum Cologne Germany. Retrieved: Sep. 2017 from <http://www.worldtravelingmilitaryfamily.com/chocolate-museum-cologne-germany/>
58. Hui Mao (2012) An Introduction To Thermoelectric cooling module. Retrieved Sep 2017 from <http://www.huimao.com/about/show.php?lang=en&id=4>
59. Wavelength Electronics (2010) Temperature Controller Basics. Retrieved: Sep. 2017 from <https://www.teamwavelength.com/info/temperaturecontrollers.php>
60. Farsalinos, K. E., & Polosa, R. (2014). Safety evaluation and risk assessment of electronic cigarettes as tobacco cigarette substitutes: a systematic review. *Therapeutic advances in drug safety*, 5(2), 67-86.
61. Giroud, C., de Cesare, M., Berthet, A., Varlet, V., Concha-Lozano, N., & Favrat, B. (2015). E-cigarettes: a review of new trends in cannabis use. *International journal of environmental research and public health*, 12(8), 9988-10008.
62. Gang, P. E. N. G., & Feng, S. H. I. (Eds.). (2013). *Eastward Flows the Great River: Festschrift in Honor of Professor William SY. Wang on His 80th Birthday*. City University of HK Press.
63. Rhodes, J., Clay, C., & Phillips, M. (2013). The surface area of the hand and the palm for estimating percentage of total body surface area: results of a meta-analysis. *British Journal of Dermatology*, 169(1), 76-84.
64. U.S. Food and Drug Administration (2016) Vapes, E-Cigs, Hookah Pens, and other Electronic Nicotine Delivery Systems (ENDS). Retrieved: Sep. 17 from <https://www.fda.gov/TobaccoProducts/Labeling/ProductsIngredientsComponents/ucm456610.htm>.
65. What Is (2012) Bluetooth 2.0+EDR. Retrieved: Sep 17 from: <http://whatis.techtarget.com/definition/Bluetooth-20EDR>.
66. HC-03/05 Embedded Bluetooth Serial Comm. Module AT command set. (2011)