A Portable Device for Five Sense Augmented Reality Experiences in Museums

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Abstract: - Augmented reality (AR) nowadays is focused in two senses, sight and hearing. The work presented here is part of the Mobile Five Senses Augmented Reality system for Museums (M5SAR) project, which has the goal of developing an AR system to be a guide in cultural and historical events and museums, complementing or replacing traditional guides, directional signs or maps, while enhancing the user's experience by adding multisensorial information to multiple museum objects. The existing solutions for this type of devices either lack portability or fail to implement all the human senses at the same time. This paper presents a new device capable of extending augmented reality experiences to all five human senses, through the use of a portable device that can reproduce stimulus of touch, taste and smell. The proposed apparatus is meant to be paired with a mobile application that controls which sensorial interface is activated and when, relaying that information to the portable device. The application, running on the user's smartphone or tablet, sends the activation instructions via Bluetooth, using a communication protocol, which is then received by the device's core microcontroller. Then, the microcontroller acts accordingly, activating the requested physical interfaces to deliver the multisensorial media to the user.

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

1 Introduction

This work is part of the Mobile Five Senses Augmented Reality System for Museums (M5SAR) project [1]. The complete system consists of a smartphone application (out of the scope of this paper) and a physical device (the present work) hence referred as "gadget" or "portable device", to be integrated in the smartphone to explore the 5 human senses: sight, hearing, touch, smell, and taste. The device should be portable and small, but it adds touch, smell and taste experiences to the complete augmented system, to improve and augment as much as possible the museum visit, i.e., to see, hear, touch, feel and experience all the interesting objects that exist.

Traditional AR systems return sensorial feedback for only two senses – sight and hearing. Unlike those, multisensory media focuses on providing immersive communications and enhancing the user's quality of experience [2].

The existing systems related to augmented sensing experiences are big hardware systems, far from being portable. By developing a new augmented reality device, the first major 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 major 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 reproduces the three senses of touch, taste and smell. The remaining senses, sight and hearing, should be reproduced in the user's smartphone or tablet, connected to the device.

Moreover, the device should be flexible enough to adapt itself to different sizes of smartphones or tablets. It should be powered by a rechargeable battery, which gives the module the ability to keep the system running during the museum visit.

Section 2 focuses on the state of the art for sensorial interfaces, whether they are technologies, academic projects or commercial products; section 3 analyses the project's goals and requirements to start designing a concept, while section 4 details the constructions steps. The conducted tests and results are presented in section 5, and section 6 finalises this paper with the main conclusions.

2 Background

It is a generally accepted fact in psychology that the more informational channels used, the better the transmitted information will be perceived [3]. Still, many existing multimedia systems actually in use are focused only on the two senses of sight and hearing. It is difficult to digitally convey compelling sensations for the other senses, which might explain this absence. Even though there have been a series of attempts to achieve this, almost none of those were embraced by developers, product designers, manufacturers or consumers. In this analysis, the focus will be on the three human senses that are not generally stimulated by technological devices and commercial products, which are the senses of touch, taste and smell.

In terms of singular sensorial systems, one example broadly used are vibration motors that stimulate the sense of touch through haptic feedback. It has been in use for years and it was mostly introduced by videogames and mobile phones. The first videogame to use haptic feedback was the 1976 arcade racing game “Fonz”, developed by Sega, which had vibrating handlebars during collisions [4]. Newer generation consoles now include built-in haptic feedback features in their controllers, like Sony’s DualShock technology, which became a standard feature in videogame controllers.

However, most people are probably familiar with this technology thanks to the mobile phone industry, which has also 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.

Electrovibration is another existing way to create sensations of touch, although not yet present on the consumer market. It works by controlling electrostatic charges on the surface of the touchscreen, this way varying the friction between the surface and the user’s finger [5].

Ultrasounds have also been used to reproduce tactile sensations. The authors in [6] have developed a prototype that uses ultrasonic air pressure waves to create contactless vibration feedback. Still, research on this area is just beginning, and 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 [7].

The use of air as a mechanism to stimulate our sense of touch is also in the haptic feedback category. One of the earlier uses of this technique was a wind display called the WindCube [8]. Other virtual reality applications have since then been using similar approaches to enrich their experiences. Disney Research, however, introduced a different system called AIREAL [9]. However, these technologies are not yet distributed to the consumer’s market.

An interesting approach to mechanical haptic feedback is using pneumatic tactile displays, which use air chambers between layers of acrylics and latex to create simple shapes and buttons [10]. 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 [11]. A company called AxonVR is currently developing a 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 [12]. Although these technologies are certainly interesting, some of them would be impractical on a mobile device.

Another way to stimulate the sense of touch is through thermoreception, or perception of temperature, although sometimes this is categorized as a sense apart from the traditional 5 human senses. The application of thermal feedback in devices is not exactly new [13], but with the dissemination of Peltier devices (thermoelectric modules), more studies and experiments have been conducted.

However, the use of Peltier devices on mobile applications is problematic from the point of view of efficiency and energy consumption, which is likely one of the main reasons why this technology is not yet present in everyday consumer products.

As to reproduce the sense of smell in a small or portable digital device, there have been some 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. The first combination of smell with video was back in 1906 when a cinema owner diffused a rose scent in the audience during a screen of the Rose Bowl [14]. After that, a 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 [15] considered it one of the 25 worst tech products of all time.

One 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 [16]. Another peculiar prototype is the Smelling Screen, which combines a display with four fans to carry the scent and work together at different settings, to change the odour's point of origin on the screen [17].

Recently, the Ophone Duo was presented, which allowed the user to send a photo tagged with a specific odour to another person with the device. The system later evolved to a company, Onotes, that sells a digital scent releaser called Cyrano [18].

Finally, there is the sense of taste, 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 [19] 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 [20].

There is some research however on a real digital taste interface that attaches to the user's tongue via two silver electrodes, and by applying pulses with different electric properties like current, frequency and voltage, seems to produce sour, bitter and salty sensations [21]. 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 [22]. 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 [23].

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.

There are not many examples of systems that combine together multiple senses (Multisensorial Systems) to offer a more immersive sensorial experience. The better-known systems 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, such as rain, wind, temperature changes, strobe lights, vibrations, smells, fog and chair movements, among other things. 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.

In the virtual reality (VR) consumer market, there have been also some developments, as the example of the FeelReal VR Mask, presented in 2015. 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 [24].

The Museum of Food and Drink (MOFAD), in New York, also developed a very interesting odour interactive display, called The Smell Synthesizer. 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 [25], working with a logic of 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.

However, their multisensory approach was not exactly integrated into a single system, and the taste aspect of it was recreated separately using gumball machines. 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 sense of smell has been used for a while, as for example in the Lindt Chocolate Museum in Cologne, Germany, where people can try the odours of spices and ingredients used in their chocolates. 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 stimuli in one single object, product or display.

3 Concept Design

The objective of this work 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 pertains on the design and construction of the device or gadget, considering that it is meant to be coupled with the user's mobile device. This means it should be flexible enough to adapt to 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 of touch, taste and smell, at the appropriate time, when instructed by the application via wireless commands.

The initial objectives and design requirements can be summarized as: to be a portable device that can reproduce touch, taste and smell stimulus; the dimensions should be small, with a maximum size of 7x7x25 cm for each part (two parts, one on each side of the mobile device); it should also be lightweight; capable of adapting easily to multiple sizes of mobile devices; able to reproduce sensations of touch such as wind, heat, cold, and vibration; able to generate 3 to 5 different odours; able to recreate sensations of taste with 3 to 5 different flavours; to have a wireless communication between the device and the application; a simple communication protocol to activate sensorial interfaces; and finally, a battery powered operation to allow portability.

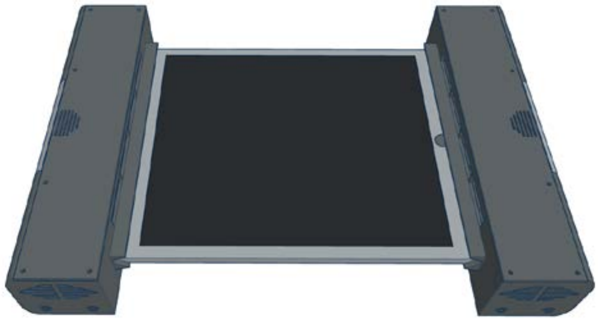

Fig.1 – Initial concept of the prototype

Figure 1 presents a sketch of the proposed portable device. The system consists of two similar hardware parts, placed on each side of the user's device where the mobile application is running, and it is connected at the bottom through the adjustable supports.

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. The communication between the device and the mobile application is possible through wireless communication using a Bluetooth interface. The communication between the remaining interfaces will be wired. The physical output interfaces will be responsible for reproducing the multiple sensorial stimulus for the three senses. The left and right hardware parts are very similar to each other, and they should have the same modules, components and connections, with the main difference that only one has a Bluetooth communication interface. The side that has the Bluetooth module (left) will have the master microcontroller, and the slave microcontroller will be on the other side (right). They are similar in terms of software and hardware, and the firmware running on both microcontrollers can be mostly the same code. The difference between them is how they receive and replicate their instructions.

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.

3.1 Touch Stimulus

Different types of possible touch stimulus were analysed for the touch sense reproduction. 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, which makes it not feasible. The three types of touch stimulus selected are thermal touch, vibration and air flow.

Starting with temperature, the objective is to have the user somehow experience sensations of heat and cold through the portable device. With that in mind, the direct contact seems to be the ideal approach for a portable device; by changing the temperature on the device's handles, the user could immediately feel the temperature sensation in their hands.

In order to change the temperature in the device's handles three things are needed: a heating module, a cooling module and thermal conductive handles. Regarding the handles, that can be easily solved with a 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.

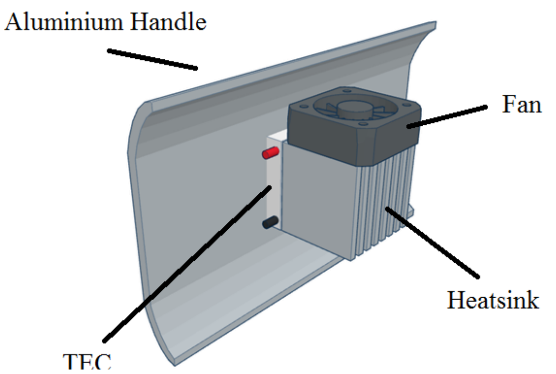

Fig.2 – Thermal module design.

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.

Therefore, by using and tuning heatsinks (Fig.2) on one or both sides of the device, it is possible to generate a desired temperature on a specific side. Since they can be used both for cooling and heating just by reversing the electrical current, it seems practical to use them, in order to save space and money. In terms of desirable temperatures for the sense of touch, the range between 0ºC and 40ºC seems like a good selection, which is safe for the user, yet still sufficiently noticeable to convey the intended sensations.

Vibration is another way to represent another stimulus related to the sense of touch. Since this type of stimulus is relatively easy to implement, it was decided to use it in the portable device. Although the gadget is supposed to be used together with the user's mobile device, which most likely already has vibration features, implementing it on our system will make it definitely available to be used, not depending on the user's device, and obviously, it will allow the design of a few new extra features that wouldn't be possible through the user's smartphone.

One particularly useful application 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 subtlety 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 a common and cheap technology, with a lot of different sizes and shapes available.

Still regarding the sense of touch, there is also the possibility to use an airflow to recreate the idea of wind or a small breeze in a given scenario. Some VR games already use this technique. Besides, fans can be found everywhere and are budget friendly, so it makes sense to adapt it on the portable device. Size is also not a problem, since there are fans as small as 15x15 mm, and are quite easy to use and 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.

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.

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 [17], 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.

The ventilation channels (Fig. 3) consist on a tube with a fan on each end 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. By varying the speed of the fans and their relations between each other, different points of origin and flow rate are possible.

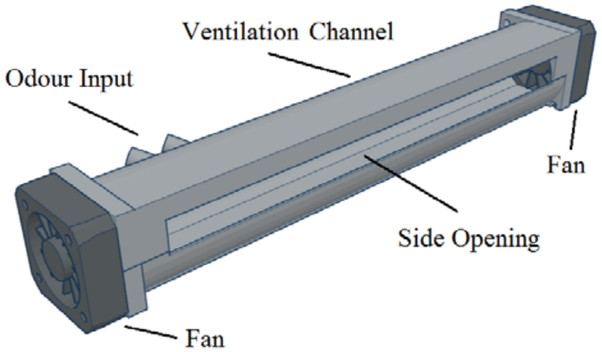

Fig.3 – Air channel design.

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

3.2 Taste Stimulus

There are not many solutions available for the sense of taste; 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 this technology is still on its inception, 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, which would unlock and open 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 approached them, being the portable device responsible for giving the machines the instruction to release the snack. Both of these options require an external process of producing or getting unusual flavoured snacks for the museum system, and the second option even needs an actual vending machine, which would be either time consuming to develop or expensive to buy and maintain, making the system complex and dependent on external entities.

That considered, another option comes to the top: using electronic vaporizers, also known as electronic cigarettes. 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 [26]. 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 store, 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 given the space limitation, a direct approach to each vaporizer was later adopted.

The device should thus be developed with four vaporizers, two on each side, providing a total of four different flavours per visit. To guarantee the hygiene of the system, each visitor would receive with the device a disposable tube to connect to the flavour outlet, and at the other end the respective mouthpiece to sample. This means that there will be two taste outputs per side of the device, and to let the user know which one to use, they should have an output indicator like a small LED nearby.

This system also has the advantage to change and replace flavours easily, and it is not necessary to develop the flavours themselves, since food grade aromatizers are readily found and commercially available.

3.3 Smell Stimulus

There are a few different odour releasing techniques available. 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 undesirably aromatized. Considering those conditions, the possible solutions were analysed to compare vantages and disadvantages.

Most techniques 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 at a museum. 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 designing 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 for the wind/breeze sensation, redirecting a part of that flow for the smell system, but after a few tests, this proved ineffective.

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.

Regarding odour releasing techniques there are a few different options, the most common include: (a) vaporizing an aromatized solution from the electronic vaporizer; (b) pushing a flow of air through a scent filter or fragrance recipient; (c) fragrance spray; (d) pressurized scented cans; (e) ultrasonic scent atomization.

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 a moist effect that could accumulate 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.

The first two options remain as possibilities, (a) and (b). Initially, the taste vaporizer solution seems to be the ideal one (a), as it gives the advantage of reusing components and there is no risk of spills; 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. Besides, this would limit the odours available to the same flavours present in the tasting interface.

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, and the risk of spill can be reduced, for example, with cotton soaked with the desired fragrance. It does, however, require valves, which can be a problem.

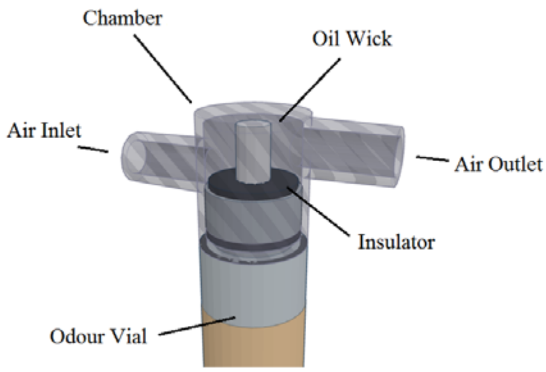

Fig.4 – Fragrance chamber design.

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, which will release 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. The fragrance container or chamber is represented in Fig. 4.

3.4 Mechanical Design

With the sensorial interfaces studied and selected, it comes the moment to think about 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 not present a 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 25x7x7cm and then, if possible, start to reduce the prototype to an optimal size.

The system should be light, practical and intuitive. As depicted in Fig. 1, the prototype will consist of two almost independent and identic, 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, 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. 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 a way that are exactly the same and yet to 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 devices' thickness. 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 in inserted into the prototype, which would be from above.

Regardless of the design concepts that are going to be used, 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

The representations on this section 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 ignored for now, since it is basically a hardware copy of the master side with some minor modifications. That said, all information, images, and diagrams are representing the hardware of the master side, unless specified otherwise.

Considering the concept requirements for this project in terms of size, sensorial interfaces and practicality, a sketch for the structure was designed with round edges, a lower height of 52mm and also a reduced width of 57mm, to improve comfort while holding the device. The length is kept at 250mm. The idea is to design the 3D model of the entire structure, considering all components and interfaces to be used, their dimensions and positions. All requirements should be respected, 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.

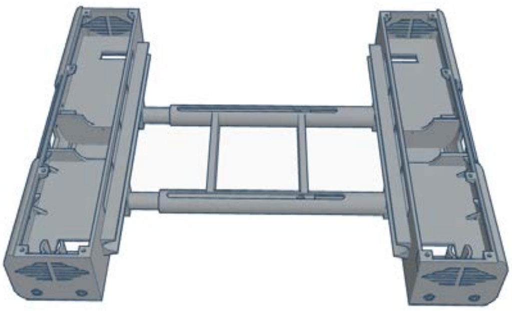

Fig.5 – 3D model for the portable device's structure.

Figure 5 shows the final 3D model, without covers, for the portable device. It consists of two sides attached together via the adjustable supports. 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. To optimize the use of space, the inside volume was separated into two levels: In the top level goes the thermoelectric module, the holder for the odour vials, the supports for the micro fans for the aroma dispersion, and the ventilation channel.

The middle section is an empty area that will serve as an air duct for the Peltier heatsink forced airflow. The bottom level will be composed of two compartments, one for a battery with a size of up to 100x30x13mm, and the other is meant to be an easy access to the odour and flavour reservoirs. By opening the cover of this area, the fragrance vials or taste vaporizers can be easily replaced.

4.1 Sensorial Interfaces

Starting with the temperature module, the selected approach was the use of a Peltier module. 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 cold, and conveys the thermal sensation to the user through an aluminium handle.

One way to do the power inversion is by using a transistor bridge using MOSFET's, however this will add more heating losses, a need for heat dissipation, and decrease the overall efficiency of the system, which could be excessive for a battery powered device. Therefore, the chosen solution was to use a DPDT (Double Pole Double Throw) relay wired in a polarity reversal configuration. 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, which is why a second output for the TEC module is needed. The selected Peltier is a TES1-3104 module, it has a 3.8V nominal voltage, 4A rating, a maximum temperature difference of 68ºC (*DTmax*), a maximum refrigerating power of 12.5W (*Qmax*) and a size of 20x20mm.

The TEC module also has a heatsink fan that turns on at the same time as the Peltier, to help the interior side to stay near the ambient temperature, so that the exterior handle can reach higher or lower temperatures. Both the relay and the Peltier device and fan are powered by switching transistors.

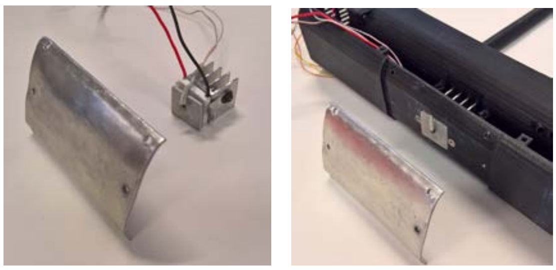

Fig.6 – Thermal module assembly.

The temperature reading of the handle is done via a 100k NTC thermistor, which is placed between the outer side of the Peltier and the haptic handle, configured with also a 100k pull-down resistor, and the middle node later connected to an analogue input of the microcontroller. It is also critical to obtain the correct proportions of the heatsinks, and since the inside space will be limited. it will be difficult to get a heatsink with the desired specifications. Another important detail is the fact that the aluminium handle outside also serves a heatsink. For that reason, it should be as small as possible, otherwise that side will get closer to the ambient temperature and, instead of the cold side getting cold, the hot side will get even hotter, possibly overcoming the maximum 80ºC allowed for the thermoelectric module.

On the left image on Fig. 6, 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.

The vibration system 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. Just like the thermal system, the motor will be activated from a switching transistor. 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 motor really close to the haptic handles, which 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. The selected motor has a 3.3V operating voltage and 90mA rated current, with the dimensions of 12x6x3.6mm. However, if more intense vibrations were necessary to convey stronger sensations, another motor could be considered.

Fig.7 – Ventilation channel assembly.

The airflow or wind sensation is based on the Smelling Screen prototype [17], using a ventilation system with four fans, two in each side of the device. By varying the speed of each individual fan, it is possible to control the air flow point of origin on the screen of the user's device. As depicted in Figure 7, 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 into the ventilation system. The airflow 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. The electronic circuit for the fans' driver is straightforward: two fans (on each side) are activated by two switching transistors. The fans in use have a 12V operating voltage, 0.44W consumption power, and a 30x30x10mm size.

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 mentioned 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, being the most common ones the atomizer itself, the cartomizer and the clearomizer. 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. The clearomizer is the most common type of vaporizer, consisting of a clear polycarbonate plastic or Pyrex glass tank, which allows to see the level of the liquid inside; 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 liquid is absorbed by silica wick and delivered to the heating coil.

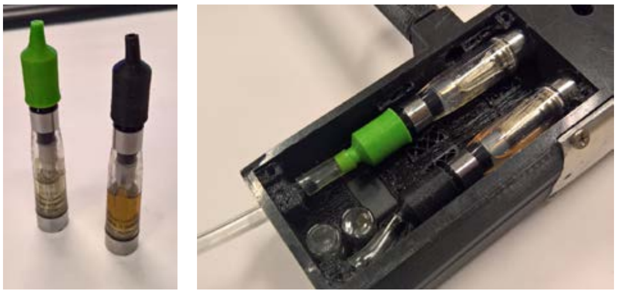

Fig.8 – Clearomizers assembly.

The selected atomizers for this prototype are the clearomizers, shown in Figure 8, and have a liquid capacity of 1.6ml. The left image (on Fig.8) shows the clearomizers with different flavoured liquids and the image on the right shows the vaporizers screwed in position. 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 LEDs working as taste output indicators. They tell the user when to draw from the pipe.

The electronic driver is quite similar to the wind system circuit; the vaporizers, which are basically just resistors, are connected through switching transistors. These vaporizer resistors are typically very low, which means that currents are also relatively high. 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. The clearomizers have a threaded pattern connector on their base that will be the system used to plug them in and out of the prototype, which also allows a simple and quick replacement of the tank or flavour if desired.

Fig.9 – Fragrance bottles and system assembly.

The selected system for the smell module was the use of a forced flow of air through an aromatized container, which is then inserted into the fan ventilation channels. It basically consists of an oil wick air freshener, where the oil fragrance in a small bottle is absorbed by the wick to the top of the chamber. This chamber, depicted in Fig. 4, has an air inlet and outlet, and when the smell system is activated a small fan pushes the air through the chamber inlet and exits through the outlet, directly into the ventilation channel (Fig. 9). There should be a rubber insulator between the odour vial and the oil wick to serve as a cover to protect against spilling, since this is a portable unit in the user's hands, with 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, which is later connected to the air inlet of the fragrance chamber.

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. This fan can be as small as 20x20mm and still generate a sufficient airflow to carry and disperse the aroma. Regarding the flow valves, for now they are being ignored, since the insulator guarantees there is no fluid leaks, and the available space is not sufficient for them.

During the construction, the fragrance chambers were fused into just one piece, 3D printed in flexible material (shown in green on Fig. 9), 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. On the left image of Fig. 9 it is visible the fragrance vials (small glass flasks, similar to perfume samples.), while on the right is the smell system assembled in the device structure.

The electronic driver is similar to the one used for the taste system, the only difference being the use of two micro fans instead of vaporizers, which are both activated by switching transistors. The fans have a 5V operating voltage, 0.2W consumption power and a 20x20x10mm size.

Fig.10 – Portable device assembled with a tablet.

The finished prototype is shown in Fig. 10, with an Asus Zenpad 3S 10 tablet, which has a size of 240.5x163.7mm. One the frontal bottom side, the air inputs and the taste outputs are visible.

4.2 Communication

The communication between the user's device, either a smartphone or a tablet, and the portable multisensorial device is done via Bluetooth. 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 will communicate with the master device, sending commands through its own Bluetooth interface to the HC-05 Bluetooth module, which then redirects those serial instructions to the master microcontroller through a wired UART link. This HC05 module has a low power operation of 1.8V to 3.6V, average consumption of 50mA, a UART interface with programmable baud rate and an integrated antenna.

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. Depending on the desired sensation, the parameters that the command instruction will need as inputs.

5 Results

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 users, where they classify the intensity of the stimulus they felt.

5.1 Tests

The first one is the thermal system since temperature is something quantifiably. The first test was executed with an external thermometer on the haptic handle, when a cold instruction for 10ºC was requested for 60 seconds, with an 100% power PWM. The initial ambient temperature was 24ºC. The second test followed the same settings, but with a heat instruction instead of 35ºC for 60 seconds, with an 30% power PWM. The handle was resting for a few minutes until it reached the initial ambient temperature of 24ºC as before. Both results are presented in Fig. 11.

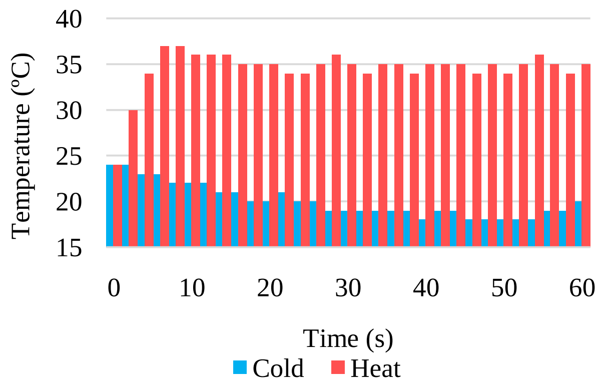

Fig.11 – Temperature test results.

The results presented in the graph show that the temperature never reached the desired set point of 10ºC during the 60 second test. In fact, it probably never would, since the lowest temperature achieved was 18ºC, and near the end of the graph the temperature starts rising again. Another noticeable issue is the fact that the temperature decreases very slowly, and the system needs 40 seconds to reach the lowest point of 18ºC. Regarding the heat test, 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 presents no problems reaching the desired temperature of 35ºC, being also relatively faster at achieving a determined temperature, taking less than 6 seconds to reach 37ºC.

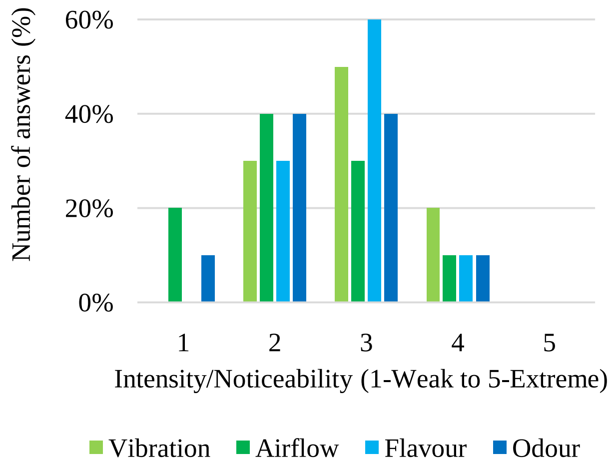

Fig.12 – Subjective interfaces test results.

The vibration system is hard to quantify. For this reason, the portable device was handled to a group of ten users in a laboratory environment. The vibration instruction was sent, with the pattern of left handle 5Hz intermittence vibration for 5 seconds, then a 2 second rest, followed by a right handle 5Hz intermittence vibration for 5 seconds. The subjects were asked to rate the level of intensity they felt, from 1 to 5, 1 being “weak” and 5 being “extreme”. Results are presented in Fig. 12.

The airflow interface was also tested by users’ feedback. The same sample group of ten subjects was used, this time with a wind instruction in the device for 10 seconds, with the origin of airflow being the top right quadrant. The subjects were informed to keep their faces 20 to 30cm away from the gadget’s tablet, to simulate a normal use. The results are also presented in Fig. 12. It was requested for the subjects to qualify the intensity of the airflow they felt in a scale from 1 to 5.

The taste module is yet another interface that cannot be quantified, therefore relies on the users’ feedback. The test was conducted with the same sample group and consisted of simply sending a taste instruction of the flavour “red fruits” for 25 seconds, which consists of three tasting periods, considering a five second on/off intermittence. The subjects were asked to draw on the disposable tubes whenever they saw the LED of the taste output indicator light up. They were then asked to qualify the intensity of flavour they perceived in a scale 1 to 5; the results are presented in Fig. 12 as well.

A test was also conducted for the smell system. The same sample group was used, this time with a smell instruction in the portable device, for 10 seconds with the odour of pine tree. The subjects were informed to keep their faces 20 to 30cm away from the gadget’s tablet to simulate a normal use, as it was done in the airflow test. Next, they were asked to qualify the intensity of the fragrance in a scale from 1 to 5, from “weak” to “extreme”. The results are also shown in Fig. 12.

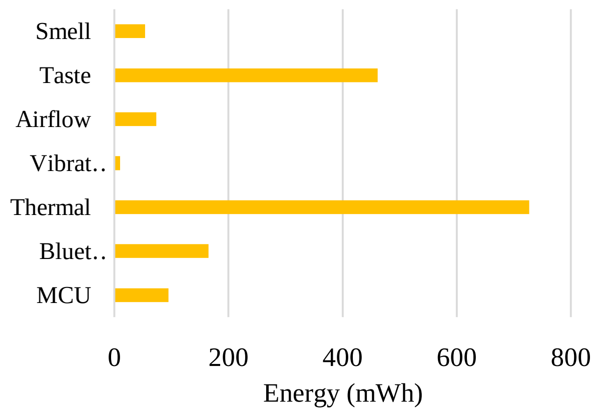

Fig.13 – Energy consumption estimation.

Regarding the power supply, since the sensorial interfaces are not yet completely tested and finalized, it was not possible to have a real museum visit and verify 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. Since each portable device’s side has its own battery, only the side with the Bluetooth module needs to be calculated. With an estimation of all the interfaces added together, excluding drivers and LEDs for simplification, it was achieved a total energy consumption of 1.581Wh for a visit with this interface usage pattern. The individual modules estimated consumption is represented in Fig. 13.

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, 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 first results on the airflow system show 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.

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.

The smell interface seems to be too weak to be noticed by some users. Despite the majority of subjects reported feeling the odour, still 50% reported below average (intensity levels 1 and 2), 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 becoming 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, in the same way it was difficult to perceive the air breeze, 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.

Nonetheless, future tests should be conducted with a larger number of subjects, in order to have more solid results.

The battery estimation results were quite positive. Naturally, there are few losses 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 pattern of use for this museum visit scenario might be too optimistic, but still, these results show a relatively low power consumption, providing 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 become something better.

6 Conclusion

The objective of this work 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, which together with the application (out of this paper'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 work 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 on the prototype are also presented here; 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 showed positive results, although they could benefit from some improvements. For example, the heat control could be faster and more accurate, and the vibrations could be stronger. Regarding other finishing details, since the sensorial interfaces still needed to change, designing a final PCB is yet 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, even though presenting satisfactory results, namely the wind sensation. And there are interfaces with results already in a very acceptable stage for a final solution, namely the heat sensation. In resume, for a prototype developed as a proof-of-concept, this has fully accomplished its purpose, since it allowed to validate the main idea, also allowing to receive feedback from 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.

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