Trumpet Augmentation: Rebirth and Symbiosis of an Acoustic Instrument

Joseph L N Thibodeau



Music Technology Area Schulich School of Music McGill University Montreal, Canada

January 2011

A thesis submitted to McGill University in partial fulfillment of the requirements for the degree of Master of Arts.

 \bigodot 2011 Joseph L N Thibodeau

Abstract

This thesis contributes to the field of instrument augmentation, with a focus on trumpet augmentation. Augmented instruments are acoustic instruments onto which electronics (such as sensors) have been mounted for the purpose of controlling digital sounds. Trumpets make ideal candidates for augmentation. They have both spare performer "bandwidth", conducive to interaction, and spare physical space, affording augmentation.

The underlying concepts of augmented instrument design are explored, followed by a review and discussion of existing augmented trumpets. There are common aspects to many of these examples, such as the use of buttons placed at or near the left-hand playing position and the focus on measuring or mimicking trumpet valves. To investigate the common focus on valve position measurement, three valve position sensing technologies based on historical precedents as well as a fourth technology identified by the author are compared using a specially constructed sensor chassis.

Finally, a modular augmented trumpet design platform is proposed as an alternative to entirely custom-built projects. The prototype implementation of this system is presented and evaluated. The results of the prototype evaluation point towards future improvements and research directions towards standardizing elements of augmented trumpet design.

Sommaire

Cette thèse contribue au domaine de l'augmentation des instruments de musique et plus particulièrement de la trompette. Les instruments augmentés sont des instruments de musique acoustiques sur lesquels sont installés des composants électroniques (par exemple des capteurs) dans le but de contrôler les sons numériques. La trompette est un candidat idéal pour l'augmentation parce que cet instrument possède beaucoup d'espace physique libre sur lequel on peut monter les composants électroniques, et beaucoup d'espace mental libre qui peut servir à interagir avec les augmentations.

Les idées centrales à la conception des instruments augmentés sont explorées, suivies d'un examen et d'une discussion des trompettes augmentées existantes. Il y a des aspects communs à bon nombre de ces exemples, tels que l'utilisation de boutons placés près de la position de performance de la main gauche et la mesure ou l'imitation des pistons de la trompette. Pour étudier le point commun de la mesure de position des pistons, trois capteurs de position des pistons de trompette basée sur des précédents historiques, ainsi qu'un quatrième capteur identifié par l'auteur, sont comparés en utilisant un chssis de capteurs spécialement conus.

Enfin, une plate-forme modulaire pour la conception de trompettes augmentées est proposée comme une alternative à des projets complètement faite sur mesure. La mise en oeuvre d'un prototype de ce système est présentée et évaluée. Les résultats de l'évaluation suggèrent des améliorations futures et des directions de recherche vers la standardisation des éléments de conception de trompette augmentée.

Acknowledgments

I would like to thank my supervisor Marcelo Wanderley, my research partner Avrum Hollinger and all my comrades at the IDMIL for their wisdom and antics. Darryl Cameron provided critical technical support at every step, as well as vital comedy relief. Thanks to all the instrument designers who sent me information about their projects, and to Antoine Lefebvre for his generous help in designing the sensor chassis described in chapter 4.

Thanks to my true love Laura and my parents Richard and Sylvia for helping me through the madness of graduate studies, and special thanks to Timothy Sutton for inspiring me to pursue music technology in the first place.

Contents

1	Introduction							
	1.1	Motivation for Instrument Augmentation	1					
	1.2	Accessibility of Augmentation Technology	1					
	1.3	Trumpet Suitability	2					
	1.4	Scope of Research	2					
	1.5	Thesis Structure	3					
2	\mathbf{Des}	Designing a Trumpet Augmentation						
	2.1	Musical Goals	4					
	2.2	Gestural Design	5					
		2.2.1 Performance Gestures and Overloaded Techniques	5					
		2.2.2 New Gestures	9					
		2.2.3 Interface Defines Gesture	10					
	2.3	Measurement of a Gesture	11					
	2.4	Performance Feedback	13					
	2.5	Placement	13					
		2.5.1 Real Estate \ldots	13					
		2.5.2 Attachment Mechanisms	14					
	2.6	Signal Flow for Mapping and Synthesis	15					
	2.7	Playing and Evaluating	16					
3	Exi	sting Implementations	17					
	3.1	Trumpet Performance System	17					
	3.2	Meta-Trumpet	20					
	3.3	Mutantrumpet	22					

Contents

	3.4	Trump	bet MIDI Controller	25
	3.5	Electr	umpet	27
	3.6	Gluipł	n/Gluion Trumpets	29
	3.7	Electr	umpet	29
	3.8	Mouth	piece Pressure Studies	31
	3.9	Comm	nonalities	32
4	Valv	ve Sens	sing Experiment	36
	4.1	Introd	uction	36
	4.2	Sensor	Details	37
		4.2.1	Hall Effect	37
		4.2.2	Visible-red LED	39
		4.2.3	Linear Slide Potentiometer	41
		4.2.4	LVDT	43
	4.3	Experi	imental Method	46
		4.3.1	Sensor Placement	47
		4.3.2	Measurement Setup	49
		4.3.3	Procedure	49
	4.4	Result	s	50
5	Svn	nbiote:	Modular Augmented Trumpet	56
-	5.1	Motiva	ation \ldots	56
	5.2	Backg	round	57
	5.3	Design	1	58
		5.3.1	Hub	59
		5.3.2	Node	59
		5.3.3	Communications	59
		5.3.4	Mapping and Synthesis	60
		5.3.5	Workflow	60
	5.4	Impler	nentation	60
		5.4.1	Hub	61
		5.4.2	Node	62
		5.4.3	Communications	62

 \mathbf{v}

		5.4.4	Mapping and Synthesis	63
		5.4.5	Attachment of Augmentations	64
	5.5	Evalua	tion	64
6	Con	clusio	ns and Future Plans	66
	6.1	Conclu	sions	66
	6.2	Future	Plans	67
		6.2.1	Valve Sensing	67
		6.2.2	Mouthpiece Pressure Sensing	67
		6.2.3	Symbiote	68
		6.2.4	Final Word	68
R	efere	nces		69

\mathbf{vi}

List of Figures

2.1	Force applied to valve cap used as unobtrusive "after-touch" control parameter.	6
2.2	Example of how alternate fingerings could be used as unobtrusive control	
	parameter	7
2.3	Using "improper" technique (left) to allow unobtrusive interaction with bell-	
	pipe augmentations. Proper finger position shown at right	9
2.4	A simple threshold distance sensor can still allow nuanced variations using	
	temporal information. \ldots	12
2.5	Trumpet with playing positions highlighted.	14
2.6	Two examples of augmentation attachment mechanisms	15
3.1	Dexter Morrill holding the augmented trumpet he made with Perry Cook,	
	and a detailed view of the trumpet's user interface (images courtesy of Perry	
	Cook)	18
3.2	Morrill-Cook electronic augmentations.	19
3.3	Impett-Bongers "Meta-Trumpet"—note custom valve bottom caps (image	
	courtesy of Bert Bongers)	20
3.4	Meta-Trumpet electronic augmentations.	21
3.5	Ben Neill's "Mutantrumpet", with acoustic and electronic augmentations	
	(image courtesy of Ben Neill)	23
3.6	Mutantrumpet electronic augmentations (acoustic augmentations not shown).	24
3.7	Craig-Factor "Trumpet MIDI Controller" uses underslung valve position sen-	
	sors [Craig and Factor, 2008] (image courtesy of Thomas Craig) $\ldots \ldots$	25
3.8	Trumpet MIDI controller electronic augmentations.	26
3.9	"Electrumpet" by Hans Leeuw, notable for its LCD feedback augmentation	
	(images courtesy of Hans Leeuw)	27

3.10	Electrumpet electronic augmentations (acoustic augmentation not shown).	29
3.11	Axel Dörner's Gluion-based augmented trumpet. Breath pressure sensor not	
	shown (image courtesy of Sukandar Kartadinata)	30
4.1	The Hall effect.	37
4.2	Hall effect differential sensing circuit.	39
4.3	Morrill and Cook's optical sensing principle, where a drilled valve piston	
	extension blocks two opto-pairs to produce four positional states. $\ . \ . \ .$	40
4.4	Craig-Factor optical distance sensor using visible-red LEDs	40
4.5	Potentiometer circuit	42
4.6	LVDT operation. A primary excitation is echoed at the secondary coils in	
	opposite phases	44
4.7	LVDT signal conditioning board based on design by Jean-Loup Florens at	
	ACROE	45
4.8	Signal flow through the LVDT signal conditioning board. Secondary outputs	
	are summed and sampled in-phase with the peak of the sinusoid	45
4.9	Sensor chassis, bare and populated	47
4.10	Side-mounted sensors, "P" indicating potentiometer and "L" indicating LVDT	
	(embedded in chassis). Under-mounted sensors (one valve shown), with inset	
	highlighting sensor placement. Two Hall effect sensors are used in opposite	
	polarity for increased sensitivity	48
4.11	Wooden support structure	49
4.12	Closeup of overhang and actuation mechanism	50
4.13	Caliper measuring position	51
4.14	Experimental results of four sensors averaged from three trials	52
4.15	Experimental results without potentiometer averaged from two trials	54
5.1	Architecture underlying the Symbiote design platform.	58
5.2	Symbiote prototype (some assembly required)	61
5.3	Symbiote prototype node arrangement	64
5.4	Symbiote prototype with attached augmentations.	65

List of Tables

2.1	Trumpet fingerings, alternates in white. Fingerings show values states with	
	"000" indicating all values open and "100" indicating value#1 depressed	
	with valves #2 and #3 open. Adapted with permission from [Spang, 1999]	8
3.1	Summary of well-documented augmented trumpets.	33
3.2	Summary of well-documented augmented trumpets (continued)	34
4.1	Experimental results of four sensors averaged from three trials. *The high	
	nonlinearity of the potentiometer is due to limited range-of-motion. If only	
	the active range is considered, its nonlinearity is 5.5%	50
4.2	Experimental results without potentiometer averaged from two trials	53

Prologue

I began my work on trumpet augmentation for entirely personal reasons. I wanted to create an instrument that would have the parts of the trumpet that I loved and that would produce the electronic sounds I craved. Over the course of my studies my motivations changed to include as paramount the dissemination of augmentation concepts and technology. I believe that acoustic musicians need not be confined by the dedication and practice they put into their craft.

As an engineer and a musician I am in a privileged position to modify a beloved instrument to create the sounds I desire. I hope dearly that my current and future work into trumpet (and instrument) augmentation will make this kind of technology more accessible and comprehensive to all musicians.

Chapter 1

Introduction

1.1 Motivation for Instrument Augmentation

There are musicians and instrument-builders in the world who are not satisfied with the sonic limitations of acoustic instruments. The existence of $augmented^1$ instruments as a field of study states this point quite definitely. This is not to imply that acoustic instruments are somehow inadequate; simply that they are bound by their physical characteristics. Electronically augmenting an acoustic instrument through the attachment of sensors to measure performance gestures [Miranda and Wanderley, 2006] gives it nearly limitless potential as a controller and producer of sound.

As a subject of study, augmented instruments represent a fascinating intersection between traditional technique and modern technology. They are a crossbreed of extremely mature acoustic musical theory with as-yet immature but immensely powerful gestural sound control.

1.2 Accessibility of Augmentation Technology

Progress towards a better understanding of how to build and use augmented instruments would benefit from large-scale experimentation. The concept of *accessibility* is of great importance, from the standpoint of the technical expertise to build a project as well as the theoretical knowledge to approach one without having to "reinvent the wheel".

¹effectively synonymous in the literature with the terminology hyper, hybrid, extended and meta [Miranda and Wanderley, 2006]

1 Introduction

Most important of all is the musical experimentation that would result from a large population having access to augmentation technology. The expressive capability of music and the vital social dialogue catalyzed by artistic expression—would be augmented along with the tools.

1.3 Trumpet Suitability

Many different types of acoustic instruments have been augmented [Miranda and Wanderley, 2006], each posing different challenges in design and construction. For example, Cléo Palacio-Quentin found that augmenting the flute posed a challenge "because of the complexity and small size of its key mechanism". Trumpets are ideal candidates for augmentation due in large part to the players "spare bandwidth" [Morrill and Cook, 1989] [Cook, 2001]–that is to say the parts of the body that are unoccupied by performing the instrument. The left hand does not critically affect performance and can be used to interact with sensors instead of just supporting the weight of the horn. Contrast this with a clarinet where both of the player's hands are occupied, or with a harmonium where the player's hands and feet are all busy manipulating the instrument. An instrument with less "spare bandwidth" can certainly be augmented, however the almost unavoidable clash between augmented and normal interaction creates obtrusiveness problems which on a trumpet are easier to avoid.

In terms of the physical form of a trumpet, there is a large amount of free space upon which to place augmentations. There aren't any linkages that on a clarinet would impose difficult challenges and limitations, and the hand positions on a trumpet are for the most part static.

Finally, the way that the trumpet projects sound makes it suitable for augmentation. Since the grand majority of the sound emitted by the horn is projected outwards from the bell, it can be muffled and/or recorded easily if so desired. It is difficult to perform a similar function on instruments whose sound projection is more complicated.

1.4 Scope of Research

The focus of my research on augmented trumpets is mainly due to personal musical goals and the practical suitability of trumpets as "host" instruments for augmentation. Another contributing reason for the focus on trumpets is the wealth of trumpet augmentation

1 Introduction

projects in the literature. A study of these projects yields valuable information on the way in which people have approached augmentation and the realities of building and playing such an instrument. My ultimate goal is the creation of a type of augmentation technology which:

- can be attached and detached from any model of acoustic trumpet
- does not require damaging modification to the host trumpet,
- is reconfigurable by the addition or subtraction of modular elements,
- inspires new trumpet playing techniques that harness digital synthesis.

1.5 Thesis Structure

- **Chapter two** builds a conceptual foundation for augmented instrument design, with focus on augmented trumpet design.
- **Chapter three** reviews existing trumpet augmentations that are documented and/or referenced in the academic literature.
- **Chapter four** compares three trumpet valve sensing alternatives identified in chapter three, plus a fourth alternative not yet documented in an augmented trumpet.
- **Chapter five** proposes a design and presents an implementation of a modular trumpet augmentation design platform.
- Chapter six discusses the conclusions of this work and my plans for future research

Chapter 2

Designing a Trumpet Augmentation

Designing an augmented instrument involves many separate—sometimes competing—elements. It is in many ways the same as designing a digital musical instrument from scratch. Basing it on an existing acoustic instrument brings unique opportunities and limitations. In the following steps I have outlined a design approach that takes into consideration the particularities of designing an augmented instrument, and more specifically an augmented trumpet. If you are planning on tackling an augmentation project, this should help form a good conceptual foundation.

2.1 Musical Goals

It is vital to start any project with a goal, and likewise to start a musical project with a musical goal [Cook, 2001]. Goals can take many forms: specific sounds, processing techniques, aesthetic manifestos and compositional roles but to name a few. To avoid becoming lost in the possibilities, think about how the end product will be used. Every part of the design will be affected by questions of purpose.

To which style(s) of music will it be well-suited? Will it be played in a very fast and technically demanding way or will long tones be of primary interest? Will the natural sound of the trumpet be processed, muffled, or analyzed in any way? Will it be played with quantized music, requiring some synchronization with other machines? Will it be played with spectacular body motions or in a subdued manner?

For that matter, will the existing gestural interactions with the instrument be measured and exploited in some way?

2.2 Gestural Design

Firstly, what is a gesture? The word is used differently by different authors, and I choose to employ it as defined by Miranda and Wanderley [Miranda and Wanderley, 2006]:

...the term gesture is used in a broad sense to mean any human action used to generate sounds. The term refers to actions such as grasping, manipulation, and noncontact movements, as well as to general voluntary body movements.

Furthermore, in this augmented instrument design context I assume that gestures are made with the intention to generate sounds (i.e. performance gestures) [Miranda and Wanderley, 2006] In other words, gestures are the human movements that translate the ideas of music into the music itself.

In the design of a digital musical instrument there are an almost limitless variety of gestures and ways to measure them. Augmenting an acoustic instrument provides some limitations to the designer's palette of feasible gestures because of the existing performance gestures which have been developed over centuries of acoustic practice. Performance gestures may or may not be used in an augmentation, but they surely must be taken into consideration.

2.2.1 Performance Gestures and Overloaded Techniques

The traditional interactions between the performer and the trumpet are straightforward to approach because they are the most familiar. For example, a trumpet player will press on the valves of the trumpet with the fingers of the right hand and will press on the mouthpiece of the trumpet with her lips. Perhaps less obviously, a performer will tend to move and sway their body and the instrument during performance [Wanderley et al., 2005].

The main question involved in considering performance gestures as sources of electronic sound control is whether or not the instrument should be playable in the normal way in addition to the augmented way. Granting augmented control to existing and practiced motions is an advantage precisely because of the practiced nature of these motions; the player has already developed nuanced techniques. On the other hand, intruding upon the trumpet performance techniques of the instrument—known as *overloading* the techniques limits the degree to which the instrument can be played in the normal way.

A good example of overloading a technique can be seen in Todd Machover's hypercello as played by YoYo Ma [Machover, 1992]. In one mode of operation, the bow is divided into sections, each controlling the playback of a different recorded sound. The normal bowing technique is changed by this additional responsibility and the cello cannot be indiscriminately used as though it were purely acoustic. There are of course various degrees of overloading, and there are even ways of augmenting trumpet performance techniques with negligible intrusion upon acoustic playability.

On a trumpet there is at least one example of augmenting a trumpet performance technique without intrusion, and that is to measure the pressure applied to the tops of the trumpet valves—provided that these will have no effect until the valve is fully depressed (figure 2.1). In such a way one augments the trumpet with a sort of "after touch" capability. This highlights the importance of identifying which trumpet performance gestures (or parts thereof) have an acoustic consequence.



Fig. 2.1 Force applied to valve cap used as unobtrusive "after-touch" control parameter.

There is an even less obvious interaction that can be exploited during trumpet performance. It is the use of *improper* or *alternate* technique, and on a trumpet it can be measured and used without affecting the normal use of the trumpet. Two examples of such improper technique on the trumpet are the use of alternate fingerings and the use of the knuckles to press the valves.

Table 2.2.1 shows the notes produced by depressing different combinations of the valves. For example, to play an E5 (concert D5), the trumpet player can use three different fingering positions (000, 110, 001) of which one is the primary (000) and two are alternates (110 and 001). Alternate fingerings are not used in every register, but of particular interest is the fact that the third valve is *never used* on its own during normal trumpet performance, even though it is a perfectly valid interaction with the instrument. The reason for this is that the alternate fingerings produce, depending on the register, out-of-tune notes (the player must "correct" for this by bending the note). The use of alternate fingerings—including the solitary third valve—isn't unheard of¹, but for the purposes of augmentation it can be exploited with negligible intrusion upon the playability of the horn. Figure 2.2 illustrates an example of such use.



Fig. 2.2 Example of how alternate fingerings could be used as unobtrusive control parameter.

Sometimes, a trumpeter might press the valves down with their knuckles instead of the pads of the fingers as shown in figure 2.3. This is a bad habit that can cause the valves to stick due to lateral force applied along with the desired vertical force. There is some salvageable augmentation to be had in this habit since it frees up the pads of the fingers to interact with augmentations such as switches or distance sensors mounted on the bell

 $^{^{1}}$ Jazz trumpeters such as the late Freddy Hubbard used them in unison rhythmic passages as an articulation mechanism by alternating between two or three fingerings of the same note.

Fingering	000	010	100	110	011	101	111	001
F#3							•	
G3						•		
Aþ3					•			
A3				•				0
Bþ3			•					
B3		•						
C4	•							
C#4							•	
D4						•		
Eb4					•			
E4				•				0
F4			•					
$F \sharp 4$		•					0	
G4	•					0		
Ab4					•			
A4				•				0
Bb4			•				0	
B4		•				0		
C5	•				0			
$C \sharp 5$				•			0	0
D5			•			0		
Eþ5		•			0			
E5	•			0			0	0
F5			•			0		
$F \sharp 5$		•			0		0	
G5	•			0		0		
Aþ5			0		•		0	
A5		0		•		0		0
Βþ5	0		•		0			
B5		•		0		0		
C6	•		0		0			

Table 2.1 Trumpet fingerings, alternates in white. Fingerings show valves states with "000" indicating all valves open and "100" indicating valve#1 depressed with valves#2 and #3 open. Adapted with permission from [Spang, 1999]

pipe of the trumpet. There is no documented evidence of the use of the knuckles as an *intentional* design element, however some augmented trumpets such as the Meta-Trumpet [Impett, 1994] would be usable in this fashion, since it has buttons mounted on the bell pipe alongside the valves.



Fig. 2.3 Using "improper" technique (left) to allow unobtrusive interaction with bell-pipe augmentations. Proper finger position shown at right.

The question of *how* to augment performance gestures towards the musical goals determined earlier is very difficult to answer. Trumpet performance gestures can be well-defined, so the sound control must conform to match the characteristics of these gestures to some degree. On the opposite end of the spectrum are entirely new gestures created by augmenting interactions with the instrument that are not normally used, and that might not even have sonic consequences without augmentations. In such cases the gesture can be created (practically) from scratch to match the desired musical goals.

2.2.2 New Gestures

There is a wealth of "spare bandwidth" available in trumpet augmentation, particularly with regards to the left hand. Coupled with the relatively small size and mass of the horn (ease of manipulating the instrument), this provides the augmented trumpet designer with a great deal of possibilities and questions.

Beyond the hands (manipulations of the horn's surface), there is potential for augmenting gestures in the stance of the player and the position of the trumpet relative to the body and the surrounding environment [Impett, 1994]. The way the player moves and sways their body and the instrument was given previously as an example of an existing gesture,

and hints at the types of new gestures that can be created.

By creating a new trumpet gesture, one creates a new channel of expression. The musician's potential in applying the new gesture is hard to judge quickly due to its novelty, but generally speaking a gesture definition that leaves some room for variations and subtleties will be usable in creative and nuanced ways—although this statement depends heavily on the ability of the *mapping scheme* to translate the gesture into sound [Rovan et al., 1997].

The definition of the gesture also has an effect on the ability of the audience to interpret the instrument in performance. Gestures that are "simple to correlate" to the resultant sound have the potential to convey their impact on the music quite directly [Stewart, 2010], and it follows that the correlation between gesture and sound can be manipulated to control the audience's level of understanding. Seemingly simple gestures can be *measured* in ways that reveal their subtleties and *mapped* in ways that communicate them.

For example, consider the following arbitrary trumpet augmentation as defined by a gesture:

The trumpet player slides their hand down the bell of the trumpet away from their body, and as their hand gets closer to the bell the sound of the trumpet becomes more and more muffled, as though by a mute.

While at the outset this may seem like a simple definition to implement, there is much to think about regarding its design. Does it matter which parts of the hand are used; is a finger enough? Could there be different musical consequences to using different parts of the hand, and is it therefore important to be able to measure which parts are being used? For that matter, does it make a difference which hand is being used? How far back along the bell-pipe does this gesture apply? Does the lateral position of the hand on the horn affect anything(such as the timbral effect of the muting)?

For the moment it is not strictly necessary to address these questions, but they must be understood and prioritized. The inevitable limitations encountered during practical design and implementation can thus be accommodated and the match between gesture and sound can be as close as reasonably possible.

2.2.3 Interface Defines Gesture

Instead of designing a gesture explicitly, one might simply place interface components on the trumpet and allow the gestures to follow. These components can even be quite familiar such as the knobs and sliders used on the majority of audio gear. The distinct advantage of such an approach is the ease with which an augmentation can be designed and built, explaining why it is the most common approach to augmented trumpet design (refer to chapter three). However, by forfeiting aesthetic control over the gesture I believe that one forfeits a rich vein of creative design ideas.

2.3 Measurement of a Gesture

A defined gestural control method requires measurement by a sensor before it can be mapped to sound. "A sensor is a device that responds to stimuli by producing electrical signals" [Miranda and Wanderley, 2006] and is usually associated with some degree of signal conditioning. The signal conditioning prepares the electrical output of the sensor to be used in mapping and synthesis (for example, by amplifying the sensor output into an optimum voltage range for a computer's digital-to-analogue converter).

For a given gesture, there will be many possible sensing solutions each with distinct advantages and disadvantages. Consider the desired level of detail in the measurement and the properties of the outgoing signal. Is it important to be able to measure a continuous value, or are a few discrete steps sufficient? For example a Hall Effect sensor is a magnetic position sensor that outputs either continuously or as a threshold-switch, depending on the model (for more information on Hall effect sensors refer to section 4.2.1). Some intentions, such as cueing the start of a new section of a composition, would be sufficiently represented by a binary value. Other intentions, such as setting an effect parameter, would be predisposed to a continuous value.

Beware, however, that with clever conditioning and analysis a simple type of measurement can adequately represent a complicated gesture! An on/off distance threshold could be analyzed temporally to represent many variations, shown in figure 2.4.

The key point is to narrow down the available sensing options to a set of feasible alternatives which can be tested and compared to determine the most suitable one. There is a wealth of published information about the general use and comparison of different types of sensors in print(eg. [Miranda and Wanderley, 2006], [Nyce, 2004], [Wilson, 2005]) and online (eg. *Sensorwiki* [Wanderley et al., 2006]). Chapter four presents a detailed comparison between sensing alternatives in an augmentation context. Meanwhile, here are some terms that I find very useful for evaluating and comparing sensors in augmentation:



Fig. 2.4 A simple threshold distance sensor can still allow nuanced variations using temporal information.

- **Intrusiveness** is the degree to which an augmentation requires physical (possibly nonreversible) modification of the instrument. Physical modification is time–consuming and potentially damaging, making an *intrusive* augmentation generally less desirable.
- **Obtrusiveness** is how much an augmentation will physically hinder the performance of the instrument. Not to be confused with *overloaded technique*, which is the augmentation of existing performance technique.
- **Restrictiveness** is similar to physical obtrusiveness, but refers to the mobility of the performer within the performance environment. For example, distance measurements between the floor and the instrument are more restrictive than distance measurements between the performer and the instrument.
- **Robustness** refers simply to the physical endurance of the augmentation, its projected lifespan. This is dependent on the quality of construction, type of electronic components used, physical placement on the instrument and performance style.

2.4 Performance Feedback

An acoustic instrument inherently provides multimodal performance feedback to the player. It takes the form of heard and felt vibrations, visible and touchable instrument state. Feedback is how a player knows the coupling between their actions and the produced sound, and there is a significant body of research on the subject of feedback design [Miranda and Wanderley, 2006].

An electronic instrument, and for that matter electronic augmentations, needn't have any feedback mode at all except the sound produced—which conceivably needn't even be played back to the player [Miranda and Wanderley, 2006]. Non-contact instruments such as the theremin demonstrate low-feedback possibilities. It is wise to consider feedback in augmentation design—even something as simple (and clichéd) as a few LEDs to show the state of the instrument, as used in the Buchla Lightning [Rich, 1991].

The considerations of *intrusiveness, obtrusiveness, restrictiveness and robustness* in designing sensors apply to designing performance feedback augmentations. In addition there are particular restrictions, such as line-of-sight and viewing angle in the case of an LCD display, which will factor into the overall configuration of an augmentation on the body of the instrument.

2.5 Placement

2.5.1 Real Estate

Each type of acoustic instrument will have different affordances for the physical placement of augmentations. The less room there is to play with, the more difficult it is to arrange augmentations without obtruding performance. As mentioned earlier, the trumpet has a lot of free space upon which to put augmentations. Figure 2.5 shows the various parts of the trumpet. The highlighted areas represent the normal hand positions during play.

The valves and mouthpiece are easily accessible, although care must be taken not to obtrude too much on the playing positions. Augmentations around the valves are least obtrusive when underslung or mounted under the right-hand position. This being stated, the left hand acts mostly as a structural support and can deal with bulky augmentations as long as there is something to comfortably grip.

In general it is common to place buttons in close proximity to the normal hand positions on an augmented instrument (such as the *Hyperflute* [Palacio-Quintin, 2003], the *Meta*-



Fig. 2.5 Trumpet with playing positions highlighted.

Saxophone [Burtner, 2003] and all of the augmented trumpets reviewed in chapter three) for fast access. Needing to move the hands from the playing positions in order to interact with augmentations slows the interaction but provides an obvious gestural cue.

Along the top of the instrument the player's visibility of augmentations is unblocked an obvious choice for placement of visual feedback augentations, but it depends on who should be able to see the feedback. Something worth considering is that visual feedback for the audience can help them to understand the instrument in performance, as employed in Gabriel Vigliensoni's SoundCatcher [Vigliensoni and Wanderley, 2010].

2.5.2 Attachment Mechanisms

The shape of a trumpet makes it easy to attach augmentations. Vise-like mechanisms can be used on virtually any part of the instrument and can even host large augmentations. Clamps made out of molded plastic can mount sensors onto tubing as used by Cléo Palacio-Quentin². Even something as simple as velcro serves as a versatile and easily modifiable augmentation attachment mechanism.

Trumpet valve caps are removable for ease of maintenance and repair. This is both an

 $^{^2 \}rm Based$ on personal consultation with Cléo Palacio-Quentin regarding attachment mechanisms for the Hyper Bass Flute [Palacio-Quintin, 2008] in summer 2009



Fig. 2.6 Two examples of augmentation attachment mechanisms.

advantage and a disadvantage owing to the act of twisting the cap. On the one hand, a set of augmented valve caps could be easily swapped in and out for the use of the trumpet in its traditional mode without the added bulk of sensors. On the other hand, the wiring of the augmentations must be able to rotate several times around, either through lengthly wires (which are prone to entanglement) or through a free-rotating mount under the sensor. The latter would be more structurally and aesthetically sound, reducing the risk of sensor damage and keeping wires out of the way.

2.6 Signal Flow for Mapping and Synthesis

The signals created by various sensors must be transported to a computer for mapping and for synthesis. A common approach is to marshall all the sensor data with a microcontroller (such as an Arduino³) or FPGA (such as a Gluion [Kartadinata, 2006]) and to translate these data into serial, MIDI or OSC data for digital synthesis on a personal computer. The advantage to this is in computing power, but with reliance on a personal computer comes the restrictiveness of being chained to it and the risk of software crashes.

Using wireless microcontroller technologies such as Bluetooth is a sure way to decrease

³http://www.arduino.cc/

the restrictiveness of an augmented instrument, allowing much more flexibility for the placement of processing units without the need for entangling wires. Along these lines the recently presented MiniBee [Baalman et al., 2010], a collaborative project between McGill and Concordia Universities, could prove to be an attractive option. An augmented trumpet could broadcast its sensor outputs to more than one computer for mapping and synthesis, thus mitigating the damage in the case that any one of the processing machines goes down.

In the most self-contained example, all of the sensor data acquisition, mapping and synthesis would take place on a computer mounted on the trumpet itself, which would be a robust solution. Such an instrument would have a voice all to its own and would be independent from crash-prone personal computers. This would come at the cost of processing power and necessary technical expertise.

2.7 Playing and Evaluating

As with any design, testing is absolutely necessary to determine whether the product meets the specifications. Fortunately, testing musical controllers can be a fun and rewarding experience regardless of the outcome (unlike, say, testing an automated telephone menu system). Each performance can reveal shortfalls and possible improvements, of unexpected behaviours which may even end up being desirable, of anything that will help you to figure out whether or not the instrument satisfies your needs.

Evaluation of existing projects is just as important as evaluation of your own design. A few minutes reading about someone else's work can save a lot of effort, and can inspire creativity. In the next chapter I review and compare the trumpet augmentations that have already been built.

Chapter 3

Existing Implementations

Many augmented trumpets have been made over the years. What follows is a review of documented projects that represent a good starting-point for discussions on how augmentation has been historically approached.

3.1 Trumpet Performance System

This first example was made in 1989 for Wynton Marsalis to perform a composition by Dexter Morrill entitled "Sketches for Invisible Man". The instrument was intended "...to increase the bandwidth of control information for interactive musical performance" [Morrill and Cook, 1989]. Morrill and Cook's work is thorough, including a detailed comparison of trumpet pitch detection techniques [Cook et al., 1992] for use in the project.

Augmentations:¹

- 1. Micro switches mounted so that they can be operated with the thumbs or fingers.
- 2. A slide pot with finger ring which can be actuated with the thumbs or fingers.
- 3. Three switches mounted under the valves, actuated by either depressing the valves, or by pressing the switch actuator extensions below the valves.

¹List of augmentations quoted directly from Hardware, Software, and Compositional Tools for a Real Time Improvised Solo Trumpet Work [Morrill and Cook, 1989]



Fig. 3.1 Dexter Morrill holding the augmented trumpet he made with Perry Cook, and a detailed view of the trumpet's user interface (images courtesy of Perry Cook).

- 4. A transducer for pitch detection. On the trumpet, this is a transducer mounted in the mouthpiece. [...]
- 5. An envelope follower which provides a logic signal when signal is detected. The input for this circuit is the horn-mounted transducer.

Communications and Processing:

1. sensor outputs processed on an NeXT computer via serial communication



Fig. 3.2 Morrill-Cook electronic augmentations.

Their interface design (illustrated in figure 3.2) focuses on the normal playing positions and the immediate area around the hands, allowing quick access to the new controls. Sensors are stimulated directly (in the case of micro switches, slide pot and switch actuator extensions) or indirectly (in the case of valve position sensors), and always by the fingers and thumbs.

Morrill and Cook attempted various control schemes using the newly available bandwidth. They experimented with simple MIDI control of synthesizers using normal trumpet playing, hand-operated pitch control combined with normal valve technique "leaving the

3 Existing Implementations

player's mouth free to speak or sing" [Morrill and Cook, 1989], manipulation of various audio effects on a computer, accompaniment, harmonization, and live-sequencing².

3.2 Meta-Trumpet



Fig. 3.3 Impett-Bongers "Meta-Trumpet"—note custom valve bottom caps (image courtesy of Bert Bongers)

One of many electronic instruments constructed by Bert Bongers [Bongers, 2007], the Impett-Bongers "Meta-Trumpet" is a custom augmentation project for Johnathan Impett. He wanted "...to permit a close and dynamic relationship between performer, instrument and improvised or composed musical material..." [Impett, 1994], and includes a large assortment of sensors in the design.

Augmentations:

1. a cluster of ultrasound transmitters on the bell of the trumpet (receivers are on the floor and the wall of the performance environment)

²The live sequencing required composing note-patterns using the switches on the augmented trumpet and then replaying and layering them in different ways. Years later in *Principles for Designing Computer Music Controllers* [Cook, 2001], Cook said that this control scheme put too much mental load on the player.

- 2. an accelerometer mounted on the bell
- 3. two mercury switches mounted below the centre of the bell
- 4. two pressure sensors on the third valve casing under the left index and middle finger playing positions
- 5. three magnetic (Hall Effect) sensors mounted under the valves measure the position of magnets glued to the bottoms of the valve pistons
- 6. four buttons mounted on the bell pipe
- 7. clip-on microphone to capture natural horn sound

Communications and Processing:

- 1. a STEIM Sensorlab unit converts control data into MIDI events for consumption by other devices
- 2. an IVL Pitchrider derives pitch and volume information from the natural horn sound



Fig. 3.4 Meta-Trumpet electronic augmentations.

It is a testament to Bongers' skill that he is able to minimize the intrusiveness of the augmentations such that they could "...be easily removed, so that Impett could play baroque or classical music on it..." [Bongers, 2007]. The magnetic valve-position sensors are housed in "specially built extended lower valve caps" [Impett, 1994] and some of the electronics are affixed to "semicircular brass base plates" [Bongers, 2007](figure 3.4).

Bongers and Impett explore an even greater increase in control bandwidth than Morrill and Cook. In addition to the positions and motions of the fingers, the *position and motion* of the entire horn in space is made musical.

The Meta-Trumpet is proposed as "an integrated interactive instrument-interface-composition system" [Impett, 1996], and the way in which Impett uses it for both composition and performance is idiosyncratic to say the least. The functionality of the Meta-Trumpet system is difficult to understand fully as the technical details of the data processing he describes in abstract terms:

Performance data is processed on two levels—system and composition—behind which run a variable number of independent schedulers. Each scheduler can be switched in and out separately from the composition level, or have its contents transformed in some way without affecting the other generated material. [Impett, 1996]

Nonetheless, it is clear from the breadth of discussion around *Mirror-Rite* [Impett, 1996] that Impett's personal connection with his instrument-interface-composition system has given him intimate understanding and control over the music that he creates.

3.3 Mutantrumpet

The "Mutantrumpet" is an augmented trumpet designed and played by Ben Neill³, originally made in the early 1990s and since upgraded⁴. It is an impressively built instrument having both acoustic and electronic augmentations:

³http://www.benneill.com/

⁴From STEIM project blog at http://steim.org/projectblog/?p=320



Fig. 3.5 Ben Neill's "Mutantrumpet", with acoustic and electronic augmentations (image courtesy of Ben Neill)

Acoustic Augmentations:

- 1. two additional trumpet bells (harmon mute and piccolo) extend parallel to the original
- 2. three additional piston values, placed behind (closer to the player than) the original three, selectively divert airflow into the bells
- 3. piccolo trumpet bell attached to a piece of a trombone slide enabling a glissando, operated by the right hand

Electronic Augmentations:

- 1. four switches mounted horizontally along the harmon bell-pipe
- 2. four switches mounted vertically on the crook of the harmon bell-pipe
- 3. a slider mounted just under and behind the normal left-hand position
- 4. three knobs in the crook of the harmon bell-pipe
- 5. two joysticks mounted atop the original bell pipe

- 6. one knob mounted on the first valve slide of the instrument
- 7. a microphone drilled into the mouthpiece
- 8. a clip-on microphone at the harmon bell

Communications and Processing:

- 1. STEIM Junxion box and other electronics mounted on either side of the original set of valves acquires all the control signals and forwards them to software running on a PC
- 2. Roland VP 70 Pitch to MIDI device is used for pitch sensing



Fig. 3.6 Mutantrumpet electronic augmentations (acoustic augmentations not shown).

Neill uses the mutantrumpet to control software-based synthesizers and effects, and prominently features live sampling. Like the previous examples the sensors on the Mutantrumpet are placed close to the hand positions (particularly the left hand). The inclusion of acoustic augmentations is unique and effective, the additional valves and bell pipes integrated in an unobtrusive way, as *intrusive* as they are to the "host". The bandwidth of control information is quite wide compared to Morrill and Cook's trumpet, but does not include the same type of gestural measurements used by Impett and Bongers. Perhaps this is unsurprising seeing as the Meta-Trumpet was developed around the same time as the Mutantrumpet, but in a different milieu.



3.4 Trumpet MIDI Controller

Fig. 3.7 Craig-Factor "Trumpet MIDI Controller" uses underslung valve position sensors [Craig and Factor, 2008] (image courtesy of Thomas Craig)

Craig and Factor wanted "...to create a functional MIDI controller that [...] can be played the same as a typical trumpet" [Craig and Factor, 2008]. They analyzed the trumpet signal in a similar manner to Morrill and Cook, using valve position measurements to inform their analysis and produce a pitch estimate. It is interesting that the augmentations on this trumpet are so similar to those designed by Morrill and Cook, considering that Craig and Factor give no reference to the previous augmentation project, citing commercial trumpet MIDI controllers as sources of inspiration.

Augmentations:

- 1. three visible-light LED distance sensors mounted under the valves
- 2. a Yamaha Silent Brass mute/microphone seated in the bell
Communications and Processing:

1. an Atmel microcontroller and associated circuitry placed in the crook of the bell pipe sends MIDI information to a computer or MIDI instrument



Fig. 3.8 Trumpet MIDI controller electronic augmentations.

The bandwidth of the Trumpet MIDI Controller is certainly more than that of an unmodified trumpet; however, there is no priority on expanding the normal gestures, focusing instead on creating MIDI events using only what gestural measurements are necessary.

An interesting aspect about this augmented trumpet is that the design is documented openly online [Craig and Factor, 2008]. It was designed for no particular performer and they built it with easily obtainable parts, unlike the three previous examples. Even though the Meta-Trumpet and Mutantrumpet include and exceed the Trumpet MIDI Controller's capabilities, they do not attempt to publish their designs openly. In this way Craig and Factor's project represents an important development in trumpet augmentation.

The musical control examples provided with the project documentation are simplistic and do not give a good impression of the potential of the controller. What is very hard to measure is the number of anonymous people who have put Craig and Factor's work to test in their own music. The dissemination of the technology and the musical results thereof will surely be revealed in due time. Meanwhile, references to this project in the literature give a hint as to its impact.

3.5 Electrumpet



Fig. 3.9 "Electrumpet" by Hans Leeuw, notable for its LCD feedback augmentation (images courtesy of Hans Leeuw)

In 2009 Hans Leeuw presented the product of his research, the "Electrumpet" [Leeuw, 2009]. It is the first published augmented trumpet project to include extensive visual feedback augmentations on the body of the instrument (rather than relying entirely on a PC display). It is an excellent example of *accessible* augmentation technology, with all the design details available online⁵ à la Trumpet MIDI Controller. It has removable augmentations

⁵http://www.electrumpet.nl/

(nonintrusive) and wireless power and communications (nonrestrictive).

Acoustic Augmentations:

1. a spring-return tuning slide actuator operated by the right thumb (for quarter-tones)

Electronic Augmentations:

- 1. a breath pressure sensor and attached trumpet mouthpiece mounted beside the original mouthpiece
- 2. three potentiometers ("electronic valves") placed alongside the acoustic valves
- 3. five buttons lining the top of the lead pipe just below the right-hand playing position
- 4. two force sensors on the third valve casing under the left index and middle finger positions
- 5. a ribbon controller mounted on the underside of the bell-pipe (left thumb-operated)
- 6. two "slider buttons" mounted under the mouthpiece receiver (right thumb-operated)
- 7. a 20x4 character LCD screen seated on the bell $% \left({{{\rm{A}}} \right)$

Communications and Processing:

- 1. an Arduino microcontroller drives the LCD display and receives serial data from...
- 2. ...another Arduino mounted in the crook of the bell pipe that communicates using bluetooth with a PC

The driving design concept behind this augmented trumpet is that of a "double trumpet"⁶—one electronic and one acoustic. The electronic mouthpiece (breath-pressure sensor) and valves (potentiometers) allow "virtual" trumpet playing based on the same techniques

 $^{^{6}} http://electrumpet.nl/Site/Philosophy.html$



Fig. 3.10 Electrumpet electronic augmentations (acoustic augmentation not shown).

used acoustically, but clearly there is no need to play the instrument *exclusively* as one or the other.

Leeuw mostly works with spectral processing of the trumpet sound using the ribbon controller. He uses single- and double-clicks on the buttons to double their usefulness, as both recording controls and mode switching controls. His use of a static air pressure sensor allows him to map both positive and negative pressures in his "electronic mouthpiece" to control the envelope and level of processing on the sound. The "slide buttons" control general volume, spectral shift and buffer step size. Leeuw plans to replace the LCD display with an iPhone that will be able to display his PC-based synthesis patches using wireless desktop sharing⁷.

3.6 Gluiph/Gluion Trumpets

3.7 Electrumpet

With his Gluiph [Kartadinata, 2003] and Gluion [Kartadinata, 2006] technology, Sukandar Kartadinata has created or helped create augmented trumpets for Rajesh Mehta, Jonathan

⁷Based on email correspondence with Hans Leeuw, July 2010.



Fig. 3.11 Axel Dörner's Gluion-based augmented trumpet. Breath pressure sensor not shown (image courtesy of Sukandar Kartadinata).

Impett (a different version of the original Meta-Trumpet) and Axel Dörner. Information about these projects is sparse, but I have gathered a list of their augmentations from research papers, the Glui website⁸ and email correspondence with Sukandar Kartadinata⁹.

Augmentations:

Rajesh Mehta

- 1. 2-dimensional Gyro sensor
- 2. set of four buttons mounted along the left side of the bell pipe
- 3. small display on the top of the bell
- 4. (acoustic) trombone-like tuning slide
- 5. ultrasound distance sensor for measuring position of trombone-like slide

Jonathan Impett

⁸http://www.glui.de/

⁹August 2010.

- 1. adaptation of original augmentations to Gluion platform
- 2. additional gyroscope

<u>Axel Dörner</u> (figure 3.11)

- 1. four high-resolution rotary encoders positioned at left side of bell pipe closest to player
- 2. two faders mounted vertically beside the rotary encoders
- 3. three "rotato-faders", rotating/slide potentiometers at left hand position, alongside valves)
- 4. eight buttons mounted atop the bell pipe
- 5. breath controller(not shown in photo)

Communications and Processing:

All of these examples use the Gluiph or Gluion platform and offload their sound processing to a personal computer.

These examples are of interest because of their shared design platform, a concept that is very appealing to me. The construction of the trumpets must have gotten easier each time due to the fact that the underlying communications and processing system remained the same, and only the associated sensors and feedback augmentations changed. Improvements to the underlying system must be common and therefore easily propagable between projects without extensive modifications. The configurations of each example are idiosyncratic to the target performer's needs, and have similar sensor arrangements to the examples we have seen previously.

3.8 Mouthpiece Pressure Studies

I have yet to find a documented augmented trumpet in which the pressure applied to the mouthpiece is measured (Hans Leeuw measured the breath pressure being blown into a separate mouthpiece, not the force/pressure applied to the mouthpiece by the lips). As I mentioned in chapter two, mouthpiece pressure is one of the main forms of normal interaction with the instrument. It seems odd that no-one has augmented it thus far for musical use, although there are several studies that involve measuring this variable for musical and medical research.

In 1988 Barbenel et al measured the forces applied to the mouthpiece using a specially constructed tube fitted with strain gauges [Barbenel et al., 1988]. This gave them two dimensions of force measurement which they associated with the performance behaviour of sixty subjects. I find it interesting that these researchers focused on making a force transducer that was easily installed and removed from each subject's trumpet. Other than slightly lengthening the tubing and therefore lowering pitch of the trumpet (compensated by the tuning slide), the design is nonintrusive and unobtrusive. It could be recreated without significant difference for use in musical control—although the control would likely overload the original playing technique somewhat.

Mayer and Bertsch built upon the work of Barbenel et al by attaching three strain gauges to a special mouthpiece receiver, thus giving them trilinear force measurement with which they could tell "the nature of of bending and shear forces eventually created by musicians during playing" [Mayer and Bertsch, 2005]. Their transducer design is much more complicated than its two-dimensional predecessor although it builds on the same principles and is also easily installed and removed. For those that are interested in three-dimensional pressure measurements for mouthpiece augmentations the design is well described and could be recreated.

There are also studies that measure air pressure in the mouth [Fletcher and Tarnopolsky, 1999] and force *between* the lips and teeth [Kourakata et al., 2001] during trumpet performance, but the obtrusiveness of such measurements makes them undesirable for trumpet augmentations.

3.9 Commonalities

The most common area of placement of augmentations was, understandably, around the normal hand positions. This shows a desire to maintain as much as possible the original playing technique of the trumpet while still affording vast increases in bandwidth. From Morrill and Cook's original work to present there is certainly a trend towards exploiting

Augmented Trumpet	Trumpet Perfor- mance System	Meta-Trumpet	Mutantrumpet	Trumpet MIDI Controller	Electrumpet
Designers	Morrill and Cook	Impett and Bongers	Neill	Craig and Factor	Leeuw
Purpose	Performance by	Performance by	Performance by Ben	Course project,	Performance by
	Wynton Marsalist	Jonathan Impett	Neill	open design	Hans Leeuw, open
					design
Measurements	Valve position, nat-	Valve position, horn	Natural horn sound	Valve position, nat-	"Electronic mouth-
	ural horn sound	position accellera-		ural horn sound	piece" breath
		tion and orientation,			pressure, "electronic
		natural horn sound			valve" position
Sensors	Optical switches,	Hall effect (linear),	Clip microphone,	Visible-red LED	Air pressure sensor,
	mouthpiece pickup,	clip microphone, ul-	mouthpiece pickup,	distance sensors,	linear slide poten-
	slide potentiometer,	trasound, mercury	switches, slide po-	pickup mute	tiometers, buttons,
	switches	switches, accelerom-	tentiometer, rotary		slider button, FSR,
		eter, FSRs	potentiometers,		ribbon controller
			joysticks		
Trumpet Modifi-	Valve piston ex-	Custom valve bot-	Additional bell	Removal of valve	Spring-return
cations	tension, removal	tom caps, magnets	with harmon mute,	bottom caps	plunger on tuning
	of valve bottom	glued to valve pis-	additional piccolo		slide
	caps, installation of	tons	trumpet bell with		
	pickup		trombone-style		
			slide, three ad-		
			ditional trumpet		
			valves, installation		
			of pickup		
Performance	User-interface on	User-interface on	User-interface on	n/a	Horn-mounted dis-
Feedback	PC	PC	PC, live-controlled		play, User-interface
			video		on PC

Table 3.1 Summary of well-documented augmented trumpets.

Augmented Trumpet	Gluiph (Mehta)	Trumpet	Gluion Trun (Dörner)	apet	Gluion Trumpet	Meta-	2D Force Sensor	3D Force Sensor
Designers	Kartadinat	ta and	Kartadinata	and	Kartadinata	and	Barbenel, Kenny,	Mayer, Bertsch
	Mehta		Dörner		Impett		Davies	
Purpose	Performan	ce by Ra-	Performance	by	Performance	by	Characterization of	Presentation of
	jesh Mehta	-	Axel Dörner		Jonathan In	ipett	musician behaviour	transducer technol-
								ogy
Measurements	Horn	rotation,	Breath pressure		Same as	Meta-	Force applied to	Force applied to
	trombone-]	like slide			$\operatorname{Trumpet}$	plus	mouthpiece	mouthpiece
	distance				trumpet rot	ation		
Sensors	2D gyroscc	ope, ultra-	Air pres	sure,	Same as	Meta-	Strain gauges	Strain gauges
	sound, but	tons	buttons, fa	ders,	$\operatorname{Trumpet}$	plus		
			"rotato-faders"		trumpet gyr	oscope		
			rotary encoders	_				
Trumpet Modifi-	Trombone-	-like slide	None		Same as	Meta-	None	None
cations					$\operatorname{Trumpet}$			
Performance	Small displ	lay on bell	Unknown		Same as	Meta-	Acquisition software	Acquisition software
Feedback	pipe				Trumpet		on PC	on PC

Table 3.2Summary of well-documented augmented trumpets (continued)

more and more available space on the acoustic trumpet for hand-operated sensors. Only Impett and Mehta ventured into the realm of less obvious gestural design, and perhaps it is the *saturation* of peoples' understanding of *how* a trumpet *should* be played that make them unlikely to *reallocate* control (and mental) bandwidth towards less easily understood interactions. Certainly there must be a point after which the theoretical bandwidth of control information available to the player is greater than the player's "real-time" mental capacity.

With the exception of the Trumpet MIDI Controller, the selected examples were customdesigned for a particular performer or composition; tailored to an idiosyncratic performance style. The Electrumpet showed that with an openly-published design, this idiosyncratic approach needn't obfuscate the technical details of the instrument's design and construction. Still, a significant degree of technical skill and academic support was necessary for these projects to bear fruit. The Gluion is an inspiration to me for standardizing design components and speeding experimentation, but I don't believe that it goes far enough. I believe that what is needed is a *modular design platform* that combines low technical and resource requirements with the general applicability of designs by Craig, Factor and Kartadinata with the capabilities of those made by Morrill, Cook, Impett, Bongers, Neill and Leeuw.

The concept of *valves* was central to many designs seen here. Even for Neill and Leeuw—who didn't augment the original valves *per se*—the idea of using valve control gestures as a means of sound control was important. Interestingly enough, the type of sensing used in each case (excepting Neill, who didn't measure the positions of his normal or additional valves) was different. Morrill and Cook used two optical switches per valve to detect four positions [Cook et al., 1992], Craig and Factor using a continuous optical sensor for each valve as a threshold detector, giving binary up/down positional information [Craig and Factor, 2008]. Impett and Bongers glued magnets to the bottoms of the valve casings and measured the resulting magnetic fields with Hall Effect sensors at the bottoms of the valves [Impett, 1994]. Hans Leeuw didn't measure the acoustic valve positions, but his "electronic valves" were represented by potentiometers mounted alongside—only a mechanical linkage was missing in order to make them valve position sensors. In the next chapter, the common goal of valve sensing is examined in detail from the perspective of a instrument designer making a choice for their augmented trumpet.

Chapter 4

Valve Sensing Experiment

4.1 Introduction

There are three values on a standard trumpet that control the length of the instrument's tubing and therefore its resonant harmonics. For the most part, the values are used in a binary fashion: a value can either be in a closed or open state. Is it therefore sufficient to capture only the binary state of the values for use in sound generation? It is certainly a much simpler goal than attempting to precisely ascertain continuous value position but it neither takes advantage of the possibilities of the mechanism nor does it take into account the use of *throttling* (partly opening the values) as an established technique.

The choice of how to adequately capture the valve positions is very important and must follow not only from a thorough research of available sensing options but also from the intended use of the instrument. Several valve sensing options are examined and compared in this chapter based on the designs of the augmented trumpets in chapter three. We have identified a fourth option, the linear variable differential transformer, which has never been used in an augmented trumpet but which has favourable characteristics (discussed in section 4.2.4) for valve position sensing.

4.2 Sensor Details

4.2.1 Hall Effect

The Impett-Bongers Meta-Trumpet (section 3.2) used Hall Effect sensors to detect the continuous position of magnets glued to the bottoms of the trumpet valves. Their design is not openly available, however their publications include enough detail to make a reasonable facsimile.

Operation

The Hall effect is a physical phenomenon in which a magnetic field passing through a conductive material causes the electrons in the conductor to migrate to one side or the other, depending on the direction of the magnetic flux. This has the effect of creating a voltage difference between the two sides of the conductor (see figure 4.1). Because they measure the density of magnetic flux, they require a magnetic target for measurement—thus the magnet glued to the bottom of the valve piston as seen on the Meta-Trumpet.



Fig. 4.1 The Hall effect.

Signal Conditioning

Signal conditioning with Hall effect sensors is simple because of their prepackaged form. Only three connections are needed: power, ground and output. The sensing surface should face the target, and the output voltage rises or falls from half-supply, depending on the polarity of the magnet. This behaviour can be exploited by installing two sensors with opposite sides facing the target (differential mode). When one output rises, the other will fall—the difference gives a voltage between zero and supply. An added bonus to differential sensing is that any noise that is common to both sensors will be cancelled out. The differential circuit used in the experiment at the end of this chapter is shown in figure 4.2. Bongers improved the sensitivity of his sensors at longer ranges by using mu-metal shielded neodymium magnets that shape the magnetic field towards the sensor [Bongers, 2000]. I was unable to locate a source of shielded magnets for the experiment and I use unshielded neodymium magnets instead.

Availability

Hall effect sensors are packaged with either linear (continuous) or threshold (binary) output and are cheaply and easily available¹, making them an attractive choice for valve position sensing.

Advantages

- Small size
- Non-contact
- Simple signal conditioning
- Inexpensive

Disadvantages

- Requires magnetic target
- Sensitive to magnetic interference

¹www.digikey.ca

• Short measurement range



Fig. 4.2 Hall effect differential sensing circuit.

4.2.2 Visible-red LED

Two of the designs seen in chapter three used optical sensors in their projects. Morrill and Cook opted to measure four discrete positions per valve using two pairs of optical switches. The switches were positioned such that, as a drilled shaft crossed between them, they output two bits of positional information as illustrated in figure 4.3. Craig and Factor used visible-red LEDs for a continuous measurement which was later translated into a threshold (therefore acting as a single optical switch). Craig and Factor's design is openly available and their signal is continuous, so it is the one I chose for this experiment.

Operation

LED distance sensors are set up as emitter/receiver pairs. The emitter shines light towards the measurement target, and the amount of reflected light that falls on the receiver is proportional to the output voltage. The sensor circuit on the Trumpet MIDI Controller uses such a configuration, circuit shown in figure 4.4.

Signal Conditioning

The sensor proposed by Craig and Factor was compared against a threshold value and thus behaved like a switch. For their purposes it was sufficient to know the binary state of each valve, but for this chapter the "raw" output voltage of the sensing circuit was of more interest (therefore no further conditioning was performed).



Fig. 4.3 Morrill and Cook's optical sensing principle, where a drilled valve piston extension blocks two opto-pairs to produce four positional states.



Fig. 4.4 Craig-Factor optical distance sensor using visible-red LEDs.

Availability

Optical sensors are commonly available with built-in signal conditioning, such as the Sharp GP2 series of infrared distance sensors each of which is calibrated to a different measurement range. For trumpet valve sensing these types of units have a minimum range that makes them unusable, and their emitter/receiver pairs are spaced too widely to "look" into the valve casing properly. There are smaller packages more appropriate for this type of application that combine an infrared LED (emitter) and phototransistor (receiver), such as Optek's OPB series of reflective object sensors. The components used in scratch-built designs such as the one made by Craig and Factor are cheap and quite easy to find and to assemble.

Advantages

- Small size
- Non-contact
- Simple signal conditioning
- Inexpensive

Disadvantages

- Sensitivity to ambient light
- Needs line-of-sight to target

4.2.3 Linear Slide Potentiometer

Hans Leeuw used linear slide potentiometers as "electronic valves" on his Electrumpet, independent from the action of the acoustic valves. If the tops of the slide potentiometers had been physically linked to the tops of the acoustic valves, the "electronic valves" would act as valve position sensors.

Operation

A slide potentiometer—also known as a resistive sensor [Nyce, 2004]—is composed of a resistive strip and a wiper that is always in contact with the strip. The total resistance between the two ends of the strip is static, but the resistance between either end and the wiper is proportional to the position of the wiper. The wiper moves according to the position of the measurement target and therefore the resistance between one end of the resistive strip and the wiper is also proportional to the position of the target.

Signal Conditioning

Using an operational amplifier in an inverting voltage follower configuration, the voltage at the wiper can be measured as shown in figure 4.5.



Fig. 4.5 Potentiometer circuit.

Availability

There are multitudes of different slide potentiometers on the market, and they vary widely in price and quality. The linear conductive-plastic slide potentiometers used here are rather expensive, costing at the time of writing approximately sixty Canadian dollars apiece. Cheaper models, ranging all the way down to a handful of cents apiece, are easy to find but may not be as linear or as long-lasting (potentiometers are traditionally associated with short lifetimes because of oxidation of the wiper and resistive strip [Nyce, 2004]).

Advantages

• Linear

• Simple signal conditioning

Disadvantages

- Requires mechanical link to and alignment with target
- Measurement range limited by sensor dimensions

4.2.4 LVDT

Linear variable differential transformers are simple and robust position sensors known for their high linearity, repeatability and accuracy [Nyce, 2004] [Wilson, 2005]. Originally invented in 1940 [Hoadley, 1940], refined in 1946 [Schaevitz, 1946] and essentially identical ever since, LVDTs have proven their value in both military and industrial applications [Nyce, 2004].

Operation

An LVDT is primarily composed of three coils of wire and a ferromagnetic core (figure 4.6). A sinusoidal input applied to the middle (primary) coil will appear at the two secondary coils to a degree relative to the position of the core. When the core is in the centre of the assembly, the secondary coils will be *equally coupled* to the primary and the amplitudes of the output signals will be equal. Moving the core to one side causes one of the output amplitudes to increase and the other to decrease. Finally, since one of the secondary coils is wound in the opposite direction to the primary, its output will be in opposite phase; therefore the summation of the output signals gives a sinusoid whose *phase* indicates core direction and whose *amplitude* indicates core distance from the centre position.

Signal Conditioning

As simple as they are in construction, LVDTs are complicated in signal conditioning. The conditioning circuit must supply an excitatory signal to the sensor and collect the opposite-phase sinusoidal outputs. The *desired* output is a DC voltage that varies within a usable range around a centre point—usually it will be centered around zero volts.



Fig. 4.6 LVDT operation. A primary excitation is echoed at the secondary coils in opposite phases.

I built a signal conditioning board (figure 4.7) based on a design by Jean-Loup Florens (used in the ERGOS force-feedback devices²) that serves as an example of how to interface an LVDT sensor. First, an oscillator circuit supplies the excitatory signal to the LVDT. It also supplies a synchronized timing signal to a sampling circuit that comes into play later. Second, the input circuit uses an operational amplifier to sum both of the secondary signals from the LVDT. Third, the sampling circuit takes measurements in phase with the peak of the summed signal, giving a DC value corresponding to the position of the core³. Finally, the output circuit uses another op-amp to bring the DC signal to within a desired voltage range (refer to figure 4.8).

Availability

It is possible to construct the entire LVDT and signal conditioner in a DIY manner, as documented by Mike Powell [Powell, 2003]. LVDTs are otherwise easy to find but expensive

²http://acroe.imag.fr/produits/TGR/TGR.html

 $^{^{3}}$ Steven Sinclair at the IDMIL astutely observed that this limits the sampling rate to the frequency of the excitatory signal, which is around 10kHz



Fig. 4.7 LVDT signal conditioning board based on design by Jean-Loup Florens at ACROE



Fig. 4.8 Signal flow through the LVDT signal conditioning board. Secondary outputs are summed and sampled in-phase with the peak of the sinusoid.

compared to other sensors⁴. It is possible, given enough patience, to find an LVDT that meets your needs for a reasonable price on eBay. For example, I purchased an LVDT which normally cost approximately \$1250.00CAD⁵ for less than a tenth of that price.

There are LVDT sensors that come with internal signal conditioning known as DC LVDTs. They are significantly more expensive than their AC cousins and tend to have a more limited range. There are other optional features on commercially-available LVDTs, such as spring-return (known as "gage-head" LVDTs) and hermetic sealing for use in hazardous conditions.

Advantages

- Linear
- Repeatable
- Accurate

Disadvantages

- Complex signal conditioning
- Expensive
- Requires mechanical link to and alignment with target
- Measurement range limited by sensor dimensions

4.3 Experimental Method

To compare the four sensor technologies, they are mounted on a Bach Mercedes trumpet (circa 1970s) in a manner similar to their use in the literature. Discrete measurements are then taken and the results compared.

⁴Based on my experiences purchasing Shaevitz (http://www.schaevitz.com/) sensors from the manufacturer directly as well as Digikey (www.digikey.ca).

⁵Purchased in early 2009, included integrated signal conditioning and spring-return

4.3.1 Sensor Placement

There are two places where sensors can measure the position of the valves, either at the top or the bottom. For placement at the top, obtrusiveness plays a large part because of the proximity of the player's hands. Under the valve this problem diminishes, but the need to open the bottom valve caps incurs the risk of component damage due to grease and condensation leaking onto the under-mounted sensors.



Fig. 4.9 Sensor chassis, bare and populated

An aluminum sensor chassis⁶ holds all four sets of sensors (figure 4.9). The Hall effect and optical sensors are held under the valves and the other two sensors sit alongside the valves (figure 4.10). Acrylic valve cap replacements link the potentiometers and LVDTs to the valves. All of the signal conditioning circuits are attached to the chassis as well *except* the LVDT board, which sits beside the trumpet and also provides power regulation to the sensors.

⁶designed in collaboration with Antoine Lefebre at the Computational Acoustic Modeling Laboratory (CAML) and built by Guy Lecours at Euréklair Prototypes



Fig. 4.10 Side-mounted sensors, "P" indicating potentiometer and "L" indicating LVDT (embedded in chassis). Under-mounted sensors (one valve shown), with inset highlighting sensor placement. Two Hall effect sensors are used in opposite polarity for increased sensitivity.

4.3.2 Measurement Setup

The trumpet and attached sensors are all mounted in a wooden support structure (figure 4.11). An overhang holds threaded rods (figure 4.12) which are used to actuate the valves. The output signals of the setup are sampled at 10kHz by a National Instruments PCI 4472 capture card in a nearby desktop computer. The experimental trials focused on one valve (valve #1, closest to the mouthpiece) with four captured sensors and a second valve (valve #2) with one sensor hooked up as a "marker" during trials (refer to procedure).



Fig. 4.11 Wooden support structure

4.3.3 Procedure

- 1. Lower the actuation rod until it touches the valve cap (but doesn't displace it from resting position)
- 2. Start the data acquisition software
- 3. Position the digital caliper for measurement (figure 4.13) and zero its position
- 4. "Mark" the data point by pushing down value #2, then wait a moment to let the sensor signals stabilize (in case they were jarred by the movement of value #2)



Fig. 4.12 Closeup of overhang and actuation mechanism

- 5. Lower the actuation rod until the caliper reads a displacement of 1mm
- 6. Repeat steps 4 and 5 to generate all of the data points across the range of motion of the valve

4.4 Results

The combined results are shown in figure 4.14 and table 4.4, with additional normalized plots to exaggerate their response curves. Remarkable features are the differences in range, sensitivity and linearity.

	Optical	Hall Effect	Potentiometer	LVDT
Range(V)	2.9	1.2	4.2	3.7
Sensitivity(V/mm)	0.22	0.094	0.33	0.28
Nonlinearity(%)	17	24	15*	2.8

Table 4.1 Experimental results of four sensors averaged from three trials. *The high nonlinearity of the potentiometer is due to limited range-of-motion. If only the active range is considered, its nonlinearity is 5.5%.



Fig. 4.13 Caliper measuring position

The range of the Hall effect sensor was by far the smallest, meaning that analogue-todigital conversion of such a signal would cause much more quantization noise than for a signal using a larger voltage range. An amplification stage for the Hall effect sensor would therefore be useful to minimize quantization noise, and using shielded magnet would help as well [Bongers, 2000]. Note also the way that the Hall effect signal gets much more sensitive as the target approaches, seen in figure 4.14 particularly in the last twenty millimetres of displacement. This is due to the fact that, even though the sensor's response to a magnetic field is linear, the way that the magnetic field changes according to distance to the target is not.

The LED sensor had a sigmoid response with a greater range than the Hall effect. It was also nonlinear, but to a lesser overall degree. This nonlinearity may be the result of two main sources, the transistor nonlinearity in Craig and Factor's design and the way in which the reflected light falls upon the receiver LED. The low effort required to build and install this sensor, not to mention the lack of necessary modifications to the instrument, makes it an attractive option for valve sensing. This sensor is not without its problems, however, and a further optimization would make it much more robust without adding very much complexity. Changes in ambient light conditions can easily interfere with the calibration of the sensor. In a performance environment it is almost guaranteed that the ambient light



Fig. 4.14 Experimental results of four sensors averaged from three trials.

conditions will change, causing the receiver LED to pick up much noise. There is a simple solution, and that is to pulse the output of the emitter such that the ambient light can be measured when the emitter is off. The difference between receiver voltages when the emitter is on and off gives the noise-compensated signal. Avrum Hollinger makes use of this solution in his GGT instrument [Hollinger et al., 2010].

The potentiometer was easy to set up and the signal conditioning was extremely simple. It had a near-linear response over the course of its range of measurement, however the physical range limitation of the particular component used in this experiment is shorter than the range of motion of the valve. The component in question was chosen because it was the same one used by Hans Leeuw, and its 12mm travel is adequate for some trumpet makes and models but not, unfortunately, for the one (eventually⁷) used in this experiment. Due to this, a second trial was performed with the potentiometer decoupled from the measured valve. Results of the trial without the potentiometer are seen in figure 4.15 and table 4.4.

	Optical	Hall Effect	LVDT
Range(V)	2.9	1.1	3.6
Sensitivity(V/mm)	0.22	0.084	0.28
Nonlinearity($\%$)	20	24	1.0

Table 4.2Experimental results without potentiometer averaged from twotrials.

The LVDT showed the best performance overall. Its linearity (especially with the potentiometer uncoupled) was better than any of the other sensors, and the offset of the measurement was adjustable such that it could start out at the null position (zero volts). The complexity of the signal conditioning paid off, but the effort required to set the LVDT up was still above and beyond that required for the other three. Perhaps the final negative point about this type of sensor is the large size of the sensor and related circuitry. LVDTs would not be recommended for designers seeking a low-budget and quick solution to the problem of valve sensing; however, people who are interested in making very accurate, repeatable and linear measurements of valve position for experimental purposes are very much encouraged to use the LVDT.

⁷The original test candidate had a 12mm valve range, but after considering the poor quality of the valves and their excessive lateral play, a better-quality trumpet was used instead.



Fig. 4.15 Experimental results without potentiometer averaged from two trials.

Both the potentiometer and LVDT required exact mechanical alignment with the motion of the valves so that they did not interfere with valve motion. The sensor chassis used in this experiment is expensive and heavy, and I would not recommend it for an instrument intended for performance. Alignment of the physically linked sensors was a definite cause of frustration and future experimenters should be aware of this.

Questions about which types of sensing to use for an augmentation, and more generally how to configure a set of trumpet augmentations, would benefit from a modular design platform on which to quickly put together working instruments for experimentation and performance. In the next chapter I propose such a system and present a working prototype.

Chapter 5

Symbiote: Modular Augmented Trumpet

5.1 Motivation

For the most part, augmented trumpets have been "craft-built" instruments, made-to-order for a performer's idiosyncratic needs. The trumpet MIDI controller is the only example that was made for musicians in general, however its implementation was fixed. There is no question that a skilled technician could take Thomas Craig and Bradley Factor's design, add to it and build an improved version. Likewise, Hans Leeuw's Electrumpet design, as idiosyncratic as it was, could be rebuilt and/or modified to fit another performer's needs. Either way an augmented trumpet must be built from scratch even if the design is openly available. This means having technical skill, lab resources (personal or institutional) and time. Having said this, Hans Leeuw proved that a relatively nontechnical person with academic support can, in a few months, come up with a working augmented trumpet. So what is the issue? It is that each new design, in effect, must "reinvent the wheel" to some degree. What's more, reconfiguring and experimenting with different designs of a given augmented trumpet requires further wheel reinvention. In the simplest terms, both building and changing an instrument is difficult.

In my studies it occurred to me that by standardizing the underlying architecture of an augmented trumpet design, I could open the door for fast prototyping, experimentation and reconfiguration towards finding the best fit for my own idiosyncratic needs and also those of other trumpet players. I wanted a modular system with which to easily try out augmentation ideas, from the configuration of interface components to their physical arrangement, the mapping of control data to sound generation, and distribution of processing. Extending this thought, a modular augmented trumpet design platform would allow different designers to share and try each other's ideas as well, thus furthering our understanding of the trumpet's potential as a modern musical instrument.

That being said, there are obvious upsides to application-specific implementations. Mainly, they use only the resources that are needed for the intended purpose (low overhead) therefore they can be optimized to their specific task (high performance). On the downside, their inevitable maintenance and possible reconfiguration require the same level of technical expertise as needed to implement in the first place. A modular system would ensure that parts could be replaced if needed and even reused, staving off obsolescence and minimizing electronic waste.

Expanding in scope, a carefully designed modular system would make augmented trumpets *accessible* to performers who lack the technical expertise and resources to build an instrument from scratch. The fruits of the designers' experimental dialogue would be available to a larger population of players who would in turn *apply* and *expand* upon augmentation ideas through musical dialogue. This system would be the evolutionary seed for a species of trumpet-hosted digital musical instruments; a technological **Symbiote**.

5.2 Background

There are already many platforms on which to design musical controllers, such as the previously seen Gluion [Kartadinata, 2006] (chapter three) and the ubiquitous Arduino¹. These are not intended to perform any synthesis, but rather to acquire sensor data for PC-based processing. Their acquisition infrastructure is limited by the number of analogue inputs/outputs and their architecture is not predisposed to on-the-fly hardware reconfiguration. In the case of the Gluion, the hardware is FPGA-based and therefore able to accommodate virtually any number of inputs/outputs but it is programmed with a *specific* configuration. The Arduino is limited to a handful of analogue inputs (more or less depending on the model) and lacks analogue output.

¹http://www.arduino.cc/

More generally, the existing solutions are based on a central processing unit which interfaces directly with a known configuration of interface components. I wanted the Symbiote to avoid specifying a single configuration of interface components, allowing a designer to change the configuration while the system is running. Moreover, I wanted it to accommodate virtually any number of inputs and outputs while still having the processing power to perform sound generation. My goal was to have modularity akin to the *Pin & Play* [Van Laerhoven et al., 2002] (where the player builds the interface as part of the performance) combined with the independence and musical identity of a hardware synthesizer. This project shared fundamental research needs with Avrum Hollinger's work on fMRIcompatible musical instruments [Hollinger et al., 2007].

5.3 Design

The Symbiote is based on the idea of *distributed processing*. A central processing unit called the *hub* connects to any number of peripheral processing units called *nodes* via a shared communication infrastructure (figure 5.1).



Fig. 5.1 Architecture underlying the Symbiote design platform.

5.3.1 Hub

The hub is the "brains" of the Symbiote. It performs mapping and sound synthesis while managing the nodes—identifying them and subsequently pulling/pushing data as needed. It also performs analogue conversion on necessarily high-speed inputs (such as audio inputs). An important function of the hub is direct communications with a PC for programming (see below). The type of device used for the hub—an FPGA or microcontroller, and what model—is not set in stone but must have significant processing power.

5.3.2 Node

A node can interface with sensors and feedback augmentations, condition data, detect salient events, perform a specialized computing function, or fill any number of yet-to-be conceived roles. It acts as an extension to the capabilities of the hub, but can be removed without disasterous consequences. A node needs only be as powerful as necessary for its task, and it uses a standardized physical connection to the hub for communications and power.

5.3.3 Communications

Bus networks are ideal for connecting an unknown or changing number of nodes. The communication lines are shared and therefore the number of connected nodes doesn't affect the hardware requirements. This is also an advantage in terms of physical connectivity because there is no practical difference between connections on the bus—it doesn't matter in what order or to which port you connect nodes, and they can all use the same type of cable.

The disadvantage to a bus is that its throughput is limited by the number of nodes. This combined with the time taken during serial bus communications means that the rate at which data can reach the hub is relatively low but feasible for most control signals. The previously mentioned high-speed inputs on the hub handle signals that need to circumvent the limitations of the bus.

5.3.4 Mapping and Synthesis

Each node has a certain number of inputs and outputs which it updates during bus transactions with the hub. These data have to be associated with synthesis functions running on the hub to control sound generation and performer feedback. The link between the hub and the PC allows the user to change these associations. A user-friendly programming interface hosted on the PC makes this possible without requiring low-level interaction with the hardware.

5.3.5 Workflow

A typical start-to-finish instrument using the Symbiote would progress as follows:

- 1. Mount the hub on the trumpet and connect it to the PC
- 2. Using the programming interface load synthesis functions onto the hub
- 3. Attach the nodes on the trumpet in the desired arrangement and connect them to the communication bus on the hub
- 4. Using the programming interface map the node outputs to the synthesis functions and map desired outputs to node inputs, if applicable
- 5. Perform the instrument, and repeat the previous steps as necessary until the configuration meets your needs
- 6. Save the configuration so that you no longer need the PC
- 7. Plug the Symbiote's audio output into an amplifier and play to your heart's content

5.4 Implementation

In late 2009 we had developed a basic version of the system which demonstrated the feasibility of our design. Avrum Hollinger used it to implement the "GGT Instrument", an fMRIcompatible gestural controller made of silicone and fibreoptic cables [Hollinger et al., 2010]. I used it to implement a proof-of-concept Symbiote that is similar to the Trumpet MIDI Controller (section 3.4), but with embedded synthesis instead of MIDI output.



Fig. 5.2 Symbiote prototype (some assembly required)

5.4.1 Hub

For the hub we used an ARM7 LPC-E2468 development board by Olimex², a 32-bit computer that runs at 72MHz. It is powerful enough to manage its responsibilities including synthesis, and includes power regulation that feeds the nodes as well. As powerful as the ARM7 is, we ran up against its limits—such is the reality of embedded applications for processor-intense uses like sound synthesis. The key to making things work is to optimize as much as possible the underlying code, and to find clever solutions for reducing the processing necessary for a given task.

For example, in my Symbiote prototype I used an envelope follower on the trumpet microphone. I thought it would be a light task, but as it ends up it can be quite intense. My original attempt was a "leaky integrator", a running sum which decays over time. The computations involved quickly ate up nearly all of the ARM's computing resources and were completely unfeasible. A much cheaper alternative lay in a combination of signal following and repeated comparison. Envelope following is an important and common enough task that it should be implemented in hardware for future versions of the system.

²http://www.olimex.com/dev/lpc-e2468.html
5.4.2 Node

Since the computing demands on the nodes were much lower than on the hub so we chose simpler devices in their implementations. Mostly we used PSoC chips (Programmable System-on-Chip by Cypress Semiconductor [Cypress Semiconductor, 2006]) which are highly versatile. They have programmable analogue and digital hardware blocks which cut down on the need for peripheral circuitry and make them behave somewhat like a hybrid between a microcontroller and an FPGA. The model that we used has an 8bit, 24MHz core which handles communications quite ably, while the programmable hardware blocks took care of signal acquisition.

The Symbiote prototype uses two PSoC-based nodes (one pitch tracker and one fourslider interface) and one Arduino-based node (valve sensing). The Arduino isn't quite as powerful as the PSoCs but it cooperated with the overall system admirably. The reason I used an Arduino was to prove that it was possible to easily implement the node functionality into a commonly used microcontroller. It took about two days of work to build and integrate the Arduino node from scratch. I arranged the nodes in a configuration reminiscent of the Morrill/Cook and Craig/Factor trumpets, detailed further in section 5.4.4.

5.4.3 Communications

An I2C bus ended up being the most attractive option for the communication system. We chose it because it only uses two wires (cutting down on physical bulk), it is simple to control and it is available on many different types of hardware. It is not the *fastest* type of low-level bus communication but it is capable of serial communication speeds of up to 400 kilobits per second [NXP, 2007], which is fast enough for control-rate data.

The nodes can be successfully connected to the hub at run-time without needing a previously defined I2C address:

- 1. Node powers up
- 2. Node requests address from hub
- 3. Hub provides next available I2C address
- 4. Node sends its input and output capabilities

5. Hub registers the node's capabilities and can now poll the node as needed

Thanks to this protocol, the hub "knows" at any given moment which nodes are connected and what each of them can do. This information is vital for mapping and synthesis.

Some tweaking of the communications system was necessary before it met our reliability needs. The (uncontrolled) rate at which the hub was polling the nodes for data ended up being too much for one of the nodes to handle on top of its normal duties. This was because the processing load of handling a transaction on the bus used a significant amount of the (relatively low-performance) node's resources. Adjusting the polling rate to a more reasonable value alleviated this issue.

We had to fine-tune the timing of the address negotiations on startup such that the nodes wouldn't all try to request an address at once. Towards this, the hub can send out a "general call" that signals the nodes to wait a random length of time before requesting an address. This way, the nodes will all wait until the hub is ready before starting communications, and they can be re-initialized if desired.

5.4.4 Mapping and Synthesis

To map control signals to sound we needed a computationally efficient way to mix and scale different signals together. A mix is simply a weighted sum of scaled signals that allows the use of many-to-one mappings. Scaling is necessary to translate a given range of output values into a range of input values that make sense for a given synthesis parameter (ex. a linear range of values should be exponentially scaled for control of frequency).

You need some freedom in choosing a mathematical scaling definition because different types of curves can significantly change the way that a mapping translates control data into sound. A simple linear scaling function is insufficient for instrument design (ex. scaling exponentially for frequency control), but using arbitrary mathematical functions can easily overwhelm an embedded processor. We chose to implement a polynomial scaling function that allows up to a third-order curve—complex enough for most mapping needs and simple enough to conserve computing resources. Avrum Hollinger made extensive use of mixing and scaling functions in his GGT instrument to map fibreoptic data to a physical modeling synthesizer.

The Symbiote prototype's mapping and synthesis scheme is simpler than that of the GGT, using simple one-to-one mappings with minimal scaling of control to sound gener-

ation. One of the PSoC nodes estimates a pitch based on the output of a Yamaha Silent Brass pickup mute. The Arduino node, mounted under the valves, uses three infrared distance sensors to determine the valve states. The hub uses the valve states to refine the pitch estimate and to subsequently drive a pulse wave generator. The second PSoC node interfaces four sliders that control the frequency, width and mix level of two other pulse waves relative to the primary one (figure 5.3).



Fig. 5.3 Symbiote prototype node arrangement.

5.4.5 Attachment of Augmentations

The effort of developing the Symbiote didn't leave me room for thorough experiments with attachment mechanisms, but I found a cheap and eco-friendly solution just before we presented our work at the International Computer Music Conference in June 2010 [Hollinger et al., 2010]. Using recycled cardboard packaging and twine, I simply hitched all of the circuitry onto the trumpet (figure 5.4). This happily turned out to be a great way of trying out different physical configurations of the system because it was easy to attach and detach the parts. In the future I will use a more permanent but nonetheless detachable mechanism, like those mentioned in chapter two.

5.5 Evaluation

When I made the Symbiote prototype I was proving the technological worth of the underlying system and I've yet to use it in serious performance. That being said the sound that it makes is very pleasing (if you can appreciate the musical value of a Nintendo), and it has proven to be a very robust instrument. The last time that I programmed it was



Fig. 5.4 Symbiote prototype with attached augmentations.

the morning of May 27th, 2010. Ever since then during multiple demonstrations up to the writing of this thesis, the Symbiote has worked without fail. All that is required is to plug it into a power source and an amplifier and to wait a few moments for booting up, which highlights perhaps the best part of a wholly self-contained system: *setting up the instrument takes seconds, not minutes.*

I have worked with several musical controllers that require a PC for synthesis, and by far the most irritating part of running a demo or playing a gig is muttering "I swear it should work now" while furiously patching cables and debugging software. The Symbiote overcomes this issue, showing that a self-contained augmented trumpet can streamline performance logistics—an advantage in terms of setup time but also in terms of physical transportation and stress management.

Chapter 6

Conclusions and Future Plans

6.1 Conclusions

The art of trumpet augmentation is still young. We do not yet know the best way to design them towards an artistic need, and as much as *best* is a subjective term there are objective facets to the problem.

The existing augmented trumpets reviewed in chapter three reveal common design considerations:

- **Inclusion of existing performance gestures:** trumpet valve positions are either sensed directly or mimicked with further valves or valve-like controls.
- Familiarity of hand-operated controls: buttons, knobs and sliders are common augmentations and are common to many electronic musical instruments (and more generally, interfaces) throughout history.
- Fast access to controls: hand-operated augmentations are mounted close to the normal hand positions.

Expanding upon the first point, valve position can be sensed with several different technologies, the most accurate but most expensive of which is the linear variable differential transformer. Linear potentiometers are simpler to operate than LVDTs but require the same type of precise mechanical linkage to and alignment with the valves. Visible-red LED distance sensing is cheap and nonintrusive but nonlinear compared to the LVDT and potentiometer—nonetheless it is sufficient for augmentation where high accuracy is not necessary. Hall effect sensors require some physical modification to the trumpet, are nonlinear and have a short range, but share the unobtrusiveness of optical sensing. More importantly, the comparison of different valve position sensors showed that certain augmentation design questions can be approached quantitatively.

Two of the more recent existing augmented trumpets had open designs, indicating a willingness to share and build upon augmentation ideas. Three of the existing trumpets used a common design platform, which made the incorporation of augmentation ideas between projects using the common platform easier. I believe that the concepts of open design and of standardized design elements can and should be combined. The Symbiote modular design platform proposed in chapter five represents such a combination, which lowers the effort required to implement augmentation ideas across different projects while standardizing common design elements.

6.2 Future Plans

6.2.1 Valve Sensing

The comparison experiment in chapter four tested the range, sensitivity and nonlinearity of four sensor systems based on counterparts from existing augmented trumpets. There are some improvements to the sensor designs and component choices (such as using shielded magnets, and compensating for ambient light) that could be made in order to compare them in an optimal configuration. Equally important is the design of the experiment, in particular the use of automated valve actuation. If a robotic actuator with a known linear position reference were used, it would be easy to generate large amounts of *continuous* data instead of taking discrete measurements. This would facilitate a detailed comparison of not only the range, sensitivity and nonlinearity but also the rise time, hysteresis and repeatability.

6.2.2 Mouthpiece Pressure Sensing

As with valve sensing, it would be interesting to compare different methods of measuring the pressure applied to the mouthpiece. Some sensing candidates include strain gauges (which have been implemented in this way before), load cells, and force-sensing resistors.

6.2.3 Symbiote

Based on my experiences building the Symbiote prototype, there are necessary improvements I must make before the technology matures:

- 1. Upgrade hub and node to a more powerful processor (likely the ARM Cortex M3)
- 2. Identify and implement common signal processing functions into the hardware of the hub (such as envelope following and spectral analysis)
- 3. Implement a user-friendly programming interface for mapping and synthesis on the hub
- 4. Create a set of modules based on the extant augmented trumpets seen in chapter three

Beyond building the technology its self, I need to foster a community of designers such that the technology can propagate and improve beyond my personal needs. The modularity and resulting share-ability of augmentation configurations would be most beneficial if I were not alone in using the platform—this is a point which will become more important as time goes on.

6.2.4 Final Word

My work will be usable for design projects at the IDMIL, and I am hopeful that the idea of modularity will resonate with instrument builders generally. I am equally hopeful that augmented instruments will appear more and more in nonacademic projects and I will do my utmost to disseminate augmentation technology.

References

- [Baalman et al., 2010] Baalman, M., de Bellval, V., Malloch, J., Thibodeau, J., Salter, C., and Wanderley, M. (2010). Sense/stage - low cost, open source wireless sensor infrastructure for live performance and interactive, real-time environments. In *Proceedings of the Internation Computer Music Conference*, pages 242–249.
- [Barbenel et al., 1988] Barbenel, J., Kenny, P., and Davies, J. (1988). Mouthpiece forces produced while playing the trumpet. *Journal of biomechanics*, 21(5):417–419.
- [Bongers, 2000] Bongers, B. (2000). Physical interfaces in the electronic arts. interaction theory and interfacing techniques for real-time performance. *Trends in Gestural Control of Music*, pages 41–70.
- [Bongers, 2007] Bongers, B. (2007). Electronic musical instruments: Experiences of a new luthier. Leonardo Music Journal, pages 9–16.
- [Burtner, 2003] Burtner, M. (2003). The metasaxophone: concept, implementation, and mapping strategies for a new computer music instrument. *Organised Sound*, 7(02):201–213.
- [Cook, 2001] Cook, P. (2001). Principles for designing computer music controllers. In Proceedings of the 2001 conference on New Interfaces for Musical Expression, pages 1–4.
- [Cook et al., 1992] Cook, P., Morrill, D., and Smith, J. (1992). An automatic pitch detection and MIDI control system for brass instruments. Special Session on Automatic Pitch Detection, Acoustical Society of America.
- [Craig and Factor, 2008] Craig, T. and Factor, B. (2008). Trumpet midi controller. Technical report, Cornell University. Available: http://instruct1.cit.cornell.edu/Courses/ee476/FinalProjects/s2008/twc22_bef23/twc22_bef23/index.html (accessed 2010-08-27).
- [Cypress Semiconductor, 2006] Cypress Semiconductor (2006). CY8C27143, CY8C27243, CY8C27243, CY8C27543, and CY8C27643 PSoC mixed-signal array final data sheet. Technical report, Cypress Semiconductor Corp. Available: http://download.cypress.

com.edgesuite.net/design_resources/datasheets/contents/cy8c27443_8.pdf (accessed 2010-08-27).

- [Fletcher and Tarnopolsky, 1999] Fletcher, N. H. and Tarnopolsky, A. (1999). Blowing pressure, power, and spectrum in trumpet playing. The Journal of the Acoustical Society of America, 105(2):874–881.
- [Hoadley, 1940] Hoadley, G. (1940). Telemetric system. US Patent 2,196,809.
- [Hollinger et al., 2007] Hollinger, A., Steele, C., Penhune, V., Zatorre, R., and Wanderley, M. M. (2007). fMRI-compatible electronic controllers. In *Proceedings of the 2007* conference on New Interfaces for Musical Expression, pages 246–249.
- [Hollinger et al., 2010] Hollinger, A., Thibodeau, J., and Wanderley, M. M. (2010). An embedded hardware platform for fungible interfaces. In *Proceedings of the Internation Computer Music Conference*, pages 26–29.
- [Impett, 1994] Impett, J. (1994). A meta-trumpet(er). In Proceedings of the International Computer Music Conference, pages 147–150.
- [Impett, 1996] Impett, J. (1996). Projection and interactivity of musical structures in mirror-rite. Organised Sound, 1(03):203-211.
- [Kartadinata, 2003] Kartadinata, S. (2003). The gluiph: a nucleus for integrated instruments. In Proceedings of the 2003 conference on New Interfaces for Musical Expression, pages 180–183.
- [Kartadinata, 2006] Kartadinata, S. (2006). The gluion advantages of an fpga-based sensor interface. In Proceedings of the 2006 conference on New Interfaces for Musical Expression, pages 96–100.
- [Kourakata et al., 2001] Kourakata, I., Moriyama, K., and Hara, T. (2001). Identification of control parameters for brass player embouchure by measuring contact pressure on the teeth buccal surface. JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing, 44(4):1142–1151.
- [Leeuw, 2009] Leeuw, H. (2009). The electrumpet, a hybrid electro-acoustic instrument. In Proceedings of the 2009 conference on New Interfaces for Musical Expression, pages 194–198.
- [Machover, 1992] Machover, T. (1992). Hyperinstruments a progress report 1987 1991. Technical report, Massachusetts Institut of Technology.

- [Mayer and Bertsch, 2005] Mayer, A. and Bertsch, M. (2005). A new 3d transducer for measuring the trumpet mouthpiece force. In Proceedings of the 2nd Congress of Alps-Adria Acoustics Association and 1st Congress of Acoustical Society of Croatia, pages 217–223.
- [Miranda and Wanderley, 2006] Miranda, E. R. and Wanderley, M. M. (2006). New Digital Instruments: Control and Interaction Beyond the Keyboard. A-R Publications, Middleton, Wisconsin.
- [Morrill and Cook, 1989] Morrill, D. and Cook, P. R. (1989). Hardware, software and compositional tools for a real-time improvised solo trumpet work. In *Proceedings of the International Computer Music Conference*.
- [NXP, 2007] NXP (2007). I2c-bus specification and user manual. Technical report. Available: http://www.nxp.com/documents/user_manual/UM10204.pdf (accessed 2010-08-27).
- [Nyce, 2004] Nyce, D. (2004). Linear position sensors: theory and application. Wiley-IEEE.
- [Palacio-Quintin, 2003] Palacio-Quintin, C. (2003). The hyper-flute. In Proceedings of the 2003 conference on New Interfaces for Musical Expression, pages 206–207.
- [Palacio-Quintin, 2008] Palacio-Quintin, C. (2008). Eight years of practice on the hyperflute: Technological and musical perspectives. In Proceedings of the 2008 conference on New Interfaces for Musical Expression.
- [Powell, 2003] Powell, M. (2003). Lvdts. Technical report. Available: http://www. mikesflightdeck.com/lvdts.htm (accessed 2010-08-27).
- [Rich, 1991] Rich, R. (1991). Buchla lightning MIDI controller: a powerful new MIDI controller is nothing to shake a stick at. *Electronic Musician*, 7(10):108.
- [Rovan et al., 1997] Rovan, J. B., Wanderley, M. M., Dubnov, S., and Depalle, P. (1997). Instrumental gestural mapping strategies as expressivity determinants in computer music performance. In Kansei, The Technology of Emotion. Proceedings of the AIMI International Workshop, pages 68–73.
- [Schaevitz, 1946] Schaevitz, H. (1946). The linear variable differential transformer. Proceedings of the SASE, 4(2).
- [Spang, 1999] Spang, A. (1999). Bb trumpet fingering chart. Available: http://www. lyricbrass.com/spang/fctrumpet.pdf (accessed 2010-08-27).

- [Stewart, 2010] Stewart, D. A. (2010). Vigorous music-making: The inherent "liveliness" of a t-stick instrumentalist. In *Proceedings of the International Computer Music Conference*, pages 116–122.
- [Van Laerhoven et al., 2002] Van Laerhoven, K., Schmidt, A., and Gellersen, H. (2002). Pin&Play: Networking objects through pins. Proceedings of UbiComp 2002: Ubiquitous Computing, pages 1–8.
- [Vigliensoni and Wanderley, 2010] Vigliensoni, G. and Wanderley, M. M. (2010). Soundcatcher: Explorations in audio-looping and time-freezing using an open-air gestural controller. pages 100–103.
- [Wanderley et al., 2006] Wanderley, M. M., Birnbaum, D., Malloch, J., Sinyor, E., and Boissinot, J. (2006). SensorWiki.org: a collaborative resource for researchers and interface designers. In *Proceedings of the 2006 conference on New interfaces for Musical Expression*, page 183.
- [Wanderley et al., 2005] Wanderley, M. M., Vines, B. W., Middleton, N., McKay, C., and Hatch, W. (2005). The musical significance of clarinetists' ancillary gestures: An exploration of the field. *Journal of New Music Research*, 34(1):97–113.

[Wilson, 2005] Wilson, J. (2005). Sensor technology handbook. Newnes.