DIGITALLY STIMULATING THE SENSATION OF TASTE THROUGH ELECTRICAL AND THERMAL STIMULATION

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This is for you, mom, dad, and my lovely wife....

This would not have been possible without your kind and caring support....

Declaration

I hereby declare that the thesis is my original work and it has been written by me in its entirely. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.

R. A. Nimesha Ranasinghe Singapore 23-Aug-2012

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"nothing's forgotten, nothing is ever forgotten...."

- "Robin of Sherwood" (1985)

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"Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning."

- Sir Winston Churchill

- Nimesha Ranasinghe (August 2012)

Contents

Co	onter	ts	VI					
Li	st of	Figures	1					
Li	st of	Tables	5					
1	Introduction							
	1.1	Motivation	5					
	1.2	Background	9					
		1.2.1 The sense of taste	10					
		1.2.2 The sensation of flavor	14					
	1.3	Approach	16					
		1.3.1 Design	17					
		1.3.2 Prototype developments	17					
		1.3.3 Technical evaluation	18					
		1.3.4 User experiments	18					
	1.4	Dissertation Structure	19					
2	\mathbf{Rel}	ated Work	20					
			VI					

	2.1	Difficulties of using the sensation of taste as a digital media .				
	2.2	Chemical based approaches				
	2.3	Non-chemical based approaches				
	2.4	The human tongue based interactive systems				
	2.5	Contri	ibution	31		
	2.6	Conclu	usion	34		
3	\mathbf{Des}	ign Me	ethodology	35		
	3.1	System	n components design	35		
		3.1.1	Tongue interface design	36		
		3.1.2	Characteristics of the tongue	37		
		3.1.3	Measurements on the threshold of electrical stimulus $\ .$	38		
		3.1.4	Stimuli and control system design	40		
	3.2	Second	dary design factors	43		
		3.2.1	Re-configurability	43		
		3.2.2	Usability	43		
		3.2.3	Safety	44		
	3.3	Conclu	usion	44		
4	\mathbf{Sys}	tem De	escription	46		
	4.1	Digita	l Taste Interface	46		
		4.1.1	Electrical Stimulation	48		
			4.1.1.1 Voltage controller	49		
			4.1.1.2 Constant current source	50		

VII

		4.1.1.3	Measurements of electrical stimulation module	51
	4.1.2	Thermal	Stimulation	53
		4.1.2.1	Measurements of thermal stimulation module	53
	4.1.3	Power co	onsumption	56
	4.1.4	Software	e Implementation	57
		4.1.4.1	Firmware	57
		4.1.4.2	UI	58
4.2	Exper	imental R	esults	60
	4.2.1	Taste Re	ecorder	60
		4.2.1.1	Participants	61
		4.2.1.2	Apparatus	62
	4.2.2	Experim	ental method	62
		4.2.2.1	Performance metrics	64
		4.2.2.2	NULL Control and non-tasters	66
		4.2.2.3	Procedure	67
	4.2.3	Results		68
		4.2.3.1	Electrical stimulation	69
		4.2.3.2	Thermal stimulation	73
		4.2.3.3	Hybrid stimulation	76
4.3	Contro	ollability	of taste sensations	77
	4.3.1	Protocol	l	79
	4.3.2	Results	and discussion	79
4.4	Discus	ssion		81

	4.5	Concl	usion	82
5	Tec	hnical	Refinements and Supporting User Experiments	84
	5.1	Furthe	er experiments on thermal and hybrid stimulations \ldots .	85
		5.1.1	Refinements to the system	85
		5.1.2	Thermal stimulation on different regions of the tongue	90
		5.1.3	Experimental setup	91
		5.1.4	Thermal stimulation	94
		5.1.5	Hybrid stimulation	98
	5.2	Furthe	er experiments on electrical stimulation	103
		5.2.1	Digital Taste Lollipop	104
		5.2.2	Electrical stimulation on different regions of the tongue	113
			5.2.2.1 Procedure	114
			5.2.2.2 Results and Discussion	115
		5.2.3	Comparison with real taste sensations	120
			5.2.3.1 Procedure	121
			5.2.3.2 Results	122
	5.3	Discus	ssion and future work	125
		5.3.1	Discussion	125
		5.3.2	Future work	128
			5.3.2.1 Magnetic stimulation of brain	132
	5.4	Concl	usion \ldots	136
6	Fut	ure Us	sage Scenarios	138

	6.1	Overal	ll benefits	138
		6.1.1	Digital communication media	139
			6.1.1.1 Multisensory digital communication	139
		6.1.2	How this can be used in family environment \ldots .	140
		6.1.3	Virtual reality	141
		6.1.4	Medical	142
		6.1.5	Entertainment	143
	6.2	Taste/	'IP: A future digital taste communication platform \ldots	144
		6.2.1	Mode of operation	144
		6.2.2	Transmitter	145
		6.2.3	Communication	146
	6.3	Possib	le future implementations	152
		6.3.1	The digital taste capsule	152
		6.3.2	Mobile integrated digital taste solution	153
		6.3.3	Digital taste enhanced drinking straw	154
	6.4	Conclu	usion	155
7	Con	clusio	n	156
Bi	Bibliography			161
$\mathbf{A}_{]}$	ppen	dix A:	List of Selected Publications	177
	Rele	vant pu	blications	177
	Othe	er Publ	ications	179

Awards	181		
Appendix B: Digital Taste Interface	182		
Circuit schematic diagram of the control system $\ldots \ldots \ldots$	182		
PCB layout of the control system	184		
Firmware of Digital Taste Interface	185		
Appendix C: Firmware of Digital Taste Synthesizer			
Appendix C: Firmware of Digital Taste Synthesizer	217		
Appendix C: Firmware of Digital Taste Synthesizer Appendix D: Digital Taste Lollipop	217 225		
	225		
Appendix D: Digital Taste Lollipop	225 225		

Abstract

Gustation (the sense of taste) is one of the fundamental and essential senses, which is given a little attention as a digital media. The sense of taste is almost unheard of on Internet communication, mainly due to the absence of digital controllability over the sense of taste. Digital manipulation of the sensation of taste is not achieved in practical systems at present due to two main reasons: 1) analog (chemical based) nature of the sense of taste and 2) limited knowledge and understanding of the sense of taste. Being a complex sensation, existing literature uncovered a little on the sense of taste. Furthermore, thus far, fundamental model or components of a particular taste sensation are not identified. At present, the only viable method for stimulating taste sensations is to use an array of chemicals together and deliver them to users' mouths using a mechanical mechanism.

Therefore, this thesis explores the possibility of simulating the sensation of taste using non-chemical means on human. We describe a new methodology to enable the sensation of taste as a digital media, which delivers and controls the experience of taste electronically on the human tongue. Based on the limited literature (studies and experiments) available on medical domain, we propose electrical and thermal stimulation as possible means of stimuli to simulate the sensation of taste. Thus, the proposed solution, Digital Taste Interface, simulates the sensation of taste through thermal and electrical stimulation on human tongue. It has two main modules: the control system and the wearable tongue interface. The control system formulates different properties of stimuli (magnitude of current, frequency, and the temperature) as below. Then the tongue interface applies the stimuli on user's tongue to simulate different taste sensations.

- Magnitude of current between $20\mu A$ and $200\mu A$
- Frequency between 50Hz and 1200Hz
- Temperature both heating and cooling between 20°C and 35°C

The tongue interface acts as an interface between the control system and the tongue. It consists of two silver electrodes, a Peltier element, and a thermistor. The control system has several submodules for electrical stimulation, thermal stimulation, communication, and the power management. A constant current source is implemented to maintain constant current levels for all the participants in the electrical stimulation submodule. In the thermal stimulation submodule, a motor driver is used to control the direction (heating or cooling) and the time difference (through Pulse-width modulation (PWM)) to achieve a predefined temperature change. For safety reasons, a current sensor is integrated to control the maximum current allowed for a given configuration. Results from rigorous user experiments suggested that the prototype system could simulate different taste sensations through electrical and thermal stimulation. The user experiments were conducted under three categories, electrical only, thermal only, and the hybrid (thermal and electrical together) stimulation. In addition, a comparison study was conducted to compare the natural and artificial sour taste sensations, thus to demonstrate the controllability of artificial sour taste on human tongue effectively. There were several sensations reported from the user experiments such as sour, salty, bitter, sweet, minty, and spicy. Sour, salty, and bitter sensations were reported from electrical stimulation; minty, spicy, and sweet (minor) sensations were reported through thermal stimulation.

Overall, this technology would enable new application possibilities for digital multisensory interactions. For example, tasting virtual food can be considered as a potential application in future virtual reality and gaming systems. The sensation of taste can be easily integrated with remote communication systems, where people may send taste messages to a remote friend. Additionally, this technology may shed new light on taste based entertainment systems such as creating taste symphonies on human mouth. This would be achieved by effectively manipulating the sensations through aforementioned methods. Finally, the findings presented in this dissertation serve as a valuable knowledge base to researchers in the field of Human-Computer Interaction (HCI) in developing systems for the sensation of taste.

List of Figures

1.1	Schematics of Digital Taste Interface	3
1.2	Correspondence between natural and artificial stimuli	4
1.3	Method of stimulation	4
1.4	A cross-sectional view of different taste papillae	12
1.5	Distribution of papillae along the surface of the human tongue	13
1.6	Electron microscope image of various papillae	14
1.7	Arrangement of a taste bud including taste cells	15
1.8	Ascending Gustatory Pathway from tongue to the brain \ldots .	16
3.1	The system architecture of Digital Taste Interface	36
3.2	The tongue interface attached to a user's tip of the tongue \ldots	37
3.3	Change of sensitivity and comfort level of the tongue	38
4.1	Implementation of the Digital Taste Interface	47
4.2	Circuit diagram of the control system	48
4.3	Primary components of the electrical stimulation subsystem \ldots	49
4.4	Implementation of electrical stimulation subsystem	51

4.5	Output waveforms before and after connecting the tongue	52
4.6	Implementation of thermal stimulation subsystem \ldots	54
4.7	Primary components of the thermal stimulation subsystem \ldots .	55
4.8	Warming up and cooling down performance	55
4.9	Algorithm design of the digital taste interface	56
4.10	Text based serial user interface developed for debugging \ldots .	59
4.11	Graphical user interface developed	59
4.12	The taste-recorder developed	61
4.13	The experimental setup of the Digital Taste Interface	63
4.14	Perceived taste sensations (electrical stimulation - current) $\ . \ . \ .$	70
4.15	Perceived taste sensations (electrical stimulation - frequency)	70
4.16	Taste sensations and change of frequency	72
4.17	Perceived taste sensations during warming up	74
4.18	Perceived taste sensations during cooling down	75
4.19	Perceived taste sensations during hybrid stimulation	77
5.1	Arrangement of the components in the tongue interface	86
5.2	Implementation of Digital Taste Synthesizer	87
5.3	System architecture of Digital Taste Synthesizer	88
5.4	Warming up and cooling down performance	89
5.5	Different stimulated surface areas on the tongue	91
5.6	A participant interact with the system	92
5.7	Typical setup of the Digital Taste Synthesizer	94

5.8 Perceived taste sensations (thermal stimulation) 95
5.9 Transitions of reported taste sensations (thermal stimulation) \therefore 96
5.10 Implementation of constant-current source
5.11 Digital Taste Synthesizer with electrical stimulation 99
5.12 Integrated design of tongue interface
5.13 Perceived taste sensations during hybrid stimulation 101
5.14 Transitions of taste sensations during hybrid stimulation $\ldots \ldots 102$
5.15 Perceived intensity of sour, minty, and spicy sensations 102
5.16 Everyday objects people use to interact with mouth $\ldots \ldots \ldots \ldots 104$
5.17 The wire model of the final design of tongue interface $\ldots \ldots \ldots \ldots 104$
5.18 The system architecture of Digital Taste Lollipop 105
5.19 The implementation of lollipop tongue interface 106
5.20 A close-up of the tongue interface connects with the tongue \dots 107
5.21 The linear increment of output current based on DAC step values 109
5.22 Implementation of Digital Taste Lollipop
5.23 Non-inverted output voltage values from DAC
5.24 Inverted output voltage values from DAC
5.25 The experimental setup of the digital taste lollipop $\ldots \ldots \ldots \ldots 112$
5.26 Different placements of the Digital Lollipop on the human tongue during the experiments 113
5.27 Reported taste sensations (tip - current is non-inverted) $\ldots \ldots 116$
5.28 Reported taste sensations (tip - current is inverted $\ldots \ldots \ldots \ldots 117$
5.29 Reported taste sensations (left side - current is non-inverted) 118
5.30 Reported taste sensations (right side - current is non-inverted \therefore 119

5.31 Reported taste sensations (left side - current is inverted) \ldots 119	9
5.32 Reported taste sensations (right side - current is inverted 120))
5.33 Preparing three intensities of lime juice: mild, medium, and strong 121	1
5.34 Participants and their interactions with the instrument $\ldots \ldots 123$	3
5.35 Mean values of thresholds for three intensities of sour taste 123 $$	3
5.36 All sour taste sensations occurred during the user experiments 124	4
5.37 Mean scores with standard error for three groups $\ldots \ldots \ldots \ldots 124$	4
5.38 Taste sensations reported from electrical stimulation $\ldots \ldots \ldots 125$	5
5.39 Taste sensations reported from thermal stimulation $\ldots \ldots \ldots \ldots 126$	3
5.40 The high level system diagram for taste and smell brain stimulation 133	3
5.41 Stimulating taste and smell perceptions by magnetic stimulation . 134	4
6.1 Future application for internet marketing	1
6.2 Architecture of Taste over IP system	5
6.3 Android application developed for digital taste messaging 146	3
6.4 A future digital taste sharing social networking service 151	1
6.5 Concept diagram of the taste capsule interface	2
6.6 Digital taste device integrated with a mobile phone	3
6.7 Concept diagram of the digital taste enhanced drinking straw \therefore 154	4
1 PCB layout of Digital Taste Interface	4
2 PCB layout of Digital Taste Lollipop	3

List of Tables

3.1	Stimuli parameters for level of comfort and sensitivity experiments	39
4.1	Digital POT values and corresponding output current values	49
4.2	Power consumption during different operational states \ldots	56
4.3	Taste responses received by changing the magnitude of current	71
4.4	Taste responses received by changing the temperature	74
4.5	Two different stimuli used for controllability experiment \ldots .	79
4.6	Reported sensations against two different stimulus over three days	80
5.1	Taste responses received by thermal stimulation	95
5.2	DAC step and the magnitude of output current	108

Chapter 1

Introduction

Today, the importance of electronic media is enormous as it is highly associated with daily interactions of people. However, it is still dependent on limited senses or channels such as text, sound, image, and video alone or in combinations, whereas, in face-to-face situations, people are able to exploit multiple senses (audition, vision, tactition, olfaction, and gustation) along with expressions, gestures, and interaction with the artifacts for communication. Likewise, lots of real experiences produce significant multisensory cues. Therefore, novel multisensory digital remote interaction technologies are required to expand the existing media technologies [33].

Visual and auditory simulation appliances have dominated the digital world for a long time. With the help of such sensory simulation, people's lives have been improved tremendously. We have televisions, computers and various mobile devices, which provide immensely creative and exciting experiences. Current technologies have also been incorporating the sense of touch into digital systems. These are commonly known as haptic interfaces [43, 40, 109]. However, at present, both the sense of smell and taste are generally stimulated using chemical substances and digital controllability of these two senses has yet to be achieved. For example, a virtual reality helmet developed by British scientists can simulate five human senses. The helmet releases different chemicals in order to stimulate both the sense of smell and taste while hearing, sight, and touch senses are simulated digitally [23]. The main drawback of these solutions is the use of different chemicals to stimulate the sense of smell and taste at present. These solutions are analogues and associated with manageability, transferability, and scalability issues.

Of the two chemical senses, taste is more important and yet it gets remarkably little attention in digital media. A new methodology is needed to simulate the sensation of taste digitally to enable digital interactions through the sense of taste.

To achieve electronic simulation of taste sensations, we describe Digital Taste Interface (Figure 1.1), which is a digital instrumentation system to generate taste sensations on human tongues. It uses both electrical and thermal stimulation methods (Figure 1.2) to generate different taste sensations. The system has two main modules: the control system and the tongue interface. The control system configures the output properties (electrical and thermal) of the tongue interface. The tongue interface consists of two silver electrodes, which attach to the tip of the tongue and a Peltier^{*} module to control the tem-

^{*}http://www.peltier-info.com

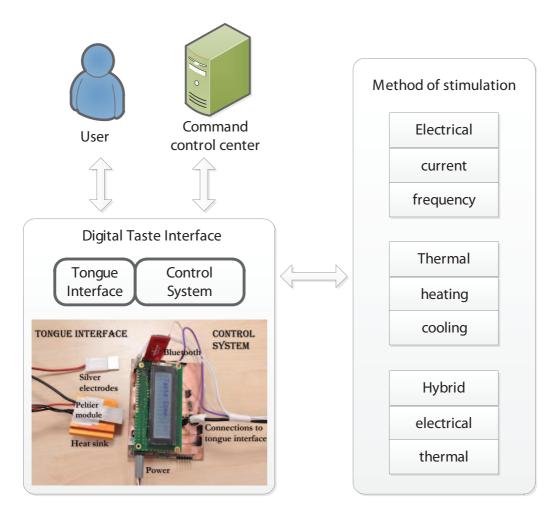


Figure 1.1: Digital Taste Interface Schematics: Interaction channels and main modules.

perature. The novelty of this work primarily has three aspects: 1) studying the electronic simulation and control of taste sensations achievable through the Digital Taste Interface against the properties of current (magnitude and frequency of current) and change in temperature, 2) the method of actuating taste sensations by electrical and thermal stimulation methods, either individually or in combination, and 3) the demonstration of the possibilities of a practical solution to implement virtual taste interactions in human-computer interactive systems. In summary, this work demonstrates a novel controllable

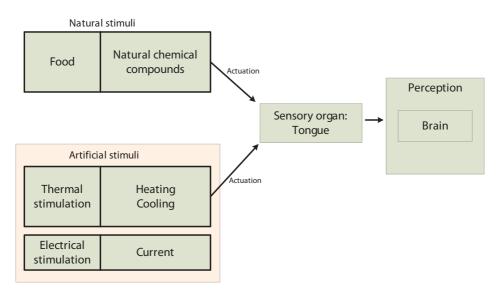


Figure 1.2: Correspondence between natural and artificial stimuli to actuate the sensation of taste on human tongue.

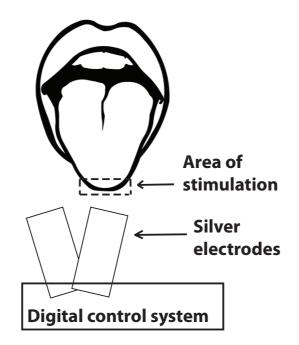


Figure 1.3: The system utilizes electrical and thermal stimulation methods to generate different taste sensations. Different stimuli are applied by attaching two silver electrodes to the tip of the tongue.

taste instrument which may be used in interactive computer systems. The concept of digital taste interface is displayed in Figure 1.3.

Preliminary experiments have shown that correlations exist between the

amount of current applied and the taste sensation generated [64]. Furthermore, a similar correlation exists between thermal stimulation and taste sensations generated [22]. Consequently, the goal of the presented study is to analytically and experimentally determine the characteristics of electrical and thermal stimulations on the tip of the human tongue for electronically generating and controlling the primary taste sensations known as sweet, salty, sour, bitter, and umami, which is also known as savory [69].

The subsequent sections describe the motivation, associated research questions, background of the sense of taste and the approach. A more detailed discussion of previous literature and the contribution of this work are presented in Chapter 2.

1.1 Motivation

Taste, as one of the five basic senses, plays a significant role in human life. When people refer to the sense of taste, they typically refer to the taste of food. When people eat, the taste of the food directly affects the amount of food they consume. More importantly, the sensation of taste may change people's mood. Research shows that when people consume their favorite foods it stimulates the release of β -endorphins, which is a substance that enhances mood [29]. This explains children's preference for candies, because the taste of candies makes them happy. Thus, it is said that, if food is the nutrition for the body, the taste is the nutrition for the soul [29]. Alternatively, the sense of taste acts as a defensive mechanism for human. For example, based on a certain taste sensation, people judge the quality of the food and avoid consuming toxic substances [21].

However, at present, among the five primary senses, the sense of taste is the least explored as a form of digital media and it is considered the final frontier of Human-Computer studies. Additionally, ubiquitous computing, multimodel interaction, and virtual reality research domains are also in need of digitizing the sense of taste to create or enhance new digital experiences [57]. Currently, there are several research projects being conducted on the electronic sensing of taste (ex: electronic tongue presented in [92] and tea tasting through etongue [13, 65, 86, 60]); however, remarkably few reports are made of such work in literature related to electronic taste actuation. The technical and chemical unawareness of the gustatory sensory system are the two main reasons. Therefore, the motivation of the work presented in this thesis is two-fold. The first is to present a new electronic interface to simulate taste sensations digitally. Secondly, this work aimed to measure the efficiency, accuracy, and repeatability of this approach for simulating the sensation of taste. Thus, the main research question of this thesis addresses is,

• How do we engineer a novel interactive system to stimulate taste sensations digitally?

We recognize the golden opportunity to conduct doctoral research on an innovative topic such as digitally stimulating the sensation of taste to contribute to the field of human-computer interaction by introducing the sensations of taste as a form of digital media. This thesis aims to provide answers to the above research question by developing and evaluating several Digital Taste Simulating instruments. Moreover, this thesis details various design problems, engineering decisions and solutions that are implemented to solve these problems, including technical and physiological measurements as well as the measurements of intensity levels of taste sensations were recorded through these devices. The research is conducted in a step by step approach to gain a deeper understanding of the problem domain as well as to improve the taste sensations obtained from this approach. The user experiments and interviews conducted with the participants also details the limitations and future improvements for such systems.

We believe, in the future, the digital controllability of the sensation of taste will enable effective sharing or distribution of taste sensations through the Internet. Applications of this technology extend not only towards multimodal interactions but also to several other disciplines such as medicine, food and flavor technologies, mixed/virtual reality, gaming, and entertainment. In addition, this research has important implications for forming theories and concepts for the future of Internet with multisensory interactions by integrating the sense of taste into the existing web architecture [48, 118]. Furthermore, as an example of a medical application, some people (for example, diabetes patients) will have a new way to experience taste sensations (for instance, the sweet taste) without any serious health concerns. In gaming or virtual environments, users may taste as though they are in a natural environment by incorporating the proposed device into their gaming systems. For example, suppose the player is in a virtual kitchen; through the proposed method, the user can taste different virtual dishes prepared in the kitchen. Although this work is at a fundamental stage of engineering research rather than a fully working product, we believe that developing digitized taste experiences will enable novel and innovative applications in the future.

Moreover, using artificial chemical substances to improve the taste sensations of food is common in everyday life. For example, artificial taste compounds such as monosodium glutamate (MSG) is used for cooking in order to get the taste of umami. However, it has been discovered that over-consumption of MSG may cause unhealthy effects to the human body and brain [11]. Therefore, simulating taste sensations digitally would reduce the potential health effects compared to chemical-based traditional stimulations. Further, this thesis might be of interest and beneficial to researchers and engineers in the fields of:

- Human-computer interaction
- Interactive computing
- Multimodel interactions
- Mixed and Augmented reality
- Ubiquotous / pervasive computing

The experiences of taste are often richly layered with emotions and memories, and the mutual enjoyment of food flavors is a common means of bonding between people. However, currently, it has been difficult to share taste sensations remotely other than the verbal descriptions of those sensations; there has not been a standard methodology to actuate taste sensations digitally [98, 57]. This also highlights the need of a new methodology to digitally simulate the sensation of taste.

1.2 Background

The sensation of taste is an essential part of our everyday life. The experience of taste is often richly layered with emotions and memories, and the mutual enjoyment of food flavors is a common means of bonding between people. Human beings use the sensation of taste to register memory as a significant part of everyday life experiences [30]. For instance, taste sensations give us fond memories of a delicious meal, a visit to a place, or a close acquaintance. By digitally recording and communicating this sense, we would be able to enrich daily digital activities, which is currently dominated by audio and vision based interactions. For the visually/hearing impaired, enriching alternative sensory stimuli will enhance their life experiences. Optimization of the sensation of taste is another example of how this technology could be applied. Current technologies have only explored the sense of taste to some extent with primary chemical compounds, yet the sensations generated are limited and not rich enough for detailed communication.

If we consider the taste to be a language, to have fundamental character components such as alphabets, the glyph of the alphabet is not identified yet. Therefore, we have not been able to digitize the sensation, and little is explored in digital control over this sense, let alone realistic transmissions, communication, digital amplification and optimization technologies. As a solution, this thesis investigates a new form of digital technology to induce taste sensations electronically on human tongue.

1.2.1 The sense of taste

The sense of taste (gustation) provides enjoyment of consuming food and defensive capabilities to identify rotten food or poisons. Human-beings are used to assess food based on their taste, whereby a particular food is accepted as delicious or rejected as inappropriate. Although we interpret tasting as a direct and simple process, it is a complex interaction between multiple sensory mechanisms which also involves people's prior experiences and their cultural backgrounds [30].

Presently, five basic (primary) taste sensations have been recognized. They are sweet, sour, salty, bitter, and umami. Generally, research literature on the sense of taste identifies four basic sensations, sweet, sour, salty, and bitter [5, 66]. Recently, the sensation of umami (savoriness) is identified as a primary taste, which usually refers to the taste sensations elicited by Monosodium glutamate (MSG) [61]. In addition, fattiness [74] and calcium [39] are recently identified as two other potential primary taste sensations. However, further research is needed for nominating them as primary sensations. Conversely, according to Ayurveda, the sense of taste has six main sensations, Sweet, Sour, Salty, Bitter, Pungent, and Astringent. Ayurveda categorizes hot and spicy taste (ex: chili pepper and garlic) as pungent, while dry and light (ex: popcorn and beans) as astringent taste [99].

Furthermore, the chemical characteristic of a substance is responsible for its taste quality. Typically, most acidic compounds, commonly found in citrus fruits (such as lemon and lime) results sour taste. Salty taste is commonly found in natural sea salt and sea vegetables such as seaweed and kelp. Sweet taste mostly associates with sugary foods or sugar made of sugarcane, and largely responsible for building human tissues [58]. It is also found in grains such as rice and barley and fruits like mango and banana. Conversely, bitter is a less attractive sensation that stimulates the human appetite often found in herbs and spices. Some of the natural bitter foods are grapefruits, coffee, tea, olives, and bitter melon. In spite of the fact that the primary sensations are identified, the interactions among them and perfect chemical composition of a taste sensation are still under experimental research [14, 42, 112]. Moreover, the cultural influences and physiological differences (such as age, sex, adaptation) on taste perception can also make it more difficult to study [116, 29]. In addition, the flow of saliva is necessary for the sensation of taste and in preparing food for mastication, for swallowing [72, 106].

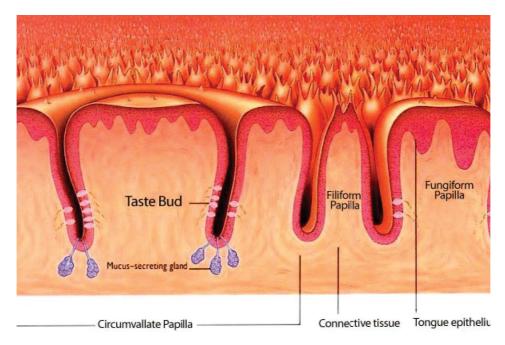


Figure 1.4: A cross-sectional view of different taste papillae showing the clusters of taste buds.^{\dagger}

The sense of taste refers to the perceptions that results from the contact of substances with receptors (called tasting) on the tongue and some other parts in the mouth such as throat [115]. The human tongue has the unique cell structures called "papillae", which contains basic receptor structures known as taste buds as in Figure 1.4. There are four types of papillae known as fungiform, foliate, filiform, and circumvallate [50] as displayed in Figure 1.5. Electron micrograph of various papillae is shown in Figure 1.6. Each type of papillae contains taste buds, which has different sensitivity for the different taste sensations [19]. However, the filiform papillae contains no taste buds [46].

Taste buds inside a papillae has a number of gustatory cells as shown in Figure 1.7. The gustatory cells send taste information detected by clusters

 $^{^{\}dagger}\mbox{Image}$ obtained from: http://universe-review.ca/I10-85-papillae.jpg

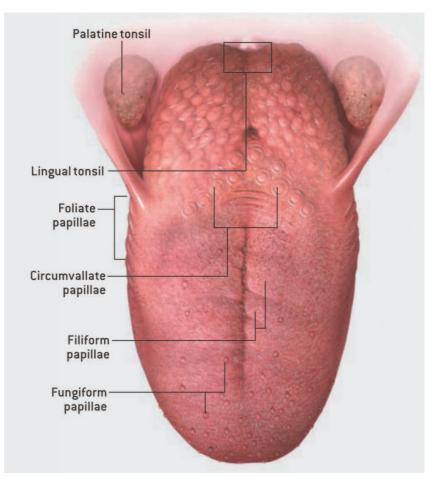


Figure 1.5: Distribution of papillae along the surface of the human tongue.[‡]

of different receptors and ion channels to the brain through the seventh (face nerve), ninth and tenth cranial nerves as shown in Figure 1.8 [4, 10]. This system is complex and still partially unknown. There are two main models identified for neural coding of taste, Labeled Line Model and Across Fiber Theory. Labeled Line Model suggests that different tastes have segregated pathways to the brain, whereas Across Fiber Theory suggests different tastes are represented by different activity across a neural population [95, 104].

 $^{^{\}ddagger}\mbox{Image obtained from: http://bsclarified.wordpress.com/2011/07/07/are-you-tasting-saltiness-sweetness-sourcess-or-bitterness$

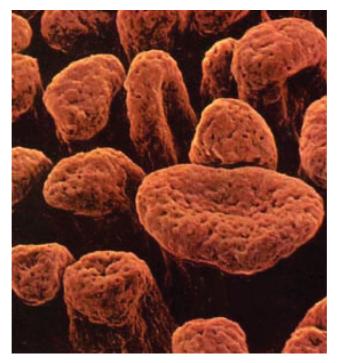


Figure 1.6: Electron microscope image of various papillae.§

1.2.2 The sensation of flavor

It is important to clarify the difference between basic taste sensations and the complex perception known as flavor. People often misunderstand taste as the flavor and do not understand the difference [30]. Taste is a sensory function directly associated with human tongue and sensitive for chemical stimuli. Additionally, all the parts of the tongue can sense five primary tastes more or less equally [103]. On the other hand, flavor is a complex perception and is recognized as a combination of both taste and smell sensations [35]. Taste is typically the five sensations, whereas flavor is infinite and cognitive. In this thesis, we are particularly interested in generating fundamental taste sensations through the aforementioned approach. In the future, we will extend

[§]Image obtained from: http://www.nicks.com.au/index.aspx?link_id=76.1354

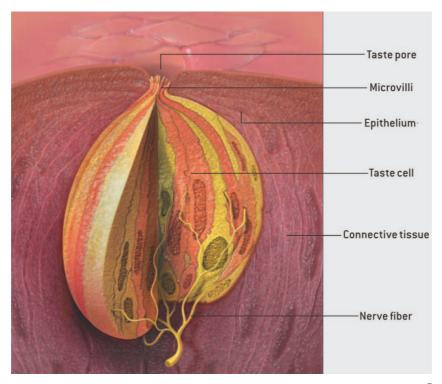


Figure 1.7: Arrangement of a taste bud including taste cells.[¶]

this work to include the sensation of flavor too.

Furthermore, apart from smell and taste sensations, flavor associates with factors such as texture, color, temperature, and even the sound or ambient noise of the environment. Some of these interactions are explained in [26] with relation to food and drinks. Narumi et al. developed a system to superimpose virtual color on the same drink and showed that people often taste different flavors when the color is different [83]. In addition, there are several experiments conducted on flavor and ambient noise and reported that people enjoy their food or drink more in less noisy environments compared to noisy environments [101].

 $^{^{\}P}$ Image obtained from: http://bsclarified.wordpress.com/2011/07/07/are-you-tasting-saltiness-sweetness-sourness-or-bitterness

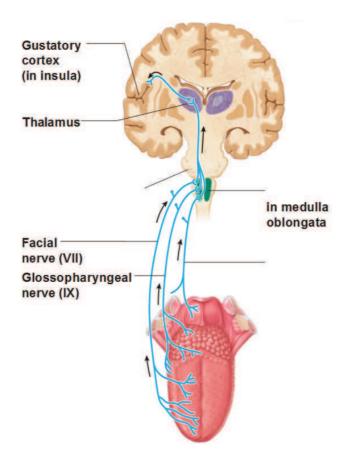


Figure 1.8: Ascending Gustatory Pathway from tongue to the brain. $^{\parallel}$

1.3 Approach

The work discussed in this thesis is mainly applied research, which means ideas and theories have resulted in engineering prototypes that should be relatively easy to deploy and evaluate. First of all, a feasibility assessment was conducted using existing literature and through discussions with experts. Electrical and thermal stimulation methodologies were selected as the experimental approach thus knowledge is gained through an iterative process with designing, implementing and evaluating practical engineering prototype systems [34].

 $[\]parallel$ Image obtained from: http://explow.com/Gustatory_nucleus

Furthermore, the research presented in this thesis is an interdisciplinary effort, combining knowledge from different domains (such as engineering, computing, design, medical, neurosensory, and the like) to understand and implement an electronic taste simulation system. It also enabled us to learn some of the cross-modal interactions between taste, smell, visual, and auditory channels as a means of improving the electronic tasting experience. This understanding would not have been possible to be derived from a purely theoretical perspective due to the limited awareness of taste perceptions in the brain.

1.3.1 Design

During the design phase, stimuli and system components design are given a considerable attention. Since electrical and thermal stimuli are used to stimulate the tongue, comfort, safety, and sensitivity thresholds of the stimuli are experimentally analyzed at the beginning. The main concern is given on engineering aspects of the prototype systems and on improving the quality of taste sensations. Therefore, when designing different prototypes, the same design is used with minor modifications.

1.3.2 Prototype developments

A detailed discussion on the development of individual prototypes for simulating the sensation of taste is provided in this thesis. Technical or usability aspects are improved in each phase of prototype development. At the end of each prototype, a technical evaluation and user experiment is conducted to improve the next version of the prototype.

1.3.3 Technical evaluation

Technical evaluation of each prototype version helped to identify technical functionality of the system as well as to determine the improvements for the next prototype. This thesis presents several noteworthy technical measurements of the prototype systems as well as the characteristics of the human tongue for the stimuli applied. For instance, the effects on the electrical signal applied and the performance of the thermal stimuli are two of them.

1.3.4 User experiments

User experiments are one of the most crucial step in the development process of the digital taste systems. From the beginning, we considered user trials are vital for the design, implementation, and performance analysis of a functional prototype. Moreover, the experiments are conducted not only to evaluate the prototypes but also to obtain different parameters to improve the effectiveness of the approach. Additionally, we understood the ethical issues behind this research and obtained the necessary approval from the University Institutional Review Board (Approval No: NUS 1049).

1.4 Dissertation Structure

The rest of this thesis is organized as follows:

- Chapter 2 provides a detailed literature review related to different aspects of this technology. In addition, the contribution of the work presented in this thesis is also highlighted.
- Chapter 3 details the design methodologies of the stimuli and primary and secondary parameters of the system design.
- Chapter 4 presents the system description and technical measurements of the device. Details on initial user experiments conducted to evaluate the effectiveness of the approach are also given in this chapter.
- Chapter 5 explains refinements made to the initial prototype system and provides supporting user experiments on electronic tasting test and different assumptions made. A detailed discussion is also stated highlighting qualitative findings and the possible future experiments of this technology.
- Chapter 6 describes future work and application scenarios of the work presented in this thesis.
- Chapter 7 concludes the thesis by summarizing the findings of this approach.

Chapter 2

Related Work

This chapter reviews relevant research work from both scientific and other referenced sources of literature pertinent to this research to arrange the work presented in the next chapters in perspective. In the literature, chemical stimulation of gustatory sense has been used to develop interactive systems especially in the area of Human-Computer Interaction (HCI). Thus, the review begins with a discussion on current difficulties of using the sense of taste as a form of digital media. This follows a review of studies where the chemical based approaches are used; then the section on non-chemical stimulation methodologies focuses on several related works to highlight the possibilities of generating taste sensations through electrical and thermal stimulation methodologies. Next, a few studies on tongue based interactive systems are reviewed.

2.1 Difficulties of using the sensation of taste as a digital media

The sense of taste is one of the two chemical senses humans use in their everyday interactions. Chemically stimulated receptors located in the human mouth (in particular on the tongue) are responsible for identifying different taste sensations. Thus, stimulating the sensation of taste involves one or more chemical substances in the mouth. Additionally, the stimuli must be a dissolved or soluble substance that dissolves in saliva. Therefore, to incorporate the sensation of taste as a media, there should be a method to manipulate chemical substances accurately. However, storing and manipulating chemical substances in an interactive system is complicated. On top of that, controllability of stimuli is difficult to achieve, since it requires sophisticated mechanical controls and mixing methods. It is difficult to predict the specific product of taste mixtures due to complex interactions between the primary taste qualities. Thus, the sensation of taste is not yet widely used as a digital media.

Furthermore, lack of understanding and complex cross-sensory interactions of the sense of taste also make it complicate to explore as a form of digital media [100]. The sense of taste is still being explored, and the fundamental model is not understood up until now. For example, in computer vision RGB or CMYK models are available as fundamental elements [88], and in audition Fourier Transformation (FT) techniques are used to split sound into frequencies [96]. These methods are computationally efficient methods for computing digital stimuli for vision and audition. However, for the sense of taste, the primary parameters of a stimulus are yet to be uncovered.

On the other hand, the sensation of taste is a complex multisensory sensation. Different sensory systems such as smell, color, texture, and temperature are highly correlated with the sense of taste. At present, whether and how these integrations occur is a crucial question to study [30]. Therefore, such cross-model integration makes understanding of the sense of taste more difficult.

In addition, the perception of taste is subjective and varies from taster to taster based on several reasons such as differences on structural and papillae density of the tongue, age, sex, and genetical differences of people [63, 9, 59, 78]. On top of these, taste adaptation make studying the sense of taste even more complicated. It decreases the sensitivity of the tongue to a chemical stimulus due to continuous exposure [77]. Additionally, various medical procedures and conditions may also affect the sense of taste.

However, a few attempts have been made to study the characteristics of the tongue for electrical stimulation in medical and neurosensory experiments, most of those attempts are focusing on treating patients with taste disabilities. Among these studies, several participants have reported weak taste sensations through electrical stimulation on the surface of the tongue [52, 3, 18]. Furthermore, studies have shown that heating and cooling small regions on the tongue induce taste sensations [8, 22]. We have chosen these two phenomena as the basis of the work presented in this thesis. A detailed review on these two non-chemical stimulation methods is given in section 2.3.

2.2 Chemical based approaches

Although using chemicals in an interactive system to simulate taste sensations is fairly complicated, chemical stimulation of the sensation of taste has been used to develop new systems in the area of Human Computer Interaction (HCI). For example, the 'Food Simulator' uses chemical and mechanical linkages to simulate food-chewing sensations by providing flavoring chemicals, biting force, chewing sound, and vibration to the user [57]. The mechanical section of the device consists of mainly a vibration motor, vibration sensor, and the linkages. The section inside the mouth has a rubber cover. The rubber cover is intended to resist a user's bite and the motor provides appropriate resistance to the mouth along with chemicals and chewing sound. The study presented in [57] mainly focuses on studying cross sensory interactions of taste with sound, texture, and force.

Another example of using chemicals to actuate the sense of taste is Taste-Screen [75]. The system, which attaches to the top of the user's computer screen, holds 20 different chemical flavoring cartridges to mix and spray toward the display. Then the user is capable of tasting the dispensed taste by licking his/her computer screen. However, this approach is questionable in two aspects. Firstly, the use of a computer screen as the delivery method for chemicals as they may damage the screen. Secondly, the suggested user behaviors may not be feasible since most users may find licking their screens distasteful.

In 'Virtual Cocoon', the system sprays chemicals into a wearer's mouth to create different taste sensations [23]. It stimulates not only the sense of taste but also the other senses, touch, smell, vision, and audition. A tube connected to a container of chemicals sprays into the user's nose and mouth to produce different flavors. However, the developers of the virtual cocoon have overlooked important aspects of their approach to, mainly the practical usage of the system and the size. The system is considerably larger in size since it uses several arrays of chemical to stimulate smell and taste senses, hence the system is not portable. In addition, refilling, cleaning, and durability are several other aspects to improve in this approach.

Additionally, in recent years there are several studies that have shed some light on virtual taste systems. For example, Narumi et al. describes a pseudogustatory display based on the virtual color of a real drink [83]. They used a wireless LED (Light Emitting Diode) module attached to the bottom of a transparent plastic cup, thus to super impose the virtual color of the drink. Results of their experiments show that different colors induce users to interpret different flavors of the same drink. However, their motivation behind this research is to study cross-sensory effects of visual feedback and flavor interpretation of real drinks.

In addition, the 'Tag Candy'* and 'Meta cookie' [82] systems use aug-*http://www.diginfo.tv/v/10-0245-f-en.php

mented reality based approaches to create different sensations. The Tag Candy uses vibration and hearing through bone conductivity to deliver various sensations while a user enjoys a regular lollipop attached to the system. Conversely, the Meta Cookie system uses visuals and smell information to provide various taste sensations to the user while consuming a regular cookie. The printed augmented reality marker is used to cover the real cookie with a virtual cookie in the system. Furthermore, based on the user's choice, smell information is delivered to the user, thus to produce different sensations although the user consumes the same regular cookie in real.

Moreover, Nakamura et al. demonstrated the use of electricity for augmented gustation in [81]. They apply electric current through isotonic drinks (which contains electrolytes) and food (juicy vegetables, fruits, and cheese) to change the taste perception of those drinks and food. In this study, they are mainly concerned with the level of voltage and augmented sensations of food items. However, in both [83] and [81], they are still incorporating chemical substances and concerning only on augmenting the taste sensations.

As the above literature describes, there are several research works conducted based on the chemical stimulation of taste. However, there are numerous issues incorporated with this approach as explained. Unfortunately, chemical stimulation is analogues in nature; using chemicals in an interactive system is unrealistic since it is difficult to store and transmit those chemicals. Therefore, it is impractical to use this approach for digital interactions/communication. Alternatively, as evident by those prior studies, chemical based solutions have scalability issues for long-term implementations. From the above review, it is evident that a new non-chemical approach is required to achieve the digital controllability of taste. The next section presents several non-chemical experiments conducted on taste stimulation on human.

2.3 Non-chemical based approaches

The technology for actuating the human sense of taste with non-chemical methods is still in its infancy. Alessandro Volta, known for the invention of electric cell and discovery of Voltage is one of the first scientists that studied the sensory effects of electrical stimulation on human senses specifically for touch, taste, and sight. He placed two coins, made out of different metals on both sides of his tongue (up and down) and connected them through a wire. He mentioned that he felt a salty sensation during the experiment [113].

There are several evidences of generating taste sensations through electrical and thermal stimulation in medicine and physiology, primarily in electrophysiology. In [89], a single human tongue papillae was electrically stimulated (84 trials) with a silver wire for five young subjects. They used electrical pulses of both negative and positive polarity with a frequency range of 50 - 800 Hertz. The results provided some exciting and effective responses for the sour taste (22.2%) and some small responses for the bitter (3.8%) and salty (1.8%) tastes. However, this experiment was conducted in a controlled environment, only utilizing a single papillae of the tongue. Also, the study did not consider the controllability aspects of stimuli.

Lawless et al. presents another related research, the metallic taste generation from electrical and chemical stimulation [64]. Their study was designed to observe the similarities and differences between stimulations with metals, electrical stimulation, and solutions of divalent salts and ferrous sulphate in particular. In the experiment, they investigated sensations occurring across oral locations using electrical stimulation with different metal anodes and cathodes. They presented evidences of sour and salty tastes on users' tongues through electrical stimulation.

Furthermore, electrogustometry is a clinical tool, which uses electrical stimulation on the human tongue to estimate the taste detection thresholds of patients with taste disabilities [107]. The Rion-TR-06[†] is an electrogustometer which uses direct current with stainless steel electrodes to measure the threshold of excitement on patients' tongue [111]. This work is useful for research on taste actuation as it provides knowledge on electrical current levels required for stimulation of taste receptors.

Conversely, Philips Electronics has a patent on a mechanism to stimulate taste sensations using electrical stimulation [16]. They have built a tongue apparatus, which can measure the saliva flow in relation to the stimuli to determine a users taste preferences. Although this patent is particularly relevant and useful for this research, they have not detailed the stimuli preferences and properties. Whereas in our research, we developed various apparatus, evalu-

[†]http://sensonics.com/taste-products/tr-06-rion-electrogustometer.html

ated with human participants, and discussed refinements to improve the results in the future. Moreover, we introduced hybrid stimulation methodology by stimulating the tongue concurrently with electrical and thermal stimulations.

In addition, another interesting aspect to pursue is the thermal stimulation of the sensation of taste. In "Thermal stimulation of taste" Cruz et al. studied the effects on temperature change (heating and cooling) and perceptions of taste sensations [22]. They experimented on the anterior edge of the tongue using an ice cube (which has no taste) and found evidences of sweet, sour, and salty sensations. In [6], the authors highlight this fact as a taste-temperature illusion, which is a confusion between the sense of temperature and the sense of taste.

A related work which is very useful to our research is done by Talavera et al. who examined the thermal activation of TRPM5 ion channel (Transient receptor potential cation channel subfamily M member 5) in the taste buds of the tongue [108]. TRPM5 ion channel has a key role in the perception of sweet, umami, and bitter tastes. The interesting feature of TRPM5 channels is that the activation of this channel could immensely activate the corresponding tastes of that channel due to the activation of G-proteins (guanine nucleotidebinding proteins) associated with taste receptor cells. Furthermore, they have showed that TRPM5 is a highly temperature sensitive and heat-activated channel. Even more interestingly, they have mapped the thermal - voltage characteristics of the TRPM5 cells and the current - voltage relationships at different temperatures using the whole-cell patch-clamp technique. In addition, increasing the temperature from 15°C to 35°C enhances the gustatory nerve response to sweet sensation.

From the above review, the possibility of using electrical- and thermalstimulation methods to stimulate taste sensations digitally can be seen. However, the above reported studies are conducted in the medical domain (with controlled environments) and only in the experimental stage. Therefore, before introducing the electrical and thermal stimulation methods as a means of actuating the sensation of taste, many aspects of this approach need to be carefully studied. The most significant aspect is the controllability of generating taste sensations through electrical- and thermal- stimulation in uncontrolled conditions. Thus, it is desirable to propose a digital control system for stimulating the sensation of taste through electrical- thermal- and hybridstimulation (hybrid: both electrical- and thermal- stimulation at the same time), in order to introduce the sense of taste as a new digital media for remote communication and/or interactions.

2.4 The human tongue based interactive systems

In the literature, we found several studies on tongue based interactive systems mainly for people with physical disabilities. Such interfaces generally use the movements of the user's tongue as an alternative input methodology for computers. For example, Huo et al. presents a system using the human tongue as an input device [47]. The authors attach a magnet on the tongue and observe the changes in the magnet field using Hall-Effect sensing, when the user changes the position of his/her tongue. The information is then transfers to the computer through the head mounted processing unit. Similarly, Kim et al. describes a tongue based switch array as a hands-free alternative communication method between human and machines [53].

In addition, Sampaio et al. uses the tongue as a visual actuator [94]. The authors present a tongue display unit (TDU) with an array of electrical stimulators (144 points) to stimulate the 'visual' acuity of blind people. The wearable TDU is connected to a camera through a computer, which transforms the visual images from the camera into the TDU coordinates.

Although these research works are not focusing on taste stimulation, they help during the design process of the prototype systems presented in this thesis. In particular, we understood that the contacting apparatus on the tongue needs to be simple and lightweight for better results. Thus, the prototypes are developed as two separate modules, the control system and the tongue interface. Moreover, the tongue interface has a compact form to be effortlessly placed in the mouth.

2.5 Contribution

The above review explains the importance of merging the sensation of taste with the domain of digital interactions, which further advances the digital multisensory interactions. Furthermore, the significance of non-chemical based solutions to stimulate taste sensations is also explained. Therefore, the main objective of this thesis is to propose a new methodology for digital taste simulation to facilitate remote digital taste communication. Next, the specific objectives within this general objective and the significance of the work are discussed.

As reviewed in section 2.2, existing solutions for taste interfaces based on chemicals do not provide realistic solutions for digital interactions. Although the approach of using an array of chemicals for taste stimulation is more direct and accurate, there are difficulties in maintaining and transmitting these chemicals over long distances. Therefore, the main aim of this thesis is to investigate non-chemical methodologies to simulate taste sensations. As evaluated in section 2.3, there are several experiments conducted on electrical and thermal stimulation on the human tongue to actuate taste sensations in the medical domain with controlled environments. Consequently, this aspect is investigated thoroughly.

The specific aims are,

• To develop an interactive system to digitally simulate primary taste sensations (sweet, bitter, sour, and salty) by using electrical, thermal,

and hybrid stimulation methodologies.

- To determine the parameters for stimulation (electrical: range of current and frequencies, thermal: heating and cooling / min and max temperatures, position on the tongue)
- To determine the controllability and repeatability of generated taste sensations
- To compare and evaluate the differences between natural and digital taste sensations

The findings of this thesis should introduce a new approach for electronic taste simulation and facilitate different application possibilities in various domains including human-computer interaction, new media, entertainment, and medical. Moreover, knowledge is gained through designing, implementing and evaluating workable engineering prototypes, formulating research questions and working hypotheses, and user experiments [34]. Although this thesis has shown the possibility of using the proposed technology for stimulating primary taste sensations, developing a new mechanism for stimulating flavors is beyond the scope of this thesis. Taste is a sensory function directly associated with the human tongue and often sensitive to chemical stimuli. Alternatively, flavor is a complex perception and recognizes a combination of both taste and smell sensations [35].

In this approach, only the electrical and thermal stimulation methodologies

are used to stimulate different taste sensations. Additionally, the tip of the tongue is used as the primary place of contact with the tongue. Pure silver and gold electrodes are used for the experiments since other metals may develop toxic components by reacting with saliva on the tongue. The control system is developed with several in built safety mechanisms such as over current and heat protections. The stimuli parameters are finalized by conducting focused user trials on the level of comfort and sensitivity.

The significance of the study are summarized below:

- The results of this thesis may have significant impact on both multisensory digital interaction domain and as a novel means of simulating the sensation of taste on human.
 - This work may provide the basis for gaining digital controllability over the sense of taste.
 - This thesis investigates if electrical and thermal stimulation methodologies can be used as an effective taste stimulation mechanism.
 Furthermore, the controllability of the developed system is analyzed through experiments conducted.
- In addition, the proposed methodology of taste stimulation would be useful in several application domains as explained in section 1.1. This technology may also shed new light on taste based entertainment systems such as creating taste symphonies on human mouth. This would

be achieved by effectively manipulating the sensations through aforementioned methods.

2.6 Conclusion

In summary, this chapter has reviewed several related works on simulating the sensation of taste on human tongue based on three categories, chemical stimulation of taste, non-chemical stimulation of taste, and tongue based interactive systems. From the literature review, it is apparent that electrical and thermal stimulation of human tongue could generate taste sensations. However, the apparatus and experimental methods used in these experiments are rather general and not specific enough. Furthermore, very little research has been conducted to assess their effectiveness and the applicability in interactive computing domain. We address this gap by proposing a user-centered approach, primarily by developing several prototype systems for effectively and reliably control the stimuli. Then by employing a series of user studies, we explore the effectiveness of this approach (electrical, thermal, and hybrid) as presented in chapters 3, 4, and 5.

Chapter 3

Design Methodology

The design of the Digital taste interface is described in this section. First, an overall system design is presented followed by a discussion on factors we have considered for the final implementation.

3.1 System components design

The Digital Taste Interface is designed as two separate modules as illustrated in Figure 3.1. They are the tongue interface and the control system. They are connected over a six wire bus that carries two control lines (for Peltier module and electrical stimulation) and thermistor data. This arrangement allows plug-and-play use of the tongue modules (one control module and several tongue modules), thus improving the scalability, portability, and wearability of the system. For instance, a single control system may be shared among all members of a family with individual tongue interfaces. In a future wearable system, a compact edition of the control system can be integrated with the

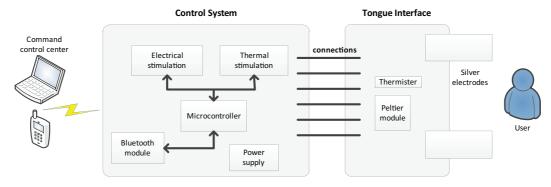


Figure 3.1: The system architecture of Digital Taste Interface, showing the nodes of important subsystems in the system: 1) Electrical stimulation module 2) Thermal stimulation module 3) Tongue interface consists of Peltier module and silver electrodes. In addition, a laptop/mobile device is used as the command control center for remote commanding the device.

mobile phone or personal music player, while the tongue interface can be plugged in whenever it is needed.

3.1.1 Tongue interface design

The tongue interface consists of two silver (95%) electrodes (each has dimensions of 40mm x 15mm x 0.2mm), a Peltier module, and a thermistor. Silver is selected due to its high conductivity (thermal [97] and electrical [80]) and the non-toxic behavior with human tissues [73]. The tongue is placed in between these two electrodes. The dimensions for the silver electrodes were selected to fit into the user's tip of the tongue effortlessly and comfortably as shown in Figure 3.2. The metal pieces are contacting the users top and bottom surfaces on the tip of the tongue. The tip of the tongue was specifically examined since it is the most sensitive area of the human tongue [93]. In addition, it requires a heat sink for effective temperature control with a Peltier module,



Figure 3.2: The tongue interface attached to a user's tip of the tongue. The dimensions for silver electrodes were selected based on the average size of human tongue and to place electrodes on the tongue inside users' mouth effortlessly.

specifically when cooling down.

3.1.2 Characteristics of the tongue

The impedance of the tongue is varies from person to person due to the differences in the types and density of papillae on the tongue surface [62]. Therefore, we implement a mechanism to provide a constant current to all participants using a constant current source. The rationale of employing a constant current source is such that the differences of participant's tongue impedance will not affect the current that is being supplied. As a result, this design helps to assess the quality and quantity of the taste simulated against the applied current and frequency. This is necessary when finalizing a standard set of

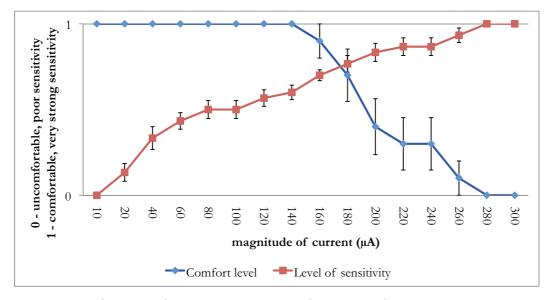


Figure 3.3: Change of sensitivity and comfort level of the end user's tongue over the magnitude of current supplied (error bars showing standard error and n = 10)

stimuli to develop an interactive taste system in the future. Furthermore, according to [91] in electrogustometry research it has been shown that using the frequency range of 10Hz - 1000Hz results in the maximum sensitivity for electrical stimuli. Therefore, we adopt a similar frequency range from 50Hz to 1000Hz.

3.1.3 Measurements on the threshold of electrical stimulus

A primary user experiment was conducted to determine the threshold of electrical stimulus and the comfort level of the end user. The first experiment was conducted to determine the variation of sensitivity on the tongue using electrical stimulation over the magnitude of current supplied. The second ex-

Current (μA)	10, 20, 40, 60, 80, 100, 120, 140, 160, 180, 200,
	220, 240, 260, 280, and 300
Frequency (Hz)	600

Table 3.1: Stimuli parameters for level of comfort and sensitivity experiments

periment measured the comfort level of user's tongue over the magnitude of current supplied. The results of this experiment were used to configure the output of the system to be well within the safety margins and especially in the comfort zone for the users.

Ten participants were recruited for both experiments aged between 22-30; M=27.5; SD=2.66. All the participants were non-smokers and instructed not to consume spicy, too hot, or too cold food or beverages at least two hours before the experiments as these may affect the results. During the experiments, they were instructed to attach the tongue interface to their tongue while the control system gradually increased the magnitude of current. Stimuli parameters for both experiments are given in TABLE 3.1. Frequency was controlled at a constant level of 600Hz for both experiments since it is approximately the mid value of the experimental frequency range selected (as mentioned above the experimental range was up to 1000Hz). Further, both experiments were designed to increase the magnitude of current in series of steps of five second intervals.

Prior to any measurement, the participants were instructed on the procedure and a trial was conducted with each participant. During the first experiment, participants were instructed to rate the intensity of the sensation as one of four categories (1: poor, 2: fair, 3: strong, and 4: very strong) using a computer keyboard. Moreover, for the second experiment (same protocol), participants were asked to remove the tongue interface module when it gets uncomfortable on the tongue (1: comfortable, 0: uncomfortable). Results of sensitivity level and comfort level of the tongue with respect to the electrical stimulation from both experiments were recorded, and normalized mean values are displayed in Figure 3.3.

According to Figure 3.3, the sensitivity of the tongue towards electrical stimulation is almost linear. Furthermore, participants reported that magnitudes over 160μ A and 180μ A were uncomfortable especially for long term actuation. Stimulations over 200μ A were described as a tingling sensation by some participants. Additionally, few participants commented that they could even feel the effects from stronger stimulations (250μ A - 300μ A) for a few minutes after the experiment. Based on the findings, suitable experimental parameters for electrical stimulation were finalized as 20μ A to 200μ A.

3.1.4 Stimuli and control system design

As explained, electrical and thermal stimuli is used to stimulate the tongue for generating taste sensations. The control system is designed with three individual subsystems: electrical stimulation subsystem, thermal stimulation subsystem, and communication subsystem. In the electrical stimulation subsystem, the waveform (square), current, and frequency of electric pulses are controlled. Temperature is controlled (heating and cooling) within 20°C - 35°C using the thermal stimulation subsystem. The communication subsystem is developed to control the desired output through Bluetooth.

The stimuli parameters, the magnitude of current, frequency, and temperature are derived based on literature [90, 64, 107, 70, 22, 89] and pilot studies conducted.

They are finalized as follows.

- Waveform: For the experiments in this thesis, square wave pulses are used with different levels of frequency and magnitudes of current. Square wave pulses were used due to several reasons: it is power efficient and repetitive square wave may give both DC and AC effects to the tissues [91]. However, effects of other waveforms are equally important and will be studied in future experiments.
- Stimulation frequency: the frequency range from 50Hz to 1000Hz is used since lower frequencies has a clear effect on human tissues as mentioned. The control system outputs 50Hz, 100Hz, 200Hz, 400Hz, 600Hz, 800Hz, and 1000Hz based on control parameters. At frequencies larger than 1000Hz the sensitivity is reduced significantly. Further, during higher frequencies the heat effect may reduce the effectiveness of the electrical stimulation (Electrosurgery is using higher frequencies [2]). On the other hand, very low frequencies (<50Hz) cause only the vibration effects on the tongue.

- Magnitude of current: the output current is chosen from 20μA to 200μA based on the threshold study presented. The control system outputs 20μA, 40μA, 60μA, 80μA, 100μA, 120μA, 140μA, 160μA, 180μA, and 200μA based on users' selection on command control center.
- Temperature: controlled within 20°C 35°C (both heating and cooling). This temperature range is approximately between the room temperature and the average body temperature; thus the temperature changes will be more stable and smooth; also consider as normal conditions. Furthermore, the rate of the temperature change is essential for the sensation. This range has proven to be effective to control the temperature with the limitations of the Peltier elements. Additionally, to reach lower temperatures above 35°C may be uncomfortable for the participants and could temporary damage their tongue surface. The thermal shutdown of motor driver (used to drive the peltier module) is another reason to choose this range. Within this range we could effectively control few thermal cycles (20°C 35°C 20°C) before it triggers the thermal shutdown of the motor driver.
- Electrode material: pure (95%) silver electrodes are chosen to be used since it has high thermal and electrical conductivity.

3.2 Secondary design factors

In addition to the primary design factors, several secondary design factors have been considered for the design of the Digital Taste Interface. The system should be easy to setup and portable enough for conducting experiments in laboratory and for use in everyday life. It should also be comfortable for the end user. Based on these requirements, re-configurability and safety are defined as key factors.

3.2.1 Re-configurability

It is necessary to achieve results in real time for such a system. Therefore, a serial control interface (through Bluetooth technology) is implemented to configure the system in real time. Through this control interface the system can be easily reconfigured to achieve different taste sensations.

3.2.2 Usability

Usability is one of the main concerns and a fundamental factor for any interactive system. The system is implemented in such a way that it can be configured and powered on easily. Differentiation of tongue interface and control system is another advantage for the end users' as well as for the laboratory experiments. However, since this work is at the fundamental stage of engineering research we may not address all the usability aspects in our prototypes at this stage.

3.2.3 Safety

To operate the system efficiently, the stimuli has to surpass a certain threshold. At the same time, the stimuli must not exceed a certain limit since it may cause faradaic reaction between electrodes. Therefore, careful design of stimulation protocol is crucial to address these concerns. In addition, there are several safety mechanisms that need to be implemented to control current flow effectively. A current sensor is also used to control the current through the Peltier module thus avoiding the overheating of the Peltier module in the thermal stimulation module.

3.3 Conclusion

This chapter discussed main design specification of the Digital Taste Interface. The central question of this research is whether or not the sensation of taste can be stimulated using non-chemical stimuli to obtain the digital controllability of the sensation. Thus, a digital instrumentation system is designed to produce taste sensations on human tongues through electrical and thermal stimulation methodologies. First, an overall system design is presented followed by several minor form factors such as re-configurability and safety of the system. As explained, the system is designed as two separate modules, the control system and the tongue interface.

In addition, finalizing the parameters of stimuli is essential for the user experiments. A preliminary experiment is conducted to determine the levels of sensitivity and comfort of the tongue for electrical stimulation. Thereby, different parameters such as waveform, magnitude of current, frequency, and the material of the electrodes are finalized.

Next chapter 4 will describe the system description of the Digital Taste Interface developed. Furthermore, several user experiments and technical measurements of the system are also described.

Chapter 4

System Description

This chapter presents the technical description and measurements of the Digital Taste Interface followed by initial experimental results with the human participants. For all the measurements, two silver electrodes of the tongue interface are connected to the users tip of the tongue. The dimensions of silver electrodes (each has dimensions of 40mm x 15mm x 0.2mm) are selected to fit into the users tip of the tongue effortlessly and comfortably. The participants tongue is placed in between (top and bottom surfaces) these two electrodes for digital taste simulation.

4.1 Digital Taste Interface

The Digital Taste Interface has two main modules: 1) the control system and 2) the tongue interface. The control system is designed and developed in the laboratory environment using a PIC microcontroller. The PIC18F2620*

^{*}http://www.microchip.com/wwwproducts/Devices.aspx?dDocName=en010284

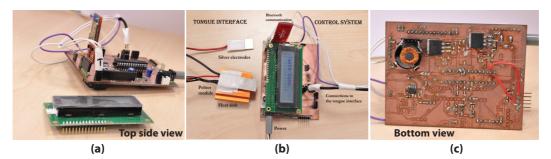


Figure 4.1: Implementation of the Digital Taste Interface (a) shows the top side view of the control system (b) shows both control system and the tongue interface (c) shows the bottom side of the control system

is used with a 40MHz clock. This microcontroller is selected since it has a USART for serial communication, a SPI interface to configure the voltage controller, and two CCP modules for PWM output. It also has an analog-todigital converter with 10-bit resolution, which we use with the thermistor and current sensor. The computer attached to the control system functions as the command control center. It delivers configuration and control commands to the system through Bluetooth. The current implementation of the system is shown in Figure 4.1.

Based on the control commands, the PIC microcontroller configures the output signal of the control system (input of the tongue interface) using two subsystems for electrical and thermal stimulation. Separate power and control signals are transferred through six wire bus connection between the control system and tongue interface. Different modules of the control system is shown in Figure 4.2.

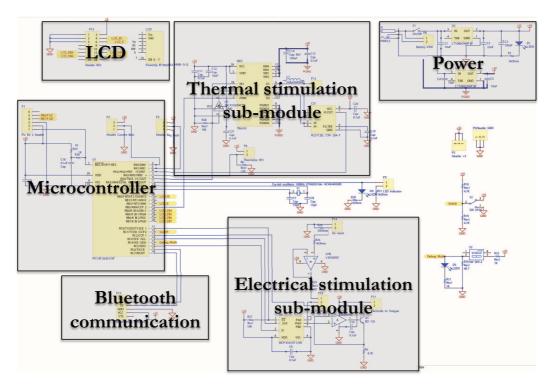


Figure 4.2: Circuit diagram of the control system of Digital Taste Interface with different sub-modules

4.1.1 Electrical Stimulation

The electrical stimulation subsystem, as shown in Figure 4.3, generates small constant current pulses to be applied on the human tongue. The pulse generator implemented on the microcontroller provides square-wave pulses using the Pulse-width modulation (PWM) technique to control the frequency of stimuli. The voltage controller combined with constant current source produces varying magnitudes of current on the user's tongue. Consequently, this setup helps to assess the quality and quantity of taste sensations generated by manipulating the properties of the applied current.

Table 4.1: Digital POT values and corresponding output current values from the electrical stimulation subsystem

POT value	Current (μA)
102	199.574468
92	179.478649
82	159.528058
72	140.045242
61	119.617188
51	100.925643
40	79.5744681
30	60.212766
20	40.8510638
9	19.1489362

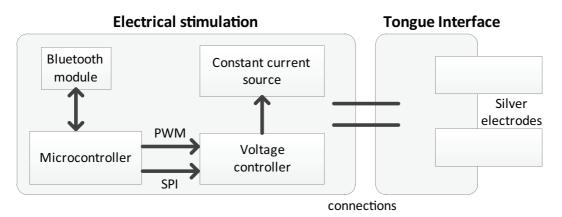


Figure 4.3: Primary components of the electrical stimulation subsystem including the voltage controller, constant current source, and two connections between electrical stimulation subsystem and the tongue interface

4.1.1.1 Voltage controller

A 256 position single digital potentiometer (POT), MCP41010[†], with Serial Peripheral Interface (SPI) is used in the electrical stimulation subsystem. This setup allows the digital potentiometer to output a voltage proportional to input voltage. The output voltage is configured using the wiper position of the digital POT (MCP41010), which is configured through the SPI interface

 $^{^{\}dagger} http://ww1.microchip.com/downloads/en/devicedoc/11195c.pdf$

of the microcontroller. Several POT values with corresponding output current values from the electrical stimulation subsystem are presented in TABLE 4.1. The output of the voltage controller (digital POT) is the input of the constantcurrent source (OP-AMP) as shown in Figure 4.3 and Figure 4.4.

4.1.1.2 Constant current source

The constant current source is implemented using an operational amplifier (OP-AMP) and a NPN transistor, as shown in Figure 4.4. The output current is based on the input voltage from the voltage controller as well as the resistance between the ground and the constant current source (R5 in Figure 4.4). Therefore, the current delivered to the load (tongue) I_{P11} is (tongue electrodes are shown as P11 in Figure 4.4),

$$I_{P11} = V_{PW0} / R_5$$

where, V_{PW0} = output voltage of the digital potentiometer.

The current error is measured and has a value around 1 μ A. For BD135-16 NPN transistor (Q1 in Figure 4.4) the current gain β has values from 100 to 250 [1]. To verify this, for example, if the target current is 100 μ A and β is 100, the error can be calculated as (100 μ A / 100) = 1 μ A (maximum), and if the target current is 100 μ A and β is 250, the error can be calculated as (100 μ A / 250) = 0.4 μ A (minimum). Therefore, the current error can be a

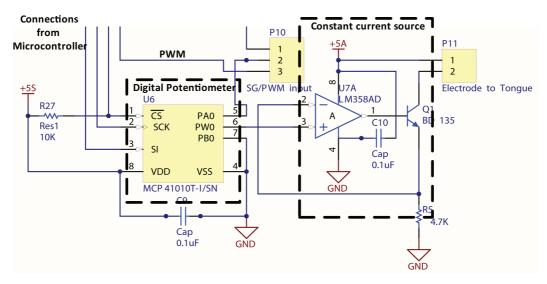


Figure 4.4: Implementation of electrical stimulation subsystem. The dotted squares show the digital potentiometer used for voltage control and the implementation of the constant current source. (+5A and +5S represent different +5V Vcc connections from the power supply submodule)

value between 0.4μ A and 1μ A. The current error is less than 1μ A and it is acceptable since it is beyond the sensitivity level of human perception.

4.1.1.3 Measurements of electrical stimulation module

Figure 4.5 illustrates different stimulation signals monitored through the YOKO-GAWA DLM2022 2.5GS/s 200MHz[‡] digital oscilloscope. It shows properties of electrical stimuli with output current of 60μ A and frequency of 800Hz. The voltage levels are measured through the resister R5 (between constantcurrent source and ground) in the electrical stimulation circuit to show the voltage differences when the tongue is connected and not connected. Similar to a traditional non-inverting amplifier, the output current through the load is independent of the resistance of the load, and depends only on the input

[‡]http://tmi.yokogawa.com/

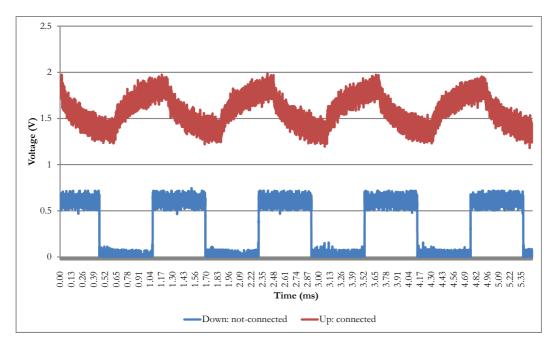


Figure 4.5: Output waveforms before and after connecting the tongue (properties of electrical stimuli: 60μ A and 800Hz)

voltage.

As shown in Figure 4.5, the waveform changes when electrodes are connected to the tongue. The change in the signal indicates that it is low pass filtered due to the capacitive effect and the inductance of the human tongue; however more experiments should be conducted in the future to confirm this physiological observation. In addition, at the moment we only conduct experiments on wet tongue surfaces. Increase of dryness (high impedance) over time during the experiments is controlled by the short intervals in between the stimuli.

4.1.2 Thermal Stimulation

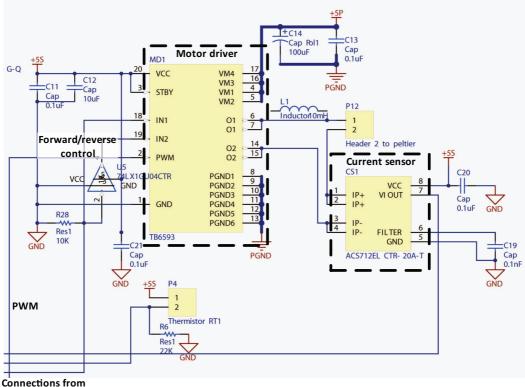
Figure 4.6 depicts the thermal stimulation subsystem, which is capable of exerting a temperature change on the silver electrode through the use of a Peltier module [105]. The peltier module is driven by a full-bridge DC motor driver IC (TB6593[§]) and controlled using a PWM signal from the microcontroller. The PWM duty cycle is used to control the time required to achieve a distinct temperature change using a proportional-integral (PI) controller algorithm. The PWM duty cycle is calibrated based on the input from the temperature sensor, which is attached to the silver electrode. Furthermore, a current inverse mechanism is implemented using the motor driver IC to manages the forward and reverse control (heating and cooling) of the peltier module. In addition, to increase the safety of the user, a "current sensor" is utilized in conjunction with the peltier module. Interactions between different components in this subsystem are shown in Figure 4.7.

A Peltier module of 15mm x 15mm is used in the tongue interface module. The size is chosen to fit the size of the silver electrodes and to achieve desired temperature change with fairly low current as mentioned in Chapter 3.

4.1.2.1 Measurements of thermal stimulation module

The efficiency of the heat-sink and the PWM percentage are the main factors associated with the thermal stimulation performance of the current setup. Figure 4.8 shows the warming up and cooling down performance of the tongue

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Microcontroller

Figure 4.6: Implementation of thermal stimulation subsystem. The dotted squares show the motor driver IC (TB6593) used for forward/reverse control and the current sensor used for safety purposes.

interface module (peltier module with the heat-sink). The temperature values are recorded through the wireless link between the device and the computer at a sampling period of 100ms. The current setup of the tongue interface is able to meet the requirements of heating from 20°C to 35°C and cooling from 35°C to 20°C. All the measurements were conducted at room temperature (24°C, air-conditioned).

Moreover, the current setup of the tongue interface module is able to cool down from 35°C to 20°C within approximately 53 seconds with 30% PWM. The time-lag to achieve a desired temperature change is effortlessly controlled

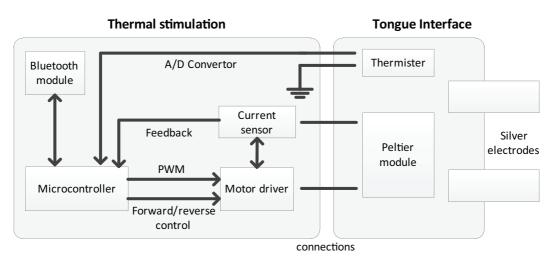


Figure 4.7: Primary components of the thermal stimulation subsystem including the motor driver, current sensor, and four wire connection between thermal stimulation subsystem and the tongue interface (thermistor - 2 connections, peltier - 2 connections). (+5S and +5P represent different +5V Vcc connections from the power supply submodule)

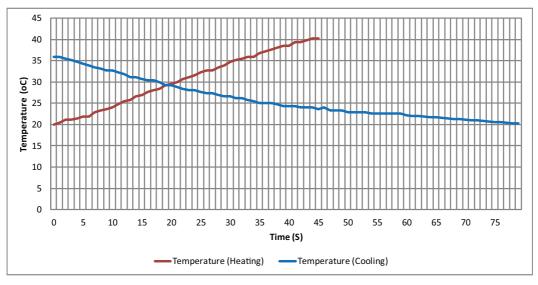


Figure 4.8: Warming up and cooling down performance of the system for one cycle from 20°C to 35°C and continuously 35°C to 20°C (room temperature = 24° C, PWM percentage=30%)

by increasing the PWM duty cycle.

Table 4.2: Power consumption during different operational states of DigitalTaste Interface

System state	Power (W)
Idle	< 0.7 W
Electrical stimulation	< 0.7 W
Thermal stimulation	$\approx 8W$
Hybrid stimulation	$\approx 8W$

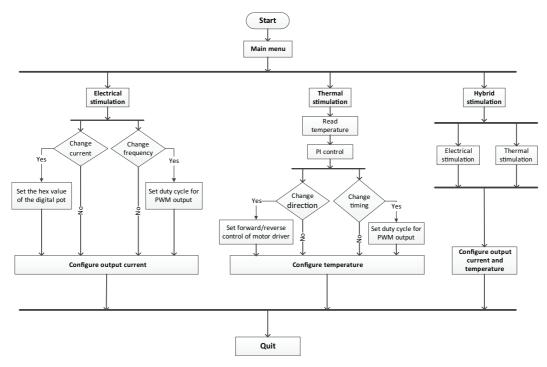


Figure 4.9: Algorithm design of the digital taste interface (hybrid stimulation is a combined stimulation of electrical and thermal subsystems)

4.1.3 Power consumption

The Digital Taste Interface is powered by a laboratory DC power supply with +5 volts DC. Although the system can be battery powered, a laboratory power supply is used due to the high power consumption of the peltier module (≈ 8 W). Power consumption during different system states are given in TABLE 4.2.

4.1.4 Software Implementation

The software components of the system are in two main divisions. They are the firmware implementation on the microcontroller and the user interface (UI) for the command control center. The UI allows changing of different output parameters of the control system such as frequency, current, and the temperature change. Figure 4.9 depicts the algorithm design of the control system.

4.1.4.1 Firmware

The firmware programmed on the microcontroller configures the communication between the command control center and the tongue interface.

Bluetooth communication: Communication between the command control center and the digital taste interface is managed through the Bluetooth wireless module. A standard class 1 bluetooth modem[¶] (Bluetooth v2.0) is used with Serial Port Profile (SPP). The network throughput of the communication channel is 115200bps. We recommend a minimum throughput of 9600bps to manage unexpected deviations of temperature and magnitude of current from the experimental parameters for safety reasons. This module reads and writes data on a continuous loop. In this way, the command control center is continuously updated. A bluetooth command parser inside the microcontroller handles commands received from the command control center.

[¶]http://www.sparkfun.com/products/10268

Command parser There are several primary user modes implemented as stated below:

- Electrical stimulation: Only allows user to configure the parameters for electrical stimulation on user's tongue (current, frequency, and square waveform)
- Thermal stimulation: Only allows user to configure the parameters for thermal stimulation on user's tongue (heating, cooling, and the rate of change)
- Hybrid stimulation: Allows user to configure the parameters for both electrical and thermal stimulation at the same time on user's tongue

These modes allow users to configure the output of the tongue interface accordingly.

4.1.4.2 UI

There are two types of User Interfaces (UI) developed for the digital taste interface. First, a direct serial command interface (serial UI as in Figure 4.10), then, a graphical user interface (GUI). The serial UI is a text only version, which mainly used for testing and debugging of the system during the developmental stage. The GUI is developed (using Visual C# .NETTM on Windows XPTM) for both configuring the device and obtaining user information during experiments (both digital taste interface and the evaluation module are

I - HyperTerminal	
Eile Edit View Gall Iransfer Help	
Digital Taste Interface	
Please select one of the options:	
'E' - Electrical stimulation	
'T' - Thermal stimulation	
'H' - Hybrid (Electrical & Thermal stimulations together)	
'Q' - Quit from stimulation	
ManualCommand: h	
Please select one of the options for Hybrid stimulation:	
'1' - Step by step	
'2' - Continuous	
'Q' - Quit from stimulation	
onnected 0:00:49 Auto detect 115200 8-N-1 SCROLL CAPS NUM Capture Print echo	

Figure 4.10: Text based serial user interface developed for debugging



Figure 4.11: Graphical user interface developed to configure digital taste interface and to conduct user experiments

connected to this software). In Figure 4.11, a part of the GUI interface is displayed. This GUI is used to obtain user inputs and record them with the corresponding output configurations of the control system during the user experiments described in this thesis.

4.2 Experimental Results

The Digital Taste Interface was experimentally evaluated to determine the effectiveness of this approach to simulate basic taste sensations electronically. Furthermore, there are several usability factors to consider such as sensory adaptation, reproducibility of taste sensations through this method, and the comfortability of using such a system. In addition, a new tool was developed for recording perceived taste sensations during user experiments.

4.2.1 Taste Recorder

We developed a new tool for recording information during the evaluating process of the digital taste interface. We discuss it as a taste-recorder, similar to an audiometer used for hearing tests [49]. The taste-recorder device consists of a hardware unit, which connects to the computer and eight test subject feedback buttons. When a user selects the taste and intensity, the UI updates the selection and queries the digital taste interface to obtain current output configurations. Then it updates the database with output configurations of the digital taste interface against the perceived taste and level of intensity. This method helps to correlate perceived taste with electrical and thermal stimulation settings.

As shown in Figure 4.12, the taste-recorder has two rows of buttons for selecting the corresponding primary sensation and the strength of the sensation (level of intensity). First row has five buttons for the five primary tastes:



Figure 4.12: The taste-recorder developed for recording taste sensations and their intensity levels

Sweet, Salty, Bitter, Sour, and Umami. Second row has three buttons to record the intensity of the sensation: Mild, Medium, and Strong. In addition, it has a USB port to connect with a computer. The computer records information in a database through the USB connection. Additionally, the LED indicator indicates a successful connection with the computer. The taste-recorder is powered by the USB connection.

4.2.1.1 Participants

Fifteen participants (8 male and 7 female) were recruited for the experiment aged between 21-28; M = 23; SD = 2.54. The participants were randomly chosen and had no training before being tested. All participants were in good

health and reported no taste or smell problems. All participants involved were asked not to smoke, nor to eat or drink strongly spiced meals or alcoholic beverages two hours prior to the testing period as that may affect the results. After each experiment, participants are asked to describe their experience and any important information related to their perceptions. Key findings from these short interviews are presented as discussion.

4.2.1.2 Apparatus

The experiments were conducted in a quiet meeting room inside the laboratory. As shown in Figure 5.25, a notebook computer (command control center), Digital Taste Interface system, Taste Recorder, and a laboratory power supply were used for the experiments. The stimulus is presented in the form of a 40mm x 15mm x 0.2mm silver electrode connected to the device as described. Participants use the anterior ("tip") of the tongue to interact with silver electrodes, since it is the most sensitive area of the human tongue [7]. Before each experiment, both electrodes were rinsed using tap water, then sterilized using 70% isopropyl alcohol swabs, followed by deionized water [28].

4.2.2 Experimental method

The experimental setup of the digital taste interface and the taste-recorder is shown in Figure 5.25. As mentioned, the experiment was organized to determine the correlation of the taste quality and perceived intensity elicited by thermal and electrical stimulation of the tip of the tongue. It is hypothesized



Figure 4.13: The experimental setup of the Digital Taste Interface, Command control center, and the Taste Recorder

that there is a correlation between the dependent variables (taste sensation and perceived intensity), and the independent variables (temperature change, magnitude of current, and frequency). Then, the identified relationship can be applied on the control system to stimulate corresponding taste sensations.

As we observed during the pilot studies, participants were hesitant to put the tongue interface into the mouth at the beginning. Therefore, the experiment was designed to run in two phases. For the first part of the experiment, participants were asked to place the tongue interface on the tip of the tongue and conducted two trial sessions before the formal experiments with each subject. For these trial sessions, the properties of current and temperature were randomly configured through the command control center. For the second part of the experiment, the formal experiments were conducted by changing the temperature, magnitude of current, and frequency. Furthermore, participants rinsed their mouth with deionized water between each stimulus and relaxed five minutes to prevent bias and counterbalancing [27].

4.2.2.1 Performance metrics

Dependent Variables (DV) Taste Quality and Perceived Intensity of the stimulated taste were identified as dependent variables (DV).

- DV1: Taste sensation: Although there is a shortcoming of research to confirm the concept of five primary tastes [25], this concept is common to almost all the research in gustation at present (including studies on taste stimulus, taste receptors, and neural and psychophysical aspects of taste) [32]. Similarly, we also utilized the concept of primary taste sensations (known as sour, salty, sweet, bitter, and umami) to conduct the experiments and organize the data.
- DV2: Perceived intensity of the stimulated taste: The level of intensity is recorded on a scale of four steps: 0 means no taste, 1 corresponds to mild, 2 is medium, and 3 represents strong. Similar models are also used in [22] and [89] to record the intensity levels of taste sensations. Furthermore, later in the experiment we realized this model is more familiar and easier to use with the participants as it is commonly used in our daily lives to describe the strength of a taste sensation.

As it was the initial stage of this research, we only focused on electronically simulating the primary taste sensations. Therefore, responses were recorded in terms of basic taste qualities and in three levels of perceived intensities. When recording responses, mixed tastes were also taken into consideration by allowing participants to select more than one button pertaining to the taste that they sensed. These sensations were recorded and reported as "Other". Finally, the intensity or the strength of a taste sensation was recorded in a familiar manner for the ordinary people in their daily lives, i.e. mild, medium, and strong.

Independent Variables (IV) Temperature change and magnitude of current and frequency were considered as Independent Variables (IV).

- IV1: Magnitude of output current is changed from 20μA, 40μA, 60μA, 80μA, 100μA, 120μA, 140μA, 180μA, to 200μA, while keeping the frequency constant at 600Hz, which is approximately the mid range of IV2, such that IV2's results will be able to show if the frequency value has an impact when increased or decreased from 600Hz.
- IV2: While the frequencies are varied from 50Hz, 100Hz, 200Hz, 400Hz, 600Hz, 800Hz, to 1000Hz, the magnitude of current is held at a constant value, which yields a "medium" response, i.e. 60μ A. This is due to the fact that different people might have different levels of sensitivity and comfort for electrical stimuli. Through this method, if the increase in frequency results in an increase in the magnitude of current, the response system is still able to capture a stronger response from the participant.

In general (Figure 3.3) participants mentioned approximately 50μ A-90 μ A as the medium range (Further explained in the comparison study with the sour taste in Chapter 5). This range depends on the individual sensitivity levels of participants tongues. Within this range 60μ A was selected after considering the comfortability of the participants.

• IV3: Temperature is changed from 20°C to 35°C (heating) and 35°C to 20°C (cooling). The selected temperature range was approximately between room temperature and the body temperature. Thus, the temperature change was easier to control using a heat-sink, and was smoother. Sensations were recorded in 5°C intervals for proper analysis.

For thermal stimulation experiment, the tongue was continuously exposed for a thermal cycle (from 20°C to 35°C and back to 20°C). One of these thermal cycles needs approximately 100 seconds to complete as shown in Figure 4.8 using the first prototype.

4.2.2.2 NULL Control and non-tasters

Before the experiments, an isolated tongue interface was presented to the participant as a control probe to negate any experience of taste qualities, which are not due to the electrical and thermal stimuli. If there were any taste sensations elicited by the control probe alone, that sensation was removed from the final results of that session. Moreover, to exclude the results of nontasters, participants were asked to identify unnamed solutions of sugar, salt, lemon juice, and coffee powder to determine the sweetness, saltiness, sourness, and bitterness respectively. There were no identified non-tasters.

4.2.2.3 Procedure

First, the participants were instructed to complete an online biographical questionnaire. Next, they were taken to the meeting room, where they were introduced to the experimental setup. This room is fully closed, quiet, and no external interactions were allowed during the experiments. Then, they were asked to sit-down comfortably next to the experimental setup and undertake the NULL control and non-taster tests as explained. Next, silver electrodes of the tongue interface were cleaned in front of each participant. Subsequently, the participant was explained on how to position the tongue interface and how to respond to the taste sensations through the taste recorder (see Figure 5.25).

As mentioned, each session starts with five minutes of rest to create separation between sessions. They were also instructed to rinse their mouth with deionized water between trials to minimize the carryover effects [27]. Furthermore, they were entitled to refuse to participate or discontinue participation at any time during the experiments.

After the participants familiarized with the equipment, they were informed that the first part of the experiment would consists of two trial sessions. Then, the trial sessions were conducted with random stimuli configured in the control system. Instructions were given to select appropriate buttons at the taste recorder during the trial sessions as well, though we did not record them. After the trial sessions they were allowed to ask questions to clarify any unclear points. However, they were only allowed to clarify information on the experimental procedure, not on stimuli or sensations.

When they were ready to start the formal experiment (the second part), the lights were switched off and they were asked to close their eyes during the experiments, thus minimizing distractions from other sensors. Next, different stimuli were utilized to record corresponding taste sensations as explained in section 4.2.2.1. Based on the participant's feedback through the taste recorder, we were able to capture stimulated taste sensations (sour, salty, sweet, bitter, and other) with corresponding level of intensity (mild = 1, medium = 2, and strong = 3) against the different electrical and thermal stimuli. If there is no taste recorded during a trial, the level of intensity is automatically recorded as 0, which means no taste. After each experiment, participants were asked to describe their experience and any important information related to their perceptions.

4.2.3 Results

Among the five basic taste sensations, this method successfully generated salty, sour, and bitter sensations using electrical stimulation. In addition, participants also expressed several other sensations such as minty and spicy during the thermal experiment.

It is noted that the practice sessions assisted participants to become famil-

iar with the new device and the method of interaction. As expected, they were hesitating at the beginning of the study but after the practice sessions they became fairly familiar with the device and the experiment. At the end, most of the participants expressed their attraction for this new digital experience and even began to discuss further improvements and applications of this new technology.

When presenting the experimental results throughout this thesis, mean intensity values of reported taste sensations, displayed in graphs, are calculated relative to all the trials conducted with participants (without considering a taste sensation is reported or not for a particular stimulus), whereas, percentage values of taste sensations, displayed in tables, are calculated relative to the total recorded taste sensations of a particular experiment.

4.2.3.1 Electrical stimulation

As illustrated in Figure 4.14, average perceived intensity across all taste responses is much stronger than the average perceived intensity during the thermal stimulation experiment as in Figure 4.18 and 4.17. It is observed that the mean responses of perceived taste intensities are increased when the magnitude of current is increased, especially when the magnitude of current is less than 120μ A (see Figure 4.14). However, when the magnitude of current is higher than 120μ A, the graph shows more complex and unpredictable intensity responses for 'bitter' and 'other' categories. There are no evidences of sweet sensation perceived during the electrical stimulation other than for one

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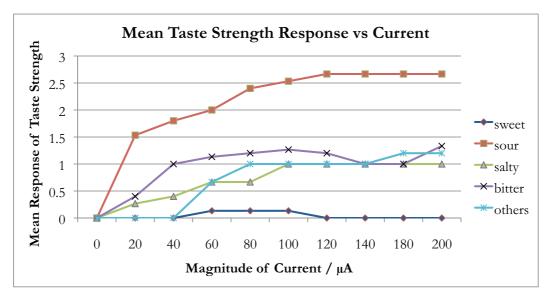


Figure 4.14: Perceived intensity of taste sensations during electrical stimulation, "others" includes mainly spiky and tingling sensations. (frequency = 600Hz, and magnitude of current is varied at 20μ A, 40μ A, 60μ A, 80μ A, 100μ A, 120μ A, 140μ A, 180μ A, 200μ A).

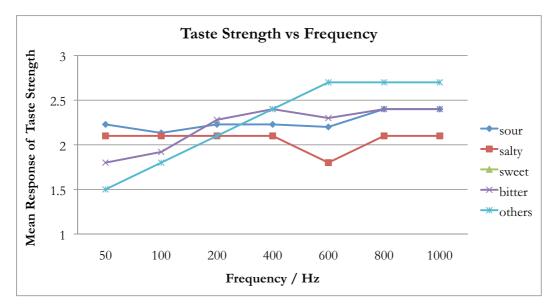


Figure 4.15: Perceived intensity of taste sensations during electrical stimulation, "others" includes mainly spiky and tingling sensations. (magnitude of current = 60μ A, and the frequency is varied at 50Hz, 100Hz, 200Hz, 400Hz, 600Hz, 800Hz, and 1000Hz).

subject. Sourness on the other hand is the prevailing taste that was perceived, accounting for 45.12% of the total responses as presented in TABLE 4.3.

Table 4.3: Taste responses as a percentage of all recorded taste sensations by changing the magnitude of current (IV1) from the electrical stimulation experiment

Taste	Percentage (%)
Sour	45.12
Salty	15.85
Bitter	21.95
Sweet	1.82
Others	15.24

The results does not show a clear trend for the frequency sweep experiment in electrical stimulation. We believe, answers to these questions may give good clues on why "the minimal contribution of the frequency towards taste perception": 1) Which is the filtering response of the tongue?, 2) Is it a linear filter?, and 3) If so, could we estimate the frequency response of the filter?.

Furthermore, there is a small effect of increasing perceived taste intensity when there is an increase in frequency of the current as in Figure 4.15. The results for this particular situation are expected as Lackovic and Z. Stare. (2007) observed that the tongue impedance decreases with the increase in frequency [62]. A decrease in impedance might slightly increase the magnitude of current thus the increase in the intensity perception of taste sensations. This possibly accounted for the increasing trend-line with the increasing frequency. To observe this effect in detail, we have plotted all occurrences of taste sensations during the electrical stimulation (IV2) in Figure 4.16.

The reported intensities of the taste sensations (not including sweet) have a proportional relationship with the magnitude of current applied on the human tongue (Figure 4.14). The intensity of sour sensation is distinguishable and

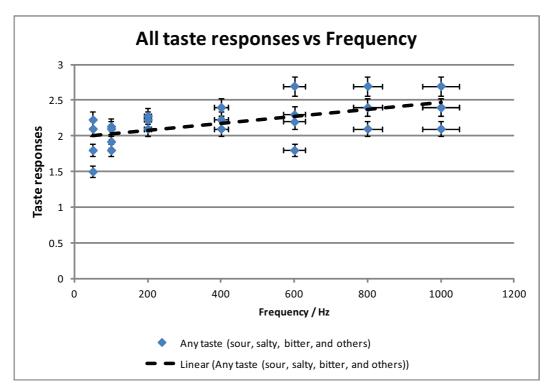


Figure 4.16: Perceived intensity of taste sensations during electrical stimulation (magnitude of current $=60\mu$ A, and the frequency is varied at 50Hz, 100Hz, 200Hz, 400Hz, 600Hz, 800Hz, and 1000Hz)

increases initially but reaches a plateau around 120μ A. However, intensities of salty and bitter sensations were not clearly distinguished due to the unpredictable behavior during higher magnitudes of current. One of the probable reasons why sour and salty sensations are expected is due to the fact that salty and sour sensations associate with ion channels. These ion channels are highly affected by electrical stimulation as compared to sweet and bitter sensations, which work through a signal connected to a G-protein coupled receptor [68]. Neuroscientists may use electrophysiological techniques such as patch clamp technique to experimentally confirm this in the future [108].

Additionally, it was interesting to observe several reports on the bitter

sensation, especially from the bottom surface of the tip of the tongue, as participants explained in several occasions. This finding indicates the importance of experimenting with different electrode positions on the tongue in the future. Moreover, taste sensations classified as "Other" included "spiky" and "tingling" sensations which participants explained as resembling the acidity of pineapple flesh.

Some participants also reported a time lag in the taste actuation of a few seconds for some of the test-cases, since some participants could not explain the taste sensation immediately after the stimulation. They had to conduct the stimulation for two or three seconds to explain the effects clearly. We suspect this happens due to this new form of presentation of the taste sensations. Alternatively, the sensation of taste depends on previous experiences and associates with texture, color, vision, and other human senses. Without contributions from these channels sometimes it may hard to describe the sensations immediately.

4.2.3.2 Thermal stimulation

Figure 4.17 and Figure 4.18 suggests that sour and sweet are the main sensations that can be evoked through thermal stimulation on the tongue. Bitter and Salty sensations are the least detected during the thermal stimulation (IV3).

The warming up experiment (from 20° C to 35° C) (Figure 4.17) suggests that there are negligible contributions from salty, sweet, and bitter sensations.

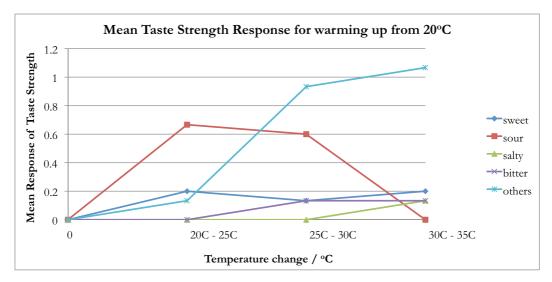


Figure 4.17: Perceived intensity of taste sensations during thermal stimulation - warming up from 20° C to 35° C ("others" includes mainly spicy and minty sensations)

Table 4.4: Taste responses as a percentage of all recorded taste sensations by changing the temperature (both heating and cooling) on the tip of the tongue (IV3) from the thermal stimulation experiment

Taste	Percentage $(\%)$
Sour	29.78
Salty	4.25
Bitter	6.38
Sweet	23.40
Others	36.17

Average perceived intensity levels of all reported taste sensations are generally at the mild level. Other than the sweet sensation, sour taste is perceived at 20°C to 25°C. Interestingly, increasing the temperature causes the sourness effects to weaken.

When cooling down from 35°C to 20°C (Figure 4.18), average perceived intensity of sweet and sour sensations are promptly increased. As presented in TABLE 5.9, approximately 23% of participants reported that they felt a spontaneous sweet sensation when the experiment was conducted continuously

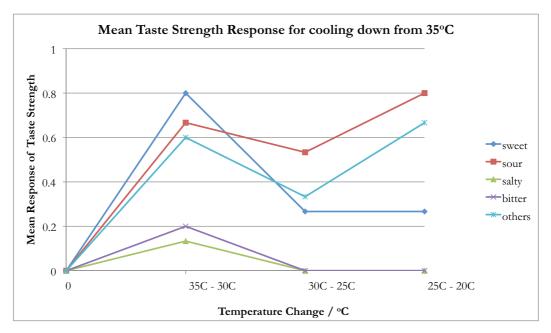


Figure 4.18: Perceived intensity of taste sensations during thermal stimulation - cooling down from 35° C to 20° C ("others" includes mainly spicy and minty sensations)

from heating to cooling (from 20°C to 35°C and continuously from 35°C to 20°C). As in Figure 4.18, these responses were recorded during the first 5°C (from 35°C to 30°C) when cooling down from 35°C. This implies the possibility of being able to deliver the sweet sensation using thermal stimulation, although more experiments on this should be conducted in the future. Moreover, some participants perceived sweet sensation (as an after-taste) over the stimulated area when the mouth is rinsed with running water after the thermal stimulation experiment.

Furthermore, several participants reported that they felt the minty taste or a refreshing taste (around 20°C - 22°C), also slight spiciness (above 33°C). These non-primary taste qualities are reported under the "Others" category.

4.2.3.3 Hybrid stimulation

After conducting experiments with electrical and thermal stimulation separately, we conducted another experiment using the hybrid approach (both electrical and thermal stimulation simultaneously). We were motivated to explore thermal stimulation further to report the possibility of improving the results of thermal stimulation by applying small electrical pulses simultaneously. Furthermore, it was necessary to determine whether hybrid stimulation activates different or improved taste sensations.

An user experiment was conducted with 12 participants (7 male and 5 female) aged between 24 - 30; M = 26, SD = 2.06. The output current and frequency were preconfigured respectively as 60μ A and 600Hz while the temperature was changed from 20°C to 35°C (heating) and 35°C to 20°C (cooling). Results observed from the hybrid experiment are displayed in Fig. 5.14.

Primarily, results from the mixed stimulation (hybrid) of electrical and thermal on participants' tongue has shown the increased sensitivity of sour sensation. Transition of the sensation is clear when the temperature is increasing and decreasing according to the 5.14. On the other hand, introducing the electrical stimuli for thermal stimulation shows the dominance of sour sensation reported through electrical stimulation. One observation for poor results through thermal stimulation is the slower temperature changes from the thermal stimulation submodule. In Chapter 5, more improved technical implementation is used for further experimentation.

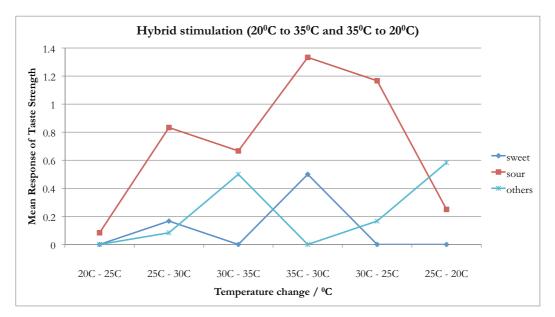


Figure 4.19: Perceived intensity of taste sensations during hybrid stimulation - heating up from 20°C to 35°C and cooling down from 35°C to 20°C, "others" includes mainly spicy, minty, and mixed sensations (current = 60μ A and frequency = 600Hz)

4.3 Controllability of taste sensations

The sensation of taste is one of the most subjective senses humans possess. Normally, food tastes different to different people, and this applies even to the primary taste sensations. The same chemical stimuli can be characterized as disgusting or perfectly flavorful by different people, based on their inherited genetic traits as well as the concentration of taste receptors on their tongue [41, 37, 31].

Similarly, in several occasions the taste qualities elicited were found to be subjective during this study. Fig. 4.14 shows that different sensations were reported for one stimulus. For instance, when the magnitude of current is 40μ A and frequency is 600Hz, salty (2/15), bitter (4/15), and sour (6/15) sensations were recorded from different participants. This happens due to physiological differences (variations in taste receptors and densities) on the human tongue [36]. In addition, several participants stated that some sensations were hard to identify and express exactly. In some occasions, they mentioned that, "it's like a combined taste... sour and sweet together". A few cases were not documented, when the participant could not detect any sensation and could not explain the sensation properly. As a negative feedback, one of the participants mentioned that she did not like the taste generated through the device, though she was surprised by the different sensations this instrument could stimulate. We suspect the lack of contributions to the sensation from other modalities such as smell, texture, and vision occasionally makes it harder for the participant to understand and properly communicate the experience to the experimenter.

Although the actual taste sensation seems to be dependent on the user, to build an interactive taste actuation system, the actuation must be repeatable for each user over time. To further confirm the controllability and repeatability of taste sensations stimulated through this approach, we have conducted a preliminary experiment with five users (3 male and 2 female aged between 21-27, M = 23; SD = 2.4). The main objective of this study was to assess the repeatability of simulating taste sensations through the approach presented. The experimental protocol was defined similarly as the previous experiments with slight modifications.

Stimulus	Magnitude of current (μA)	Frequency (Hz)
S1	40	600
S2	100	600

Table 4.5: Two different stimuli used for controllability experiment

4.3.1 Protocol

Two predefined electrical stimuli as mentioned in TABLE 4.5 were used randomly for stimulating the tip of the tongue of the participants over three days. Participants were not informed of the stimulus properties. Two different stimuli were randomly applied in one day and they were asked to report the sensations, if any. Similar apparatus and method are used as in previous experiment presented in section 4.2.

Electrical stimulation was selected for this experiment since it showed stronger intensity levels from the previous studies. Furthermore, the sour taste sensation generated through electrical stimulation had the strongest intensity levels as displayed in Fig. 4.14.

4.3.2 Results and discussion

The results from this experiment are presented in TABLE 4.6. As displayed, the sensations are repeatable much later, though the perceptions may depend on individuals. Further, it is noticed that S2 generally produced much stronger perceptions than S1. However, results reported from the third participant seem less predictable. Moreover, by the third day, all the participants perceived S2 as sour sensation.

Participant	Day 1		Day 2		Day 3	
	S1	S2	S1	S2	S1	S2
1	Salty	Salty	Sourly-salty	Sour	Salty	Sour
2	Sour	Sour	Sour	Sour	Sour	Sour
3	Sour	Bitter	Salty	Bitter	Salty	Sour
4	Sour	Sour	Sour	Sour	Sour	Sour
5	Salty	Sour	Salty	Sour	Salty	Sour

Table 4.6: Reported sensations against two different stimulus over three days

Based on above experimental results, it is evident that even for electrical stimulation, the taste sensations are individually different. Therefore, as a solution we propose a calibration procedure with the system based on individual users' perceptions. We explain an example calibration procedure as follows.

"John buys a Digital Taste System and connects to his personal computer. He installs and opens the supplied software application of the Digital Taste System and selects the option - calibration. A new UI appears with four separate buttons for sweet, sour, salty, and bitter. Once John selects one of the buttons, it will ask him to connect the tongue interface with his tongue. Then the control system outputs different combinations of stimuli by manipulating the magnitude of current, frequency, and temperature. Thus, the user may select appropriate stimuli for the selected taste sensation. In addition, if he feels other sensations such as spicy, minty, numbness, or dryness, he may customize the UI accordingly."

4.4 Discussion

The Digital Taste Interface was specifically designed and developed for electronic taste simulation on the human tongue. Therefore, both accuracy and safety issues were considered during the design process. After the first few pilot-experiments conducted on human participants, it was proven that the system works in a stable manner and is safe for user experiments.

As mentioned, results reported from electrical stimulation are stronger than the results reported from thermal stimulation. It was noted that the duration of the stimuli is a significant factor for thermal stimulation. Initially, during the pilot studies, when the experiment was conducted with slower temperature changes, taste sensations were not reported. However, the circuit was modified to draw more current (and with an efficient heat sink), thus enabling faster temperature transitions for the experiments. Moreover, we suspect that non-linear transitions of temperature may provide better and improved results, which will be explored in the future. We note this as an immediate future experiment to conduct.

In addition, we found a few limitations of the current system. The Peltier module, which is used as a heater and cooler element, is difficult to control precisely for an extended time due to its nature [79]. Furthermore, the absorption of heat by the human tongue during the stimulation process also makes difficult to control the temperature change accurately. Because of this consequence, during the studies, participants were asked to maintain contact with the electrode for a long time, which may cause discomfort. This may result in poor performance in the thermal taste stimulation. Besides, the Peltier module also required a large heat sink to dissipate the generated heat away.

4.5 Conclusion

This chapter described the development and evaluation of a prototype system to stimulate the sensation of taste electronically. The system is designed as two main modules (the control system and the tongue interface) to stimulate the tip of the tongue by manipulating the magnitudes of current, frequency, and temperature of the stimuli. Four different user experiments are conducted to evaluate the system experimentally, therefore, to learn possible refinements to the system for increasing the effectiveness. First, electrical and thermal stimulation methodologies are experimentally evaluated using fifteen participants. The possibility of stimulating sour (major), bitter (minor), and salty (minor) through electrical stimulation and sour (minor), sweet (minor), and others (minty - minor and spicy - minor) from thermal stimulation are described. Second, to examine the effectiveness, a user experiment is conducted by combining both electrical and thermal stimulations together, and we call it the hybrid (mixed) stimulation. Through this experiment, it is shown that the range of taste sensations reported is increased during hybrid stimulation. Furthermore, a repeated experiment is conducted to address the concerns of controllability and repeatability of taste sensations generated through this approach. It is found that although the taste sensations are found to be subjective we could repeatedly stimulate the sensations. Finally, to address this case we present an example calibration procedure. The overall results of the user experiments support the hypothesis that the electrical and thermal stimulation of the tongue would stimulate different taste sensations on human. Moreover, to confirm and explore further, we have made some improvements to the system and conducted several more experiments. We present these improvements and findings of several other experiments in Chapter 5.

Chapter 5

Technical Refinements and

Supporting User Experiments

In Chapter 4, we have observed positive results on using electrical and thermal stimulation to simulate taste sensations on the human tongue. However, using thermal stimulation alone did not report as much effect as expected. Therefore, alternative methods of using thermal stimuli (i.e. blended with electrical stimuli) are explored. On the other hand, since the initial version of the Digital Taste Interface received highly positive feedback, only minor technical refinements are made. Furthermore, another system is developed only for electrical stimulation with the design and shape of a lollipop (for the tongue interface) and named it as Digital Taste Lollipop. The positive feedback received for Digital Taste Interface, further verified through another set of user experiments over an extended period of time. In addition, this chapter presents two experiments using the Digital Taste Lollipop to determine the effects on different tongue regions for electrical stimulation and to compare natural and artificial taste sensations simulated.

5.1 Further experiments on thermal and hybrid stimulations

Once the refinements are made to the system, more experiments are conducted separately to evaluate the effectiveness of the two different approaches, the electrical and thermal stimulation. As explained below, at the beginning, more attention was given for thermal stimulation, then the electrical stimulation.

5.1.1 Refinements to the system

As explained in Chapter 4, we noted several limitations of the current system, particularly related to the thermal stimulation submodule. Therefore, we made several technical refinements and developed a new system for thermal stimulation. The simplest possible implementation is considered and we named the new system as the Digital Taste Synthesizer. It uses a similar system architecture as the Digital Taste Interface with few modifications to the thermal stimulation submodule. Similar to the Digital Taste Interface, there are two modules in the Digital Taste Synthesizer: the control system and the tongue interface. However, the Digital Taste Synthesizer is implemented as a single system merging both control system and the tongue interface into a single instrument. This arrangement helps to use a larger heat sink to dissipate heat efficiently.

Identical Peltier semiconductor element [71] is used for effective temperature control on the tongue. The control system consists of a thermal stimulation module and a master controller module. An Arduino Pro Mini^{*} is used as the main controller and a Pololu 2-way motor driver[†] is used to control the Peltier module. The tongue interface is developed with the Peltier module, a silver electrode, and a heat sink. These components are arranged as a sandwich in different layers. This arrangement is illustrated in Figure 5.1. The implementation of the Digital Taste Synthesizer is displayed in Figure 5.2.

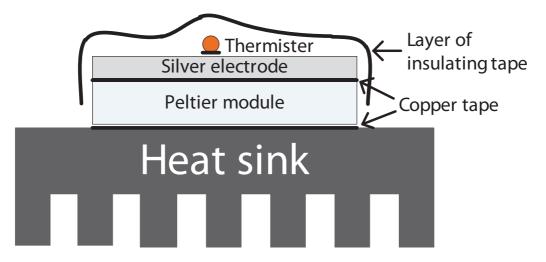


Figure 5.1: Arrangement of the components in the tongue interface. The double sided adhesive copper conducting tape is used between layers for compact structure.

As shown in Figure 5.3, a computer is connected to the control system using

a USB (Universal Serial Bus) connection to configure the output of the tongue

^{*}http://arduino.cc/en/Main/ArduinoBoardProMini

[†]http://www.pololu.com/

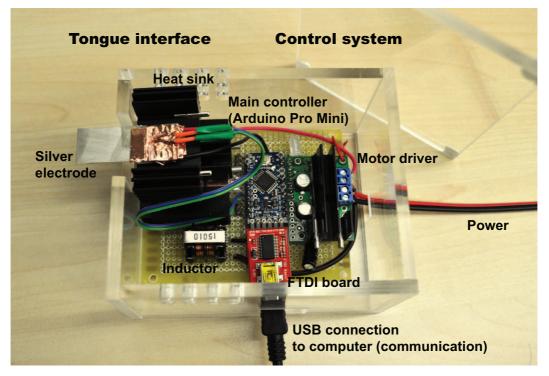


Figure 5.2: Implementation of Digital Taste Synthesizer for thermal stimulation with main components.

interface. The configuration parameters are the direction (heating or cooling) and speed of a temperature change, and a disable function, which disables the thermal system. The disable function is necessary since the motor driver needs to be shutdown during the user interviews after the experiments are conducted for each individual; otherwise thermal shutdown may occur when the additional load current is received by the motor driver. Moreover, an inductor is used for smoother and continuous operation of the Peltier element.

Similar to the Digital Taste Interface, a separate laboratory dc powersupply provides required power to drive the peltier element while the USB power is adequate for the main controller. A basic proportional-integralderivative (PID) controller is implemented to drive the peltier module for the

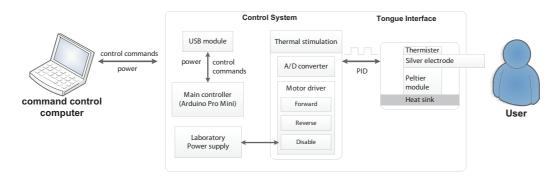


Figure 5.3: System architecture of Digital Taste Synthesizer. All the submodules and their interactions are displayed.

desired temperature. The direction, forward (heating) and reverse (cooling), is manually controlled by the user through the computer (command-control center). The real term[‡] serial capture program is used to configure the output stimuli. The system is further calibrated to work between 20°C and 35°C as explained. The PID controller is configured to use three performance settings: optimum, medium, and slow. For example, in slow mode it draws less current, hence the system works over an extended period of time before the thermal shutdown occurs. For the experiments, the medium settings is used as it allows operation of the system for a relatively extended period (approximately five full thermal cycles: $20^{\circ}C - 35^{\circ}C - 20^{\circ}C$).

The heat-sink and the PID controller efficiency are the main factors associated with the performance of the thermal stimulation module. As can be seen in Figure 5.2, we use a relatively large heat-sink for better and efficient results of the system. Figure 5.4 shows the warming up and cooling down performance of the tongue interface module with slow settings. The temper-

[‡]http://realterm.sourceforge.net

ature values are recorded through the USB connection between the device and the computer at a sampling rate of 100ms. The current setup of tongue interface is able to meet the requirements of heating from 20°C to 35°C and vice versa. All the measurements are acquired at room temperature (24°C). Moreover, based on the settings of PID controller, the current setup of the tongue interface module is able to cool down from 35°C to 20°C within approximately 53 seconds with slow, 40 seconds with medium, and 18 seconds with fast performance settings.

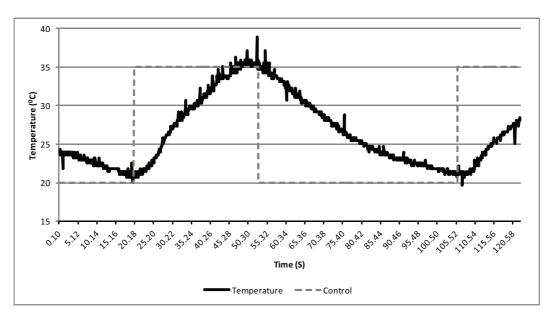


Figure 5.4: Warming up and cooling down performance of the Digital Taste Synthesizer for one cycle from 20°C to 35°C and continuously 35°C to 20°C (room temperature = 24°C, PID settings mode=slow)

5.1.2 Thermal stimulation on different regions of the tongue

One of the important factors to consider before finalizing the experimental protocol is the electrode position on the tongue. It is considered as essential for effective control of taste sensations. Although there are several studies conducted on the sensitivity of the tongue surface with chemical substances, we decide to conduct a pilot study before finalizing the experimental protocol. Thus, an informal experiment is conducted with six participants to determine the best position/positions on the tongue surface and stimuli parameters for thermal stimulation. Figure 5.5 illustrates different areas of actuation on the tongue to determine the optimal surface area.

During the pilot study, it is noted that the tip of the tongue is more sensitive for thermal taste stimulation. Only one participant responded to any occurrences of taste sensations from the left side of the tongue, i.e., sour. This confirms the higher sensitivity of the tip of the tongue as explained in [12, 7]. It is also found that the duration of the thermal stimuli is crucial for the perceptions. Two participants mentioned that with slow transition of temperature, they could only feel the temperature and nothing related to a particular taste sensation. Therefore, the formal experiments are conducted with medium PID settings mode. We do not use optimal (fast mode) PID settings due to the thermal shutdown of motor driver circuit as explained. Finally, based on these important comments, feedback, and observed taste perceptions, the

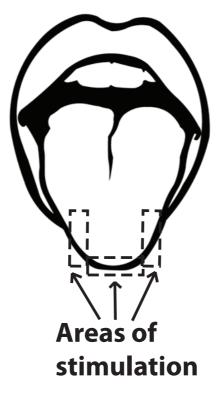


Figure 5.5: Different surface areas on the tongue stimulated through the Digital Taste Synthesizer during the pilot study.

system is adjusted, and the experimental protocol is modified for the formal experiments. Furthermore, it is plausible to observe the association of minty and spicy sensations through thermal stimulation.

5.1.3 Experimental setup

A similar experimental setup and protocol was used as in Chapter 4. Participants are randomly chosen and have no training before being tested. All participants are in good health and report no taste or smell problems. They are explicitly informed not to smoke, nor to eat or drink spiced meals or alcoholic beverages one hour prior to the testing period as they may affect the results. After each experiment, participants are asked to describe their experience and any pertinent information related to their experience. Key findings from these short interviews are presented in the next section.

The experiments are conducted in a quiet private meeting room inside the laboratory. As shown in Figure 5.7, a notebook computer (control commands), Digital Taste Synthesizer, and a laboratory power supply are used for the experiments. Participants use the anterior ("tip") of the tongue to interact with silver electrodes as displayed in Figure 5.6. Before each experiment, both electrodes are rinsed using tap water, then sterilized using 70% isopropyl alcohol swabs, followed by deionized water [28].



Figure 5.6: A participant interact with the system during one of the experiments

The experimental setup of the Digital Taste Synthesizer is shown in Figure 5.7. As mentioned, the experiment is organized to determine the correlation of the taste quality and perceived intensity elicited by the thermal stimulation on the anterior tip of the tongue. Furthermore, participants rinse their mouth with deionized water between each stimulus for counterbalancing and relaxed five minutes to prevent bias between each stimulus. As we observed during the previous studies, some participants are hesitant to put the tongue interface into their mouths at the beginning. Therefore, we have conducted two trial sessions before the experiment with each subject. Furthermore, we have to manually arrange the silver electrode on the participant's tongue for proper placement. We also continuously monitor the position of the electrodes on the tongue during the experiments. This is essential for standardized and improved results.

Through the taste-recorder presented in chapter 4, the level of intensity is recorded in three levels: mild, medium, and strong. Again, during the experiments we mainly focus on recording initial taste responses and the intensity levels from the users. To analyze the results, we assign mild as 1, medium as 2, and strong as 3 and all the non-primary taste sensations were categorized as "Others".

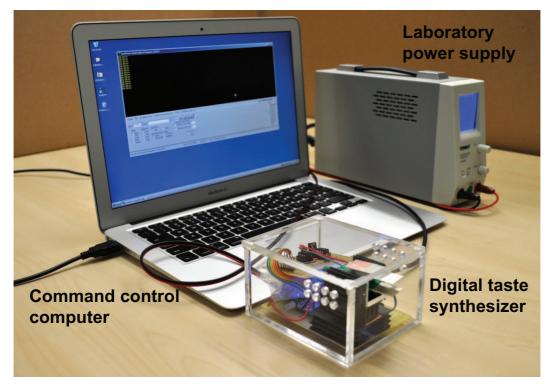


Figure 5.7: Typical setup of the Digital Taste Synthesizer system with the command control computer and DC power supply attached.

5.1.4 Thermal stimulation

For the thermal stimulation experiment 31 participants (19 male and 12 female) are recruited aged between 18-31; M = 24; SD = 3.58. Sensations are observed from warming up (20°C to 35°C) and cooling down (35°C to 20°C) experiments with 5°C experimental windows. Results from the thermal stimulation (Figure 5.8) suggest that sour and sweet sensations are the main sensations that can be evoked by thermal effects on the tongue. Bitter and salty are the least detected sensations during the thermal stimulation experiment, thus their occurrences are almost negligible.

Again, for this thermal stimulation experiment, the tongue is continuously exposed for a thermal cycle (from 20° C to 35° C and back to 20° C). With

Table 5.1: Taste responses (as a percentage of all received taste sensations) received by changing the temperature (both heating and cooling) on the tip of the tongue from the thermal stimulation experiment

Taste	Percentage $(\%)$	
Sour	25.26	
Salty	2.10	
Bitter	5.26	
Sweet	25.26	
Others	42.10	

this revised prototype, one of these thermal cycles requires only 80 seconds (approximately) to complete as shown in Figure 5.4.

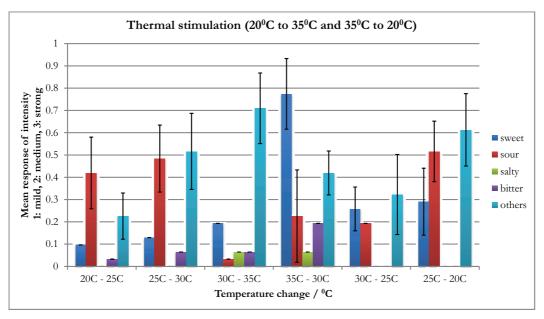


Figure 5.8: Perceived intensity of taste sensations during thermal stimulation - warming up from 20°C to 35°C and cooling down from 35°C to 20°C ("others" includes mainly spicy and minty sensations)

The results obtained from the thermal stimulation experiment is almost similar to the previous experiment conducted. Again, from the warming up experiment (from 20°C to 35°C), a negligible contribution is detected for salty and bitter sensations. There is an increased effect on the perceived sour taste

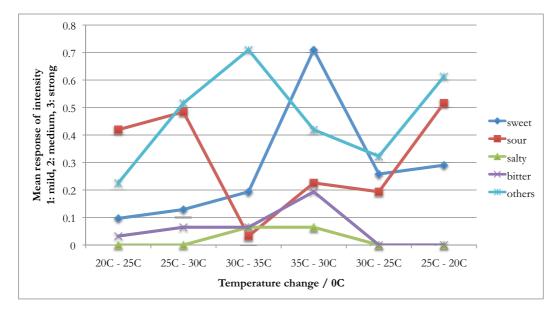


Figure 5.9: Transitions of reported taste sensations and their intensity levels against different properties of stimuli during thermal stimulation ("others" includes mainly spicy and minty sensations)

during the lower temperature changes (between 20°C to 30°C both heating and cooling). Interestingly, increasing the temperature causes a weaken sourness effect on human tongue (30°C to 35°C).

When cooling down the tongue from 35°C to 20°C, the average perceived intensity levels of sweet and sour show an increasing trend. As presented in table 5.9, approximately 25% of participants report that they feel a spontaneous sweet sensation when the experiment is conducted continuously from heating to cooling (from 20°C to 35°C and continuously from 35°C to 20°C). As in the figure 5.9, this is recorded during the first -5°C (from 35°C to 20°C) transition. Moreover, some participants report sweet sensation (as an aftertaste) when rinsing their mouth with water over the stimulated area after the temperature stimulation experiment. Furthermore, several participants report that they feel the minty taste, refreshing taste (when cooling down from 25°C to 20°C), also slight spiciness (when heating up to 35°C). These non-primary taste qualities are reported under the "Others" category. The others category includes the occurrences of minty, spicy, and mixed sensations such as minty-sour, salty-sour. It is apparent that around higher temperatures, the participants feel spicy or burning sensations and at lower temperatures most of them feel refreshing or minty sensations. In addition, the average perceived intensity across all taste sensations reported are mild in intensity.

For thermal stimulation of taste sensations, the key factor is the change in temperature; taste sensations are not reported by applying a constant temperature on the tongue. This system capable of changing temperature within 20°C-35°C in approximately 80 seconds. Furthermore, during the experiments we realized slower temperature changes could not evoke any sensation on participants' tongue. Additionally, only 83.8% of the participants could sense a sensation through thermal stimulation on the tip of their tongues.

The theory of the thermal stimulation for simulating taste sensations is different from eating or drinking different food or beverages in different temperature levels. It is the change of temperature causes the taste effects not a level of temperature on the tongue. For example, eating or drinking has a whole-mouth effect whereas stimulating through this device has a local effect on the tongue. In other words, when drinking water in different temperature levels, receptors in the whole mouth are stimulated, whereas during the thermal stimulation using the device only the receptors in the tongue tip are stimulated [22, 108].

5.1.5 Hybrid stimulation

Consequently, for the hybrid stimulation experiment we implement an electrical stimulation submodule using a digital potentiometer (POT) and a constantcurrent source as displayed in Figure 5.10. This module communicates with the main controller using Serial Peripheral Interface Bus (SPI) technology and the power is supplied from the USB connection. As in Figure 5.10, the output current of the electrical stimulation sub-module is connected to two silver electrodes. The improved, electrical stimulation sub-module attached system is displayed in Figure 5.11. The output voltage of the digital potentiometer is configured through the wiper position of digital POT and is controlled using the SPI interface. The output of the voltage controller becomes the input for the constant-current source as shown in Figure 5.10. The constant-current source is implemented using an operational amplifier (op-amp), a resister, and a NPN transistor as shown in Figure 5.10.

The electrical stimulation module provides square wave pulses to the silver electrodes with a range of currents from 20μ A to 200μ A and frequencies from 50Hz to 1200Hz. However, based on [90, 64, 107, 70], for the second experiment, we only used constant-current pulses of 60μ A and 1000Hz. A higher frequency is used in this attempt due to the increased sensitivity shown for

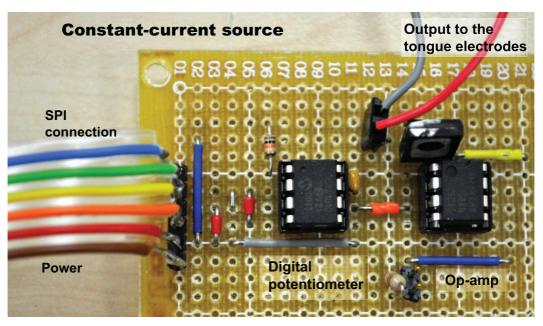


Figure 5.10: Implementation of constant-current source. The main controller is connected through a SPI connection.

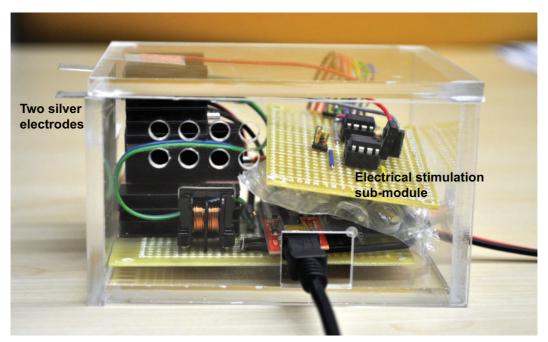


Figure 5.11: The Digital Taste Synthesizer extended by integrating electrical stimulation sub-module.

higher frequencies as in Chapter 4. These settings are preconfigured to reduce the complexity of the experiment based on user feedback during the previous experimented conducted in chapter 4. Figure 5.12 depicts the modified tongue interface with two silver electrodes and the simple mechanism used to control the distance between electrodes. As shown, Blu-tack[§] is used to control the distance between the electrodes. Besides, one more silver electrode is added to the tongue interface to facilitate electrical stimulation (for anode and cathode).

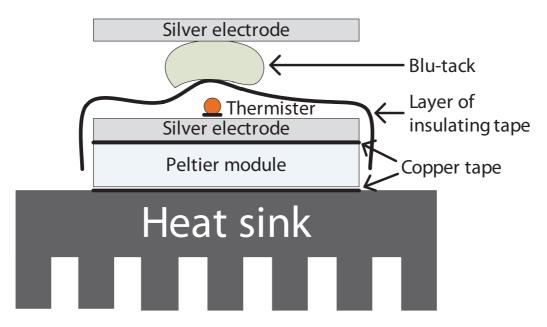


Figure 5.12: Integrated version of tongue interface for both thermal and electrical stimulation. A sample of blu-tack is used to control the distance between silver electrodes.

Followed by thermal stimulation experiment, we conduct a controlled experiment using an integrated approach (with both electrical and thermal stimulation simultaneously). Again, we hypothesize that by integrating both ther-

[§]http://www.blutack.com/

mal and electrical stimulation methodologies, we will obtain more and improved taste sensations for human.

To explore this hypothesis, we conducted another user experiment with randomly selected 20 participants (14 male and 6 female) aged between 18 -30; M = 25, SD = 3.53. The output current and frequency are configured respectively as 60μ A and 1000Hz (mid values of the experimental range), while the temperature changed from 20°C to 35°C (heating) and 35°C to 20°C (cooling). Observed results from the hybrid experiment are illustrated in Figure 5.13. One record was rejected due to the poor performance during the experiment.

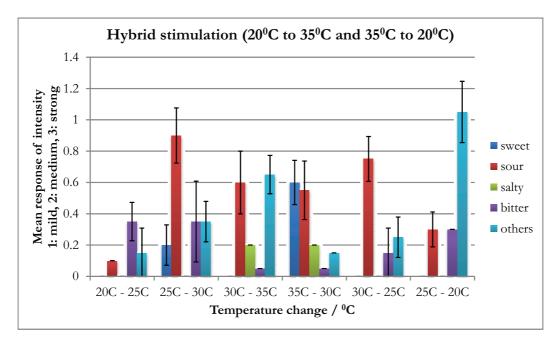


Figure 5.13: Perceived intensity of taste sensations during hybrid stimulation - heating up from 20°C to 35°C and cooling down from 35°C to 20°C, "others" includes mainly spicy, minty, and mixed sensations (current = 60μ A and frequency = 1000Hz)

Many participants comment that they enjoy the new instrument and the

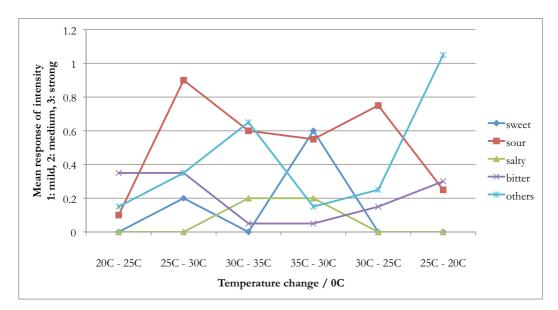


Figure 5.14: Transitions of reported taste sensations and their intensity levels against different properties of stimuli during hybrid stimulation ("others" includes mainly spicy, minty, and mixed sensations)

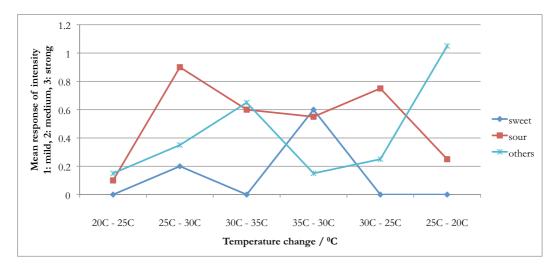


Figure 5.15: Perceived intensity of sour, minty, and spicy sensations during hybrid stimulation, minty (lower temperature) and spicy (higher temperature) are displayed in "others" category

experience we presented. In particular, many of them indicate that they enjoyed the sensation when conducting the electrical stimulation below 25°C. They explain the experience as being similar to what we taste when we put a piece of lemon on our tongue. Based on their feedback, it is clear that it is possible to obtain enhanced results by the hybrid approach. This condition enables us to explore integrations of other senses such as visual, sound, and smell in the future to improve the perceptions. Additionally, as evident in Fig. 5.14, when heating up and cooling down continuously the response change from sour taste to "other" (more noticeably for the mint taste). This trend is also clearly explained by one of the participants during the postinterviews. To illustrate this phenomenon we display only the sour, minty, and spicy sensations in Figure 5.15.

5.2 Further experiments on electrical stimulation

Followed by refinements to the thermal stimulation module, a new instrument is developed for electrical stimulation. During the experiments, we notice that some participants are hesitant to place the tongue interface in the mouth. Therefore, it is a challenge to propose a preliminary design for the system (especially for the tongue interface) to use it comfortably. Furthermore, at the same time the system should be simple and user friendly. After considering



Figure 5.16: Everyday objects people use to interact with mouth such as spoon, fork, chopstick, cigarette, lollipop, and straw

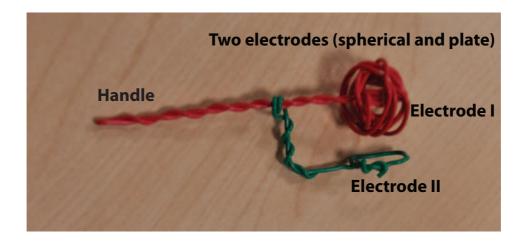


Figure 5.17: The wire model of the final design of tongue interface

several household objects that people use to interact with their mouths such as spoons, chopsticks, cigarettes, and lollipops (as displayed in Figure 5.16), we designed a modified form of a lollipop as the tongue interface as shown in Figure 5.17. The form of a lollipop is also considered due to the curved shape since it is not harmful to use inside the mouth. Thus, the new system is named as the Digital Taste Lollipop.

5.2.1 Digital Taste Lollipop

Interacting with a lollipop is a familiar concept for most people in their everyday lives. The hollow ball (electrode I) and the bottom plate (electrode II)

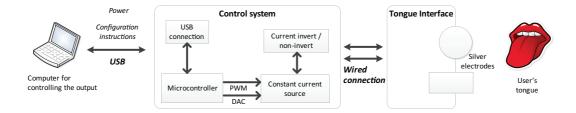


Figure 5.18: The system architecture of Digital Taste Lollipop

are the two electrodes that connect to the tongue, as shown in Figure 5.19. The wires are located inside the hollow handle and connected to the controller at the end of its handle. We have to change the original form of the lollipop to attach an additional electrode as seen in Figure 5.17 since it is necessary to connect two electrodes on the top and bottom surfaces of the tongue. Furthermore, the handles of this model are independently moving, thereby allowing people to play with the tongue interface by rotating (or spinning) and licking the spherical electrode corresponding to a real lollipop candy. We used the form of a lollipop due to the curved shape, which makes it safe to use inside the mouth.

Two separate modules of the Digital Taste Lollipop (the tongue interface and the digital control system) are illustrated in Figure 5.18. As per the design, the tongue interface consists of two silver electrodes; one in the shape of a sphere while the other is a plate. The tongue is placed between these two silver electrodes; the sphere at the top and the other electrode on the bottom of the tip of the tongue as displayed in Figure 5.20. Different electrical stimuli are then supplied through silver electrodes to the tongue to simulate primary taste sensations.

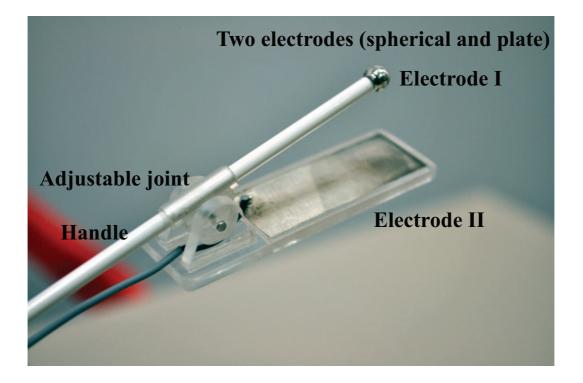


Figure 5.19: The implementation of lollipop tongue interface

The control system module is modified and uses a digital-to-analog converter (instead of digital potentiometer), which supplies a variable voltage proportional to the input configurations. This module controls the frequency as well as the magnitude of current of the tongue interface. The electrical control system provides square wave pulses to the silver electrodes with magnitudes of current from 20μ A to 200μ A and frequencies from 50Hz - 1200Hz as mentioned.

A PIC microcontroller (16F1824[¶]) with a 4MHz in-built clock is used to implement the control system. This low power microcontroller also has builtin USART for digital communication, two pulse-width modulation (PWM) peripherals, 10-bit ADC and 5-bit rail-to-rail resistive digital-to-analog control

[¶]http://www.microchip.com/wwwproducts/Devices.aspx?dDocName=en546901



Figure 5.20: A close-up of the tongue interface connects with the tongue

(DAC) with positive and negative reference selection.

DAC (Digital-to-analog control) technology is used to control the magnitude of the current in discrete steps in order to stimulate the human tongue. To adjust the frequency of electric pulses, we used a timer-interrupt based PWM technique. Furthermore, to control the output parameters a computer is connected to the control system through a USB connection. Currently, for user experiments (to configure the output current and frequency), control commands are given using the RealTerm^{||} serial terminal program. Moreover, an inverse-current mechanism is implemented using a relay for conducting experiments involving both anodic (non-inverted) and cathodic (inverted) stimulations. This technique is implemented due to the reports of bitter sen-

http://realterm.sourceforge.net/

DAC Step	Output (μA)	Expected (μA)
1	23	20
2	38	40
3	55	60
5	85	80
6	102	100
7	119	120
8	136	140
10	165	160
11	182	180
12	200	200

Table 5.2: DAC step and the magnitude of output current

sation from the lower surface of the tongue during the previous experiment on electrical stimulation.

Similar to the previous experiments, the control system is configured to output step by step magnitudes of current from 20μ A to 200μ A with intervals of 20μ A. Different output current values and corresponding DAC steps are shown in Table 5.2. Additionally, the linear increment of DAC and output current values of the system are depicted in Figure 5.21. We observe a slight variation of the output current from the expected output. This variation is acceptable since the human perception is not sensitive enough to detect that degree of difference in resolution.

The control system is connected to the silver electrodes of the tongue interface using two strands of wire as shown in figure 5.22. Figure 5.22 displays the implementation of two main components of Digital Taste Lollipop, the

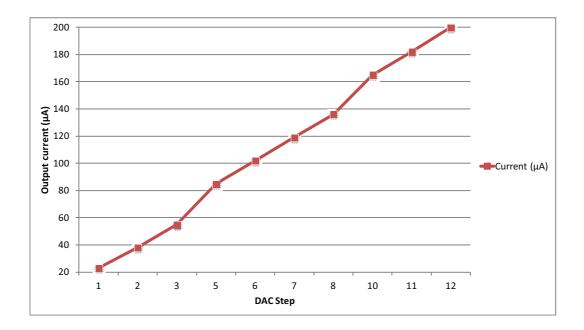


Figure 5.21: The linear increment of output current based on DAC step values

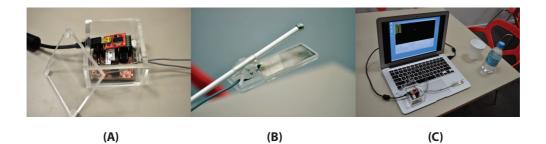


Figure 5.22: Implementation of Digital Taste Lollipop. A) control system, B) tongue interface (which has a spherical electrode with 5mm diameter and flat electrode with 40mm * 15mm * 0.2mm), and C) Typical configuration with a computer

control system (A) and the tongue interface (B).

The output voltage values from the constant-current source are monitored and plotted in Figures 5.23 and 5.24. Figure 5.23 shows the non-inverted voltage values monitored (through the constant-current source and the ground) without connecting the tongue. Additionally, the corresponding values are displayed in Figure 5.24 with invert voltage differences. The non-inverting

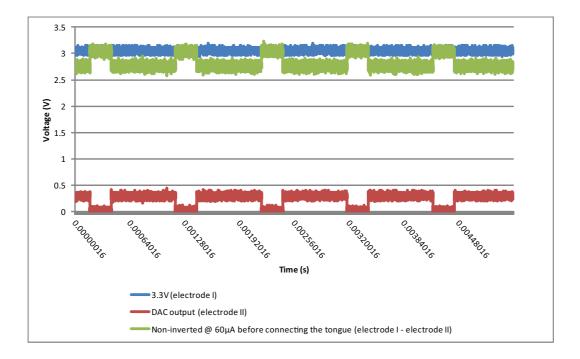


Figure 5.23: Non-inverted output voltage values from DAC and constant current source - tongue is not connected

amplifier in the constant-current source maintains a constant voltage level between the op-amp output and the ground. We used this voltage across the op-amp and the ground to show current-inverse mechanism (This is the reason it shows low voltage levels).

Two user experiments are conducted to experimentally evaluate the Digital Taste Lollipop. The first experiment studies the responses from different regions of the tongue. The second study is conducted to evaluate the effectiveness of the system and compare the virtual sour taste with the real or natural sour taste. For the second experiment, the sour taste is the focus since it receives the largest number of responses from the first study. For the second study, the tip of the tongue is selected due to its increased sensitivity. The

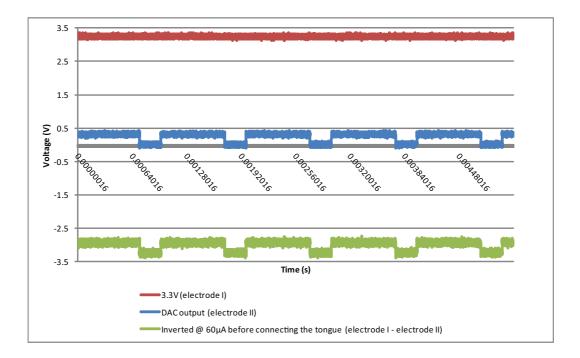


Figure 5.24: Inverted output voltage values from DAC and constant current source - tongue is not connected

experimental setup of the digital taste lollipop is depicted in Figure 5.25.

An identical procedure (the stimuli was gradually increased from 20μ A to 200μ A in steps of 20μ A intervals) is used as explained in Chapter 4 for this experiment as well. Additionally, we experiment with each participant twice due to the non-invert and invert current mechanisms that were implemented.

Before conducting formal user experiments, the developed prototype system is used to conduct an informal pilot experiment with five subjects. Based on their feedback and taste responses, the system is adjusted and the experimental protocol is modified. The formal experiment is then conducted to determine 1) taste sensations from different regions of the tongue and 2) the controllability of virtual sourcess with regards to natural sour taste. In

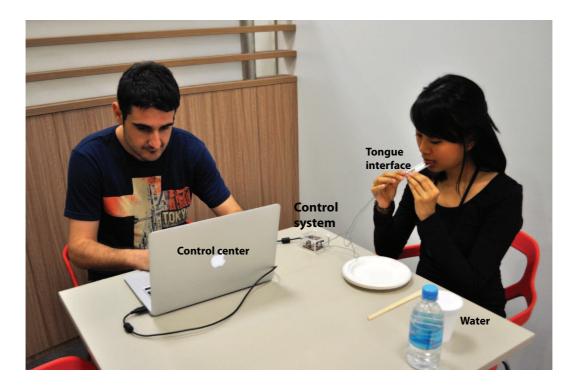


Figure 5.25: The experimental setup of the digital taste lollipop

both experiments, participants are instructed to rate the level of intensity of any taste sensation they perceived. The level of intensity is recorded at three levels: 1: mild, 2: medium, and 3: strong.

We conduct a trial session with each subject before the experiment (with the magnitude of 40μ A). Furthermore, for these experiments, we configure the frequency at a constant value. From the previous experiments presented, we found a minimum contribution from the frequency of the stimuli to simulate different sensations. [62] also observe that the tongue impedance decreases with an increase in frequency. The decrease in impedance might slightly increase the magnitude of current thus affecting the susceptibility of taste perception. Therefore, the frequency is configured at 1000Hz in order to achieve

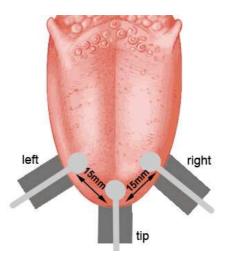


Figure 5.26: Different placements of the Digital Lollipop on the human tongue during the experiments

optimal results.

5.2.2 Electrical stimulation on different regions of the tongue

Although the tip of the tongue is considered as the most sensitive region for chemical taste stimulation [12], we have conducted an experimental study using 31 participants (6 - females, 25 - males, age = 22 - 39, M = 24, SD = 3.17) on different regions of the human tongue to study the tongues sensitivity to electrical stimulation. As shown in Figure 5.26, we use three main regions of the tongue to explore the ways in which electrical stimulation on the human tongue creates different sensations of different intensity levels.

5.2.2.1 Procedure

At the beginning, participants are informed of the experimental procedure. First, we ask them to hold and touch the tongue interface on the tip of the tongue. Then, the stimulus is gradually increased from 20μ A to 200μ A in steps of 20μ A intervals. They are instructed to disconnect the tongue interface immediately if the stimulation is too strong or uncomfortable. Participants are instructed to rest five minutes and rinse their mouth with deionized water between each stimuli to prevent bias and counterbalancing. After each stimulation we ask the participants to report the taste sensation and the level of intensity if they perceive any.

After that, we continue the experiments on other regions (approximately 15mm to the left of the tip and approximately 15mm to the right of the tip) as depicted in Figure 5.26). We closely monitor the correct placement of the lollipop interface on the tongue and advise each participant to rearrange it if they place it wrongly.

Once each step is completed (tip, left, and right), we interview them and ask several questions about the perceived sensations and the levels of intensities. Participants request to use the Digital Taste Lollipop several times to clarify their answers. Since this is an early experimental evaluation, we allow them to be more comfortable with the tongue interface while they are answering the questions. Furthermore, we believe that we would obtain descriptive answers by letting the users gain greater familiarity with the device since this technology introduced a new and unfamiliar interaction to them. Another objective of this study is to obtain their feedback on the current version of the system to improve it and make it more user-friendly in future iterations.

5.2.2.2 Results and Discussion

The results obtained from the study are encouraging and shows distinct taste sensations are associated with different regions of the human tongue in electrical stimulation. The sour taste is the most dominant among other sensations such as saltiness, bitterness, and sweetness. More interestingly, there is evidence of the sweet sensation being achieved by inverting the applied current and this deserves further study in the future. It should also be noted that the sweet sensation occurred from the anode electrode when the current is inverted, mainly from the tip of the tongue. Further, we conduct several discussion sessions with the users to acquire more information and their experiences with the device.

Figure 5.27 depicts the taste sensations and mean intensity levels obtained from the tip of the tongue (when the current is non-inverted). One of the compelling phenomena we observe from the results is the increasing of intensity of the sour taste when the current is increased. In addition, several participants mention that higher current levels may cause a tingling or "pineapple" like sensation on the tongue.

Similarly, in Figure 5.28, recorded taste sensations and intensity levels are displayed after inverting the current. It is worth noting that the perceived

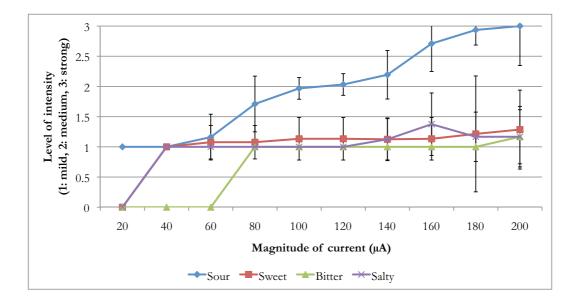


Figure 5.27: Reported taste sensations and their intensity levels observed from the tip of the tongue - current is non-inverted

intensity of sweet sensation increased when the current was inverted. We receive several comments about this apparent fact. Many participants note a subtle change when the current was inverted on the tip of the tongue. We notice that some people perceive this phenomenon as a change of taste, which is interesting. Approximately 60% identified it as a sweet taste while 20% identified it as a bitter taste. A few of them mention that when the polarity is changed they feel an atypical experience and they described it as similar to experiencing two taste sensations from the top and bottom electrodes. It is a new observation we obtained from the inverted current experiment. A slight deviation in the increment between 100μ A to 160μ A can be seen, and it appears that the more intense sweet sensation may weaken the perception of a sour taste.

Furthermore, the results appear to be showing that the side regions of the

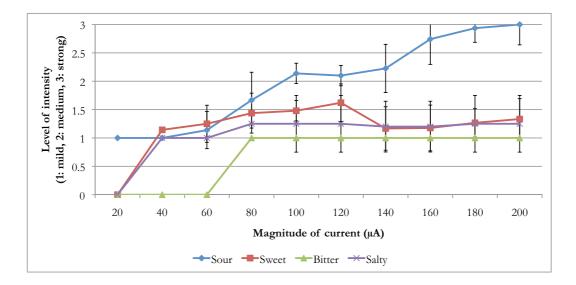


Figure 5.28: Reported taste sensations and their intensity levels observed from the tip of the tongue - current is inverted

tongue are less sensitive than the tip of the tongue. This finding is reasonable since it agrees with the existing literature on chemical stimulation [12]. In addition, we observed that, for electrical stimulation, the left side is slightly less sensitive than the right side of the tongue as shown in Figures 5.29 and 5.30. As presented in Figure 5.29, although there are several pieces of evidence for other taste sensations such as sweetness, saltiness, and bitterness, the only sensation consistently reported for the left side of the tongue is sourness. However, it can be seen that the level of intensity is slightly decreased (from 20μ A to 80μ A) even for the sour taste compared to the results reported for the tip of the tongue. As Figure 5.30 suggests, there is a increase in number of people who sensed its presence from the right side of the tongue for the sour and bitter tastes. Results reported for the other two sensations (salty and sweet) are inadequate and negligible according to the findings.

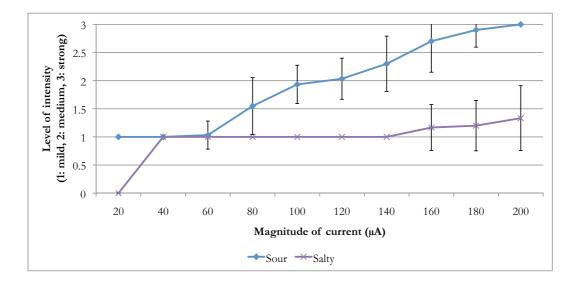


Figure 5.29: Reported taste sensations and their intensity levels observed from the left side of the tongue - current is non-inverted

Besides, the left and right side stimulations with inverted current has only resulted in sour and salty sensations according to 5.31 and 5.32. Additionally, a few participants highlight that the inverted current caused slight numbress on the bottom surface of the tongue. There are no taste sensations reported from the top surface of the tongue. Almost all the participants mention that when the electrode is rubbed on the tongue surface they perceive the sensations better. This comment is also worth further examination in future experiments.

In addition, we identified few limitations of the system and the methodology used from user experiments. One of the biggest challenges we faced during the experiments is to align the digital taste lollipop on the participant's tongue correctly. We have to monitor and correct their position during each and every experiment since we used a smaller electrode (5mm diameter) for better handling and to avoid touching other parts of the mouth.

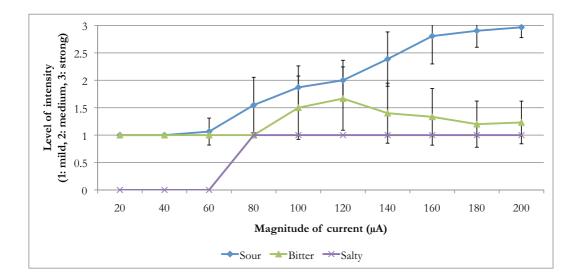


Figure 5.30: Reported taste sensations and their intensity levels observed from the right side of the tongue - current is non-inverted

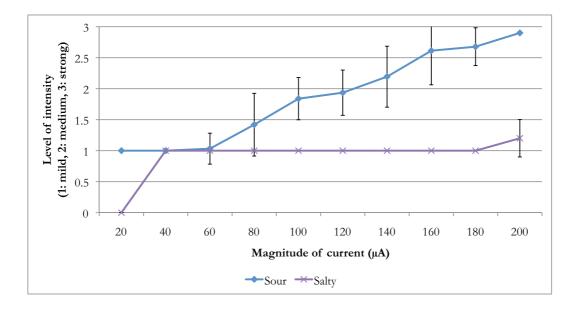


Figure 5.31: Reported taste sensations and their intensity levels observed from the left side of the tongue - current is inverted

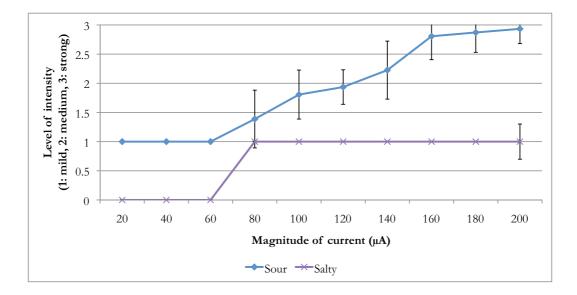


Figure 5.32: Reported taste sensations and their intensity levels observed from the right side of the tongue - current is inverted

5.2.3 Comparison with real taste sensations

Twenty participants are invited to participate in this experiment (21-28, M=23.5, SD=3.22). They are selected from the participants of the first experiment, who responded well for the artificial sour taste. Three lime solutions with mild, medium, and strong intensities are prepared for the comparison between digitally stimulated taste and natural sour taste. Figure 5.33 shows different equipments used for preparing the three lime solutions. First, three teaspoonfuls of lime juice (5ml x 3) are squeezed into each cup and mixed with deionized water respectively 30ml (mild), 16ml (medium), and 5ml (strong). Then five users are recruited to evaluate the intensities of the three sour solutions blindly. Based on their feedback, we modified the strong and medium solutions accordingly. The respective final pH values of mild, medium, and strong lime solutions are approximately 2.516, 2.38, and 2.245. The pH val-

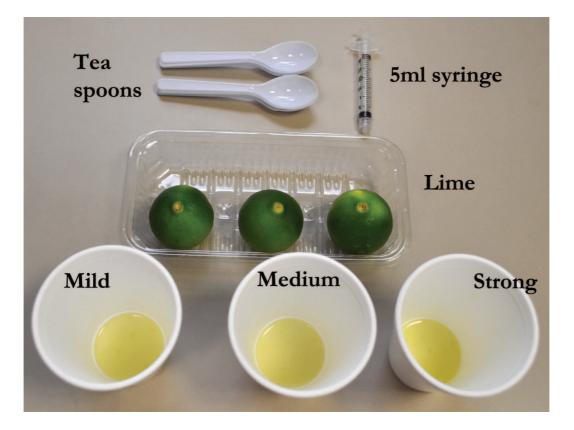


Figure 5.33: Preparing three intensities of lime juice: mild, medium, and strong

ues are measured using Thermo Scientific Orion 4-Star Plus pH/Conductivity Meter^{**} and the probe Thermo Scientific Orion pH Electrode.

5.2.3.1 Procedure

Before the experiment with the Digital Taste Lollipop, a blind sour taste test is conducted for each participant. They are asked to taste three solutions of lime (2ml per trial), and identify whether the solution had a mild, medium, or strong sour taste. Participants rinsed their mouth with deionized water and relaxed two minutes between each trial for a clearer distinction between

^{**}https://static.thermoscientific.com/images/D15562.pdf

each level of sour taste. Then they are asked to hold the lollipop and use the anterior tip of their tongue to touch the silver ball, since it is the most sensitive segment of the human tongue.

During the experiment, the magnitude of the current running through the tongue is increased from 20μ A to 200μ A in approximately 20μ A intervals. The experiment is conducted in three steps for three levels of intensities, mild, medium, and strong. In the beginning of each step they are given the natural sour taste. After a two minute interval, the Digital Taste Lollipop is used to simulate a sour taste. They are asked to interrupt and inform the researcher once they perceive a similar level of intensity generated by the Digital Taste Lollipop to the natural sour taste they perceived. Participants are informed to rest and rinse their mouth if they felt tired or uncomfortable. After all three experimental rounds, they are asked to describe their experiences during the experiments. Several user interactions with the digital taste lollipop during the experiment are presented in Figure 5.34.

5.2.3.2 Results

We are able to identify the corresponding three intensities (mild, medium, and strong) of digital sour taste similar to the natural sour sensation (lime), as illustrated in Figure 5.35. This shows the controllability of artificial sour taste through the Digital Taste Lollipop.

From the experiment, we found that most of the participants experienced mild sour sensations from 20μ A to 38.33μ A, medium sensations from 38.33μ A



Figure 5.34: Participants and their interactions with the instrument

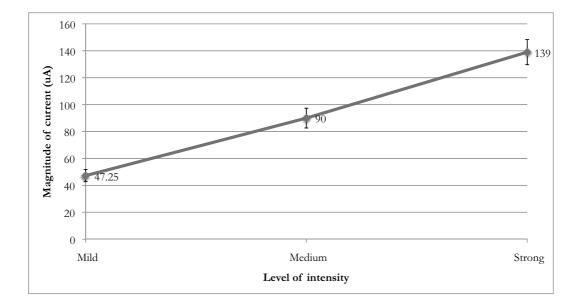


Figure 5.35: Mean values of thresholds for three intensities of sour taste (Mild: $20\mu A$ 38.33 μA , Medium: $38.33\mu A$ 88.75 μA , and Strong: $88.75\mu A$ 140 μA)

to 88.75μ A, and strong sensations from 88.75μ A to 140μ A. A few participants mentioned that although they experienced a sour taste, the sensation was less similar to the natural (lime) taste. Figure 5.36 shows the complete set of digital sour taste occurrences, which are plotted against different intensity levels; mild, medium, and strong. In general, during the comparison study

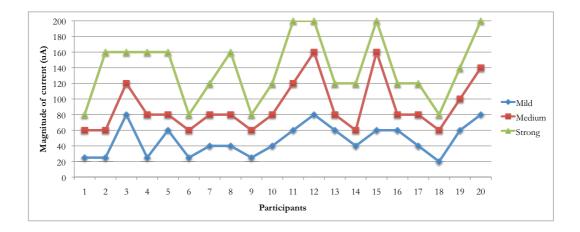


Figure 5.36: All sour taste sensations occurred during the user experiments

we observed that the participants could compare the (artificial and natural) sensations and responded quickly when the natural taste was presented.

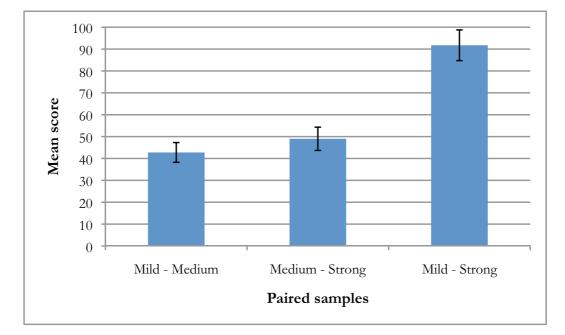


Figure 5.37: Mean scores with standard error for three study pairs (p < .01)

We also conduct several statistical measurements of the comparison data from this study. The paired sample t-test, as shown in Figure 5.37, confirms that mild-medium [t(19)=9.45, p < .01, SD=20.22, SE=4.52], medium-strong [t(19)=9.2, p < .01, SD=23.81, SE=5.32], and mild-strong [t(19)=13.057, p < .01, SD=31.42, SE=7.02] groups are significantly different.

5.3 Discussion and future work

5.3.1 Discussion

Different primary taste sensations reported from different stages of electrical and thermal stimulation are displayed respectively in Figures 5.38 and 5.39. The sensations are stated against different stimuli properties such as the magnitude of current, frequency, and the change in temperature.

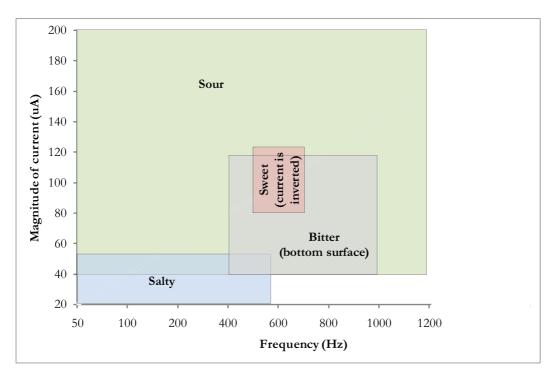


Figure 5.38: Taste sensations reported during different stages of electrical stimulation

The design of the stimuli was one of the critical factors for the efficient re-

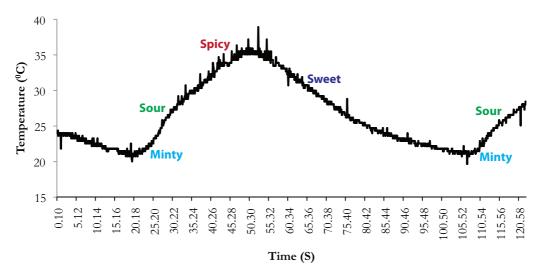


Figure 5.39: Taste sensations reported during different stages of thermal stimulation

sults of this technology. Many participants revealed that they felt uncomfortable when the current was around or over 180μ A. Two participants indicated that they could feel the vibration of the tongue around 200μ A. One of the most noteworthy comments we received was that several participants felt that a lower magnitude of current resulted in more realistic sour taste sensations. Nevertheless, several participants demonstrated an after-taste once the experiments were completed. Two female participants mentioned a slight numbness of their tongue after the electrical stimulation experiments. We suspect this could be due to the level of sensitivity of their tongues.

Salivation was an issue during the experiments. It is noticed in general that people who salivated more during the experiment were more inclined to the thermal taste. In addition, opening the mouth during the stimulation might cause the tongue to dry. This could be solved in future experiments by designing a tongue interface capable of extending into the tongue without having to open the participant's mouth fully. This will enable participants to control the salivating as well as the dryness on the tongue. In addition, several participants appreciated that the integrated design of the system improved the handheld capability as a single device.

In addition to the comfort of the stimuli as studied in chapter 3, we also concentrated on the other factors affecting to the user comfort during the experiments. At present, participants need to hold the tongue interface using his/her hands on their tongue. Several of them expressed the difficulty of holding the tongue interface for an extended period. This is another reason to give them an interval during the experiments.

In general, taste perception is a complex physiological process, even for chemical stimulation of taste sensations. This is due to the limitation of pure mono-gustatory chemicals, causing stimuli to be associated with more than one taste quality. This could be a case in which thermal taste and electrical taste both elicit complex taste qualities that encompass a portion of each basic taste quality, thus resulting in different taste qualities for the same stimulation as shown in the results. It is also evident that the results reported from hybrid stimulation are stronger than the results reported from thermal stimulation alone.

Additionally, during the experiments we realized several key aspects to be explored for the development of this technology such as reproducibility and sensory adaptation. These are fundamental and essential characteristics related to the sense of taste. During the interviews conducted after the experiments, participants commented that continuous electrical stimulation for around one minute diminishes the taste sensations. We suspect this effect to be due to the same phenomenon of sensory adaptation in the chemical stimulation of taste. As studied in [85], this phenomenon caused problems for sensory evaluation since the sensitivity towards a constant stimulus decreases over time for taste sensation. However, it is well noted that the taste sensations are reproducible at a later time in the experiments.

A training procedure would also help to improve the results obtained through the user experiments. Since the formulation and the delivery method of the stimuli are new to the participants, a training procedure may assist them to understand the sensations better. For example, when Monosodium glutamate (MSG) is introduced, many people could not taste MSG at the first time, however, after some training, they could [56, 55]. However, to verify this, further studies are required.

5.3.2 Future work

There are several possible experiments that can be conducted to improve the viability of this technology. Several more experiments will be conducted to examine effects on different waveforms and both linear and nonlinear changes of current and frequency. For example, at present, we only conducted experiments utilizing certain current and frequency levels (step by step). Next, we will experiment with different surface areas on the tongue and alter current and frequency over time to observe these effects on taste sensations. In particular, the reports of bitter sensations at the bottom surface of the tongue in several occasions deserve more investigation with controlled experiments in the near future. Moreover, we suspect that non-linear transitions of temperature may also provide better and improved results using thermal stimulation. We noted this as an immediate future experiment to conduct.

We also need to conduct further experiments to study the contributions from electrolysis of the saliva for simulating the sensation of taste, particularly when using the electrical stimulation. Under normal conditions, the mouth cavity and the tongue have a particularly thin layer of saliva. During the experiments, the participants were asked to put their wet tongue out, which has a thin layer of saliva. This thin layer of saliva may not be enough to make an effective amount of electrolysis to be sensed through the taste papillae. Alternatively, if the sensations are caused due to electrolysis, then there should not be different sensations reported from different properties of the stimuli. For example, sour taste is recorded with higher magnitudes of current and higher frequencies and salty is reported when the magnitude of current and frequency are in lower levels while the bitter sensation is mostly reported from the bottom surface of the tongue. However, more focused experiments are needed to confirm it at the moment. On the other hand, Bujas et al. described electrical stimulation of taste as: "It seems that electrical taste is due in part to the chemoelectrolytic action on the cell membrane and in part to the electrolysis of the intracellular fluid and a direct action on the nerve fibers" in 1974 [15].

Another inevitable phenomenon is the cross sensory interactions as explained in [101, 78]. During the experiment we considered minimizing visual and sound interactions with participants. To avoid such distraction, we asked participants to rest between each stimulus and close their eyes during the experiments. Additionally, the experiments were conducted in a private meeting room as explained.

The sensory experience of taste arises from taste stimuli falling on the taste receptors on the tongue, which process the information and relay it to the areas in the brain responsible for the taste. Information from other senses is necessary for a personal experience such as flavor and cross-sensory interactions [20, 51]. Therefore, another noteworthy direction would be studying the cross-sensory aspects of this sense. Human physiology is composed of five basic senses and each moment a mixture of information arriving at different senses. However, the common belief is that the human beings often focus on inputs from one modality at a given time and 'reject' inputs from others [24, 102]. Scientists also have recently proven that inputs from a secondary sensor modulate one's ability to make decisions about information from a selected one. There have been few experiments and studies conducted on human gustatory sense to observe those relationships between other sensory inputs in order to produce better sensations. Those results suggest that similar mechanisms may decide cross-modal interactions across sensory modalities. Below are some of the possible interactions for future experiments.

- Taste Light / Color
- Taste Visuals
- Taste Sound
- Taste Texture
- Taste Smell

To evaluate the Digital Taste Interface in the future we will focus on brain imaging approaches such as Electroencephalography (EEG) and functional Magnetic Resonance Imaging (fMRI). First, we will record sour, salty, and bitter perceptions by the brain using organic food substances such as lemon, salt, and coffee using the Digital Taste Interface. In both cases, the associated nucleus in the brain (brain perceptions) will be recorded through EEG and fMRI techniques. Finally, a comparison of results from both cases would confirm the desired perceptions by the brain.

Alternatively, future work will also focus on a future autonomous device for the sensation of taste based on IEEE 802.15.4^{††}. One aspect we should improve is the power consumption of the Peltier module during the thermal stimulation. A more efficient design with a low power Peltier module would enable a low power, low-rate wireless device in the future. In addition, a nonlinear mathematical model for digital taste stimulation can also be proposed in the future.

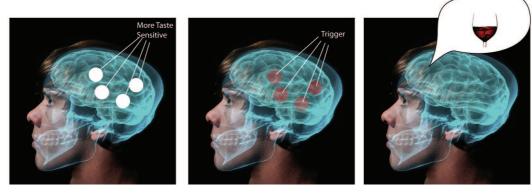
 $^{^{\}dagger\dagger}$ http://www.ieee802.org/15/pub/TG4.html

5.3.2.1 Magnetic stimulation of brain for digital taste and flavor (both taste and smell)

In the future, we may consider magnetic stimulation (deep brain magnetic flux stimulation) on the brain as a possible method to digitally activate both taste and smell sensations. As shown in Figure 5.40, this will be achieved in two distinct phases. In the first phase, the associated nucleus of basic tastes and smells in the brain will be identified through Electroencephalography (EEG) [54, 117], super high density scalp EEG system [84], and functional Magnetic Resonance Imaging (fMRI) [67] techniques. Natural food and smells will be used in this step such as sugar, chocolate, wine, mint, and lavender. After the completion of the preliminary phase, the second phase will be started for the stimulation of both taste and smell sensations. The 'Transcranial magnetic stimulation' method is proposed for the brain stimulation and it operates by inducing weak electric signals by rapidly changing magnetic fields produced by the outside circuitry [17].

With a novel mechanism of 'pulse magnetic flux nozzle', a magnetically induced deep brain electrical stimulation system (Figure 5.41) will be developed for this research. It is proven that the human brains work by firing electrical impulses in specific functional units (clusters) of neurons [110]. Further, the human brain registers specific brain functions or perceptions as forms of neural firings at specific locations on the brain [87].

For example, when students practice a lesson, the clusters of neurons that



Identification – Identify corresponding areas (nucleus) in the brain by observing fMRI data induced by natural food and chemical compounds

Stimulation - Stimulate identified nucleus by magnetic stimulation to regenerate the brain activities

Perception - Create perception of tasting real food or smelling real scent

Figure 5.40: The high level system diagram for taste and smell brain stimulation

control and drive certain function, fire repeatedly. When neurons fire frequently, they expand towards each other resulting in electrical signals [87]. It is the same for taste and smell perceptions. Understanding the firing in the brain for each of the brain perceptions could potentially provide the basis for modifying, reproducing, or creating the perception by modifying the neural firing with electrical means. Physically, such a neural firing can also be duplicated by applying electrical stimulation at the local field [76]. In this way, the taste and smell perceptions will be alleviated by modifying the neural firing with physical (noninvasive) means. The process requires three steps to be achieved:

- 1. To locate the neural firing on the brain for each of the concerned perceptions
- 2. To investigate and model the dynamic behaviors of the neural firings for

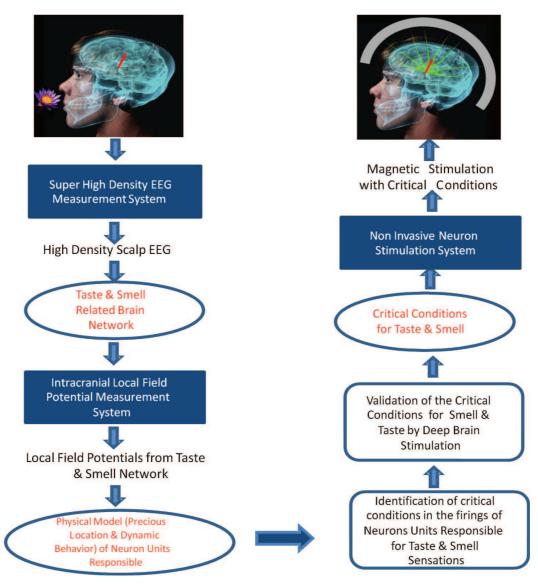


Figure 5.41: Flow of regenerating taste and smell perceptions by magnetic stimulation

each of the concerned perceptions

3. To identify and validate the critical conditions of the neural firings and accompanying local field potentials for each of the perceptions (by stimulating identified critical conditions we would stimulate the perception)

At the beginning, for brain stimulation, animal models such as mice and monkeys will be used to conduct testing procedures before test on humans. Performing such procedures indicate that the level of safety would be satisfied. The main reason for selecting animal models is because the anatomy of a mouse or monkey and their body functions are closer to humans. Providing tastes and smells of their favorite food and providing smells of their predators to observe their behaviors will be the two main approaches in conducting these experiments. Natural food and smells will be initially given to them, and their reactions to those will be measured through EEG experiments. Then the magnetic stimulation will be used to stimulate identified nucleus in the brain to simulate artificial tastes and smells. Finally, the results will be compared for further evaluations.

We have identified several limitations of this approach. For example, results of this technology could cause some cultural and ethical issues in the society, especially if we failed to develop and test the prototype in an appropriate manner. Furthermore, noninvasive brain stimulation might cause harmful effects on human when people use it for a longer period. More research works need to be conducted on the negative effects of transcranial magnetic stimulation for the human brain when people use it for longer periods.

5.4 Conclusion

In Chapter 4, the results showed that the Digital Taste Interface could be used to stimulate different taste sensations on human tongue. However, a problem remained on the repeatability and controllability of taste sensations generated through electrical and thermal stimulation methods. The initial study presented at the end of chapter 4 revealed valuable insights of these concerns. Therefore, the importance of another focused assessment is conducted and presented in this chapter. At the same time, several technical improvements were made to the system as explained.

From the results of the user experiments, it was found that all three, electrical, thermal, and hybrid stimulation methods were capable of achieving similar results again. All the systems developed received high level of satisfaction during the experiments, despite the fact that some participants were hesitating to use their tongues for the experiments. In particular, the Digital Taste Synthesizer and the Digital Taste Lollipop sustained for an extended period when they were regularly used in an hourly basis.

One noteworthy observation from the experiments conducted was, when the participants were asked to compare the sensation they could perform better, than when they just asked to express the sensations based on different stimuli. This was mainly observed during the informal experiments primarily conducted with the users to verify the technical effectiveness of the system. A possible explanation for this phenomena is the lack of multisensory information to understand the taste sensations properly. In general, when a chemical taste sensation is sensed a person has supplementary information such as visual, texture, and smell, whereas in this approach all the other contributing factors are immobilized other than the sensation of taste. Therefore, we encourage more future work on this aspect. We propose a modified system as equivalent to [82] to integrate with our approach for including visual and sound experiences.

Moreover, this phenomena also encouraged us to conduct a comparison assessment with a natural taste and artificial (electronic) taste. From the experiment presented in this chapter, we concluded that every participant could compare the strength of the artificial sour sensation. Therefore, we could classify the level of the sour taste intensity based on their feedbacks.

Finally, these different approaches individually or in combination provided insights on electronic control of the sensation of taste on human. In addition, many participants who used the system understood the importance of this work and satisfied the experiences the systems could deliver.

Chapter 6 will describe several future usage scenarios of this technology along with future example implementations. We will also explain a system for sharing taste messages through the Internet called Taste/IP.

Chapter 6

Future Usage Scenarios

The following sections will discuss overall benefits and future usage scenarios of digital taste simulation technology as elaborated in previous chapters. First, benefits of this technology are presented for different domains including virtual reality, gaming, entertainment, communication, and medical. Then, a detailed description of a communication system, which is based on the sensation of taste is explained.

6.1 Overall benefits

The sensation of taste plays a pivotal role in human lives. Additionally, it is a pleasurable sensation which associates with personal experiences. People prefer to dine together and arrange various food items for events and celebrations in their everyday lives. Thus, the sensation of taste is uniquely valuable to maintain a healthy human body, as well as for maintaining stronger relationships. Today, the digital media play a vital role in our lives through ubiquitous, daily interactions with them. In face-to-face interactions, people are able to use their full range of senses and expressions. However, presently, ubiquitous digital interactions have to rely on a limited range: text, sound, and image alone or in combinations [45]. To enhance these ubiquitous digital interactions, this research will provide a platform to integrate the sensation of taste as a ubiquitous digital media. The novelty is that, without using any chemicals this approach can stimulate taste sensations such as sour, salty, bitter, sweet, minty and spicy at present.

6.1.1 Digital communication media

The sense of taste is given a remarkably little attention as a remote communication media. Therefore, a new methodology is required to stimulate the sense of taste digitally, to enable remote communication through the sense of taste. Being able to communicate taste sensations digitally has distinct advantages in the domain of multisensory communication. Furthermore, it would be possible to develop taste sharing social networks in the future by realizing the potential of electronic sharing of taste sensations.

6.1.1.1 Multisensory digital communication

At present, audio, video, and text based remote interaction technologies are accepted as digital communication media. Many on going research works are focusing on these technologies to improve efficiency and faster connectivity. However, the organic qualities of communication to the lives at present are undermined, and intimacy between the two parties in the communication is reducing through limited technologies currently available. Therefore, most of the sociologists are discussing on using slow and analog ways of communication to enhance the organic quality of communication thus the lives. Because of these reasons, multisensory communication has become a necessity in the present communication paradigm thus to improve the natural qualities of lives [38]. This also enlightens the importance of stepping into the age of experience (not only visual, auditory, and text information but also non-verbal information such as expressions, taste, smell, gestures, and interacting with space) communication from the present age of information.

6.1.2 How this can be used in family environment

Sharing the experiences of each other is essential for stronger relationships in a family, although the members are geographically apart. For example, someone may send an email or a text message on his sisters' birthday, if he lives in a faraway place. However, these instant mediums undermine the value and the importance of the experience (receiver's as well as sender's) as it takes less effort and less time to send the message. But if we can share a moment or an experience such as sharing a taste (similar to what we are doing in the real world by sharing a piece of cake in a birthday) that will be novel and much more valuable to the receiver on the memorable day and it will eventually enable stronger relationships as well.

Furthermore, we believe that this new digitized experience of taste will stimulate novel and innovative multimodal applications at the domestic level, in the future, as illustrated in Figure 6.1. Through a similar technology, the person who makes the order may taste the quality of the dish even before the order is placed.



Figure 6.1: Future application of this technology for internet marketing and online shopping technologies

6.1.3 Virtual reality

The sensation of taste is considered as the final frontier of virtual reality technologies. Using the digital taste technology, a whole new set of interactions can be introduced to the virtual reality domain, which are based on the sensation of taste. At present, immersive virtual reality is discussed as a future technology. Similarly, the digital taste technology can be used as an immersive media to create altered mental state by deeply involving one's sense of taste. This technology will also enable much simpler interactions, yet impossible to achieve with current technologies, such as electronically tasting a virtual cookie or virtual chocolate in a virtual environment.

6.1.4 Medical

Being able to use this technology as a tool for taste disabled patients is an significant future direction for this research. There are several different taste malfunctions are discussed in the medical field as mentioned below [44].

- Ageusia no sense of taste
- Cacogeusia bad taste in the mouth
- Dysgeusia any impairment of the sense of taste
- Heterogeusia Inability to distinguish between tastes
- Hypergeusia overly acute sense of taste
- Hypogeusia diminished sense of taste
- Norgeusia the sought-after ideal
- Parageusia distorted sense of taste
- Phantogeusia hallucinogenic tastes phantom tasting

Although these conditions are not widely popular, from these nine conditions, eight of which are malfunctions of the sense of taste. Studying these conditions further with digital taste technology as presented in this thesis may enable a different sensory pathway for patients with these sensory malfunctions.

Furthermore, digital taste technology may also help when specific patients are advised not to consume certain food ingredients such as sweet for diabetics and salty for heart (congestive heart failure) patients.

6.1.5 Entertainment

The sensation of taste can be utilized for revolutionary purposes such as taste based interactive entertainment systems by enabling digital controllability of the sense of taste through this technology. Thus far, the entertainment aspects of the sensation of taste is not explored due to various reasons. Some of them are lack of controllability of the sense, fast adaptability for sensations, and need of an array of chemicals. Nevertheless, using the digital taste technology in the future, we may consider new entertainment concepts such as a "symphony of taste". A taste symphony can be created by rapidly changing taste sensations on one's tongue. This may also be combined with an output of a musical instrument or certain music beat.

6.2 Taste/IP: A future digital taste communication platform

In this section, we present a methodology (taste messaging) for integrating the sense of taste with the existing digital communication domain. We developed, Taste over IP (Taste/IP) system to remotely and digitally communicate the sensation of taste with three core modules: the transmitter, form of communication, and receiver. The transmitter is a mobile application, where the sender formulates a taste message to send. The Internet is used as the medium for communication. Furthermore, for digital communication, a new messaging format is introduced based on the extensible markup language (XML) and named it as TasteXML (TXML). In this approach for taste communication, the receiver (taste actuator) is recognized as the most significant module. As the receiver (actuator), we propose an improved and compact version of the Digital Taste Stimulator, as explained in this thesis.

6.2.1 Mode of operation

Currently, in a typical scenario, the user formulates a taste message to send using the mobile application. Then, the mobile phone sends the message in TXML format to the recipient's computer, thus to the Digital Taste Stimulator. Figure 6.2 depicts the main steps for sending a taste message. At present, the system uses an intermediate computer as shown in Figure 6.2 for redirecting the message to the Digital Taste Stimulator. As the immediate next step, we are developing a portable version, which has direct communication through the Internet (using 3G or Wi-Fi technologies).



Figure 6.2: Architecture of Taste over IP system with transmitter, receiver, and the form of communication

6.2.2 Transmitter

An android mobile application is developed as the transmitter, which allows the user to create taste messages and transmit it to the receiver. At present, based on the capabilities of the Digital Taste Stimulator, we are only focusing on transferring basic taste sensations known as sour, salty, bitter, and sweet. Furthermore, the application allows the user to select the intensity of the taste to be sent.

As shown in Figure 6.3, the mobile application has three tabs. First for creating the basic taste message, second for creating a mixed message, and third for network configurations to connect with the user's computer. The second tab is not implemented at the moment. Further studies will be conducted to produce mixed sensations in the future using the Digital Taste Stimulator. The third tab has the properties related to network communication, the IP of

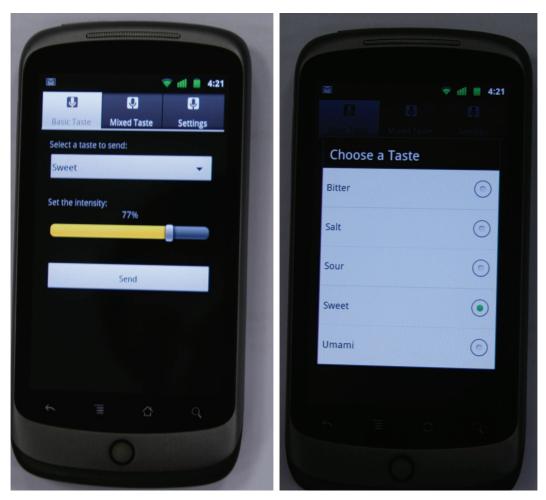


Figure 6.3: Android application developed for digital taste messaging

the server (recipient's computer) and the port. Each user is given a client ID for identification purposes.

6.2.3 Communication

Once the user crafts the taste message, the recipient can be selected by changing the IP address from the settings tab at the moment. The Internet is used as the channel of communication between the sender and the receiver. To transmit a taste message, one of the most important aspects to consider is the form of communication. As a solution, to specify the format of the message created in the mobile application, a new XML format is developed named it as the Taste Extensible Markup Language (TasteXML / TXML).

TasteXML is a Remote Procedure Calling protocol that works over the Internet. TasteXML messages are a set of encrypted requests and responses. The body of both the request and response are in XML format. When a taste message is received by the server, first it queues until the user is ready to receive the message. Therefore, immediately the server returns a response with the status as "queued". Then later once the recipient consumes the taste message the server returns a success response. We have developed the format in such a way that in the future it can be easily expanded to include other parameters such as parameters for mixed sensations and basic social networking functions (ex: friend-list management). Furthermore, procedure parameters can be scalars, numbers, strings, dates, complex records and list structures. Two samples of TasteXML messages are given below for sending a basic taste message. The intensity of the taste sensation can be represented either in three levels (1: mild, 2: medium, and 3: strong) or as a percentage (ex: 70%). Therefore, in this example, a primary bitter sensation is transferred with the intensity of 70%.

TasteXML - Basic taste message send request

< type > request < /type >

< method > SendTasteToFriend < /method >

< information >

<ID>T0001</ID>

<FriendID>4</FriendID>

<FriendName>Daniel Jackson</FriendName>

<TasteType>basic</TasteType>

<taste intensity="70">Bitter</taste>

</information>

</TasteXml>

TasteXML - Basic taste message send response

<?xml version="1.0" encoding="UTF-8"?> <TasteXml> <type>response</type> <method>SendTasteToFriend</method> <information> <TasteType>basic</TasteType> <status>queued</status> </information> </TasteXml>

In addition, future prospects of expanding the TasteXML format with more information related to the taste messaging is showed in the below example. The friend list request and response messages can be used when a social network based taste messaging system is implemented.

TasteXML - Friend List request

<?xml version="1.0" encoding="UTF-8"?> <TasteXml> <type>request</type> <method>FriendList</method> <information> <ID>T0003</ID> </information>

TasteXML - Friend List response

</TasteXml>

<?xml version="1.0" encoding="UTF-8"?> <TasteXml> <type>response</type> <method>FriendList</method> <information> <Friend> <ID>2</ID> <Name>Ron</Name> </Friend> <ID>3</ID> <Name>Rosh</Name> </Friend> <Friend> <ID>4</ID> <Name>Kening</Name> </Friend> <Friend> <ID>5</ID> <Name>Dilrukshi</Name> </Friend> </Friend>

In this scenario, after receiving the friend list response, the user can select a friend from that list and then formulate a taste. Then, the formulated message will be sent to the selected friend using the associated ID instead of IP address.

Moreover, in the future, this technology may be used to implement digital taste based social networking services as mentioned earlier of this section. Figure 6.4 shows a possible architecture for a future digital taste based social networking platform called mTaste.

Another expected future work is to integrate a new sensing mechanism

150

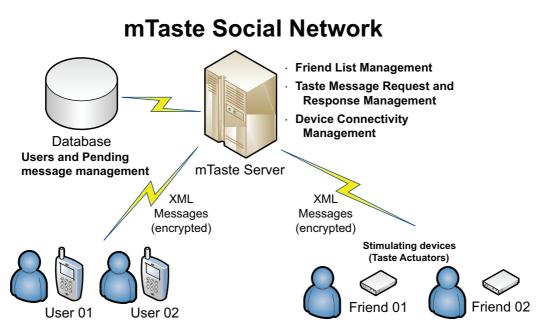


Figure 6.4: A future digital taste sharing social networking service

at the sender's side of the Taste/IP system. Currently, the sender manually formulates the taste message to be sent using the mobile application. However, there are several electronic tongue solutions already developed by a few research groups [114, 65]. By integrating a sensing mechanism, the sender will be able to capture a taste automatically. For example, if the sender wants to share the taste of his glass of wine with a friend, he/she should be able to automatically capture the taste of that wine in order to send it to the other end. Therefore, it is necessary to integrate a novel sensing apparatus with an advanced encoding mechanism in the future.

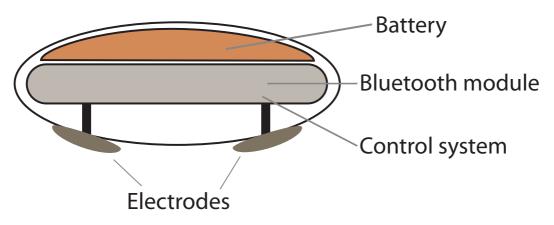


Figure 6.5: Concept diagram of the taste capsule interface (outer cover is made of special material for chewing and hygiene issues)

6.3 Possible future implementations

6.3.1 The digital taste capsule

As mentioned, applications of this technology have a lot of potential in various domains. However, before realizing real world applications there is an open issue to be solved in the next step, the design of the system. It would be possible to develop a miniaturized system where the user may wear the whole system on their tongue. For example, as an electronic tablet/capsule with tiny electrodes in built as shown in Figure 6.5. The outer cover of the taste capsule can be made of a special material to facilitate the interactions such as chewing. At the same time it should control the hygiene issues, when it is used for a long time.

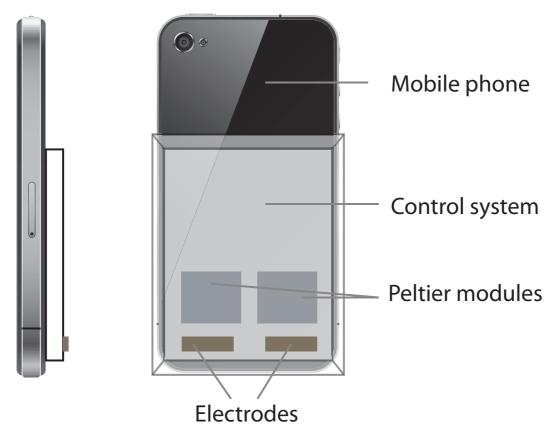


Figure 6.6: Digital taste device integrated with a mobile phone (the module is connected to the mobile phone for power and communication purposes)

6.3.2 Mobile integrated digital taste solution

In addition to the tiny version proposed, a better-integrated portable version of the device would also generate new application possibilities in daily lives. For example, as displayed in Figure 6.6, by integrating this device with a mobile phone people may share text messages along with emotional taste messages attached. By doing so, they can easily share their inner emotions with their partners. Another advantage of integrating with a mobile phone is after integrating the mobile phone can be used as the communication and power hub for the digital taste module.

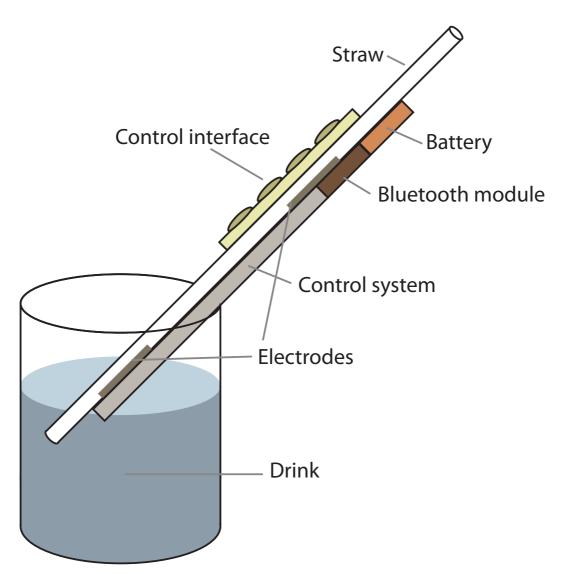


Figure 6.7: Concept diagram of the digital taste enhanced drinking straw (the control interface has touch sensitive knobs and works as control knobs in a flute)

6.3.3 Digital taste enhanced drinking straw

Another direct extension of this work is to use electrical stimulation through drinks or food substances. For example, Nakamura et al. presents a method to augment taste sensations using small electrical pulses through drinks [81]. We may use a similar approach, however, to enhance the user experience, we develop a control system and a straw like interface to control the sensations in the mouth as in Figure 6.7. This electronically enhanced straw will have a limited current flowing mechanism to stimulate users tongue through the beverage itself, and being within safety limits. Furthermore, we are designing a miniaturized current control system in order to change current pulses according to user inputs. The development process will consist of a literature review and several experiments using an electronic circuitry.

6.4 Conclusion

This chapter specially focused on describing future possibilities of this technology. To describe a wide range of possibilities, we have given several examples and future achievable implementations of digital taste technology. The chapter began with an overview for overall benefits through such a technology. Moreover, the benefits were explained under different categories based on different related domains for this technology. Then, a future potential communication platform was detailed with its implementation and operation. In addition, we explained a new messaging format called Taste Extensible Markup Language (TasteXML / TXML), which was specially designed to assist taste communication in the future. In the final section, more importantly, we described some achievable future implementations of this technology. These future implementations will useful for adapting this technology in various domains such as communication, virtual reality, and medical.

Chapter 7

Conclusion

The essence of this research work is well encapsulated by the title of this work, "Digitally stimulating the sensation of taste through electrical and thermal stimulation". This thesis has presented the systematic development of several prototype systems to stimulate the sensation of taste on human followed by several experiments on electronic taste stimulation. In this regard, the present chapter concludes this thesis by summarizing the main achievements of this research.

Thus far, the sensation of taste is used in several digital interactive systems by incorporating an array of chemical compounds into the system itself. However, these chemical based approaches may not be the most effective way of integrating the sensation of taste with digital interactive systems. Therefore, as a solution this thesis presented a new technology for stimulating the sensation of taste on human electronically. Furthermore, several experimental studies were conducted to evaluate the systems and stimuli experimentally. As detailed, two key issues were defined to be addressed in this study: firstly, stimulating taste sensations digitally without using chemical substances, secondly the controllability of taste sensations along with the level of intensity. To answer these issues, the possibility of using electrical and thermal stimulation methodologies on the human tongue was investigated.

Chapter 1 outlined the exploratory domain and the problem statement for this research. The research question of this thesis is, "How do we engineer a novel interactive system to stimulate taste sensations digitally?". Based on this research question, we defined two main directions of this research, to develop a novel device to simulate taste sensations electronically and determine the efficiency and accuracy of this approach for simulating the sensation of taste.

Using the limited research that is available in this area, we present a detailed discussion on existing studies from different domains in chapter 2. In this discussion, at first we discussed the difficulties of using the sensation of taste as a form of electronic media. Then, a review of existing literature was presented in three categories, respectively, chemical based stimulation methods, non-chemical based stimulation methods, and human tongue based interactive systems. Finally, we concluded the chapter by stating the contribution and significance of this work.

Before using electrical and thermal stimuli as methods for stimulating the human tongue, we had to consider a reasonable experimental protocol by assuring the level of comfort and safety of users. We carefully designed a stim-

157

ulation protocol as detailed in chapter 3 based on literature and experimental studies conducted.

Thereafter, this thesis presented the systematic development of a wearable system, the Digital Taste Interface, to address the aforementioned questions. The system consists of two main components, the digital control system and the tongue interface. It combined both electrical and thermal stimulation methodologies (hybrid approach) to stimulate human tongue as explained. Then the system was experimentally evaluated with human participants as described in chapters 4 and 5.

As chapters 4 and 5 revealed, sour (strong), salty (mild), bitter (mild), sweet (mild), minty (medium), and spicy (medium) sensations were stimulated through the approach presented in this thesis. Once the prototypes were completed, we have conducted several experiments to assess the effectiveness and repeatability of this technology, as well as the effectiveness of the prototypes. Based on the users' comments from preliminary studies, we also conducted several supporting experiments such as repeatability experiment, experimenting on regional differences of the human tongue for taste stimulation, and a comparison study with real taste sensations, mainly focusing on sour taste. Based on the experimental results and interviews with participants, we finalized different stimuli protocols as follows.

• Sour: magnitude of current from 60μ A to 200μ A & increasing temperature from 20° C to 30° C

- Salty: magnitude of current up to $50\mu A$ (lower frequencies)
- Bitter: magnitude of current between 60μ A 140μ A (noticeably from the bottom surface of the tongue)
- Sweet: when the current is inverted & increase temperature up to 35°C and continuously decrease from 35°C to 25°C (during the transition continuous exposure is required)
- Mint: decrease temperature from 22°C to 19°C
- Spicy: increase temperature from 33°C to 38°C

Furthermore, at the end of chapter 5, we provided an extensive discussion along with several immediate future experimental works. In these future experimental works, we primarily focused on improving the effectiveness of the approach and prototype systems. Moreover, we are also interested on expanding this technology into the domain of digital flavor production by incorporating the sensation of smell in the future.

Finally, these findings provided valuable information on stimulating the sensation of taste by non-chemical means. As shown in this thesis, digital controllability of the sensation of taste provides a useful platform for engineers, interaction designers, and media artists towards developing remote digital taste (multisensory) interactions. Furthermore, this work introduces the sense of taste as a possible digital output methodology for computer-human interactions. Several possible future usage scenarios of this technology were presented with examples in chapter 6.

It must be admitted that this thesis has presented a new methodology to simulate the sensation of taste digitally. It has also highlighted several significant technical and physiological measurements by conducting specific user experiments. Findings of these studies will help future researchers or engineers to develop further and discover exciting new digital technologies, which utilize the sense of taste.

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174

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List of Selected Publications

Significant amount of materials and results from this thesis, previously submitted and published in the following peer-reviewed publications.

Relevant publications

- N. Ranasinghe, R. Nakatsu, A. D. Cheok, and P. Gopalakrishnakone, "Digital Taste Interface: A Digital Control System for Actuating the Sensation of Taste," Journal of Instrumentation and Measurement, IEEE, May. 2012. (Under review)
- Nimesha Ranasinghe, Ryohei Nakatsu, Nii Hideaki, and Ponnampalam Gopalakrishnakone, "Tongue Mounted Interface for Digitally Actuating the Sense of Taste," in Proceedings of the 16th IEEE International Symposium on Wearable Computers (ISWC), June 2012, pp. 80-87. DOI: 10.1109/ISWC.2012.16, ISSN: 1550-4816.
- N. Ranasinghe, R. Nakatsu, A. D. Cheok, and P. Gopalakrishnakone, "Taste/IP: The Sensation of Taste for Digital Communication," in Pro-

ceedings of the 14th ACM International Conference on Multimodal Interaction, ICMI 2012, ACM [Full-paper, Accepted for publication]

- Nimesha Ranasinghe, Kasun Karunanayaka, Adrian David Cheok, Owen Noel Newton Fernando, Hideaki Nii, and Ponnampalam Gopalakrishnakone. 2011. Digital taste and smell communication. In Proceedings of the 6th International Conference on Body Area Networks (BodyNets '11). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, Brussels, Belgium, Belgium, pp. 78-84.
- Nimesha Ranasinghe, Adrian David Cheok, Owen Noel Newton Fernando, Hideaki Nii, and Gopalakrishnakone Ponnampalam. 2011. Electronic taste stimulation. In Proceedings of the 13th international conference on Ubiquitous computing (UbiComp '11). ACM, New York, NY, USA, pp. 561-562. DOI=10.1145/2030112.2030213 http://doi.acm.org/10.1145/2030112.2030213
- Nimesha Ranasinghe, Adrian David Cheok, Owen Noel Newton Fernando, Hideaki Nii, and Ponnampalam Gopalakrishnakone. 2011. Digital taste: electronic stimulation of taste sensations. In Proceedings of the Second international conference on Ambient Intelligence (AmI'11), pp. 345-349, Springer-Verlag, Berlin, Heidelberg. DOI=10.1007/978-3-642-25167-2_48 http://dx.doi.org/10.1007/978-3-642-25167-2_48

 Nimesha Ranasinghe, Kasun Karunanayaka, Adrian David Cheok, Owen Noel Newton Fernando, Hideaki Nii, and Gopalakrishnakone Ponnampalam. 2011. Digital taste and smell for remote multisensory interactions: poster abstract. In Proceedings of the 6th International Conference on Body Area Networks (BodyNets '11). ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), ICST, Brussels, Belgium, Belgium, pp. 128-129.

Other Publications

- Nimesha Ranasinghe, Owen Noel Newton Fernando, and Adrian David Cheok. 2011. Petimo: sharing experiences through physically extended social networking. In Proceedings of the 1st international conference on Human interface and the management of information: interacting with information - Volume Part II (HCII'11), Springer-Verlag, Berlin, Heidelberg, pp. 66-74.
- Nimesha Ranasinghe, Adrian David Cheok (2010) Poetry Mash-up: Poetry communication for digital youth, pp. 41-49. In proceedings of the Young Investigatorss Forum on Culture Technology 2009.
- Kening Zhu, Nimesha Ranasinghe, Chamari Edirisinghe, Owen Noel Newton Fernando, and Adrian David Cheok, "Poetry mix-up", In Computers in Entertainment, 9(2), Article 8 (July 2011), 15 pages, ACM,

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- Chamari Edirisinghe, Kening Zhu, Nimesha Ranasinghe, Eng Tat Khoo, Vidyarth Eluppai Srivatsan, Janaka Prasad Wijesena, Owen Noel Newton Fernando, and Adrian David Cheok. 2011. Modeling literary culture through interactive digital media. Virtual Real. 15, 4 (November 2011), 239-247. DOI=10.1007/s10055-009-0147-9 http://dx.doi.org/10.1007/ s10055-009-0147-9
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Awards

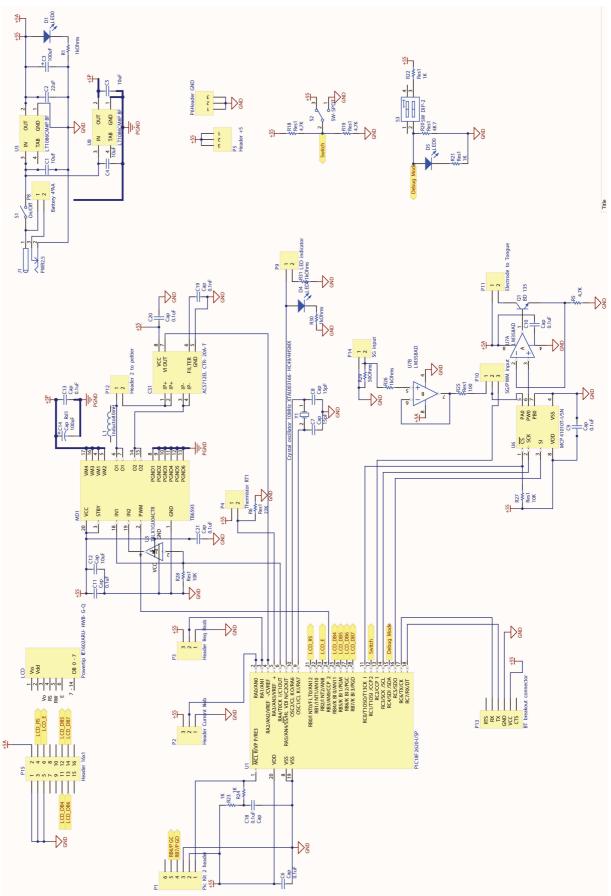
- Honorable mention at Nokia Ubimedia MindTrek Awards 2012 Competition, Tampere, Finland, Oct 2012 (Invited talk).
- YoungCT award 2009 at the Young Investigators Forum on Creative Technology in Korea, January 2010 (Invited talk).

Schematic, PCB, and Firmware

of Digital Taste Interface

Circuit schematic diagram of the control sys-

 tem



P5 **P2 (**) **()** 4 SS R21 R20 **P10** $\overline{\mathbf{\omega}}$

PCB layout of the control system

Figure 1: PCB layout of Digital Taste Interface

P13

10

Firmware of Digital Taste Interface

```
#include <18f2620.h>
```

```
#include <math.h>
```

```
#include <stdio.h>
```

#include <stdlib.h>

```
#include <string.h>
```

#use delay(clock=40M, crystal=10M)

```
\# use \ rs232 (baud = 115200, \ xmit = PIN_C6, \ rcv = PIN_C7, \ stream = USB)
```

```
#include <flex_lcd.c>
```

```
\# fuses\ H4, NOPROTECT, NOIESO, NOBROWNOUT, NOWDT, PUT, NOCPD, NOSTVREN, NOEBTR
```

```
\#fuses NODEBUG, MCLR, NOLPT1OSC, CCP2B3//, CCP2C1
```

 $\# fuses \ NOLVP, NOWRT, NOWRTD, NOCPB, NOWRTC, NOWRTB, NOFCMEN, NOXINST, PBADEN \\$

```
//initialize fast io
#use fast_io(A)
#use fast_io(B)
#use fast_io(C)
```

```
//\mathrm{PIN} definitions
```

#define peltier PIN_A4

#define pwm PIN_B3

#define led PIN_A5

#define swtch PIN_C1

#define CS_PIN PIN_C0

int debug = 1; //1 - on, 0 - offint ldelay = 100;unsigned int pot = 1;unsigned int npot = 1;unsigned int potarray $[9] = \{9, 20, 30, 40, 51, 61, 72, 82, 92\};$ unsigned int intpsarray $[7] = \{1, 3, 4, 6, 12, 24, 48\};$

//PWM settings
int pwm_duty_value = 0;
int pwm_percentage = 57;
//int pwm_percentage = 50;

//timer settings
int intps = 6 ; //interrupts per second
int int_count = 1 ; //interrupts count

```
//get raw sensor values
unsigned long raw_temp = 0;
unsigned long raw_curr = 0;
unsigned long raw_freq = 0;
unsigned long raw_curr_sensor = 0;
```

//step value of digital pot unsigned long pot_step = 1;

float tmpr;

//detect the cooling and cooled states
//for hybrid - step by step stimulation
int iCooling = 0;
int iCooled = 0;

```
//data from serial
char selection;
char *properties;
char *mode;
```

```
//thermister raw value to temperature (C) mapping
float AdcToTemp [102][2] =
{
    {
        {100,15.01},
        {101,15.37},
        {102,15.73},
        {103,16.09},
        {104,16.45},
```

- $\{105, 16.81\},\$
- $\{106, 17.16\},\$
- $\{107, 17.52\},\$
- $\{108, 17.88\},\$
- $\{109, 18.24\},\$
- $\{110, 18.59\},\$
- $\{111, 18.95\},\$
- $\{112, 19.31\},\$
- $\{113, 19.67\},\$
- $\{114, 20.03\},\$
- $\{115, 20.38\},\$
- $\{116, 20.74\},\$
- $\{117, 21.10\},\$
- $\{118, 21.46\},\$
- $\{119, 21.82\},\$
- $\{120, 22.18\},\$
- $\{121, 22.54\},\$
- $\{122, 22.91\},\$
- $\{123, 23.27\},\$
- $\{124, 23.63\},\$
- $\{125, 24.00\},\$
- $\{126, 24.36\},\$
- $\{127, 24.73\},\$
- $\{128, 25.09\},\$

- $\{129, 25.46\},\$
- $\{130, 25.83\},\$
- $\{131, 26.20\},\$
- $\{132, 26.57\},\$
- $\{133, 26.94\},\$
- $\{134, 27.31\},\$
- $\{135, 27.69\},\$
- $\{136, 28.06\},\$
- $\{137, 28.44\},\$
- $\{138, 28.81\},\$
- $\{139, 29.19\},\$
- $\{140, 29.57\},\$
- $\{141, 29.96\},\$
- $\{142, 30.34\},\$
- $\{143, 30.73\},\$
- $\{144, 31.11\},\$
- $\{145, 31.50\},\$
- $\{146, 31.89\},\$
- $\{147, 32.29\},\$
- $\{148, 32.68\},\$
- $\{149, 33.08\},\$
- $\{150, 33.48\},\$
- $\{151, 33.88\},\$
- $\{152, 34.28\},\$

- $\{153, 34.69\},\$
- $\{154, 35.10\},\$
- $\{155, 35.51\},\$
- $\{156, 35.92\},\$
- $\{157, 36.34\},\$
- $\{158, 36.76\},\$
- $\{159, 37.18\},\$
- $\{160, 37.60\},\$
- $\{161, 38.03\},\$
- $\{162, 38.46\},\$
- $\{163, 38.89\},\$
- $\{164, 39.33\},\$
- $\{165, 39.77\},\$
- $\{166, 40.22\},\$
- $\{167, 40.66\},\$
- $\{168, 41.11\},\$
- $\{169, 41.57\},\$
- $\{170, 42.03\},\$
- $\{171, 42.49\},\$
- $\{172, 42.96\},\$
- $\{173, 43.43\},\$
- $\{174, 43.90\},\$
- $\{175, 44.39\},\$
- $\{176, 44.87\},\$

- $\{177, 45.36\},\$
- $\{178, 45.86\},\$
- $\{179, 46.36\},\$
- $\{180, 46.86\},\$
- $\{181, 47.37\},\$
- $\{182, 47.89\},\$
- $\{183, 48.41\},\$
- $\{184, 48.94\},\$
- $\{185, 49.48\},\$
- $\{186, 50.02\},\$
- $\{187, 50.57\},\$
- $\{188, 51.13\},\$
- $\{189, 51.69\},\$
- $\{190, 52.26\},\$
- $\{191, 52.84\},\$
- $\{192, 53.43\},\$
- $\{193, 54.02\},\$
- $\{194, 54.63\},\$
- $\{195, 55.24\},\$
- $\{196, 55.86\},\$
- $\{197, 56.49\},\$
- $\{198, 57.14\},\$
- $\{199, 57.79\},\$
- $\{200, 58.46\},\$

```
\{201, 59.13\}
};
//change the digital pot
void DigPot(int value)
//used for MCP41xxx Microchip digital pot
// 0x00 = wiper at PB0, 0xFF wiper at PA0
{
   output_low(CS_PIN);
   delay_us(1);
   spi_write(0x13); //command byte to write data to pot
   spi_write(value);
   delay_us(1);
   output_high(CS_PIN);
}
//initialize the digital pot
void initDigPot(int InitialValue)
{
   setup_spi(SPLMASTER | SPLH_TO_L | SPLCLK_DIV_16);
   output_high(CS_PIN);
  DigPot(InitialValue);
}
```

```
//calculate PWM duty value based on clock, t2div, and period
double getPwmDuty(int percent)
{
        //double hz;
        double hz = ((40 * 100000)/(16 * 4 * (124+1)));
        return ( (40 * 1000000 * percent)/(16 * 4 * hz * 100) );
}
//init the pins related to thermal stimulation
void reset_thermal()
{
        iCooling = 0;
        output_low(pwm);
        output_low(peltier);
        pwm_duty_value = getPwmDuty(0);
        set_pwm2_duty(0);
}
//init the pins related to electrical stimulation
void reset_electrical()
{
        output_low(PIN_C2);
        output_low(PIN_C0);
        output_low(PIN_C3);
```

```
output_low(PIN_C5);
```

```
char* getProperties()
```

```
char *temp;
```

char	*ppot	=	"pot=";
char	*delim	=	" " ;
char	*pT	=	"T#";
char	*ptmpr	=	"tmpr=";
char	*ppwm	=	":pwm_duty=";
char	*picool	=	":iCooling=";
char	*pmode =	_ "	mode = ";

```
properties = "PROPS$E#";
properties = strcat(properties, ppot);
```

```
sprintf(temp, "%d", pot);
properties = strcat(properties, temp);
```

```
properties = strcat(properties, delim);
```

```
properties = strcat(properties, pT);
```

```
properties = strcat(properties, ptmpr);
```

```
sprintf(temp, "%f", tmpr);
properties = strcat(properties, temp);
```

```
properties = strcat(properties, ppwm);
```

```
sprintf(temp, "%d", pwm_duty_value);
properties = strcat(properties, temp);
```

```
properties = strcat(properties, picool);
```

```
sprintf(temp, "%d", iCooling);
properties = strcat(properties, temp);
```

```
properties = strcat(properties, delim);
```

```
properties = strcat(properties, pmode);
properties = strcat(properties, mode);
```

```
return properties;
```

 $\# {\rm int_rda}$

```
void isr()
{
```

```
selection = getc(USB);
```

```
if (stricmp(selection , '5') == 0) 
printf ("\n\rManualCommand: %s \n\r", getProperties()); 
else
```

printf (" $\n\$ rManualCommand: %c $\n\$ r", selection);

```
CLEAR_INTERRUPT(INT_RDA);
```

```
}
```

```
#INT_TIMER0
void isr_timer()
{
    if(--int_count==0)
    {
        output_toggle(PIN_C2);
        int_count = intps;
    }
    CLEAR_INTERRUPT(INT_TIMER0);
}
```

// init the PIC and ports

```
void init()
```

{

delay_ms(10); //1 - input : 0 - output //A7 A6 A5 A4 A3 A2 A1 A0 // 1 1 0 0 1 1 1 1 //B7 B6 B5 B4 B3 B2 B1 B0 // 0 0 0 0 0 0 0 0 0 //C7 C6 C5 C4 C3 C2 C1 C0 // 1 0 0 1 0 0 1 0 set_tris_A (0xCF); set_tris_B (0x00);

CLEAR_INTERRUPT(INT_RDA);

ENABLE_INTERRUPTS(INT_RDA);

ENABLE_INTERRUPTS(GLOBAL);

ENABLE_INTERRUPTS(INT_TIMER0);

setup_ccp1(CCP_OFF); // switches ccp1 pwm off

 $//2440 \,hz:intps=1:55 \,Hz-200 \,KHz$

setup_timer_0(RTCC_DIV_8|RTCC_8_BIT); setup_ccp2(CCP_PWM); // Configure CCP2 as a PWM setup_timer_2(T2_DIV_BY_16, 124, 1); // 5000 Hz

```
//AN0 - Current knob
//AN1 - Frequency knob
//AN4 - Tempareture feedback
//setup_adc_ports( AN0_AN1_AN4_ANALOG );
```

//AN0 AN1 AN4 setup as analog ports

setup_adc_ports(AN0_TO_AN3_ANALOG);

```
setup_adc( ADC_CLOCK_INTERNAL );
```

```
//init the pins of PIC related to
//both electrical and thermal
reset_thermal();
reset_electrical();
```

```
//initialize Digital Potentiometer
initDigPot(20);
```

```
properties = " ";
mode = " ";
```

```
void electricalSymphony()
{
```

}

output_low(led);

```
printf("Taste Symphony is ON(r n);
        intps = potarray [ rand() \% 6 ]; //rand from intpsarray
        pot = intpsarray [ rand () \% 6 ]; //rand from potarray
        DigPot(pot);
}
void electrical()
{
        output_low(led);
        printf("Electrical stimulation is ON(r n);
        DigPot(pot);
        if (selection = 91) // '['
        {
                pot = pot - pot\_step;
                if (pot == 0)
                         pot = 250;
                selection = " ";
        }
        //frequency selection
        if (selection = '1') //50 \text{Hz}
        {
                intps = 48;
                selection = "";
```

if (selection = '2') //100Hz

}

```
{
        intps = 24;
        selection = "";
}
if (selection = '3') //200 \text{Hz}
{
        intps = 12;
        selection = "";
}
if (selection == '4') //400 \rm Hz
{
        intps = 6;
        selection = "";
}
if (selection = 6') //600Hz
{
        intps = 4;
        selection = "";
}
if (selection = '7') //800Hz
{
        intps = 3;
        selection = "";
}
```

```
if (selection = '8') //2440 \, hz
{
        intps = 1;
        selection = "";
}
//current selection
if (selection == 's') //10 micro amp
{
        pot = 1;
        selection = " ";
}
if (selection = 'a') //10 micro amp
{
        pot = 4;
        selection = "";
}
if (selection == 'z') //20 micro amp
{
        pot = 9;
        selection = " ";
}
if (selection = 'x') //40 micro amp
{
        pot = 20;
```

```
selection = "";
}
if (selection = 'c') //60 micro amp
{
        pot = 30;
        //npot = 15;
        selection = "";
}
if (selection == 'v') //80 micro amp
{
        pot = 40;
        selection = "";
}
if (selection = 'b') //100 micro amp
{
        pot = 51;
        selection = " ";
}
if (selection == 'n') //120 micro amp
{
        pot = 61;
        selection = "";
}
if (selection = 'm') //140 micro amp
```

```
{
        pot = 72;
        selection = "";
}
if (selection == ',') //160 micro amp
{
        pot = 82;
        selection = "";
}
if (selection == '.') //180 micro amp
{
        pot = 92;
        selection = "";
}
if (selection = '/') //200 micro amp
{
        pot = 102;
        selection = "";
}
if (selection == ';') //220 micro amp
{
        pot = 112;
        selection = "";
}
```

```
if (selection = 'l') //240 micro amp
{
        pot = 122;
        selection = "";
}
if (selection = 'k') //260 micro amp
{
        pot = 132;
        selection = "";
}
if (selection == 'j') //280~{\rm micro~amp}
{
        pot = 142;
        selection = "";
}
if (selection = 'h') //300 micro amp
{
        pot = 152;
        selection = " ";
}
if (selection == 'g') //350 micro amp
{
        pot = 178;
        selection = "";
```

```
}
        if (selection == 'f') //400 micro amp
        {
                pot = 200;
                selection = " ";
        }
        if (selection = 93) // ']'
        {
                pwm_percentage = pwm_percentage - 10;
                if (pwm_percentage == 0)
                                pwm_percentage = 80;
                pwm_duty_value = getPwmDuty(pwm_percentage);
                set_pwm1_duty(pwm_duty_value);
                selection = "";
        }
// start thermal stimulation
void cooling()
        output_high(pwm);
```

```
output_low(peltier);
```

```
pwm_duty_value = getPwmDuty(pwm_percentage);
set_pwm2_duty(pwm_duty_value);
}
// start thermal stimulation
void heating()
{
    output_high(pwm);
    output_high(peltier);
    pwm_duty_value = getPwmDuty(pwm_percentage);
    set_pwm2_duty(pwm_duty_value); //10% = 12.5
}
```

```
//control the thermal output
void thermal()
{
    if (iCooling)
        cooling();
    else
        heating();
}
//get the temp from ADC value
```

```
float getTemp(float ADC)
```

{

```
//get sensor readings before set the function
void getSensorReadings()
```

```
{
```

}

```
//Current knob
set_adc_channel(0);
delay_us(100);
raw_curr = read_adc();
```

//frequency knob
set_adc_channel(1);
delay_us(100);
raw_freq = read_adc();

//frequency knob
set_adc_channel(2);

```
delay_us (100);
raw_curr_sensor = read_adc();
```

```
//raw temperature value
set_adc_channel(3);
delay_us (100);
raw_temp = read_adc();
```

```
//temp controling
        tmpr = getTemp(raw_temp);
        if (tmpr \ge 35)
                 iCooling = 1;
        if (tmpr \ll 21)
        {
                 if (iCooling == 1)
                         iCooled = 1;
                 iCooling = 0;
        }
        printf(\%Lu \ \ n\%, raw_temp);
void printMainMenu()
```

// Welcome message

}

```
printf ("Digital Taste Interface \r\n");
printf("Please select one of the options:");
printf("'E' - Electrical stimulation");
printf("'T' - Thermal stimulation");
printf("'H' - Hybrid (Electrical & Thermal together)");
printf("'S' - Taste Symphony");
printf("'Q' - Quit from stimulation");
```

```
//show the main menu and control - electrical and thermal stimulation
//'E' for electrical, 'T' for thermal stimulations,
//'H' - Hybrid (Electrical & Thermal stimulations together)
//'q' for quit
void showMenu()
{
    output_toggle(led); //test LED
```

```
// Welcome message
printMainMenu();
```

```
(selection != 't') && (selection != 'T'));
```

```
//reset everything before start
reset_thermal();
reset_electrical();
```

//if selected Q repeatedly print the main menu
if ((selection == 'q') || (selection == 'Q'))
{
 selection = ' ';
}

```
}
       reset_electrical();
}
//executes until you choose 'q' to quit
if ( (selection = 't') || (selection = 'T') )
{
       iCooling = 1; //1 = cooldown first 0 = heatup first
               = "T";
      mode
       lcd_putc(" \setminus f Thermal \setminus n");
       while (!((selection = 'q') || (selection = 'Q')))
       {
             getSensorReadings ();
             thermal();
             if (debug) delay_ms(ldelay);
       }
       //iCooling = 0;
       iCooling = 1;
       reset_thermal();
}
//executes until you choose 'q' to quit
if ( (selection = 'h') || (selection = 'H') )
```

```
211
```

//start the main loop for hybrid stimulation
printf("\r\n Please select one of the options" +
"for Hybrid stimulation: \r\n");
printf("\r\n '1' - Step by step \r\n");
printf("\r\n '2' - Continuous \r\n");
printf("\r\n 'Q' - Quit from stimulation \r\n");

```
lcd_putc(" \setminus f Hybrid (E+T) \setminus n");
```

{

```
while ( (selection != '1') && (selection != '2') &&
(selection != 'q') && (selection != 'Q') );
```

```
if (selection == '1')
{
    mode = "H_STEP";
    while (!((selection == 'q') || (selection == 'Q')))
```

```
{
```

```
getSensorReadings();
electrical();
```

 $//\,{\rm only}$ one time electrical stimulate

```
if (iCooled == 1)
iCooled = 0;
```

```
while ( (iCooled != 1) &&
       (!( (selection == 'q') \mid\mid (selection == 'Q') )) )
                 {
                         getSensorReadings ();
                         thermal();
                         if (debug) delay_ms(ldelay);
                 }
        }
        reset_thermal();
        reset_electrical();
if (selection = 2')
                    = "H_CONT";
        mode
        while (!(( selection == 'q') || (selection == 'Q')))
        {
                 getSensorReadings();
                 thermal();
                 electrical();
                 if (debug) delay_ms(ldelay);
        }
```

```
reset_thermal();
              reset_electrical();
       }
       if ( (selection = 'q') || (selection = 'Q') )
       {
              reset_thermal();
              reset_electrical();
       }
}
//executes until you choose 'q' to quit
if ( (selection = 's') || (selection = 'S') )
{
       mode
                = "SYMPHONY";
       lcd_putc("\f Taste Symphony \n");
       while (!((selection = 'q') || (selection = 'Q')))
       {
              getSensorReadings ();
              thermal();
              electricalSymphony();
              delay_ms(1000);
              if (debug) delay_ms(ldelay);
       }
```

```
reset_thermal();
         reset_electrical();
}
if ( (selection = 'r') || (selection = 'R') ) // gettemp
{
         while (!((selection = 'q') || (selection = 'Q')))
         {
                  pwm_percentage = 100;
                  output_high(pwm);
                  if (selection == 'd')output_low(peltier);
                  if (selection == 'u') output_high(peltier);
                  pwm_duty_value = getPwmDuty(pwm_percentage);
                  set_pwm2_duty(pwm_duty_value);
                  //raw temperature value
                  set_adc_channel(3);
                  raw_temp = read_adc();
                  tmpr = getTemp(raw_temp);
                  delay_ms(1000);
                  \operatorname{printf}("\setminus r \setminus n\%f, \setminus r \setminus n", \operatorname{tmpr});
         }
```

```
}
lcd_putc("\f Digital Taste \n");
lcd_putc(" Standby.... \n");
}
```

```
//entry and start the main program
void main()
{
```

```
//initialize all the devices
init();
lcd_init(); // Always call this first.
reset_thermal();
reset_electrical();
lcd_putc("\f Taste Comm\n");
```

```
while(TRUE)
{
    output_high(led);
    showMenu();
    selection = ' ';
}
```

Firmware of Digital Taste

Synthesizer

#include <PID_v1.h>

double Setpoint, Input, Output; int celsius = 0; int cooling = 0; int previousState = 0; int incomingByte; int i = 10; const int epin = 11;

//Specify the links and initial tuning parameters
PID myPID(&Input, &Output, &Setpoint, 2, 5, 1, DIRECT);

double Thermister(int RawADC) {

float Temp;

```
Temp = \log (((10240000 / \text{RawADC}) - 10000));
    Temp = 1 / (0.001129148 + (0.000234125 +
                (0.000000876741 * \text{Temp} * \text{Temp})) * \text{Temp});
    Temp = Temp - 273.15; // Convert Kelvin to Celcius
    Serial.println(Temp);
    return Temp;
}
void setup()
{
  Serial.begin (115200);
  // initialize the digital pin as an output.
  // Pin 13 has an LED connected on most Arduino boards:
  pinMode(12, OUTPUT);
  pinMode(epin, OUTPUT);
  pinMode(10, OUTPUT);
  pinMode(13, OUTPUT);
  pinMode(8, OUTPUT);
  pinMode(7, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(5, OUTPUT);
  pinMode(3, OUTPUT);
  pinMode(9, OUTPUT);
```

pinMode(A0, OUTPUT);// blue pinMode(A1, OUTPUT);// green pinMode(A2, OUTPUT);// red pinMode(A3, INPUT);

```
//initialize the variables we're linked to
Input = analogRead(3);
Setpoint = 650;
```

```
//turn the PID on
```

```
myPID\,.\,SetMode\,(AUTOMATIC\,)\,;
```

```
digitalWrite(7, LOW); //D1 - disable
digitalWrite(5, HIGH); //EN
}
```

```
void loop()
{
   //electric output
   analogWrite(epin, 40);
```

```
if ( (incomingByte != 'd') && (incomingByte != 'o') ) {
  Input = analogRead(3);
  Serial.print("Input:");
```

```
Serial.println(Input);
```

```
celsius = int(Thermister(Input));
myPID.Compute();
```

```
analogWrite(9,Output);
```

```
if (cooling = 1)
```

```
{
   //LED - Blue
    analogWrite(A0,200);
    analogWrite (A1, 0);
    analogWrite (A2, 0);
    //cooling
    digitalWrite(6, HIGH); //IN2
    digitalWrite(3, LOW); //IN1
}
if (\text{cooling} = 0)
    //LED - Red
{
    analogWrite(A0,0);
    analogWrite(A1,0);
    analogWrite (A2,200);
    //heating
    digitalWrite(6, LOW); //IN2
    digitalWrite(3, HIGH); //IN1
}
```

```
delay(20);
}
// see if there's incoming serial data:
if (Serial.available() > 0) {
  // read the oldest byte in the serial buffer:
  incomingByte = Serial.read();
  // if it's a capital H (ASCII 72), start heating:
  if (incomingByte == 'h') {
    cooling = 0;
    Serial.println("Heating");
  }
  // if it's an L (ASCII 76), start cooling:
  if (incomingByte == 'l') {
    cooling = 1;
    Serial.println("Cooling");
  }
  // if it's an D, disable:
  if (incomingByte == 'd') {
    digitalWrite (7, HIGH); //D1 - disable
    digitalWrite (5, LOW); //EN
    digitalWrite (6, LOW); //IN2
    digitalWrite (3, LOW); //IN1
```

```
analogWrite(epin, 0);
  //LED
  analogWrite (A0,130);
  analogWrite (A1,130);
  analogWrite (A2, 130);
  previousState = cooling;
  cooling = 2;
  delay(250);
  Serial.println("Disabled");
}
// if it's an E, enable:
if (incomingByte == 'e') {
  digitalWrite (7, LOW); //D1 - disable
  digitalWrite(5, HIGH); //EN
  cooling = previousState;
  analogWrite(epin, 50);
  //LED
  analogWrite (A0,0);
  analogWrite(A1,150);
```

analogWrite(A2,0);

```
delay(100);
```

```
Serial.println("Enabled");
```

```
}
```

```
// if it's an O, off:
if (incomingByte == 'o') {
  digitalWrite(7, HIGH); //D1 - disable
  digitalWrite(5, LOW); //EN
  digitalWrite(6, LOW); //IN2
  digitalWrite(3, LOW); //IN1
  //LED
  analogWrite(A0,0);
  analogWrite(A1,0);
  analogWrite(A2,0);
```

```
previousState = cooling;
cooling = 2;
```

//electric output
analogWrite(epin, 0);

delay(250); Serial.println("Off");

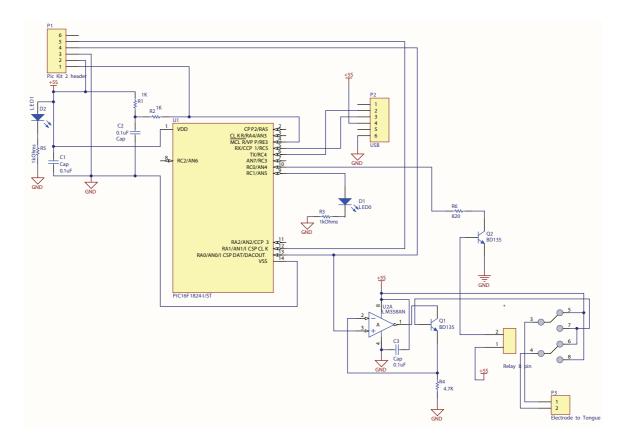
```
}
// electrical
if (incomingByte == '1')
analogWrite(epin, 60);
if (incomingByte == '2')
analogWrite(epin, 40);
if (incomingByte == '3')
analogWrite(epin, 20);
}
```

Schematic, PCB, and Firmware

of Digital Taste Lollipop

Circuit schematic diagram of the control sys-

 \mathbf{tem}



PCB layout of the control system

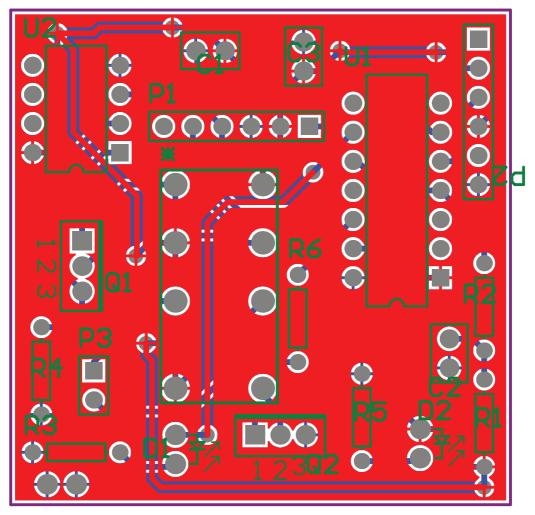


Figure 2: PCB layout of Digital Taste Lollipop

Firmware of Digital Taste Lollipop

#include <16f1824.h>

#include <stdio.h>

#include <stdlib.h>

#use delay(clock=4M, oscillator=1M)

```
#use rs232(baud=9600, xmit=PIN_C4, rcv=PIN_C5, bits=8, stream=USB)
#fuses INTRC_IO, NOPROTECT, NOIESO, NOBROWNOUT, NOWDT, BORV25, PUT, NOCPD
#fuses LVP, NOWRT, NOCPD, NOFCMEN, NOSTVREN, NODEBUG, MCLR
```

```
#use fast_io(A)
```

 $\#use fast_io(C)$

int delay = 25;//1k char selection; //timer settings = 2; //interrupts per second, lower the freq range//2 int intps int int_count = 2; //interrupts count int iCurrent = 1;int duty_cycle = 3;//75% duty cycle//3 int shape = 1;int $\min = 0;$ int max = 0;int down = 0;int show_freq = 0;int show_current = 0;int show_voltage = 0;void printMainMenu()

```
// Welcome message
printf(" Digital Taste Interface ");
printf("Instructions:");
printf("Waveform \ r \ ('Q'-square wave, 'W-sawtooth)");
printf("To select current output");
printf("'a'-25uA, 's'-40uA, 'd'-60uA, 'f'-80uA");
printf("'g'-120uA, 'h'-160uA, 'j'-200uA");
printf("Please select frequency");
printf("'1'-50Hz,'2'-100Hz,'3'-200Hz,'4'-400Hz");
printf("'5'-600Hz,'6'-800Hz,'7'-1000Hz,'8'-1200Hz");
printf("'Q' - Quit from stimulation");
```

```
void invertVoltage()
        if (selection = 'z') //negetive
        {
                if (show_voltage != 1)
                {
                         show_voltage = 1;
                         printf("Inverted Voltage(n r");
                }
                output_high(PIN_C0);
                output_high(PIN_C1);
```

```
}
         if (selection == 'x') // positive
         {
                  if (show_voltage != 2)
                  {
                            show_voltage = 2;
                            printf("Non-inverted Voltage(n(r"));
                  }
                  output_low(PIN_C0);
                  output_low(PIN_C1);
         }
}
void frequen()
{
         if (selection = '1') //50Hz actual 100Hz
         {
                  setup_timer_2(T2_DIV_BY_16, 154, 1);
                  if (\text{show}_{\text{freq}} != 1)
                  {
                            show_freq = 1;
                            printf("Freq = 50Hz \setminus n \setminus r");
                  }
                  delay = 317;
```

```
}
if (selection = '2') //100Hz
{
         setup_timer_2(T2_DIV_BY_16, 76, 1);
         if (\text{show}_freq != 2)
         {
                   show_freq = 2;
                   printf("Freq = 100Hz \setminus n \setminus r");
         }
         delay = 159;
}
if (selection = '3') //200Hz
{
         setup_timer_2(T2_DIV_BY_16, 37, 1);
         if (show_freq != 3)
         {
                   show_freq = 3;
                   printf("Freq = 200Hz \setminus n \setminus r");
         }
         delay = 79;
}
if (selection = '4') //400 \text{Hz}
{
         setup_timer_2(T2_DIV_BY_4, 77, 1);
```

```
if (\text{show}_{\text{freq}} != 4)
          {
                    show_freq = 4;
                    printf("Freq = 400 Hz \ r");
          }
          delay = 40;
}
if (selection = '5') //600Hz
{
          setup_timer_2(T2_DIV_BY_16, 11, 1);
          if (\text{show}_freq != 5)
          {
                    show_freq = 5;
                    printf("Freq = 600Hz \setminus n \setminus r");
          }
          delay = 27;
}
if (selection = 6') //800Hz
{
          setup_timer_2(T2_DIV_BY_4, 38, 1);
          if (\text{show}_f = 6)
          {
                    show_freq = 6;
                    printf("Freq = 800Hz \setminus n \setminus r");
```

```
}
         delay = 20;
}
if (selection = '7') //1000\,\mathrm{Hz}
{
          setup_timer_2(T2_DIV_BY_1, 124, 1);
          if (\text{show}_freq != 7)
         {
                   show_freq = 7;
                   printf("Freq = 1000 Hz \langle n \rangle r");
         }
         delay = 16;
}
if (selection = ^{8}) //1200Hz
{
         setup_timer_2(T2_DIV_BY_4, 25, 1);
          if (\text{show}_{\text{freq}} != 8)
         {
                   show_freq = 8;
                   printf("Freq = 1200 Hz \ r");
         }
         delay = 13;
}
```

}

```
232
```

```
void output_level_square()
{
        if (selection == ';') //step30-->895mV, 195uA (200)
        {
                iCurrent = 12;//30
                 if (show_current != 10)
                {
                         show_current = 10;
                         printf("Current = 200uA (n r");
                }
        }
        if (selection == 'l') //step30-->895mV, 195uA (200)
        {
                //dac_write(30);
                // selection = " ";
                iCurrent = 11;//30
                 if (show\_current != 9)
                {
                         show_current = 9;
                         printf("Current = 180uA (n r");
                }
        }
        if (selection = 'k') //step30-->895mV, 195uA (200)
```

```
{
        iCurrent = 10; //30
        if (show\_current != 8)
        {
                 show_current = 8;
                 printf("Current = 160uA (n r");
        }
}
if (selection = 'j') //step30-->895mV, 195uA (200)
{
        iCurrent = 8; //30
         if (show\_current != 7)
        {
                 show_current = 7;
                 printf("Current = 140uA (n r");
        }
}
else if (selection == 'h') //step-->706mV, 165uA (160)
{
        iCurrent = 7; / / 29
         if (show\_current != 6)
        {
                 show_current = 6;
                 printf("Current = 120uA (n r");
```

```
}
}
else if (selection = 'g') //step-->500mV, 115uA (120)
{
        iCurrent = 6; //28
        if (show\_current != 5)
        {
                 show_current = 5;
                 printf("Current = 100uA (n r");
        }
}
else if (selection == 'f') //step -->365mV, 77uA (80)
{
        iCurrent = 5; //25
        if (show\_current != 4)
        {
                 show_current = 4;
                 printf("Current = 80uA (n r");
        }
}
else if (selection == 'd') //step -->279mV, 60uA (60)
{
        iCurrent = 3;//22
        if (show_current != 3)
```

```
{
                   show_current = 3;
                   printf("Current = 60uA \ r");
         }
}
else if (selection == 's') //step 14--> 183mV, 39uA (40)
{
         iCurrent = 2; / / 17
         if (show\_current != 2)
         {
                   show_current = 2;
                   printf("Current = 40uA \langle n \langle r" \rangle);
         }
}
else if (selection == 'a') //step 5-->89mV, 19uA (20)
{
         iCurrent = 1; / / 5
         if (show\_current != 1)
         {
                   show_current = 1;
                   printf("Current = 20uA \langle n \langle r" \rangle);
         }
}
else
```

```
iCurrent = iCurrent;
}
void output_waveform()
{
         if (selection = 'q') //square wave
                 shape = 1;
         if (selection = 'w')
                 shape = 2;
}
\#int_rda//RS232
void isr()
{
         selection = getc(USB);
         printf ("Selection: %c \setminus r \setminus n", selection);
        CLEAR_INTERRUPT(INT_RDA);
}
#INT_TIMER2
void isr_timer()
{
         if(show_voltage == 1)
         {
```

```
if(-int_count = 0)//int_count = 2
        {
                  if (duty_cycle > 0) / / duty_cycle = 3
                 {
                          dac_write(iCurrent);
                          duty_cycle --;
                 }
                  else
                 {
                          dac_write(0);
                          duty\_cycle=3;
        //75\% duty cycle -->3/4=75\%//3
                 }
                 int\_count = intps;
        }
else
        if(--int\_count==0)//int\_count = 2
        {
                 if (duty\_cycle > 0) / / duty\_cycle = 3
                 {
                          dac_write(iCurrent);
                          duty_cycle --;
```

}

{

```
}
                             else
                             {
                                       dac_write(0);
                                       duty_cycle = 3;
                   //75\% duty cycle -{>}3/4{=}75\%//3
                             }
                             int_count = intps;
                   }
         }
}
void sawtooth()
{
         max = iCurrent;
          if ((\min <= \max)\&\&(\operatorname{down}!=1))
         {
                   dac_write(min);
                   delay_us(delay);
                   if(min = max)
                   {
                             down = 1;
                             \min --;
                   }
```

```
else
                          \min++;
        }
        else
        {
                 dac_write(min);
                 delay_us(delay);
                 if(min = 0)
                 {
                         down = 0;
                          \min ++;
                 }
                 else
                         \min --;
        }
}
void main()
{
        CLEAR_INTERRUPT(INT_RDA);
        ENABLE_INTERRUPTS(INT_RDA);
        ENABLE_INTERRUPTS(GLOBAL);
        ENABLE_INTERRUPTS(INT_TIMER2);
        setup_oscillator ( OSC_4MHZ |
```

//1 - input : 0 - output //A5 A4 A3 A2 A1 A0 // 0 0 1 0 0 0 $//\,{\rm C5}\ {\rm C4}\ {\rm C3}\ {\rm C2}\ {\rm C1}\ {\rm C0}$ // 1 0 0 0 0 0 $set_tris_A(0x08);$ $set_tris_C(0x20);$

```
setup_dac(DAC_VSS_VDD |
```

{

```
DAC_OUTPUT | OSC_NORMAL); //set dac
setup_timer_2(T2_DIV_BY_16, 154, 1);
```

```
while (1)
        output_waveform ();
        if(shape == 1)
        {
                 invertVoltage();
                 frequen();
                 output_level_square();
        }
        else
```

{

frequen();

output_level_square();

