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Harmonica-inspired digital musical instrument design based on an existing gestural performance repertoire

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Abstract

This thesis contributes to the field of electronic musical instrument (EMI) design, with a strong focus on harmonica-type gestural controllers. Harmonicas are arguably the best-selling instruments in the world, coupled with a huge community of musicians. Thus, it is surprising that little academic material about harmonica performance gestures and harmonica-related EMI design exists, as the Richter-tuned harmonica exhibits a unique set of musical techniques for sound modification.

In spite the few academic works, several patents have been filed related to harmonica-related EMI design. These are presented and compared in a patent review. The devices display many common aspects that presumably stand in relation with different harmonica types. The application of the note-bending technique on the devices is especially investigated.

In order to draw further conclusions about instrument interaction, a motion capture study of harmonica performance gestures was carried out, including a qualitative evaluation of two harmonica-related EMIs.

Finally, the findings are considered in an instrument augmentation prototype implementation based on an existing harmonica-related digital musical instrument (DMI). A sensor system adapted to the playing technique is proposed, along with tailored mapping strategies.

Résumé

Cette thèse contribue au domaine du design d'instruments de musique éléctronique (IME), plus précisement des contrôleurs gestuels liés à l'harmonica. On peut considérer que les harmonicas sont les instruments les plus vendus au monde, en lien avec une grande communauté de musiciens. Par conséquence, il est surprenant que aussi peu de matériel académique existe sur les gestes de performance d'harmonica et sur le design d'IME lié à cet instrument, si on considère que l'harmonica diatonique simple présente un ensemble unique de techniques musicales pour la modification du son.

Contrairement à la petite quantité de publications académiques, plusieurs brevets concernant les IME liés à l'harmonica ont été délivrés. Ceux-ci sont présentés et comparés dans un examen de brevets. Les dispositifs montrent beaucoup d'aspects en commun, ce qui vraisemblablement est en rélation avec différent types d'harmonica. L'application de la technique de l'altération des notes sur les dispositifs est étudiée plus en profondeur.

Afin de tirer des conclusions sur l'interaction avec cet instrument, une étude de capture de mouvement de performance d'harmonica a été réalisé, incluant une évaluation qualitative de deux IME liés à l'harmonica.

Finalement, les résultats ont été considerés dans une mise en œuvre de prototype d'instrument augmenté, basé sur un instrument musical digital (IMD) lié à l'harmonica. Un système de capteurs ajustés à la technique de jeu est proposé, ainsi que des stratégies adaptées de *mappage*.

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List of Acronyms

ADC	Analogue-to-digital converter
CIRMMT	Centre for Interdisciplinary Research in Music Media and Technology
CSV	Comma-separated values
DMI	Digital musical instrument
DOF	Degrees of freedom
EEPROM	Electrically erasable programmable read-only memory
EMD	Exponential moving deviation
EMI	Electronic musical instrument
FM	Frequency modulation
HID	Human interface device
IMD	Instrument musical digital
IME	Instrument musical éléctronique
IMU	Inertial measurement unit
IR	Infra-red
MRI	Magnetic resonance imaging
OSC	Open Sound Control
PCB	Printed circuit board
PVC	Polyvinyl chloride
QTM	Qualisys Track Manager
R&B	Rhythm and Blues
SPI	Serial peripheral interface
Std	Standard deviation
TSV	Tab-separated values
VST	Virtual Studio Technology

1 | Introduction

The harmonica is an instrument that has widely influenced popular music. It is portable and inexpensive, which makes it accessible to the low-income part of society, who in turn have developed manifold playing techniques and styles. As an integral instrument to genres such as Blues, Folk, and Country (Licht 1980), its sound has influenced many generations of music lovers.

When compared to the vast amount of literature about other wind instruments, such as the clarinet or the saxophone, the harmonica has received little attention in the academic realm. There are many reasons for this, including its history as a rather cheap non-classical instrument played mostly by the poor, as well as its association with Blues music, a genre which represents an "antithesis of mainstream European classical tradition" (Baker 1999). How can we raise awareness of this unique instrument and connect harmonica music more easily with the electronic musical genres of the Twenty-First Century?

This thesis is devoted to the development of novel musical instruments based on the rather under-appreciated harmonica, which can facilitate finding new forms of musical expression. There have been many attempts to develop harmonica-related digital musical instruments (DMIs), but the majority of them did not meet with a big response. We suggest that the lack of acceptance of harmonica-related DMIs in the community of expert harmonica players is at least partly due to inadequate design decisions with regards to the existing harmonica performance gestural repertoire.

The gestural repertoire of experienced harmonica players is rich and very personal. There are many techniques that can lead to a desired sound, some of which have been studied

more extensively only in the past two decades. Vocal tract forming techniques are especially crucial to the unique sound of the diatonic harmonica. However, they are difficult to measure in a live performance context. We outline the current state of research on this topic and present suggestions on how to translate these techniques to other body parts.
Harmonica playing techniques should be studied as a starting point for every harmonica-related DMI development, and subsequently considered in the design process so as to meet the harmonica players' needs.

We believe that harmonica-related DMIs have a great potential regarding intuitiveness and musical control. While preserving the dynamic playing possibilities of a wind controller, the note selection is not conveyed by the hands, as it would be on other wind controllers simulating, for example, saxophone or trumpet interaction. This frees up bandwidth in order to perform other musical tasks.
Furthermore, harmonicas are known in many cultures. This small, familiar instrument is easily picked up and played, even by those without a musical background.

The *Manifesto for Music Technologists* (Baym et al. 2014) calls out for a more open and democratized music technology of cultural awareness and interdisciplinary research. With the work done in this thesis, we hope not only to foster the belonging of the non-academic instrument makers into the field of music technology, but also to improve collaboration and sharing.

1.1 Thesis overview

The remainder of this document is structured as follows: Chapter 2 provides the necessary context about the history and available types of acoustic harmonicas, and also explains common playing styles and techniques.
Chapter 3 includes an extensive patent review of harmonica-related digital musical instruments, demonstrating different sensor system approaches and concepts of interaction.
Chapter 4 describes a motion capture study that gives insight into the performance gestures of expert harmonica performers.
Chapter 5 deals with the practical design of a harmonica-related digital musical instrument based on a pre-existing commercially available device.

Finally, Chapter 6 presents conclusions and points to future work that will be continued after the publication of this thesis.

1.2 Contributions

The study of harmonica playing gestures and their application to the design of a novel gestural controller yield a valuable contribution to the field of human computer interaction in music, as well as to interface design and musicology. The results will help us understand the design requirements of harmonica-inspired DMIs to suit the needs of experienced harmonica players. Existing controllers are evaluated, which provides useful feedback to the developers as well as insight towards the history of harmonica-related controllers for musicologists. We hope that, by pointing out and investigating important design decisions, developers of harmonica-related DMIs will be inspired to build devices that provide a more intuitive interaction for expert harmonica players. These devices will therefore be more widely accepted in the community of harmonica players.

2 | Harmonica Playing Techniques and Styles

This chapter presents a brief history of the harmonica and describes common playing techniques and styles from a performance perspective.

2.1 Background

2.1.1 Brief history of the harmonica

The harmonica was invented in the beginning of the 19th century in Europe. It is a free reed aerophone instrument, which means that the sound is produced as air flows past a reed that is firmly attached to one side of a closely fitting frame. The air flow causes the free reed to oscillate within the frame, which in turn produces audible sound waves.

The circumstances of the introduction of free reed instruments to the western world are not known with certainty. Some musicologists suggest that the *Sheng*, a Chinese free reed instrument invented ca. 3000 years ago, was brought to Europe across Russia at the end of the 18th century, inspiring the development of other free reed instruments (Schwörer-Kohl 1997; Krampert 1998). Other sources suggest that the development of reed instruments, mainly centred around the reed organ, led to the independent invention of *free* reed instruments, as elaborated in Ahrens (2002).

Whatever the case, it is certain that by the year 1800, free reeds were known throughout Europe. During the following decades, various free reed instruments were invented, until around 1820 when the first free reed harmonicas appeared in Austria. In 1824, the first harmonica factory was founded in Vienna.

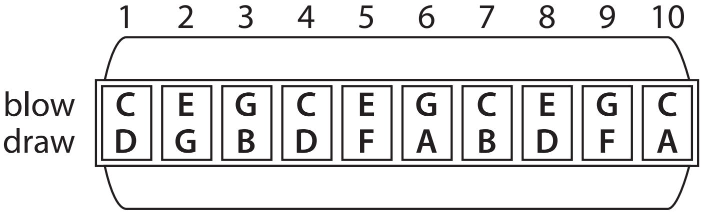

Fig. 2.1 – A diagram of the Richter-Tuning on a C-key diatonic harmonica.

Around 1825 in Bohemia the Richter-Tuning system was invented, which is used to tune the same hole blow and draw harmonicas until today. As we can see on the circle of fifths in Fig. 2.2, Richter-Tuning is centred around the tonic chord (in the case of a C-key harmonica, this would be the major triad C-E-G), where the blow notes repeat this pattern throughout the playing positions (cf. Fig. 2.1). The draw positions include notes found in the respective dominant, dominant seventh, and parallel sub-dominant chords[1]. The sub-dominant chord (here F-A-C) cannot be produced.

Richter-Tuning can be seen as a compromise between melody and harmony, enabling the performer to play both diatonic melodies, a full major scale (cf. Fig. 2.1, pos. 4-7), and chords, but limiting the set of available notes. The scheme in Fig. 2.2 can be applied to other harmonica keys by rotating it to another position on the circle of fifths.

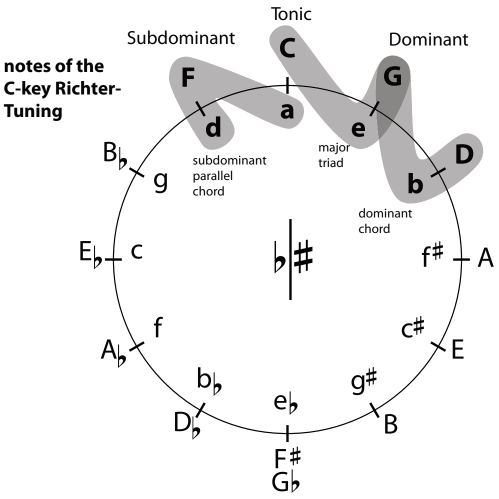

Fig. 2.2 – Richter-Tuning in the key of C shown on a circle of fifths.

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[1] Drawing air from the first or second three positions gives the dominant chord, positions 2-5 give the dominant seventh chord, and positions 4-6 give the sub-dominant parallel chord.

From 1827, an instrument factory commenced mass production of the Richter-tuned diatonic harmonica based on a design brought over from Vienna to Trossingen, Baden-Württemberg, in south-western Germany. Two years later, people also began mass producing harmonicas in the Bohemian and Saxon Vogtland, an instrument makers' centre at that time. By 1839, there were already 50 small factories there, including C.A. Seydel Söhne, which is the most well-known nowadays (Meisel 1981).
In Trossingen, the famous harmonica company Matth. Hohner began manufacturing harmonicas in the 1850's. From 1862 onwards, Hohner harmonicas were exported to the USA with huge success. One hundred and twenty years later, in 1986, Hohner passed the mark of one billion harmonicas produced (HOHNER Musikinstrumente GmbH & Co, KG 2014). Berghoff (2001) traces the reasons for the remarkable product career of the Hohner harmonica.

Fig. 2.3 – An old graphic of the Hohner "Marine Band" harmonica. Reproduced courtesy of the Deutsches Harmonikamuseum Trossingen.

With time, a plethora of harmonica variants were invented, including exotic examples like harmonica-zither hybrids (Brown 1899) and ring-shaped harmonicas (Anderson 1908). The most notable variants are described below in section 2.1.2 with diatonic and chromatic harmonicas being the most prevalent.

Common names for the harmonica include "harp","mouth organ", "French harp", "Mundharmonika", "pocket piano", or "Mississippi saxophone" (Bahnson, Antaki, and Beery 1998).

2.1.2 Harmonica types

Today, many different types of harmonicas exist. The most widely known and distributed harmonica is the Richter-tuned 10-hole diatonic harmonica. The ten holes are capable of covering three octaves, but only one full major scale can be found from holes four to seven. As seen in Fig. 2.5a and 2.5b, diatonic harmonicas are small enough to fit in a pocket. They can usually be easily disassembled to adjust or repair the reeds (cf. Fig. 2.4). The Richter-tuned harmonica's centre piece is either a plastic or wooden comb (cf. Fig. 2.5b), on which a metal plate holding the brass reeds is mounted on each side. The top and bottom caps protect the reeds and shape the sound.

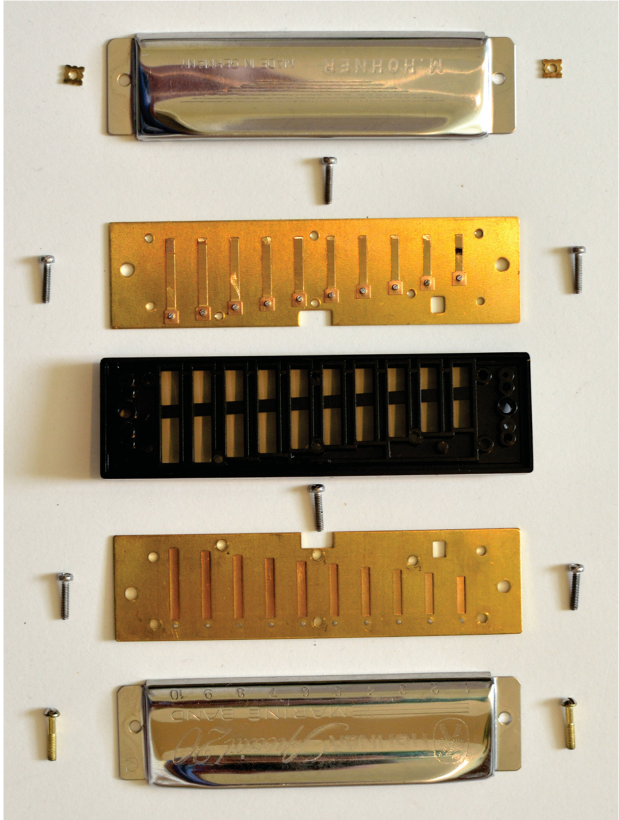


Fig. 2.4 – A disassembled Hohner "Special 20 Marine Band" showing the top and bottom caps, the reed plates, and the plastic comb.

In the following, “diatonic harmonica” refers to the standard Richter-tuned harmonica, even though a tremolo or octave harmonica is also a diatonic harmonica. As this harmonica type is the most common in the Western world, it will be more extensively discussed in this thesis.

(a) Two diatonic harmonicas. Left: plastic comb. Right: wooden comb.

(b) The plastic comb and wooden comb diatonic harmonica (side view).

Fig. 2.5 – The Richter-tuned diatonic harmonica

Chromatic harmonicas implement the full chromatic scale by adding a “slide button” that redirects the air from the hole to a secondary free reed that is (generally) tuned one semitone higher. It is not tuned according to the Richter Scale and usually has 12, 14, or 16 holes that are bigger than those of a Richter-tuned harmonica. Its full chromatic scale makes it easier to play melodies, while some chord playing is made impossible (e.g., the G draw note necessary to play a dominant chord is missing). Note bends are possible, but cannot exceed one semitone and do not sound quite the same as on a Richter-tuned harmonica, because only one reed is bent. Another disadvantage is the higher price tag.

Targeting musicians who need their hands to play another instrument while playing the chromatic harmonica, and handicapped musicians who cannot use their hands, in 2001 Vern Smith invented a Hands-Free Chromatic Harmonica (HFC), which redirects the air by changing the position of the entire mouth piece through head movement (personal communication, July 23, 2014).

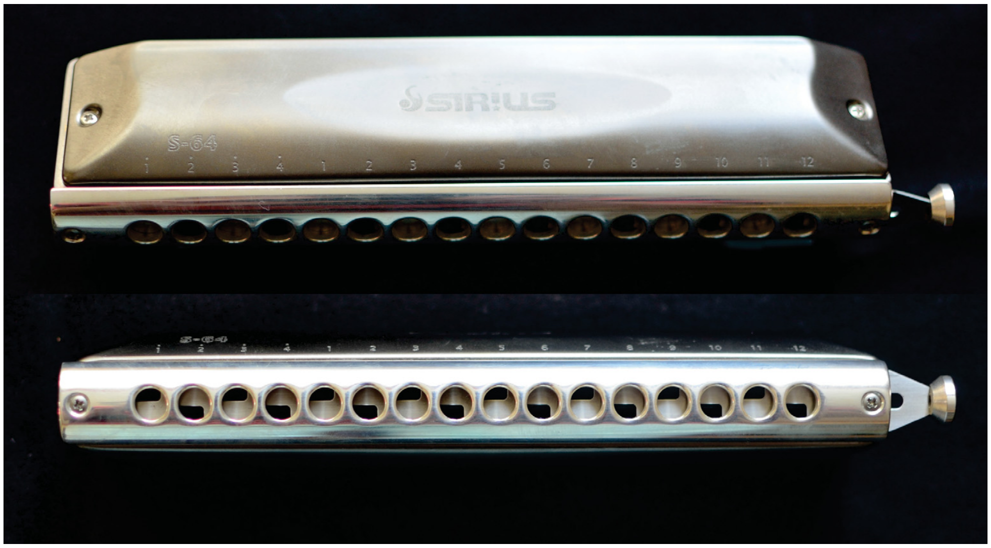


Fig. 2.6 – The chromatic harmonica (angled and side view).

The bass or double bass harmonica is actually made up of two spatially-separated harmonicas connected at the back by a hinge. The upper one is usually tuned in the scale of C sharp, while the lower one is tuned in the scale of C. This way, by only using blow notes, the full chromatic scale is available. For a richer sound, two reeds per air channel are sometimes used. The width of a bass harmonica is about 30 centimetres. This instrument is used mainly in harmonica ensembles.

Fig. 2.7 – The bass harmonica.

The chord harmonica is a very wide instrument capable of producing many different chord types, such as major, minor, seventh, augmented, and diminished. Just like the bass

harmonica, it is mainly used in ensembles and shows two rows of air channels, which are however clustered into groups of four. The major and seventh chords are usually arranged on the upper row, whereas the minor, augmented, and diminished chords are arranged on the lower row. The air channels produce a different chord, whether blown or drawn. The width of a full-size chord harmonica is about 60-80 centimetres.
Some chord harmonicas also have integrated bass reed air channels next to each set of chord channels.

Fig. 2.8 – The chord harmonica.

Tremolo harmonicas have two reeds per air channel, which are slightly detuned: one is slightly flat and the other is slightly sharp. When both reeds are in oscillation, the detuning leads to a physical phenomenon called *beating*. As the frequencies are close, phase cancelling occurs and results in a fluctuation of sound amplitudes perceived as a tremolo effect. The further the reeds are detuned from each other, the faster the tremolo. Tremolo harmonicas usually have a note arrangement very similar to the Richter-tuned diatonic harmonica, but the blow and draw holes are separate. They are very popular among South-East Asian harmonica players (Eyers 2011).

Fig. 2.9 – The tremolo harmonica.

The aforementioned harmonica types are the most common, but there were many attempts to design interesting new harmonica-like devices. One of the most recognized derivatives of the harmonica is the Hohner Harmonetta (cf. Fig. 2.10). This device possesses a sophisticated mechanical mechanism for the redirection of air flow to the desired reeds. The honeycomb keyboard layout allows the player to choose chord combinations (Bibus 1949; Mast 1953; Bibus 1958).

Fig. 2.10 – The harmonetta.

In the last few years, harmonica manufacturers have tried new radical designs, coming up with some interesting innovations in the field: The *Hohner XB-40* is about 1.5 times the size of a standard diatonic harmonica, but comes with four reeds per hole separated by a valve-like windsaver, which enables note bending on holes where it was once impossible. A somewhat similar functionality is provided by the *Suzuki Sub 30*, which adds one sympathetic reed to every air channel, keeping the dimensions of the standard diatonic harmonica.

The *Suzuki Overdrive* harmonica has an airtight design for the cover plate, shielding one air channel from another, so that every air channel has its own output air hole. By covering these holes with one finger, overblows and overdraws are achieved more easily (cf. sec. 2.2.4).

The *B-Radical* harmonica allows replacement of the reeds without having to throw away the whole instrument.

Many professional harmonica players have their harmonicas modified – “embossed” – to ease the carrying out of note bending and overbending technique.

2.2 Playing techniques

The diatonic harmonica is a very expressive musical instrument, due to its intuitive design and manifold playing techniques and styles. For generations, harmonica performers have used their imagination to find new ways of interacting with the instrument (Licht 1980). It is capable of producing sound when inhaling and exhaling into one of its ten airways. Tongue blocking or the pucking technique are used to select the input holes. The sound can be altered by several vocal tract forming techniques, as well as breathing techniques known as note bending, overblowing, and overdrawing. By forming a cavity around the harmonica with the hands and altering their shape, a filter effect can be achieved.

There have been several studies on the physics of free reed instruments, including a few specific ones on the diatonic harmonica, which indicate gestures that are necessary to perform on the acoustic harmonica (Johnston 1987; Bahnson, Antaki, and Beery 1998; Millot 1999; Egbert et al. 2013). Steve Baker’s *The Harp Handbook* (Baker 1999) is considered the standard work on this instrument (Missin 2012; Baker 2014) in the community of harmonica players, and serves as a general reference to this chapter.

The described techniques and styles apply to the Richter-tuned diatonic harmonica.

2.2.1 Holding the instrument

The Richter harmonica is usually held with the left hand so that the higher notes are on the right side. The index finger lays on top of the instrument, while the thumb clamps it from the bottom. The harmonica touches the palm of the hand between these two fingers. The index finger is sufficiently far from the front edge of the harmonica to make way for the lips, which form the embouchure.

The other (right) hand wraps around the harmonica and the left hand in order to form a cavity which impedes the free propagation of sound waves from cap openings. The inner side of the right hand thumb can be used to support the instrument and further enclose the air in the cavity.

The vertical and horizontal angle at which the harmonica is held to the mouth influences the sound of the instrument.

2.2.2 Note selection techniques

Pucking and tongue blocking

Pucking technique is also referred to as “Puckering” and “Lipping”, and describes the use of a small embouchure similar to the one taken when whistling in order to direct the air flow to one hole at a time.

Tongue Blocking techniques describe the use of a larger embouchure that directs the air flow to multiple holes at the same time, but where the tongue is used to block all the holes except one.

Pucking technique is usually acquired first in the learning process and its advantage is that the tongue can be used for other purposes like sound alterations, staccato effects, or easier control of note bending, as it is free to move in the mouth.

The advantage of Tongue Blocking is the superior speed of note selection and the possibility of additional rhythmic effects and sub-techniques such as octave playing and split intervals.

Octave playing and split intervals

For octave playing, the tongue is used to block holes in the middle of the embouchure so that the air flow is directed to the left and right side of the tongue, making it possible to play octaves and other intervals.

A variation of the Tongue Blocking technique is the so-called U-blocking (Krampert 1998), where the tongue blocks two holes but lets air pass on either side and in the middle. This technique enables the playing of additional chords.

2.2.3 Note bending

Note bending describes a technique involving altering the shape of the vocal tract while playing a note to lower its pitch. This technique enables playing chromatically on a diatonic harmonica, as well as sliding between certain notes.

Johnston (1987) states that it is only possible to bend a note if the other note in the same hole has a lower pitch. Furthermore, he found that the amount which a note can be bent depends on the interval between the notes of the same hole: The pitch can descend down to approximately one semitone above the lower-pitched note. A diagram of the available bend notes on the Richter-tuned harmonica is shown in Fig. 2.11. For draw bends, the pitch can be altered gradually, whereas blow bends tend to change the pitch abruptly.

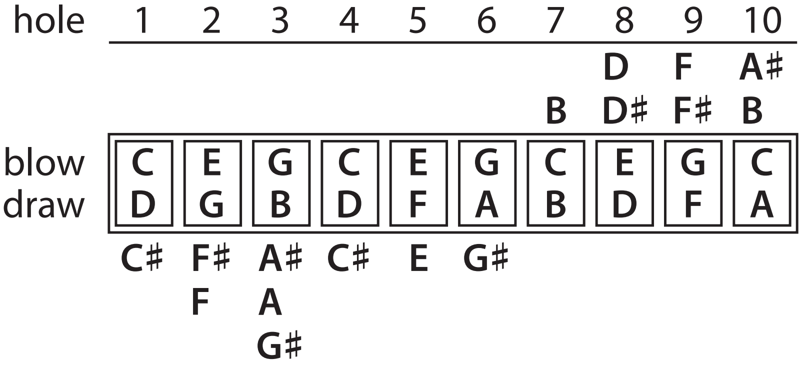


Fig. 2.11 – A diagram of the available bend notes on the Richter-tuned harmonica.

Krampert (1998) stated that bending is achieved by “arching the tongue or the lips” to alter the direction of the air flow through the harmonica.
What actually happens inside the air channel when bending a note is a primacy shift to the lower-pitched reed, which is modulated up. Note bends therefore involve an upward, as well as a downward modulation of pitch. In comparison with the simple blow and draw tone, the bent tone appears to be almost a composite of the two (Bahnson, Antaki, and Beery 1998).

The necessary alteration of the vocal tract to bend a note depends on the frequency of the played note, and is greater if the note is bent down several semitones. An analogy used to describe the alteration of the vocal tract is that of different unvocalised vowel sounds (Baker 1999).

Bends do not require increased air pressure and can be played at a minimal volume (Baker 1999). Bahnson, Antaki, and Beery (1998) found that the level of pressure also has only a slight influence on the phase relation of the reeds. Thus, varying pressure may only modulate the resulting amplitude, with no significant effect to the bent pitch.

2.2.4 Overblow and overdraw

Overblowing and overdrawing, also known as overbending technique, are rather recent playing techniques that emerged in the second half of the Twentieth Century. This technique can provide almost all the missing note pitches that cannot be achieved with either normal playing or note bends.
Even though the technique can be used theoretically on any hole, the overblows on holes 1, 4, 5, 6 and overdraws on holes 7, 9, 10 are particularly interesting (Bahnson, Antaki, and Beery 1998). Examining the diagram in Fig 2.12, we can see that the achievable notes on holes 2 and 3 blow and 8 draw are either duplicates of the already available notes on the harmonica, or can be more easily achieved using note bending.

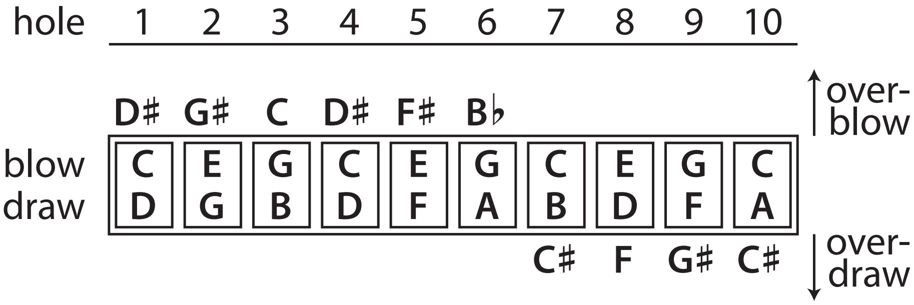


Fig. 2.12 – A diagram of the available overblow and overdraw notes on the Richter-tuned harmonica.

An overblow or overdraw is performed by "changing the position of the tongue and increasing the pressure of the upper lip, in a way similar to some techniques on the trumpet". The technique requires a significant learning effort, with holes 4 through 6 being the easiest overblow positions (Baker 1999).

The harmonica player that is most associated with overblowing and overdrawing technique is Howard Levy, who is considered a master of the technique.

2.2.5 Vibrato

Baker (1999) states three modes of vibrato: *Throat vibrato*, which is produced by the larynx (or voice box), *diaphragm vibrato*, produced by tension-relaxation recurrences of the diaphragm, and *hand vibrato*, where the harp-holding hand shakes the instrument diagonally up and down.
Baker mentions the importance of vibrato especially for harmonica performance: It smooths out tiny variations in pitch that naturally occur because the correct intonation depends on the shape of the player's vocal tract to make the sound more pleasant.

2.2.6 Trills and double notes

The rapid alteration between two adjacent blow or draw notes is called a *trill*. Here, head and/or harp movement can be used to move the embouchure to the adjacent hole.

Double notes describe the opening of the embouchure to direct part of the air flow to an adjacent hole in order to play a chord interval.

2.2.7 Hand cupping

The Hand Cupping technique consists of a modification of the cavity formed by the hands around the harmonica. The timbre of the sound can be changed by altering the cavity, and effects like tremolo and wah-wah effects can be achieved. Tremolo can be controlled by a rapid flutter of the hand(s), while a wah-wah is achieved by opening the cavity while playing a note.

2.3 Playing styles

The Richter-tuned harmonica today is mainly used in Blues, Country, Rock, and Jazz music. It plays an especially important role in Blues music.

Blues music was developed by the black population of the USA in the late Nineteenth Century by mixing African vocal singing tradition with folk music of the European tradition. The African singing tradition does not follow the same pitch scale to which European ears are accustomed, and involves many glissandi, which lead to the introduction of *blue notes* in Blues music. These notes have a slightly lower pitch than the major scale and cannot easily be reproduced with fixed-pitch instruments like the piano.
The possibility of performing note bends thus makes the diatonic harmonica a very suitable instrument for Blues music, making it easy to perform slides between notes and *blue notes*. A characteristic sound achieved using the bending technique, especially in blues music, is the hitting of an already bent-down note that is quickly brought up to its original pitch.

Licht (1980) argues that the use of ideophones and the embellishment of narratives with vocal mimicry in Afro-American folk tales lead to a specific style of harmonica performance, which similarly mimics sounds such as dog howls, train noises, car horns, etc. Harmonica *Trains* – repeating rhythmic playing patterns – are an important part of harmonica blues music.
According to Glover (1965), blues playing styles are very personal and differ a great deal. He identifies artist Sonny Terry to be the general reference in the “folk blues” style, and

Little Walter as having “set the style for R&B harp”, a more urban genre that appeared in the 1940s. Other similarly important blues harp players include Sonny Boy Williamson I and Sonny Boy Willamson II, whose styles are a mix of folk and country blues with R&B. There is also Jimmy Reed, who “blends both deep country and Chicago R&B” to make a sound that was considered modern in 1965. Krampert (1998) adds to that list by mentioning the revival of Blues Harmonica music in the 1980s, mainly due to the movie *Blues Brothers*.

Whereas the blues tonality exhibits both major and minor characteristics, Country music is generally more major and uses less heavy vibrato or wah wah effects (Baker 1999). As the harmonica is mainly a melody instrument, it can be integrated easily into Rock and its sub-genres as well.
Jazz playing depends on the style of the piece, for which a good intonation is important and different tonalities are employed. It is possible to play in many keys on any one harmonica by using various positions.

The harmonica had some appearances in classical music as well, where the chromatic harmonica is used almost exclusively. Important classical harmonica soloists include Larry Adler, Tommy Reilly and John Sebastian, Sr. Composers of harmonica concertos include Henry Cowell, Ralph Vaughan Williams, and Heitor Villa-Lobos (Krampert 1998).

2.4 Conclusion

In this chapter, necessary introductory information about the acoustic harmonica, its history, and common harmonica types were presented. Playing techniques such as note bending, overbending, and hand cupping were explained according to relevant literature.
Playing styles, and especially the use of the harmonica in blues music was also described.

3 Harmonica-related Digital Musical Instruments

With the technological development of the Western world in the second half of the Nineteenth Century, the invention of new kinds of musical instruments was made possible. Early electronic instruments include the Telharmonium, the Theremin, and the Ondes Marthenot. Later, analogue synthesizers became very popular, and the most widely used electronic musical instrument up to now is still the keyboard synthesizer (Chadabe 2001).
However, as Michel Pascal (1997) put it, “it is often not difficult to detect that a sound perfectly imitating a brass is in reality played from a keyboard”, and advocates for the necessity of tailored electronic instruments for different groups of musicians.
Expert harmonica players have excellent motor skills trained over many years of instrument practice. This existing gestural repertoire needs to be considered in the design of a novel electronic musical instrument to account for some of the unique sound characteristics of harmonica performance.

We employ the term “Harmonica-related Digital Musical Instruments” to describe a set of digital musical instruments designed to resemble the acoustic harmonica because of the ways the musician uses to interact with it in a standard performance situation. These instruments take advantage of the performance repertoire of experienced harmonica players, so that the musician can use his/her own existing knowledge and motor skills and apply it to the electronic instrument. Therefore, the learning curve is less steep, and a higher musical expression can be achieved in a smaller amount of time.
Digital musical instruments (DMIs) are defined as musical instruments whose sound generation is carried out by a computer and controlled by a gestural controller or control

surface, where the physical interaction takes place (Wanderley and Depalle 2004; Miranda and Wanderley 2006).

It is rare for a DMI to incorporate the rich interaction possibilities and feedback modalities of an acoustic counterpart. Most acoustic instruments have been developed and refined over centuries, which is why they cannot be directly compared to DMI prototypes. Furthermore, a DMI is not generally developed to replace the acoustic counterpart, but rather to add or extrapolate certain features, while others may become absent. This distinction is especially important since many people have false expectations about the capabilities of a DMI, either thinking of it as a pure limitation or a toy, or expecting science fiction. Even their expectations of a DMI's sound may be biased, perhaps since the advent of popular synthpop music in the 1970s.

The diatonic harmonica is a perfect candidate for augmentation, as well as instrument-like or instrument-inspired design. The instrument has unique interaction characteristics and playing techniques, but also many limitations that could be overcome with a DMI design. The diatonic harmonica is arguably the best-selling instrument in the world, which indicates that there must be a great community of harmonica players who could possibly be interested in a DMI design based on their instrument.

These reasons have already inspired the development of harmonica-related analogue electronic instruments and later DMIs for over half a century. However, most existing devices do not make use of a fundamental part of the gestural repertoire, and provide interaction only on the note-level. They overcome certain limitations of a diatonic harmonica, such as wear and tear of the reeds and the fixing to a particular key, but cannot reproduce the rich interaction to which the performers are accustomed.

Although the acoustic harmonica is a huge commercial success, harmonica-related electronic instruments are not. None of the reviewed materials about the instruments have suggested that they were sold to the mass market. Two recent developments failed in an attempt to crowd fund the production of the instrument (DiCesare 2012; Read 2012), and many devices invented earlier are no longer produced.
Since the acoustic harmonica is not a period instrument that is commonly found in an

orchestra, it is not a popular choice for performance studies in conservatories. It does not receive much attention in the academic world either, when compared to the piano, the violin, or the guitar. This is why it is not surprising that we could not find much academic work on electronic harmonica-related instruments either.

In the following section, we will present a review of harmonica-related DMIs. Many different design decisions were made, such as mounting the blow hole on a slide versus having multiple blow holes, adding buttons to the instrument body, etc. With a better understanding of the interaction, we can adapt design principles, and thus significantly improve the acceptance of harmonica-like controllers in the community of harmonica expert performers.

The main sources of information were chosen to be patents, as they offer great insight to thoroughly developed ideas and ensure the originality of the presented device. As many developers do not seem to work within an academic institution, but intend to invent a commercial product, patents prove to be a richer source than academic publications.

Patent review

We reviewed a total of 17 patents claiming harmonica-related electronic instruments or related inventions. The time span of these patents reaches from 1949, when Ernest Robert Workman claimed the first design of an actual electronic harmonica, to 2013, when Wayne Read claimed the invention of the XHarp. The dates refer to the issue of the patent.

The patents were investigated for information about the layout and use of different sensors on the device, descriptions of the musical gestures associated with it, as well as feature extrapolations and other design-relevant information.
If additional information about the devices was found, e.g., in manuals or through personal communication with the developer, it has been indicated with a reference.
Patent claims are often very broad and do not tell us anything about the actual manufacturing of the device. It is not known how many of the harmonica-related DMIs were actually produced commercially.

The depicted schemata were adapted from the patents.

3.1 Controller types

Digital musical instruments can be classified according to their resemblance with acoustic instruments. For example, just as a keyboard synthesizer tries to simulate a piano interaction as closely as possible, it can also be described as an instrument-like gestural controller. DMIs are generally classified into categories - "augmented musical instruments", "instrument-like gestural controllers", "instrument-inspired gestural controllers", and "alternate gestural controllers" (Miranda and Wanderley 2006). The latter does not have any resemblance to an existing acoustic instrument: The performance gestures need to be learned from scratch. All of the reviewed devices can be classified as instrument-like controllers. Some are border cases between instrument-like and instrument-inspired design, as they introduce the need for musical gestures which are not part of the acoustic harmonica gestural repertoire, while preserving elementary harmonica playing techniques.

Harmonica-related digital musical instruments must be distinguished from electric harmonicas. Electric instruments amplify the acoustic signal of the instrument, whereas digital musical instruments produce computer-generated sound. Harmonica-related electronic instruments do not have any reeds that could produce sound directly, but rely on a sensor acquisition system that measures the musician's gestures. The input signals are then mapped to the synthesized sound.

Augmented musical instruments are real acoustic musical instruments, which have been modified by adding sensors that capture originally uncaptured musical gestures or physical properties of the instruments. While leaving the original sound production of the instrument intact, computer-generated sound is either additionally produced, or the instrument's sound is modified through a computer (Miranda and Wanderley 2006).
Sometimes, however, the distinction between augmented and electric musical instruments is not easy to make. There are border cases where the only dimension measured is almost identical to the resulting acoustic signal. One example would be the *Turboharp* developed by Antaki (2001), which implements an optical sensing technique to determine the vibration frequency of the reeds.

3.2 Musical gestures

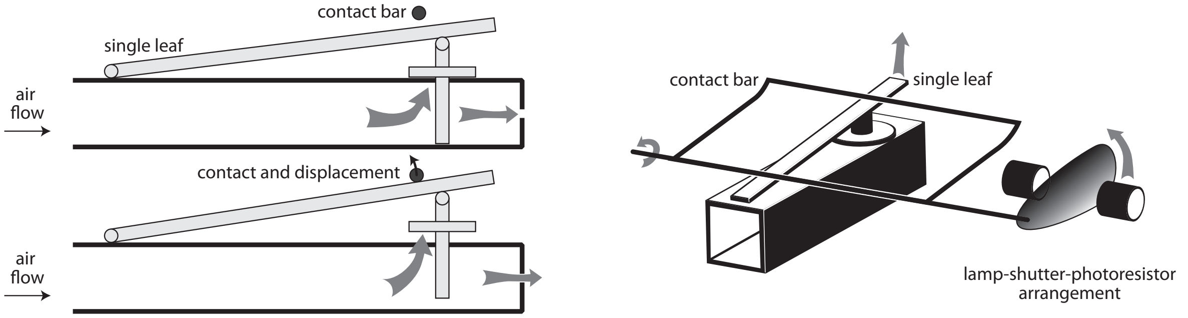
3.2.1 Excitation gestures

An excitation gesture describes a gesture that is needed to generate the sound output of a DMI. It is the gesture, that "provides the energy that will eventually be present in the perceived phenomena" (Cadoz and Wanderley 2000). In the case of harmonica-related DMI, this is inherently blowing air into and/or drawing air out from one or more air channels.
In terms of the sophistication of the excitation gesture measurement technique, it can be differentiated between mere triggering based on a threshold or physical interaction, and continuous measuring allowing for control over the amplitude envelope of the sound output.
Seven patents were found to describe a device that is only capable of triggering a tone by establishing an electrical contact in a tone generation circuit. Twelve patents described a device capable of sensing air pressure continuously, so that the sensor signal can be used to modulate the resulting tone and create an amplitude envelope.
Two devices provided both a discrete note trigger by electrical contact, as well as a means of measuring air pressure (Hillairet, Lecadre, and Wallace 1970; Mölders 1980).

Workman (1949) proposed the design of a device with five air channels, containing a flexible metal bar projection bent with the air flow of blowing into or drawing from the respective hole of the instrument. This action brings it into electrical contact with a brush or terminal, establishing a closed circuit for sound production.
In a second proposition, Workman employs a permanently magnetised metallic ball held between two metallic tubes serving as contacts. Air pressure moves the ball to either one side or the other, bringing it into electrical contact.

Wilken (1965) proposed a design containing an air channel with a double cone attached in the centre by means of elastic rubber bands. The double cone, though not further specified, would move with the air flow in either the blowing or drawing direction, and be brought into contact with an electrical switch that turns on a tone generator.

Hillairet, Lecadre, and Wallace (1970) proposed a design, where a vertically-placed piston is driven upwards to displace a leaf mounted on the air channel. This leaf establishes a contact with a hinged bar situated above the air channel and across all air channels. The bar acts as a resistor, which makes it possible to infer the position of the contact point by measuring the voltage across a voltage divider, similarly to the functionality of a linear potentiometer. The downside to this measurement technique is that only the nearest piston contact of the hinged bar's anode side will be measured, as the circuit is closed with this contact. Any other contacts will not be recognized, which makes the instrument monophonic.



(a) A graphic of the air channel profile.

(b) A graphic of the mechanism used to measure breath intensity.

Fig. 3.1 – The mechanism to measure air pressure and note position as presented in Hillairet, Lecadre, and Wallace (1970).

In order to give control not only over whether or not a tone is produced, but also over the amplitude envelope of the tone, the contact bar is hinged and can be rotated. After contact of the piston with the bar is established, the piston lifts up the bar, which results in rotational movement. A shutter plate displaying a transparent to opaque gradient is mounted at the hinge of the bar. A lamp and photo-resistor pair on either side of the shutter generate an analogue signal according to the transparency of the shutter plate. As the hinged bar is rotated, the shutter rotates along with it, swivelling the plate in front of the lamp and photo-resistor pair, and changing the resulting sensor signal.

French inventor Robert (1982) presented the *Clavier Electromechanique à Vent*; a device which enables the user to play an organ or piano by the use of a harmonica-like controller. The organ's keys are struck by the means of electromagnets each turned on or off by a mechanism in the controller's air channels. Inside each air channel, a piston is held in a neutral position by two springs. As the piston is pierced at its centre, it can be displaced by applying either positive or negative air pressure, i.e., blowing and drawing respectively. The piston comes into physical contact with two metal leaves, which closes an electrical circuit and turns on the electromagnet.

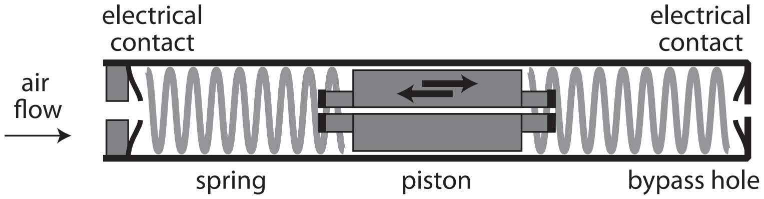


Fig. 3.2 – A simplified schematic of the air channel profile as presented in Robert (1982).

Arai (1984) propsed a design involving an elastic component that would be deformed with the air pressure inside the air channel. The elastic component is attached to the leaf of an industry-standard contact switch. Given a certain deformation, the contact is interrupted and a note onset is indicated. This solution improves the durability of the device by separating the electrical circuit from the air channel, protecting it from humidity.

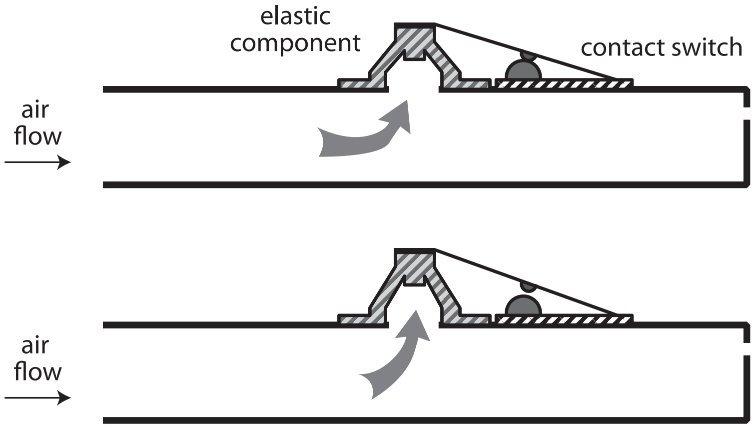


Fig. 3.3 – A simplified schematic of the air channel profile as presented in Arai (1984), embodiment alternative 1.

Kondo (1997) later proposed a similar measurement technique. It involves an elastic component whose deformation does not actuate a switch, but is measured with a displacement measurement system.

Matsuzaki (1986) proposed an air channel sensor design involving an inclined elastic member with a magnet attached. The elastic member is bent by the force of the air flow, reducing the distance between the attached magnet and an electrical switch on the exterior of the air channel.
Matsuzaki (1986) is a development based on Arai (1984). Both inventions were affiliated with Casio Computer Co., Ltd. They both take advantage of elastic members to detect a threshold of air pressure. However, the original air channel layout of the acoustic harmonica cannot be maintained, as there is no way of including a mechanism for measuring both positive and negative air pressure in a single air channel. Therefore, both have proposed an air channel layout that introduces alternating blow and draw channels.

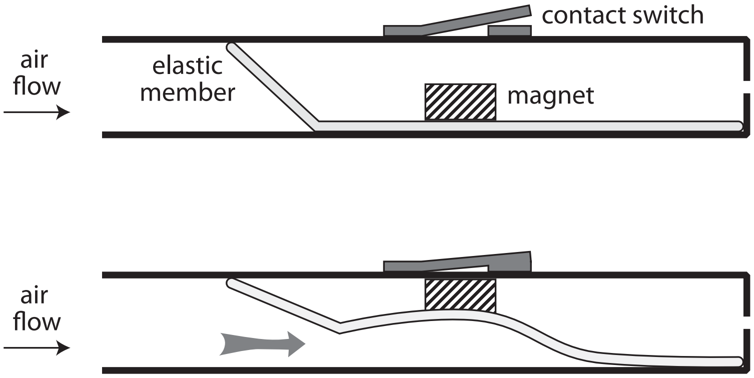


Fig. 3.4 – A graphic of the air channel profile as presented in Matsuzaki (1986).

Ziegler (1989) invented the *Elektronische Mundaharmonika (EMH)*, which uses a differential air pressure sensor (0 to ±70 mBar) to measure the pressure that results from the air flow through the air channel. Differential air pressure sensors actually measure the deformation of a diaphragm inside the sensor housing, which separates the air channel's air from the surrounding atmosphere's air. The pressure difference can therefore be positive or

negative, depending on the direction of the diaphragm's displacement. As the back opening of the air channel is relatively small in size, positive pressure is built up when blown and negative pressure is built up when air is drawn. The measurement setup is capable of distinguishing between both directions of air flow and the amount of pressure applied.
Similar to this air channel measurement setup, Whalen, Luther, and DiCesare (2011) and Read and Hebert (2013) have described their respective inventions *Jamboxx* and *XHarp* to make use of a differential air pressure sensor.

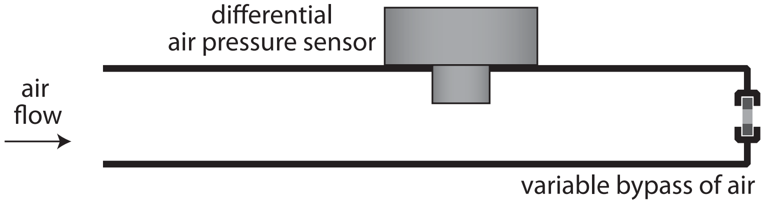
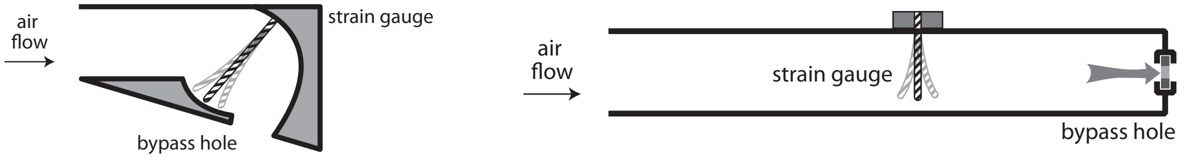


Fig. 3.5 – A graphic of the air channel profile as presented in Ziegler (1989).

Mölders (1980) proposed a *Mundharmonika* (ger.: mouth harmonica) that makes use of strain gauges to measure the air flow direction and pressure. A strain gauge is bond to a material strip in each air channel, which is bent in either direction when blowing into or drawing air from the hole. Using a Wheatstone bridge circuit, the resistance change caused by the deformation of the gauge can be measured. The resistance decreases with compression and increases with tension, so that both air flow directions can be distinguished. The amount of resistance change is then mapped to the amplitude of the sound.
Schille (1991) proposed an air channel sensing system design involving a strain gauge mounted perpendicular to the air stream inside the air channel. Similarly to the measuring technique used in Mölders (1980), the air stream bends the strain gauge in one direction or the other, resulting in a resistance change that can be measured.



(a) A graphic of the air channel profile as presented in Mölders (1980).

(b) A graphic of the air channel profile as presented in Schille (1991).

Fig. 3.6 – Air channel sensor system designs involving strain gauges.

Wheaton (1993) employs two solid state pressure sensors mounted on the top inner side of the air channel, angled 45° to either direction of air flow. Solid-state pressure sensors do not have any moving parts, as a result of the application of piezo-resistive semiconductor technology. As the two sensors are mounted triangularly in opposite directions, blowing and drawing can be distinguished while the intensity of the air stream can be determined. As an additional excitation gesture sensor, Wheaton uses a microphone to pick up singing, humming, or other sound input, although he does not specify where it is to be found on the device.

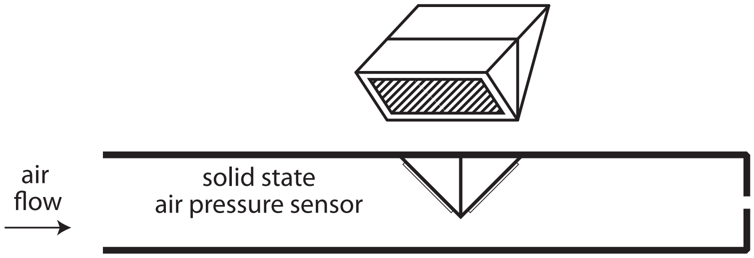


Fig. 3.7 – A graphic of the air channel profile as presented in Wheaton (1993).

There exist several other sensors capable of measuring air pressure and flow direction, which could be considered in the air channel sensor system design. Da Silva, Wanderley, and Scavone (2005) outlines the pros and cons of hot wire sensors and pressure sensors such as a Pitot tube for an application in the design of musical instruments.

3.2.1.1 Continuous control over signal amplitude

With respect to the control over the signal amplitude, two types of instrument interaction measurement could be determined:

1. **Simplified control**: The musician only has discrete control over note onset and offset (cf. Matsuzaki (1986) in Fig. 3.4).
2. **Complex control**: The musician has discrete control over note onset and offset and continuous control over amplitude of the sound. This can be made possible by
    - **Sensor-enabled complex control**: both note onset and control over amplitude are measured (cf. Hillairet, Lecadre, and Wallace (1970) in Fig. 3.1a)

- **Hardware or software enabled mixed control**: a pressure sensor signal is gated by setting a threshold value in hardware or software (cf. *Millioniser* by Blobel, Muller, and Studer (1983) in Fig. 3.9b)

Arai (1984) claimed one embodiment of the invention as having control over the amplitude across all air channels. Therefore, both blowing and drawing air channels are connected and merged into a single airway (refer to Fig. 3.8). At its end, a pressure sensor is mounted in front of the opening to the atmospheric air.

The pressure sensor consists of a magnet and a surrounding coil. The magnet inside the coil is displaced with the air flow. This induces an electrical current into the coil, which can be measured, transformed, and mapped to the amplitude of the sound.

This approach simplifies the design and lowers the production cost of the device. However, without a proper closing of the individual air channels, air can flow out of the other holes, diminishing the effect of the air pressure on the pressure sensor. Given the particular design by Arai (1984) with alternating blow and draw air channels, closing is probably difficult to achieve.

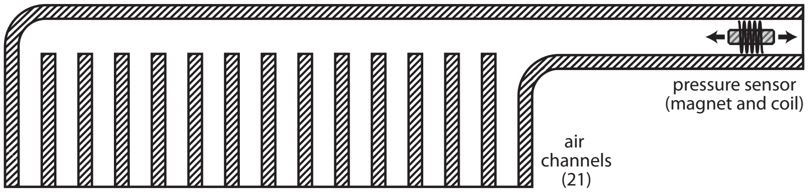


Fig. 3.8 – Arai (1984) proposed air pressure measurements across all air channels. The pressure sensor makes use of the electromotor force released by magnet displacement inside a coil.

3.2.1.2 Air flow resistance

Many inventors considered the implementation of an air flow resistance. The acoustic harmonica naturally provides a resistance to the air flow due to the inertia of the reed plates, so that the performer needs to make a certain effort to excite the system and produce a sound. Excitation effort is useful in two ways: on the one hand, an excitation gesture can be controlled more easily and the motor skills can be learned more quickly, but on the other hand, excitation effort is seen by the audience and associated with musical expression. In "Effort and Expression", Joel Ryan advocates for the consideration of excitation effort in the creation of computer music: “Form as pure freedom is empty: it has no motive. Effort is consciousness of our struggles with the matter of music, music without matter can not sound.”(Ryan 1992)

Ziegler (1989) introduced a system to limit the air flow manually by sliding a pierced bar whose holes can overlap the air channel openings, so that the hole diameter for each channel changes, depending on the position of the bar.

Blobel, Muller, and Studer (1983) described the air flow through the mouth piece of the device later called *Millioniser 2000* as being screw-adjustable (see Fig. 3.9b on page 31).

3.2.2 Selection gestures

Selection gestures are gestures used to change a setting or mode, or a note that is to be played. For example, a selection gesture on a keyboard would be to choose another sound, e.g., a harpsichord sound preset. Pressing a keyboard key also inherits a selection gesture, because the finger moves to a position so as to select a certain note. Then, pressing the key is an excitation gesture as well, as it produces sound output.

The same occurs when an acoustic harmonica is played. The note is selected by moving the mouth over to the corresponding air channel or channels and forming an embouchure. Then the air stream can be formed to excite the system and produce a sound.

3.2.2.1 Note selection

With harmonica-related DMIs, there are two types of devices with different approaches to the selection of notes. One approach is to provide a number of separate air channels, arranged just like those of an acoustic harmonica. The advantage of this is that harmonica players intuitively recognize the function of the channels, and can also jump to another note just like on an acoustic harmonica.

This is only true if the notes are accessible in the same way as on an acoustic harmonica. Several devices show an alternative note arrangement intrinsic to their design or the chosen tuning (cf. sec. 3.5 “Tunings”). If the air channel measurement setup is only able to measure the air pressure in one direction of the air flow, blowing and drawing gestures cannot be applied to the same hole and the note arrangement needs to be changed. Arai (1984), Matsuzaki (1986), and Li and Li (1990) propose a note selection arrangement of alternating blowing and drawing holes.

The other approach to note selection is to provide a mouth piece mounted on a slider. Sliding the mouth piece to a different position selects the note played when air is blown into or drawn from the mouth piece. One advantage of this approach is the lower cost of manufacturing the device, as it only needs one air channel measurement system as opposed to multiple separate measuring systems. Another advantage is the fact that the number of selectable notes can be chosen arbitrarily (if the slider's sensing resolution is continuous). Thus, the device can emulate the note arrangement of, for example, a 10-hole diatonic harmonica as well as a 14-hole chromatic harmonica.

The arbitrariness of the number of selectable notes can also be seen as a disadvantage to this approach. The player has no visual, intuitive cue of where the notes are situated. Repeatability is an important key to the learnability of a DMI (Wanderley and Orio 2002). If the same gesture does not lead to the same resulting sound, the performer cannot adapt to the instrument or learn to play it. Therefore, one school of thought in DMI design advocates for the use of more fixed mappings over very loose and often changing ones (Cook 2001)[1](Hunt and Wanderley 2002).

Furthermore, performers rely only on proprioception and ego-location, not on tactile cues, in order to slide to the desired note's position.

(a) A photo of the *Millioniser 2000*, an example of a slide-based harmonica-related DMI.

(b) A schematic of the slideable mouthpiece.

Fig. 3.9 – The *Millioniser 2000*, a device presented in Blobel, Muller, and Studer (1983).

Developers have put much thought into these shortcomings, and proposed different solutions. Blobel, Muller, and Studer (1983) employ a sliding mechanism allowing the

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[1] NIME workshop during CHI 2001: http://www.nime.org/2001/

performer to feel bumps when sliding the mouth piece. The bumps are caused by equidistant notches, which add friction to the sliding head. This direct tactile feedback may help with the task of selecting the right note, but diminishes the advantage of an arbitrarily selectable note number if the desired number of notes are not the least common denominator of the number of bumps.

Whalen, Luther, and DiCesare (2011) accounted for this problem by employing a continuous slider, and attaching a replaceable strip of bumps right underneath the actual slider, so that the bumps can be felt by the lower lip (Jamboxx Music 2014a). Several bump strips with different spacings are provided with the instrument.

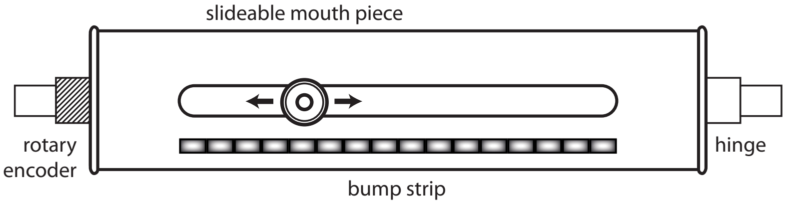

Fig. 3.10 – A schematic of the *Jamboxx* (Whalen, Luther, and DiCesare 2011).

3.2.2.1.1 Number of air channels

As can be seen in Tab. 3.1, the number of air channels proposed in the various patents varies from 5 to 30 holes. The average number of air channels across all listed devices (except *Jamboxx* as it is variable) is exactly 15.25.

Comparing the number of air channels to those of acoustic harmonicas, we can see that most of the devices implement more channels than the Richter-tuned diatonic harmonica (10). Devices with 12, 14, or 16 air channels match the number of air channels found on chromatic harmonicas.

Author	Name	**No. of air channels**
Workman (1949)	Musical Instrument	**5**
Wilken (1965)	Mundorgel	**10**
Hillairet, Lecadre, and Wallace (1970)	Electronic Harmonica	**12**
Mölders (1980)	Mundharmonika	**30**
Robert (1982)	Clavier Electromechanique à Vent	**18**
Blobel, Muller, and Studer (1983)	Operating apparatus used at an electronic instrument provided with at least one synthesizer / *Millioniser 2000*	**16**
Arai (1984)	Electronic harmonica, as well as input device for here, embodiment 1 & 2	**17**
Matsuzaki (1986)	Input device for an electronic musical instrument, embodiment 1	**11**
Matsuzaki (1986)	Input device for an electronic musical instrument, embodiment 2	**17**
Ziegler (1989)	Elektronische Mundharmonika / *EMH*	**14**
Li and Li (1990)	Multiple Tone Colour Changeable Tonal Modification Electronic Harmonica	**24**
Schille (1991)	Electronic harmonica for controlling sound synthesizers / *Electronic Chromatic Harmonica (ECH)*	**12**
Wheaton (1993)	Polyphonic breath-controlled electronic musical instrument	**10**
Zhang and Zhang (1993)	Electronic mouth-organ	**14**
Kondo (1997)	Harmonica Type Electronic Musical Instrument	**10**
Yongcai (1998)	Electronic mouth organ	**23**
Whalen, Luther, and DiCesare (2011)	Adaptive midi wind controller device / *Jamboxx*	**variable**
Read and Hebert (2013)	Multi Channel Digital Wind Instrument / *XHarp*	**11**

Table 3.1 – A comparison of the number of air channels depicted in the patent publications of corresponding harmonica-related DMIs.

3.2.3 Modification gestures

Cadoz and Wanderley (2000) describe modification gestures as “being related to the modification the instrument’s properties, without any substantial expense of energy being transferred to the final sound”. They constitute a second expressive dimension, as they “affect the relation between the excitation gesture and the sound”.

3.2.3.1 Structural modification

Structural modification gestures describe gestures to change a parameter affecting the overall functionality of the device. The gestures are used in between or during performances, but rarely together with an excitation gesture.

Workman (1949) proposes a mechanism used to change the note arrangement of the device by turning a knob on an auxiliary control unit. The knob is attached to a rotatable drum with three surface areas occupying 120°each, of which the surface facing up has a set of mounted contacts making electrical contact with a set of brushes or terminals on the unit body. If the drum is turned, a different set of electrical contacts are made, effectively changing the tonality of the instrument to C major, G major, or D major.
If the knob is pressed and displaced one step into the device, contacts with a second row set of terminals are made, adding sounders which produce tones one octave above the others to provide “full concert tones”.

Hillairet, Lecadre, and Wallace (1970) describe the layout of various buttons and switches, as well as their functions. Fig. 3.11 shows this schematically.
The switch **1** turns on the oscillator and is isolated from the other buttons and switches. One three-way switch **3** is used to select high, medium, or low octave transposition, and another **9** controls register transposition or operation. A different switch **2** is used to determine whether both register and octave transposition will be applied.
The switches **4** through **8** turn filters of a filter bank on or off, which determine the quality of the output sound. The plate **10** is called the “vibrato control plate”. Buttons **11** and **12** are arranged vertically on plate **10** and are used to sharpen or double sharpen the note.
The position of buttons **11** and **12** correspond to the button on a chromatic harmonica of the same function. This design enables immediate adaptation of experienced chromatic harmonica players.

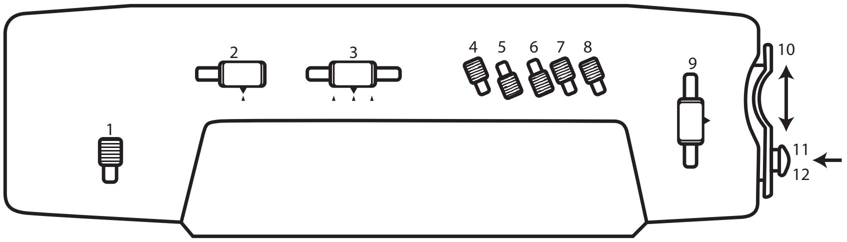

Fig. 3.11 – A top view schematic of the *Electronic Harmonica*, showing the layout of the various buttons and switches (Hillairet, Lecadre, and Wallace 1970).

Mölders (1980) proposes a layout of at least 14 buttons situated on the top of the device, arranged in several rows mirrored on the left and right side, so that they are easily accessible during performance. The keys carry out several functions, such as changing the key and key mode, changing note arrangement to embody either a chromatic or diatonic setup, and adding extra voices in octave transposition.

The position of the buttons on the top side of the instrument and their function, along with the size and shape of the instrument, suggest that the developer was inspired by the *Harmonetta*, a variation of the acoustic harmonica providing a set of buttons to select chord variations as well (cf. Fig. 2.10 in sec. 2.1.2).

C♯	G♯	D♯
A♯	F	C
G	D	A
E	B	F♯
C♯	G♯	

Table 3.2 – Three-row key change button layout (Mölders 1980).

The *Millioniser 2000*, as depicted in Fig. 3.12, shows a fairly advanced arrangement of buttons, switches and slides. On the left, two rows of four buttons serve multiple functions. In program mode, the −8 and +8 buttons are designated to transpose the base key of the DMI down or up an octave, the −− and ++ buttons transpose it one whole tone, and the − and + buttons transpose it one semi-tone.

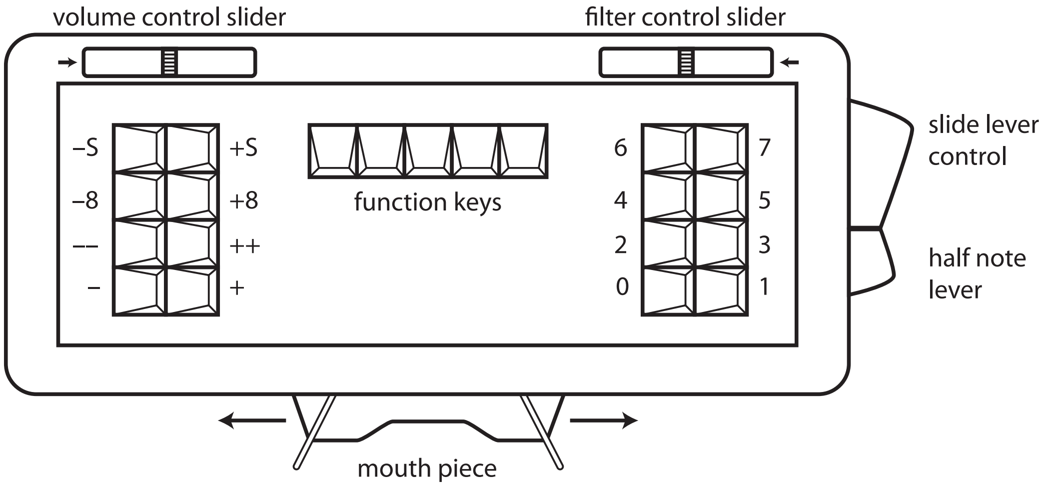

Fig. 3.12 – A top view schematic of the *Millioniser 2000*, showing the layout of the various buttons and switches (Blobel, Muller, and Studer 1983).

In the centre of the top of the device, five programmable function keys are found. They serve as shortcuts so as to quickly select another sound preset during or between performances.

On the right, eight buttons (0-7) are laid out in a similar manner, but serve a different function. These buttons are used to navigate the settings of the separate synthesizer unit, e.g., to select a sound preset or assign it to a function key.
The volume can be controlled using either the volume control slider or a knob on the synthesizer unit. On the latter device, there is another knob used to fine-tune the pitch as well (Millioniser 1984).

Arai (1984) proposed two alternative embodiments of the same invention. The first embodiment describes a harmonica-related DMI with set of keys laid out in a classic piano style on its top surface. Other than that, a variety of switches and sliders are used to choose a pre-set sound, change the volume, set a key, and change usage mode to keyboard or harmonica mode.

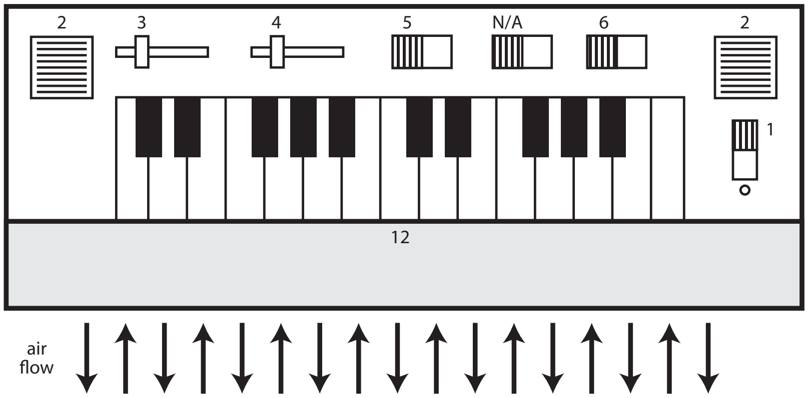

Fig. 3.13 – A top view schematic of the *electronic harmonica* by Arai (1984), first embodiment alternative. **1** on/off power switch **2** integrated piezo loud speakers **3** sound selection **4** volume control **5** key set switch **6** utilisation switch (harmonica or keyboard mode) **12** touch keys.

In a second embodiment, the classic piano key layout is absent, probably to make room for a solar cell panel. Referring to Figure 3.14, two switches **5** are used to select a chord mode, whereas the set of switches **7** are used to select the base key. Different sound presets can be chosen from the switch set **3**, and effects like tremolo can be added by using the switch set **8**.

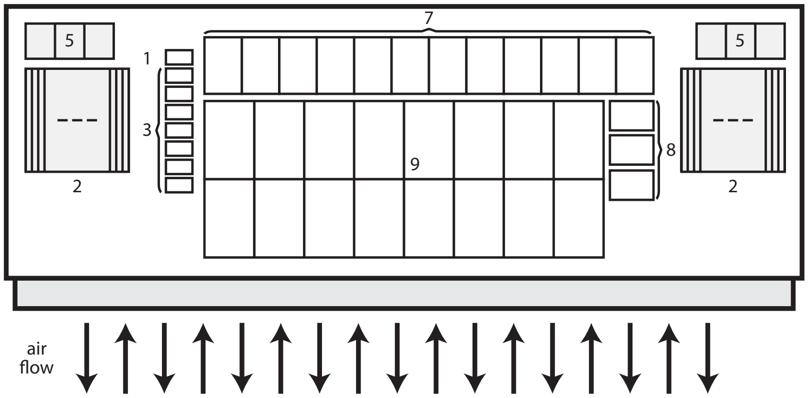

Fig. 3.14 – A top view schematic of the *electronic harmonica* by Arai (1984), second embodiment alternative. **1** on/off power switch **2** integrated piezo loud speakers **3** sound selection **5** chord mode switch **7** chord tonic keytone selector **8** effect switches (e.g., tremolo) **9** solar cell panel.

Matsuzaki (1986) presented two invention embodiments that partly build upon the work presented in Arai (1984). In the first embodiment, he presented a device consisting of a blowing and drawing input device cabled to another physically separated device, which contains several buttons and a piano button layout.

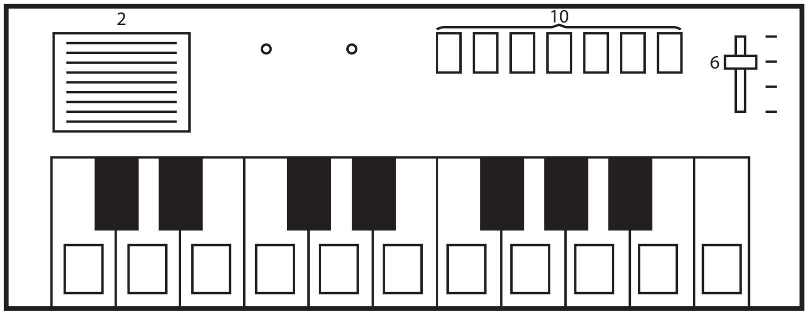

Fig. 3.15 – A top view schematic of the *Input Device for an Electronic Musical Instrument* by Matsuzaki (1986), first embodiment alternative. **2** integrated piezo loud speakers **6** utilisation switch (harmonica or keyboard mode) **10** tone color switch section.

A second embodiment (Matsuzaki 1986) describes a harmonica-type DMI on which a keyboard interface is situated on the top surface. He includes an almost completely identical schematic drawing as Arai (cf. Fig. 3.8 and Fig. 3.16). However, the mapping strategy is not the same. Matsuzaki (1986) reversed the direction of the blow and draw holes and changed the position of the volume control. He does not employ a "sound selection switch section", but a "tone color switch section" and labels the three switches **11** in Fig. 3.16 as generally "mode switch section".

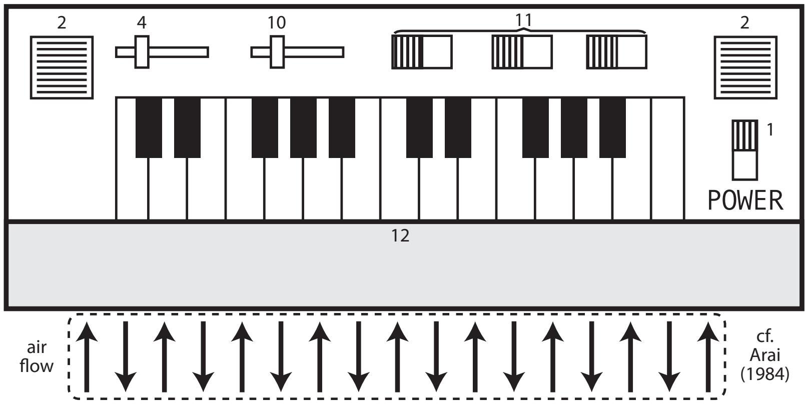

Fig. 3.16 – A top view schematic of the *Input Device for an Electronic Musical Instrument* by Matsuzaki (1986), second embodiment alternative. **1** on/off power switch **2** integrated piezo loud speakers **4** volume section **10** tone color switch section **11** mode switch section **12** touch keys. Note the inversion of air channels when compared to Fig. 3.13.

Ziegler (1989) described a function of his *Elektronische Mundharmonika (EMH)* as transposing the harmonica base key during or in between performances. The leftmost and rightmost air channels are not used for excitation gestures, but serve as a sensor for a selection gesture.

By blowing a short air blast into the hole, the entire note arrangement is transposed either upwards or downwards. These air channels do not have a bypass opening for air to pass through, so air pressure quickly builds up in the channel when blown and enhances the gesture recognition. They also have a greater spacing from the adjacent air channels, so as to avoid being accidentally mistaken for sound generating air channels.

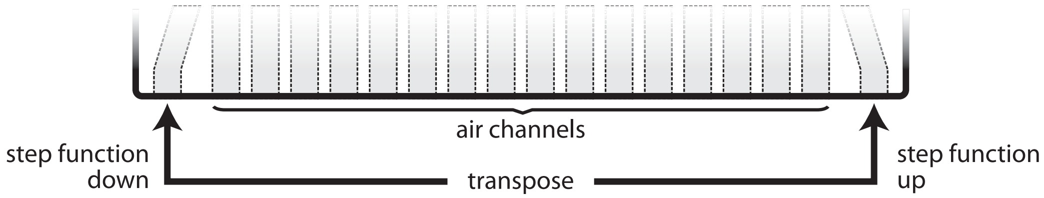

Fig. 3.17 – A schematic drawing showing the transpose function of the harmonica-related DMI as presented in Ziegler (1989).

Schille (1991) claimed the invention of the *Electronic Chromatic Harmonica*. As depicted in Fig. 3.20, at least two push buttons are situated on the top left of the device and can incorporate several functions not further described that concern the sound synthesizer, such as selecting another sound or adding chords.

Wheaton (1993) proposed a design as depicted in Fig. 3.18 also showing push buttons on the top left of the device. The six buttons have several functions, depending on the mapping chosen on a control unit worn on the belt. Their function is not exactly specified in the patent, but they might be used to change to a different note arrangement mapping, which could be customized. Furthermore, they could enable or disable the aforementioned microphone or "one or more of the tone control transducers" (Wheaton 1993, col. 3), and perform several pitch and tone modification functions. Depending on mapping, the reverberation, timbre, chord effects, etc. may be controlled with these buttons as well.

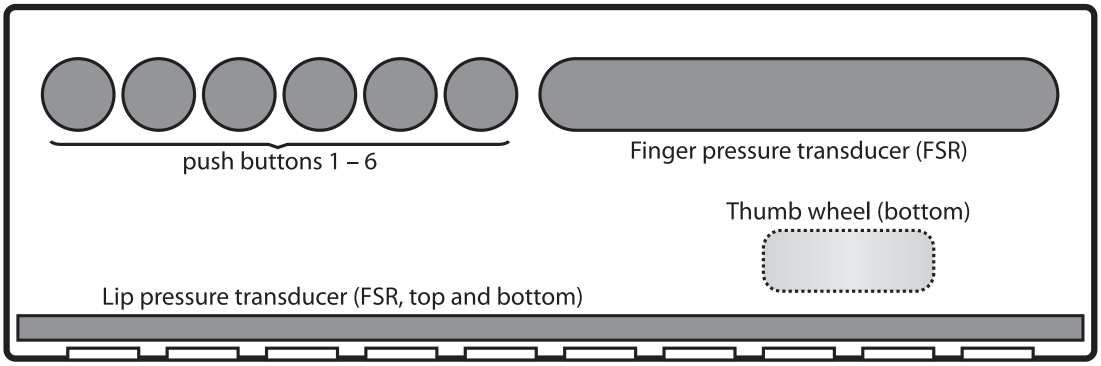

Fig. 3.18 – A schematic drawing showing the top side of the harmonica-related DMI as presented in Wheaton (1993).

Kondo (1997) filed a patent affiliated with Sony Corporation containing a harmonica-related DMI. On its top surface, a selection wheel with discrete steps for sound selection is found, as well as two push buttons for tuning and timbre selection.
Whalen, Luther, and DiCesare (2011) also claim a design showing two push buttons on the top surface of the device. Their function is software-configured and may be used to select different instruments or scales. The current implementation of the DMI has two 1/8 inch jacks, which can be used to connect accessories such as foot or thumb switches (Jamboxx Music 2014b). Software is provided in order to use the accessory signal to switch virtual instruments.

The *XHarp* invented by Read and Hebert (2013) has a LCD display on the top surface showing a menu structure, which can be navigated by the use of a turning knob that actuates a discrete-step rotary encoder. To select a feature, the knob is pressed down. That way, different sounds, as well as the key and transposition can be accessed. On the back of the device, another turning knob drives a rotary potentiometer to adjust the overall volume of the sound output.

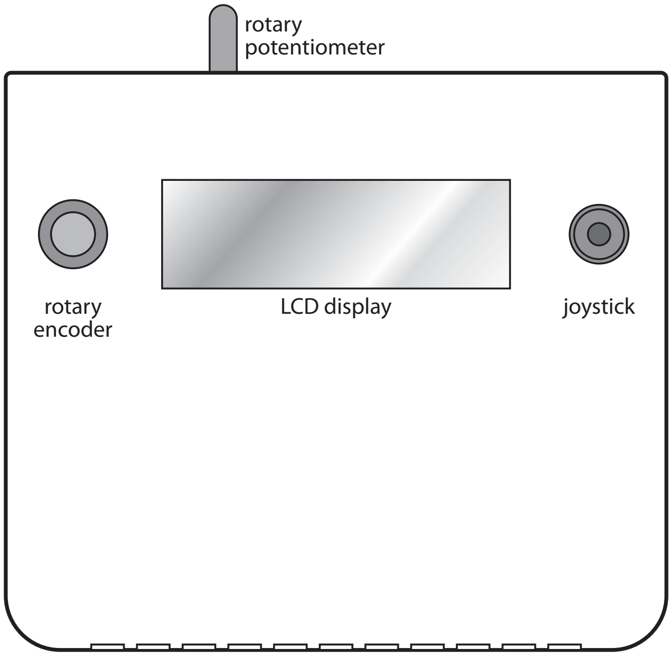

Fig. 3.19 – A schematic drawing showing the top surface of the harmonica-related DMI as presented in Read and Hebert (2013).

3.2.3.2 Parametric modification

Parametric modification gestures describe gestures used to continuously sculpt the sound while it is being produced, such as adding effects or changing various sound parameters like amplitude (e.g., tremolo), pitch (e.g., vibrato), or timbre.

The gestural controller described in Workman (1949) involves a spring-loaded "resistance element" partly hidden inside the instrument, which can be displaced further into the instrument with the fingers of the right hand. This action changes the contact point of a variable resistor with a closed electrical circuit, limiting the current, and thus the intensity of the produced tone.
Due to the spring-load, rapid successive interruptions audible as a tremolo effect can be achieved, as well as slow resistance changes that affect the sound amplitude in a more subtle way.

The harmonica-related digital musical instrument described in Hillairet, Lecadre, and Wallace (1970) shows a movable plate on the right side of the device, which has an indentation to fit a right-hand finger. Frontal displacement of the right hand then moves the plate, which actuates an inductance sensor. The sensor signal is then mapped to the amplitude of the sound output, so that a manual vibrato effect can be achieved.
Referring to Fig. 3.11, there are two buttons **11** and **12** mounted vertically on the moving plate. Pressing one button sharpens the played note, whereas pressing both buttons at the same time double sharpens the note.

The *Millioniser* invented by Blobel, Muller, and Studer (1983) as depicted on Fig. 3.12 contains a half-note lever found on the right side of the device, where the sharpening switch on a chromatic harmonica would normally be found. The lever also has the exact same function and raises the note up one semitone. Next to the half-tone lever, a slide control lever is mounted to the tap of a linear piston-type potentiometer for continuous control of vibrato or glissando, depending on the chosen mapping.
A upward or downward octave glissando or portamento can be achieved by pressing the S+ or S− button, combined with a full inward movement of the slide lever.
On the sloping top back surface of the device, two sliders actuating linear potentiometers

are located. The left one is used to adjust the overall amplitude of the sound output, and the right one is called the “filter control slide”, which is used to “modify the sound while playing” (Millioniser 1984, p. 8).
When the instrument is in “monophonic playing mode”, the left set of buttons on the top of the device consisting of −8, +8, −−, ++, −, + can be used in combination for the transposition of a note. When the instrument is in “chord mode”, a fingering scheme can be applied to these buttons in order to transform the played noted into a major, minor, augmented, or diminished chord. Using the half-tone lever, it is therefore possible to play every chord within five blowing and drawing positions (Millioniser 1984, p. 20).
The Millioniser has a docking connection for accessory controllers on the right side of the controller device. In the Millioniser Manual 1984, a trumpet accessory is described briefly as having three trumpet valve-like transducers.

The *Elektronische Mundharmonika* patent describes a “Chromat”-Button. The name indicates its use as a sharpening button similar to that used for acoustic chromatic harmonicas.

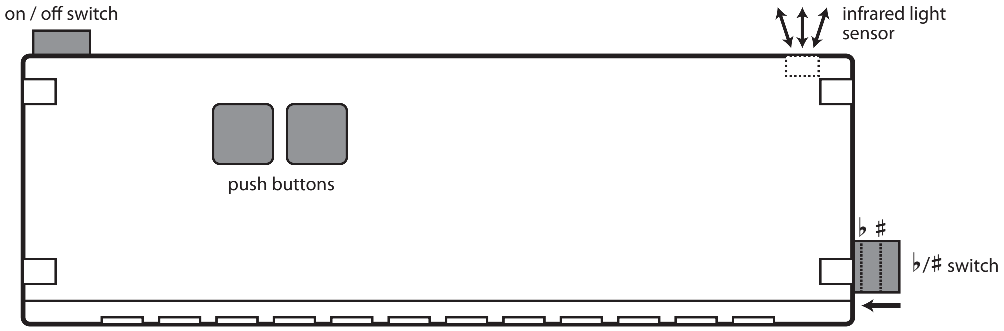

Fig. 3.20 – A schematic drawing showing the top surface of the *Electronic Chromatic Harmonica (ECH)* as presented in Schille (1991).

Referring to the *Electronic Chromatic Harmonica* by Schille (1991) as depicted in Fig. 3.20, there are two ways to alter the output sound through modification gestures. The ♭ / ♯ switch is situated on the right side of the device, where the sharp switch on an acoustic chromatic harmonica would normally be found. This switch transposes the played note one semitone up if partially pressed, and one semitone down if fully pressed.
On the right back side of the device, an infrared light source and a photo diode can be found, which measure the amount of infrared light reflected from the performer’s hand.

As this is roughly related to the distance of the hand from the sensor, it can be used to partially measure the hand cupping gesture. The sensor signal is used to control a tremolo or vibrato effect.

The attempt to measure the hand cupping gesture was an innovation in the field of harmonica-related DMI development. Up to now, it remains the only design that could be found implementing such a sensor.

Wheaton's design includes several innovations to the field as well. He introduced force-sensing resistors to measure both finger pressure on the top of the device and lip pressure on the top and bottom of the device (cf. Fig. 3.18). As the mapping is user-definable with the use of a control unit, no fixed mapping approach is described in the patent. However, Wheaton suggests the resulting sensor signals from the lip pressure to be mapped to pitch bend. The finger pressure signal could drive reverberation or other audio effects, timbre modification, or chord effects. On the bottom right side of the device, a thumb wheel can be used to gradually change the amplitude of the sound, also depending on the chosen mapping (Wheaton 1993).

The *Jamboxx* has a step-less rotary encoder on its left side. For hand use, a turning knob is attached to the encoder and can be manipulated with the left hand while playing. If mounted on a stand, the device can be tilted up or down by head movement.

The encoder's sensor signal is mapped to pitch bend by default, but this mapping can be changed software-wise. In order to be able to set the default, non-tilted position, the encoder can be calibrated using software. In a newer implementation of the DMI, a mass-spring system is used to return the instrument to the initial tilting position (Jamboxx Music 2014a).

The *XHarp* has a joystick mounted on its top surface (cf. Fig. 3.19), which allows the performer to quickly change from pre-saved menu choices, bend the pitch up or down, or add effects such as tremolo, vibrato, and distortion.

3.3 Musical control level

Digital musical instruments can enable different degrees of musical control. For example, a classic sequencer would only provide control over the *structure* of the music, but not the pitch or timbral content of the sound. Other devices only allow for control on the *note-level*, while others enable the performer to shape the *timbre* of the output sound.

All of the reviewed DMI patents were found to enable musical control on the note-level at least. As harmonica-related DMIs, they naturally emulate the harmonica air channels or measure the mouth position otherwise in order to select a pitched note. Pitch bend and vibrato or tremolo effects are seen here as note-level interaction as well.

Although several devices can be used to switch to another sound preset or adjust filters changing the timbre of the sound, only the *Polyphonic breath-controlled electronic musical instrument* (Wheaton 1993) explicitly states coherent real-time control over the timbral quality of the sound.
The *Millioniser* (Blobel, Muller, and Studer 1983) also has a continuous filter control slide on the top back of the device to change the quality of the sound, but it is not easy to reach during performance due to the dimensions of the instrument (cf. Fig. 3.9a and 3.12).

3.4 Applicable techniques

In order for the *tongue blocking technique* (cf. sec. 2.2.2) to be recognized correctly by the instrument, it needs to be polyphonic as well as supply multiple air channels. Furthermore, the technique needs to be adapted, or it might not be feasible if the note arrangement is changed, e.g. to an alternating blow and draw channel layout such as in Matsuzaki (1986). Examples of DMIs enabling tongue blocking technique are the devices presented in Robert (1982), Matsuzaki (1986, both embodiments), Ziegler (1989), Schille (1991), Wheaton (1993), and Read and Hebert (2013).

The *hand cupping technique* (cf. sec. 2.2.7) is a fairly complex interaction between the musician and the instrument, since the shape of the palm and fingers, as well as their distance from the harmonica's body, influence the output sound. In order to emulate the same degree of interaction, the shape and distance would need to be measured continuously, and a mapping strategy would be necessary in order to correspond to the behaviour of the Hand Cupping Technique as applied to an acoustic harmonica.

Schille (1991) proposed the only harmonica-related DMI design which considers the technique. On the back of the device, an infrared sensor measures the amount of reflected infrared light (cf. sec. 3.2.3).

The *overblow / overdraw technique* is not supported by any of the reviewed devices.

3.4.1 Measuring the note bending gesture

A very distinct and unique feature of diatonic harmonica performance is the *note bending technique* (cf. sec. 2.2.3), enabled by the particular design of mounting two reeds of an air channel facing in opposite directions (Bahnson, Antaki, and Beery 1998). This results in a complex physical interaction of the reeds when the resonance of the acoustic system consisting of the harmonica body and the shaped vocal tract changes, thus changing its impedance. This interaction is difficult to measure in a live performance setting, and was therefore never directly used as a control value in any known harmonica-related DMI design. On the contrary, engineers tried to translate the bending gesture so that it could be conveyed by other body parts (e.g., lips or fingers). We must then ask ourselves if any of these translations have proven to be useful and easily adaptable for expert harmonica players.

Bahnson, Antaki, and Beery (1998) used precision non-contacting proximity sensors[2] to measure the reed displacement at a sampling frequency of 10 kHz. A volume-adjustable resonating chamber (a syringe) was placed into the air stream adjacent to the harp, similarly to the resonating chamber experiment setup in Johnston (1987). Adjusting the volume of the syringe, which acts as a rudimentary equivalent to the vocal passage, simulated the alteration of the vocal tract during a note bend.

Both vibration measurements and observations from a stroboscopic light video indicated that note bends involve an upward as well as a downward modulation of pitch.

The results contradict the intuitive prediction that the nominal position of both reeds of a hole should move outward on blowing with positive pressure in the air channel, and inwards on drawing with negative pressure in the air channel. Also against intuition, the reeds vibrate in parallel motion for all holes except the high blow notes.

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[2] Kaman Instruments KD-2400 (sensor acts as the resonating coil for the oscillator on a traditional Colpritts oscillator circuit)

3.4.1.1 Measuring the shape of the vocal tract

The vibration of free reeds in an acoustic harmonica is coupled acoustically to a complex resonator: the human vocal tract. This acoustic system can be described in terms of its *impedance*. The impedance is the response of a particular passive system to harmonic excitation (Dalmont 2001). Applying this to the harmonica, one can say that the vibrating free reeds excite the system, including the vocal tract. Thus the impedance of the vocal tract influences the resulting sound. In acoustics, the specific impedance is a ratio of the pressure and the particle velocity at a specific given point. For a resonator, such as the vocal tract in the case for harmonicas, it is sufficient to describe the input impedance, which can be calculated by knowing the volume velocities and the pressure on each side (Dalmont 2001). In practice, this means that a microphone would have to be placed inside the performer's mouth during performance. This is, of course, very obtrusive and impractical. Thus, non-invasive methods of acoustic impedance measurements are needed, which renders the task more difficult.

Epps, Smith, and Wolfe (1997) described a non-invasive method for the measurement of vocal tract resonances. The method involves a loudspeaker attached to an impedance-matching horn, emitting a known signal (such as a sine sweep or white noise) to excite the acoustic system, and a pressure sensor to measure the response.

Kob and Neuschaefer-Rube (2002) refined this method by measuring the response with the use of both a pressure sensor and a velocity sensor. The methods are developed for measurements of speech resonances, but may be applied partly to the field of digital musical instruments. However, due to the use of audible excitation of the system, the methods cannot be applied directly in a live performance context.

Naumann (1979) proposed the design of an electronic musical instrument not directly related to features of the acoustic harmonica, but illustrating a possible solution to the issue of measuring the shape of the vocal tract in a real-time performance environment. A sonic or ultrasonic receiver and transmitter pair is connected to a frequency-to-analogue voltage transducer and amplifier, setting up an audio feedback in the oral cavity. The frequency of the feedback system changes with the size of the vocal tract. Naumann also employs an optical reflectance sensor to measure the distance between the tongue and the mouthpiece.

By knowing the size of the vocal tract and the position of the tongue, one can eventually estimate the shape of the vocal tract. This dimension can be used to control pitch bend and other audio features that are characteristic to a note bend on an acoustic harmonica. Experienced harmonica players would then be able to make use of their existing knowledge of the note bending technique in order to perform pitch bends on a DMI.
In order to map these measurements to coherent audio features, we need to know more about the correlation between the shape of the vocal tract and the resulting sound.
Antaki et al. (2002) reviews experiments involving laryngoscopy (fibre optics videos), ultrasonography (ultrasound scans), and fluoroscopy (X-ray scans) to gain knowledge about the embouchure, tongue position, and oral cavity volume while performing different playing techniques. Famous harmonica performer Howard Levy served as a subject in most of the experiments, of which several videos are presented on a website (Antaki 2014).

Egbert et al. (2013) investigated this relationship with a different method: the vocal tract was scanned using a magnetic resonance imaging (MRI) scanner during the performance of a hole 3 draw note bend for both tongue blocking and pucking technique (cf. sec. 2.2.2), as well as for a hole 8 blow bend. Therefore, a special non-magnetizable harmonica had to be used.
The MRI images show the tongue position for normal playing position, a semitone bend, a whole note bend, and a minor third bend. The change of the vocal tract shape is described as follows:

> When playing the 3 hole draw bent notes, the body of the tongue elevates and humps up toward the hard palate. As the bend deepens, the tongue retracts and the apex of the elevation shifts more and more back toward the pharynx. This process creates a progressively larger cavity in the anterior part of the mouth between the elevated body of the tongue and the lips [...]. Simultaneously, the width of the pharynx decreases.

The position of the tongue while note bending is very similar for both tongue blocking and pucking technique. The difference is obviously that the tongue is touching the harmonica on the left of the embouchure, which also results in a more asymmetrical shape.

Concerning the hole 8 blow bend, the investigators stated the following:

> In the bent note, the body of the tongue is elevated toward the palate and the tongue is very far forward next to the lips and harmonica. The anterior surface of the tongue opposes the palate except in the center, leaving a small central channel just as in the 3 hole draw notes. The anterior oral cavity is small. The upward and forward movement of the tongue is more extreme than that found in the images of the 3 hole draw notes, and the pharynx is correspondingly wider.

According to the findings, the movement of the tongue differs for different playing positions on the harmonica. Thus, it may be possible to determine which hole is being played based on measurements of the vocal tract size and shape.

3.4.1.2 Translating the note bending gesture

Existing harmonica-related DMIs translate the note bending gesture to another part of the body, rather than trying to solve the vocal tract measurement issue.

The *Millioniser* has a lever control that can be used to bend the note. The hand displacement and force applied to a spring-loaded lever controls the pitch bend upwards or downwards, depending on a secondary button interaction on the top left surface of the device.
Wheaton (1993) proposed translating the note bending gesture to either lip pressure, finger pressure, or thumb displacement.
The *Jamboxx* has an option to use the rotary encoder wheel on the left side of the device for pitch bend. If the *Jamboxx* is held in the hands, the left hand and/or finger movement is used to turn the wheel. If the device is mounted on a stand, head inclination and lip displacement influence the inclination of the device, and thus the position of the rotary encoder.
Read and Hebert (2013) proposed a joystick placed on the top right surface of the device, which may be used to pitch bend a note. Thus, displacement of the right hand and/or fingers controls the bend.

3.5 Tunings

Only certain patents provide information about the suggested fixed tuning or dynamic tunings of the instrument. Hillairet, Lecadre, and Wallace (1970), Robert (1982), and Blobel, Muller, and Studer (1983) proposed a tuning identical to that of the chromatic harmonica, as seen in Tab. 3.3. Ziegler (1989) suggests this very tuning, but shifted so that it starts on *G* blow and *A* draw.

All of the above-stated devices also provide a way to sharpen all notes by the actuation of a button or switch. Thus, it can be inferred that the developers intend to mimic a chromatic harmonica interaction.

blow	C	E	G	C	C	E	G	C	C	E	G	C
draw	D	F	A	B	D	F	A	B	D	F	A	B

Table 3.3 – A standard tuning as used for chromatic harmonicas. Proposed tuning for devices by Hillairet, Lecadre, and Wallace (1970), Robert (1982) and Blobel, Muller, and Studer (1983)

The device shown in Kondo (1997) is Richter-tuned (like a diatonic harmonica, cf. Fig. 2.11 and Tab. 3.4). Wheaton (1993) is Richter-tuned as well, except the draw note on position 2, which is an *F* instead of a *G*. However, this is not a fixed tuning, as the device offers a way of reassigning the note values.

Similarly, the *Jamboxx* provides a variety of assignable tunings, including user definable presets. The factory defined presets include standard Richter tuning, a major, Blues[3], Jazz[4], and “Spanish” (Phrygian dominant scale)[5] scale with same notes for blowing and drawing, and a so-called “Super Harmonica”[6] scale.

The above devices all employ some continuous measurement of a modification gesture, whether in the form of a thumb wheel, force sensing resistors, or a rotary encoder. This indicates the importance of continuous and subtle control over the sound and its pitch, suggesting that the developers intended to mimic a diatonic harmonica interaction.

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[3] e.g., C–D♯–F–F♯–G–A♯–C

[4] e.g., C–D–E–G–A–C

[5] e.g., C–C♯–E–F–G–G♯–A♯–C

[6] e.g., blow: A♯–F–F–F–A–C–F–F, draw: C–E–G–A♯–D–E–G

blow	C	E	G	C	E	G	C	E	G	C
draw	D	G	B	D	F	A	B	D	F	A

Table 3.4 – A standard Richter tuning as used for diatonic harmonicas. Proposed tuning for devices by Kondo (1997), and Wheaton (1993) (in variation).

Mölders (1980) proposed an alternate tuning of the device (Tab. 3.5). Every blow and draw note from the same hole has a pitch distance of six notes from the *twelve tone row* to each other. On the circle of fifths, the notes lie on opposing sides.

blow	F	A	E	G	D♯	D	F♯	C♯	C	G♯	B	A♯
draw	B	D♯	A♯	C♯	A	G♯	C	G	F♯	D	F	E

Table 3.5 – A non-standard tuning based on a six note distance on the *twelve tone row*. Proposed tuning for a device by Mölders (1980).

3.6 Sound synthesis

Most of the patents only describe the actual device and not the sound synthesis algorithms. Usually, the sound synthesis is described as being interchangeable and not fixed.

Generally speaking, if the sound output of the device is meant to resemble the acoustic harmonica's sound, a physical modelling approach could be taken into consideration. Physical Modelling is a sound synthesis method that computes the sound output according to a mathematical model simulating the physical characteristics of a given sound source, i.e., a musical instrument such as the harmonica. Significant work has been done in this active field of research.

The development of physical modelling algorithms for a harmonica-like sound is based on what we know about the physical properties of free reed instruments and acoustics. As early as 1830, German physicist Wilhelm Weber described a correct theory involving the influence of a compliant structure (such as the reed) on the input impedance of an air column. Henri Bouasse later refined this theory, and many more followed. These studies, however, were more concerned with the beating reeds of woodwinds such as the clarinet, rather than free reeds (Benade 2012, p. 435).

Since the past two or three decades, the acoustics of free-reed instruments have been studied with increased interest, cf. Cottingham (2011). In 1987, Robert Johnston published an article describing the note-bending technique, and presented results showing how the instrument behaves when blown mechanically through an apparatus simulating the vocal tract with a syringe-like volume-adjustable air column (Johnston 1987). Bahnson, Antaki, and Beery (1998) investigated the harmonica free reeds' vibration during normal play and note bends using both videoscopic analysis as well as a high precision proximity sensor.

A well-known French researcher on free reeds, Laurent Millot used strain gauges and a differential pressure sensor to show the reed displacement and the internal overpressure in detail. The movement of the reeds during normal play, a draw bend, and an overdraw are shown, and quantitatively confirmed to be strictly sinusoidal. Millot was able to derive the mass, stiffness, damping, quality factor, plucked eigen frequency, and rest offset of the tested reeds – an important step in the development of a complete model of the diatonic harmonica (Millot, Cuesta, and Valette 2001).
Millot and Baumann (2007) proposed a *Minimal Model of Free Reeds* which reviews and builds upon previously proposed models and theories of free reeds (Debut and Millot 2001; Tarnopolsky, Fletcher, and Lai 2000), including one model of the Asian free-reed instrument *shō* (Hikichi, Osaka, and Itakura 2003). The model takes into account the entire air escape area between the reed and the plate (*Useful Section*), as well as the reed thickness. In addition, Millot (2011) proposes a vocal tract model to account for note bending.

Cottingham (2013) explains the torsional, transverse, and lateral vibration modes of a (Western-type) free reed and their respective effect on the time and nature of the attack of the resulting sound. Cottingham has conveyed substantial research in the field of free reed instruments, especially on the American reed organ and Asian free-reed driven instruments.

An example of a (freely available) physical modelling virtual synthesizer VST is the Moloko Harmoniac. It uses audio input to feed an envelope follower, giving subtle control over the sound amplitude. Several controls can be used to modify the virtual reed's reactivity to air pressure, as well as the size and resonance of the virtual instrument body coupled to the reed.

An alternative to the physical modelling approach is the much simpler FM synthesis. The famous Yamaha DX7 FM synthesizer introduced in 1983 already had a harmonica preset sound installed, which was supposedly used in the Tina Turner song "What‘s love got to do with it". However, this example is pretty far from an accurate harmonica sound.

A harmonica sound could also be produced using a sampler and modified through filtering techniques and digital audio effects.

3.7 Feedback modalities

Many acoustic musical instruments produce sounds which can directly induce vibrations to the instrument's body and can be felt by the performer. This can give additional information about the state of the instrument.
DMIs constitute a separation between gestural controller and sound synthesis. As control does not need to take place in the same physical space as sound production, DMIs do not automatically provide this type of haptic feedback.

Vertegaal, Ungvary, and Kieslinger (1996) proposed three types of artificial feedback that a DMI can produce: *visual*, *tactile*, and *kinaesthetic*. Here, visual feedback would be more important at the learning stage, and kinaesthetic feedback would be more important at the expert stage. Feedback can also be distinguished by being *primary* and *secondary*. Primary feedback describes the aforementioned types of feedback, whereas secondary feedback describes the sound produced by the instrument itself (Wanderley and Depalle 2004). Feedback can be called *passive* if it is provided "through physical characteristics of the system", and *active* if it is actively produced by the system in response to a user action.

Most of the reviewed DMIs do not provide active feedback, and none of them provide active tactile or kinaesthetic feedback. However, some devices do provide active visual feedback with the use of light-emitting diodes or screens.
The DMI presented in Wheaton (1993) provides visual feedback on a separate unit, which can be worn on a belt. The feedback provided is thus not intended to give real-time information while performing, but rather convey semantic information about the selected configurations and modes of the instrument.

The *Millioniser* provides a similar visual display for giving feedback about selection gestures, situated on a separate synthesizer unit. Additionally, an LED array on this same unit gives active visual feedback showing which note is selected. Given that the *Millioniser* is a slide-based harmonica-related DMI, this visual feedback helps the performer in the learning process of finding the right slide position to select the desired note.
Another slide-based harmonica-related DMI is the *Jamboxx*. Fig. 3.21 shows a screenshot of the software provided together with the instrument. According to the slide position, a position indicator slides over a set of icons representing playing position, highlighting the currently selected note and hole. If the user blows into the mouthpiece, the selected icon turns yellow. The color intensifies with higher blowing pressure. For drawing, the icon turns blue and a minus is attached to the hole number. The position of the rotary encoder wheel on the left side of the device (cf. Fig.3.10) is indicated as a horizontal bar on top of the selected hole icon and on a graphic of a pitch bend wheel as found on keyboard instruments.

Fig. 3.21 – A screenshot of the software provided together with the *Jamboxx*, a device presented in Whalen, Luther, and DiCesare (2011).

The *XHarp* supplies active visual feedback for selection gestures with an LCD screen mounted on the top surface of the device. The screen displays a menu structure, e.g. to select a different sound.

The *Jamboxx* also serves as an example for passive force feedback: In a current embodiment, the wheel on the left side of the device is spring-loaded to return to the initial position. Therefore, the counter-force to that which needs to be applied on the wheel to achieve a certain effect gives information about the state of the instrument. In a similar manner, the slide lever of the *Millioniser* provides passive feedback.

Comments from the participants of the harmonica performance gesture study presented in section 5.1 suggest that expert performers are not aware of using tactile feedback during performances and think that they do not need to rely on it.

3.8 Distribution in space

Digital Musical Instruments can be classified according to their distribution in space, which "represents the total physical area in which the interaction takes place" (Birnbaum et al. 2005).

Some of the reviewed DMIs consist of a gestural controller wired to a synthesizer unit, which is also part of the interaction space. Others constitute *embedded systems* where the processing electronics for mapping and sound synthesis are found inside the gestural controller.

The dimensions of the gestural controller body are most often bigger than those of the conventional diatonic harmonica, due to the space taken up by complex excitation gesture measuring techniques or electronics inside the instrument body.

Gestural controllers significantly larger than a conventional diatonic harmonica include the *Millioniser* and the *XHarp* (cf. Fig. 3.22). The *Millioniser* needs to be bigger in size to account for the various buttons and slides that are part of the interface, whereas the *XHarp* represents an embedded system with a large amount of electronic components for sound synthesis and mapping that increase the size of the instrument body.

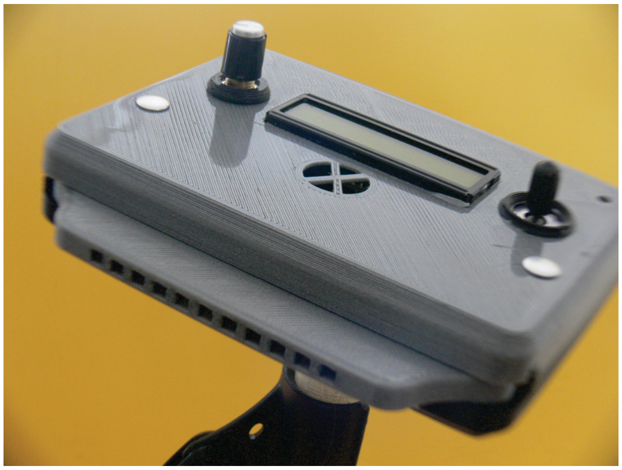


Fig. 3.22 – A current version of the *XHarp*, a device presented in Read and Hebert (2013). Photo courtesy of Wayne Read.

3.9 Feature extrapolations

Digital musical instruments are capable of incorporating several features of existing acoustic instruments, but can also extrapolate them in order to provide new ways of musical expression. In the following, selected feature extrapolations of harmonica-related DMIs are presented.

The diatonic harmonica is Richter-tuned into a specific key. If a harmonica player wants to perform together with an accompaniment or other musicians, usually a harmonica is used that matches the key of the music. This is the reason why many expert harmonica performers possess a variety of harmonicas in different keys that are used in different performances.

Harmonica-related DMIs do not encounter this problem, as the pitch values are arbitrarily assignable to the measured input gesture. Many of the reviewed patents claim a device that can change the note arrangement with a selection gesture, enabling the performer to change the key of the DMI in between performances or even during a performance.

Wheaton (1993) proposed programmable "pitch map tables" to assign note values to the air channels, in order to provide every possible scale and key configuration.

The *Jamboxx* software allows the user to choose between a large number of scales (cf. sec. *3.5 Tunings*) – including even user-definable scales.

Harmonica-related Digital Musical Instruments trying to make use of the gestural repertoire of chromatic harmonica players included the sharpening switch that can be found on conventional chromatic harmonicas.
Hillairet, Lecadre, and Wallace (1970) added a second sharpening switch, making it possible to double-sharpen a played note, and thus to achieve whole note trills.
Ziegler (1989) proposed a single switch that would sharpen the played note if pressed down completely, but which would flatten a note when held at an intermediate position.

3.10 Dimension Space

The design space analysis for musical devices provides a "general framework of theoretical and practical design decisions", whose representation "distinguishes the design rationale behind a system from the set of all possible design decisions" (Birnbaum et al. 2005).
The representation consists of a set of concentric lines, each representing a different feature dimension of the device. The device dimension space is then represented by a polygon shape connected at its edges to these lines, according to its value on each of the feature dimensions.

As the examined set of harmonica-related DMI devices already implies several features restrictions, the dimension space representation was adapted. The "Role of Sound" and "Inter-actors" axes were left out, as their value is the same for all examined devices. The role of sound is always expressive, and it always involves a single interacting musician.
The dimension "Musical Control", which originally provided three discrete values *process*, *note–level*, and *timbral*, was modified so that it now has four discrete values where *note–level* is split into *note–level (discrete)* and *note–level (continuous).* This distinction is useful, as there are harmonica-related DMIs that only provide control over "note on" and "note off", and others that provide additional control over the amplitude envelope.

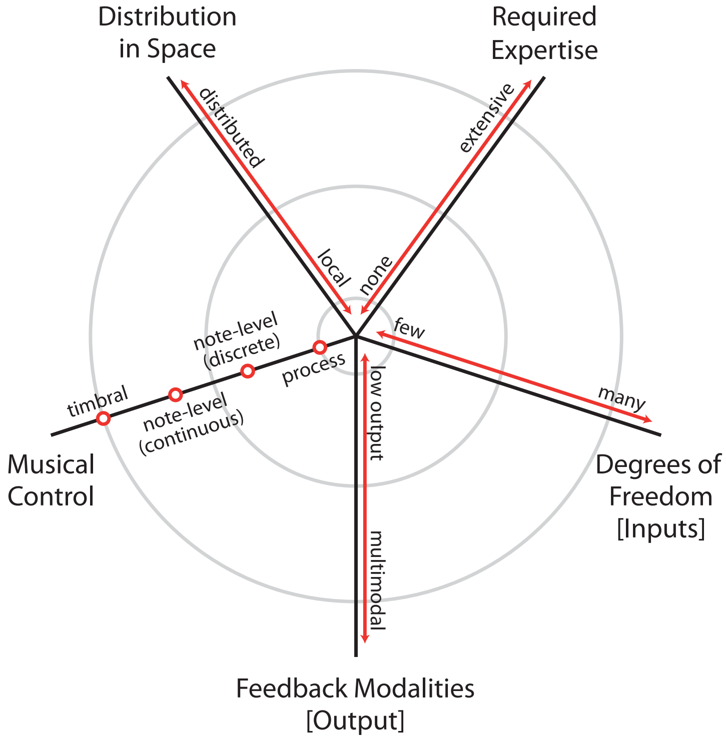
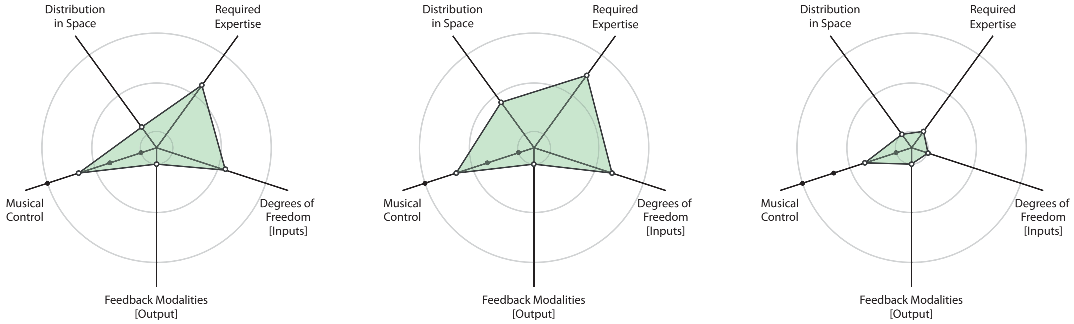
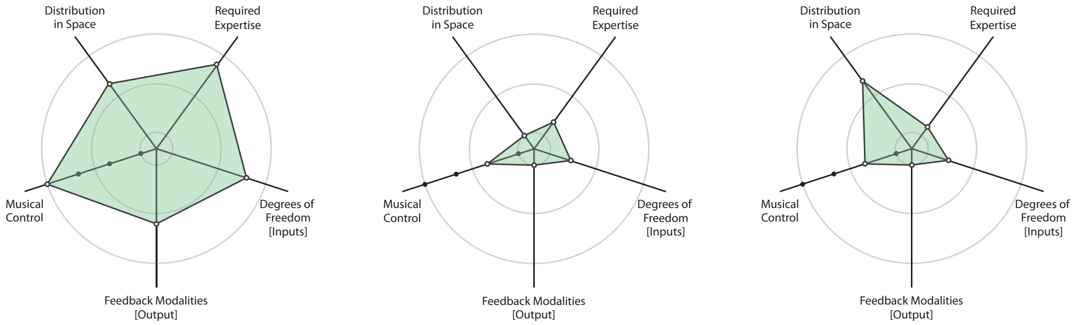


Fig. 3.23 – Dimension Space representation based on a model adapted from Birnbaum et al. (2005).

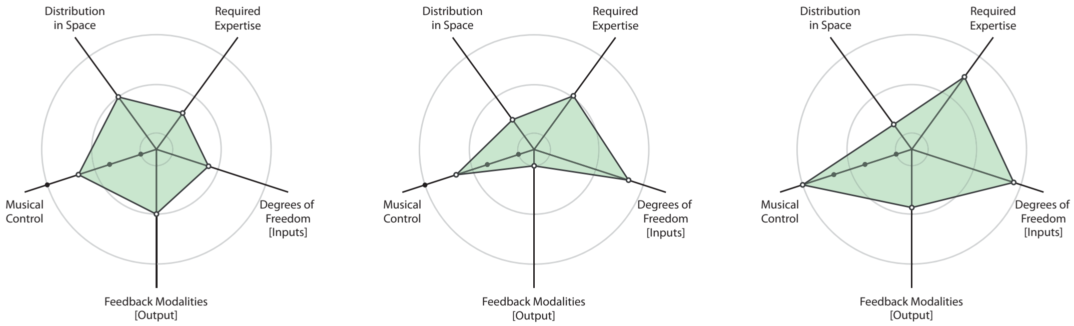
Dimension space representations were created for eleven devices and are shown in Fig. 3.24. They should not be seen as absolute measures, but are meant to give a sense of the differences and similarities of the devices in relation to each other.



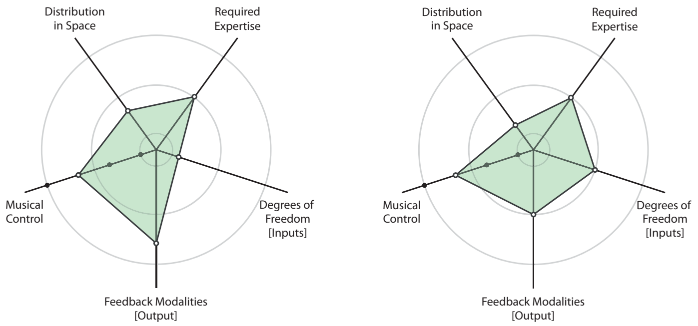
Hillairet (1970) Mölders (1979) Robert (1982)



Blobel et al. (1983) Arai (1984) Matsuzaki (1986)



Ziegler (1989) Schille (1991) Wheaton (1993)



Whalen (2011) Read (2013)

Fig. 3.24 – Dimension Space representations of various harmonica-related Digital Musical Instruments based on a model adapted from Birnbaum et al. (2005).

3.11 Geographical distribution

It is interesting to note where most of these inventions were claimed. The main countries include Germany, the USA, Japan, and France.

The harmonica was invented and marketed in the German-speaking countries, which could explain the interest of German-speaking inventors in the development of a harmonica-related DMI. The USA was always the main importing nation of harmonicas, and it is there that important playing styles and techniques were developed. Harmonicas are very popular in France as well, ever since the early importation of harmonicas from Germany (Berghoff 2001).

Japanese inventors' patents were usually associated with big electronic companies. Arai (1984) and Matsuzaki (1986) filed their patents in association with Casio Computer Ltd., and Kondo (1997) with Sony Corp. One American inventor, Wheaton (1993) filed his patent in association with Yamaha Corporation.

There are a few Chinese patents as well (Li and Li 1990; Zhang and Zhang 1993). The interest of Asian inventors could be explained with the East Asian tradition of using reed instruments such as the Chinese *sheng*, the Japanese *shō*, the Vietnamese *Khene*, and the Thai *Pi*, as well as the large, well-organized harmonica scene in Asia (Eyers 2011).

3.12 Availability

Harmonica-related DMI design is an active field of product development. At the time of the publication of this work, at least three devices were currently under development or in a beta testing phase. The *Jamboxx* is sold commercially and the *XHarp* is in a pre-ordering stage of development.

Web searches for all reviewed devices showed that most of them, including devices associated with Yamaha, Casio, or Sony, are not currently produced for the mass market.

One of the formerly most successful harmonica-related DMIs – the *Millioniser 2000* – is difficult to find today. Rock Erickson, the American spokesman and distributor of the Millioniser, stated in a phone call (personal communication, June 5, 2014) that only a total of 100 instruments were produced.

3.13 Conclusion

In this chapter, a patent review of harmonica-related digital musical instruments was presented. Different sensor system designs for the capture of musical excitation, selection, and modification gestures were described.

Devices were compared in terms of applicable harmonica playing techniques, tunings, and other categories. A focus was set on attempts to measure the note bending technique (or to translate this technique to another body part).

Possible sound synthesis approaches were discussed and Dimension Space graphs were created for a selection of harmonica-related DMI in order to highlight their main features in a glance.

4 | Harmonica Performance Gesture Study

In order to study the gestural interaction between performer and instrument, a study setting was created, involving the Qualisys[1] motion capture system available at CIRMMT. Experienced harmonica players' performances were recorded with synchronized motion capture, audio, and video footage, as well as sensor data from a force-sensing resistor mounted on top of the device.

The acquired data allowed for a better visual examination of the musicians' gestures, as well as for numerical analyses. However, the limited data set of five participants does not allow for quantitative approved statements that apply to the entirety of expert harmonica players.

Relationships between jaw opening and fundamental frequency, distance between harmonica body and cupping hand versus spectral centroid, maximum hand cupping frequency, and orientational pitch of the harmonica body were investigated.

The harmonica used in this study was a Hohner "Special 20 Marine Band", which can be considered a general standard, as indicated by Johnston (1987).

For a detailed description of the technical setup, please refer to Annex A (*Harmonica Performance Gesture Study appendices*).

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[1] http://www.qualisys.com/

4.1 Participant recruiting and study organisation

Five participants were recruited from the Montréal community of harmonica performers, as well as the Harp-L mailing list (with permission). All were males with more than 10 years of experience (17.6 years average). They all play the diatonic harmonica, but participant one performs predominantly on a chromatic harmonica.

The participants rated their *level of experience* with different playing techniques on a 1 to 10 scale. The ratings were generally very high (Appendix A, sec. A.3 *Questionnaire responses*).
Participants were asked to rate their *quality of performance* during the study on a second 1 to 10 scale. These ratings were also very high, with none of the ratings below 7, which we consider an acceptable quality for this study.

Upon showing interest for the study, the participants were provided with sample audio recordings of two piece excerpts (described below), and were asked to practice the piece at home before the date of the experiment.
The participants were compensated for their time and effort with 30$.

The study was approved by the McGill Research Ethics Board II (Appendix A, sec. **??** **??**).

4.1.1 Marker placement

In the conveyed user study, a total of 21 passive markers were attached to the right hand of the participants. Three markers were used for each finger, so that one marker was attached to the top middle surface of each finger's bone segment.
Three markers were attached to the top of the left hand.

For one task of the study, only two markers were attached to the participants' cheek and bottom of the chin (cf. sec. 4.2.1.1 *Note bending*).

The harmonica was modified with a wooden cross with markers attached, in order to be able to calculate the position and inclination of the harmonica's body at any time.

Although all the marker trajectories were correctly labelled after the capture, not all were necessary to analyse the movement. It is common practice in motion capture projects to attach more markers than predicted for the analysis task, in case of subsequent studies using the same dataset, to check the validity of results, and to perform analyses that were not initially foreseen in the course of the study.

Fig. 4.1 – John is playing the modified harmonica, with markers attached to his hands and wearing a marker head band.

4.2 Course of the study

As passive IR motion capture techniques cannot capture the vocal tract techniques in harmonica performance, a specific study was designed for the evaluation of musical gestures and techniques conveyed by hand and body movement.

The study was divided into four parts:

1. **Playing techniques**
   note bending, overblow/overdraw, and hand cupping
2. **Performance expressiveness**
   performance of two piece excerpts, three times each (immobilised/standard/expressive)

3. **Free improvisation**
   free improvisation of two sequences, one slower and one faster

4. **Evaluation of harmonica-related DMIs** (presented in Chapter 5)
   participants were presented harmonica-related DMIs *Jamboxx* and *Millioniser* to test

4.2.1 Playing techniques

In the first part, participants were asked to perform basic playing techniques, such as note bending and hand cupping.
Overblowing and overdrawing was performed as well, although the harmonica used was not "broken in" (the reeds were not embossed) to allow for easier overbending. All of the participants were uncomfortable with this condition, which is why the data was not analysed.

4.2.1.1 Note bending

Referring to the problem of measuring or translating the note bending technique, as already mentioned in Chapter 3 sec. 3.4.1, the relationship between the note bending technique and jaw opening was investigated.

There is some evidence that jaw opening is correlated to the pitch of different vowels in singing (Sundberg and Skoog 1997; Austin 2007). Given that note bending can be described in an analogy to unvocalised vowel sounds (Baker 1999) these findings might partly apply to the note bending technique as well.
The distance between a set of two markers attached to the cheek and chin of the participant was calculated for each frame, and the fundamental frequency of the audio signal was estimated using the YIN algorithm (De Cheveigné and Kawahara 2002). When plotted to the same graph, a relationship becomes obvious (cf. Figs. 4.2 and 4.3). The fundamental frequency decreases along with the distance between cheek and chin, which suggests that jaw opening is indeed connected to the note bending technique.
The jaw can, of course, be opened independently, and not just while using the note bending technique. Thus, jaw opening should only be used with caution as a direct input variable to any digital musical instrument.

However, it might still prove to be useful to investigate, as an example, the employment of a distance-measuring apparatus attached to the sliding mouthpiece of a slide-based harmonica-related DMI. This could provide a more intuitive translation of the note bending technique to another gesture – in this case, the displacement of the chin.

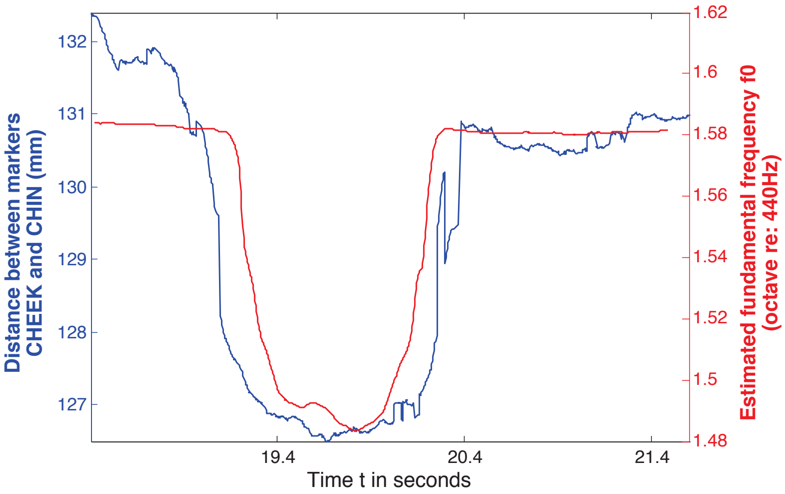

Fig. 4.2 – A graph displaying the cheek–chin distance and the estimate of fundamental frequency during a hole 8 blow bend to E♭ and back.

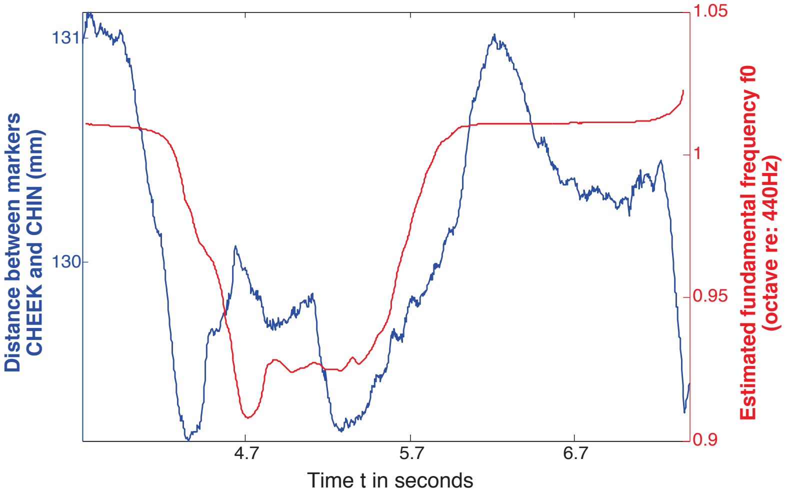

Fig. 4.3 – A graph displaying the cheek–chin distance and the estimate of fundamental frequency during a hole 3 draw bend to B♭ – A – A♭.

Hand Cupping

The hand cupping gesture can be seen as a filter to the output sound of the harmonica, affecting the sound's brightness. This effect is used extensively in harmonica performance. Thus, it is interesting to investigate how the hand cupping technique can modify the brightness in particular.

The spectral centroid is a good predictor of a sound's brightness (Grey and Gordon 1978). In figs. 4.4 and 4.5, spectral centroid is plotted against the distance of the harmonica's center point to one marker placed on the back of the hand. This, of course, is a rudimentarily simplified representation of the hand cupping gesture, but it still shows interesting results.

The participants were asked to perform a slow hand cupping gesture and were provided with a click track prior to the capture, so that they could internalize the tempo of 30 BPM. Represented by the blue line plot, the over time increasing and decreasing distance of the hand to the harmonica's body can be seen.

The red line plot, representing the spectral centroid and thus indicating higher brightness with higher values, mostly follows the tendency of the blue line. This suggests that with increasing distance (and less cupping), the brightness of the sound intensifies.

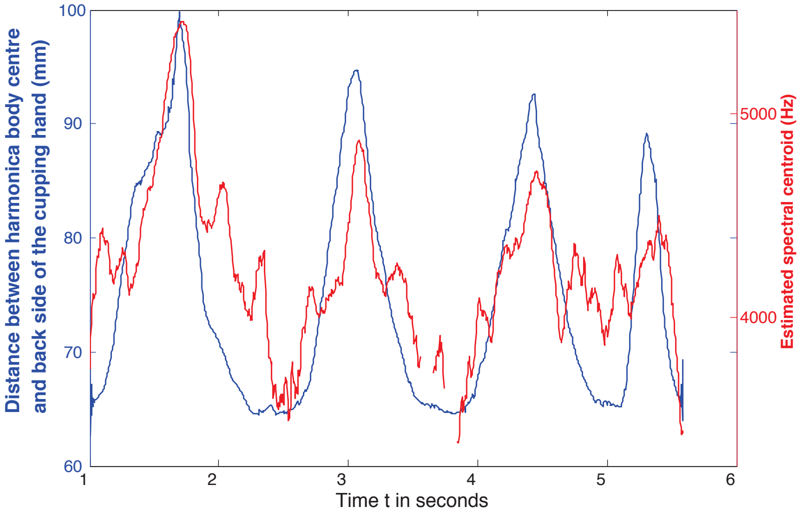

Fig. 4.4 – A graph displaying the distance between the harmonica body centre versus the spectral centroid during a performance of slow hand cupping (participant 1).

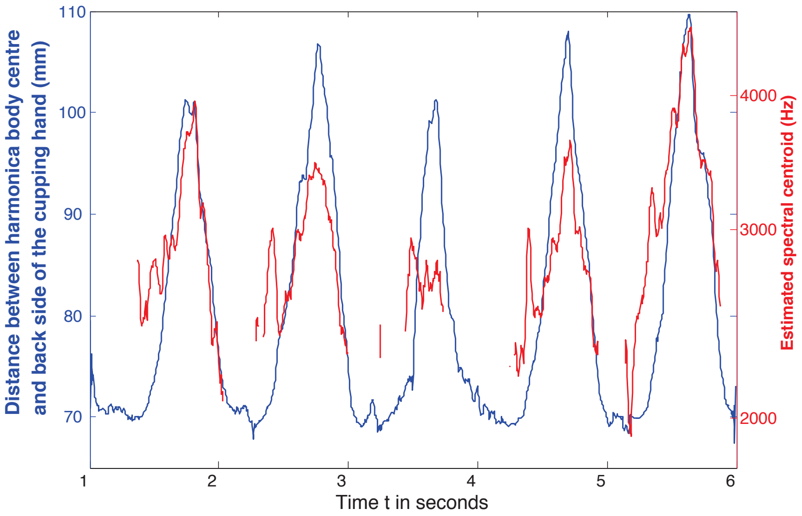

Fig. 4.5 – A graph displaying the distance between the harmonica body centre versus the spectral centroid during a performance of slow hand cupping (participant 2).

Fig. 4.4 shows that the participant's hand travelled less far with each cupping iteration, as the peak distances become lesser. The peaks of the spectral centroid plot show a similar pattern.

Contrary to the preceding figure, where the note was held for the entire measurement, fig. 4.5 shows a sequence of five self contained held notes. This accounts for an increase in the spectral centroid location toward higher frequencies preceding the displacement of the hand away from the instrument's body at every iteration of the gesture. Supported by the audio material, a possible explanation for this would be the attack of the played note, which may have a greater high-pitch frequency content influencing the spectral centroid analysis.

In a second part of the hand cupping investigation, participants were asked to perform hand cupping at the highest possible speed. Here, the marker of the upper segment of the ring finger was arbitrarily chosen as a reference point. Its velocity over time was analyzed with the autocorrelation method `mcperiod()` included in the Mocap Toolbox (Burger and Toiviainen 2013). Fig. 4.6 presents the yielded maximum hand cupping frequencies across participants.

Participants 1, 2, and 5 exhibited higher maximum frequencies than participants 3 and 4, but the frequencies are quite close together. Participant 5 showed a considerable maximum hand cupping frequency of 8.1 Hz.
The differences can not be explained with the participants' years of practice, as participant 3 and 4 showed an inferior maximum hand cupping frequency while having most years of practice. However, the participant's age could play a role: Participant 1, 2, and 5 were significantly younger in age than participant 3 and 4[2].

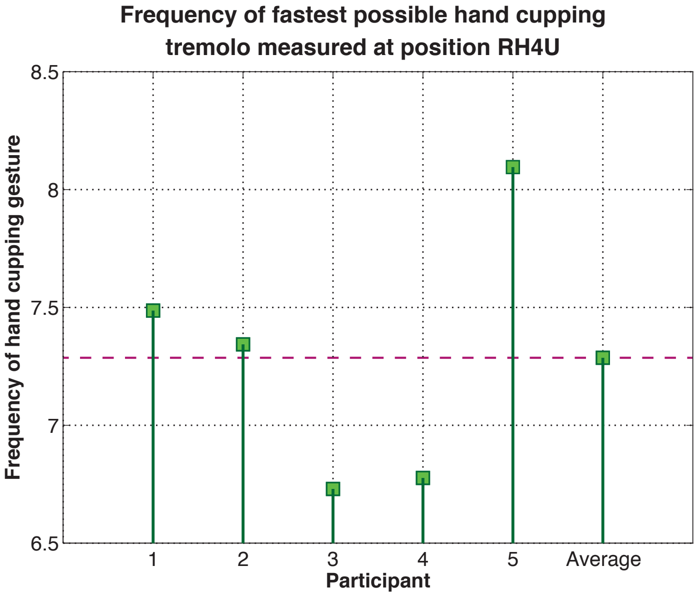

Fig. 4.6 – A plot showing the hand cupping freqency of the participants when asked to perform as fast as possible.

4.2.2 Performance expressiveness and orientational pitch

Participants were asked to perform two piece excerpts three times each. For the three iterations of the piece performance, participants were asked to perform *immobilised* ("move as little as possible"), naturally (*standard*) and *exaggeratedly expressive*. The terminology was adapted from Wanderley (2002) and describes the amount of movement.

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[2] Age differences are estimates, as information on the age was not requested in the questionnaire.

The vertical inclination angle of the harmonica was investigated. First, the harmonica cross (cf. Fig. A.5) was acquired as a rigid body representation in the Qualisys QTM software, and its absolute orientation was exported to a tab-separated values file.
The statistical orientational pitch of the harmonica across participants is depicted in Figs. 4.7 for the piece excerpt "Summertime" by George Gershwin and in Fig. 4.8 for the piece excerpt "Room to Move" by John Mayall. The vertical grey lines indicate "outliers", i.e., data points with no significant statistical importance.

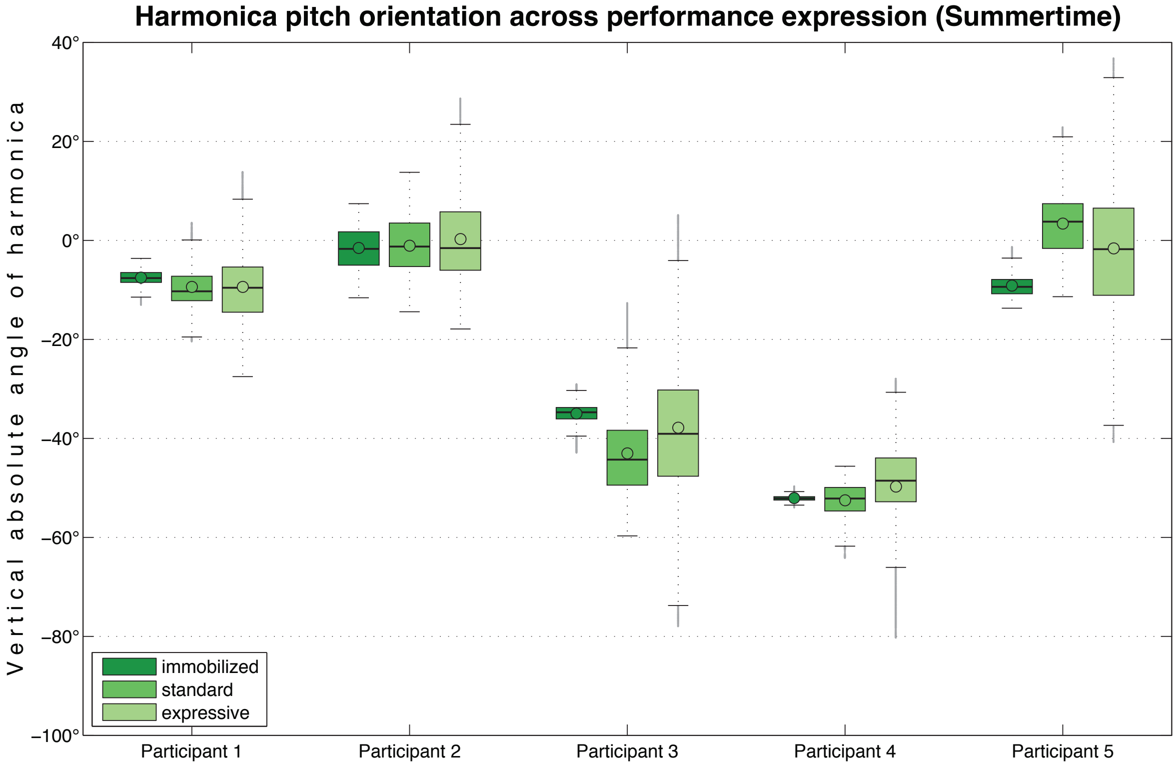

Fig. 4.7 – A boxplot showing the harmonica's absolute orientational pitch angle across participants as well as across performance expressivity, for a performance excerpt of the piece "Summertime" by George Gershwin.

The box plot shows that the deviation of the angle during a performance is increased for more expressive play. However, the mean angle is similar across performances of the same piece involving different expressiveness. This also holds true across both pieces. Thus, it can be inferred that the participants have a preferred angle at which they generally hold and play the harmonica. A subsequent user study with the same participants could further substantiate these findings.

Even though the pitch angle of the harmonica can approach and pass zero towards the positive (i.e., pass the horizontal plane towards the ceiling), it can be stated that it is generally below zero, or in other words, the harmonica is directed towards the floor.

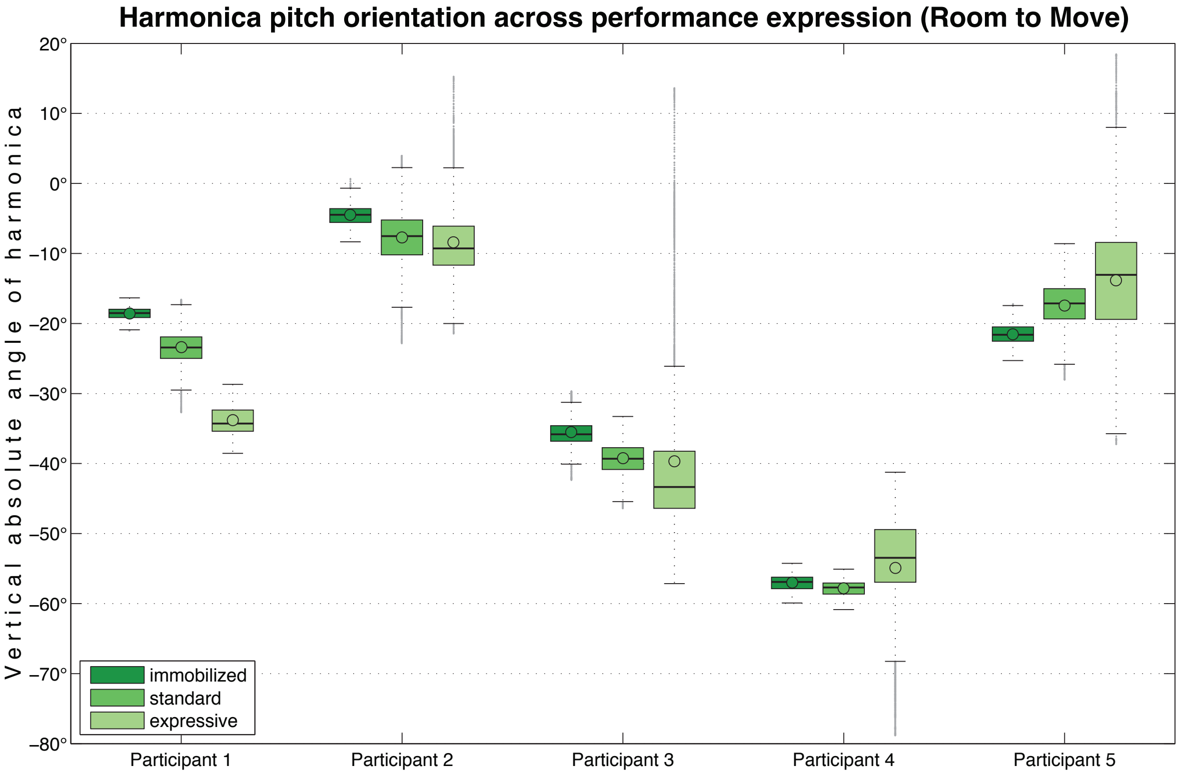

Fig. 4.8 – A boxplot showing the harmonica's absolute orientational pitch angle across participants as well as across performance expressivity, for a performance excerpt of the piece "Room To Move" by John Mayall.

It is interesting to note how the midpoints of the boxes shift across expressiveness, especially in Fig. 4.8. Considering the video material, the angle shift towards the floor with increasing expressiveness across participants 1-3 might indicate that they are more inwardly focused when performing more expressively. On the contrary, participant five would open up his posture and focus outwardly with more expressiveness.

4.2.3 Free improvisation

The participants were asked to perform one slow and one fast improvisation, without any further instructions given. The first 60 seconds of each improvisation were captured.

The material was then analysed using MATLAB. Both finger pressure and harmonica inclination plots were created and exported as scroll plots to video files. The harmonica inclination plot also included the relative angle of the harmonica's inclination to that of the head (seen as green lines in Fig. 4.9), which is found by calculating the difference between head band inclination data and harmonica cross inclination data.

The difference data can only be used to visually indicate relative changes, as the head band angle (as worn on the head) was not normalized to absolute angle values. However, when compared to the harmonica cross inclination and omitting an angle offset, it corresponds to the angle of the harmonica relative to the player's mouth.

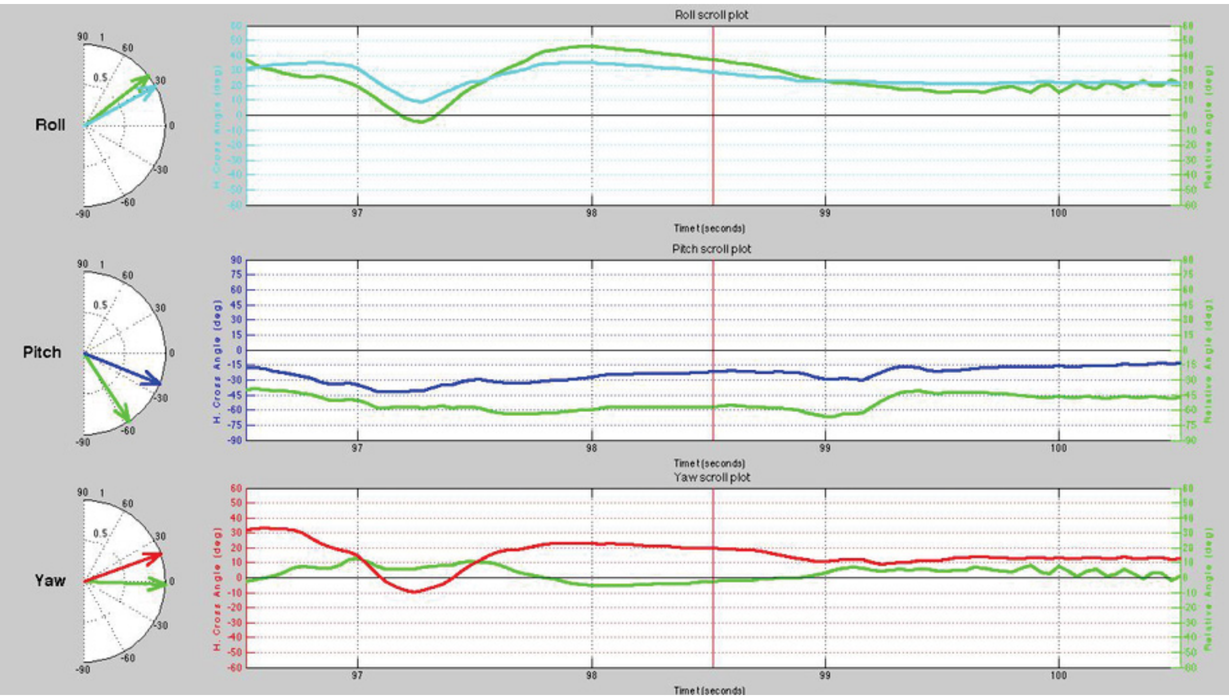

Fig. 4.9 – An example frame of a video scrollplot used in the annotation of the improvisation performance footage.

The video scroll plots were imported into the video annotation software *ELAN* (Sloetjes and Wittenburg 2008) in order to find visual indicators of the relationships present within

the data. *ELAN* was originally developed by the *Max Planck Institute for Psycholinguistics* and supports multi-layered annotation of up to four synced video files and audio.
While having an excellent feature set, unfortunately *ELAN* has no way to import and visualise data (other than annotations) directly as TSV or CSV files, which is why the data had to be imported as video footage. It was still found to be better suited for the task than other annotation software such as *VCode & VData*[3] or *ANVIL*[4].

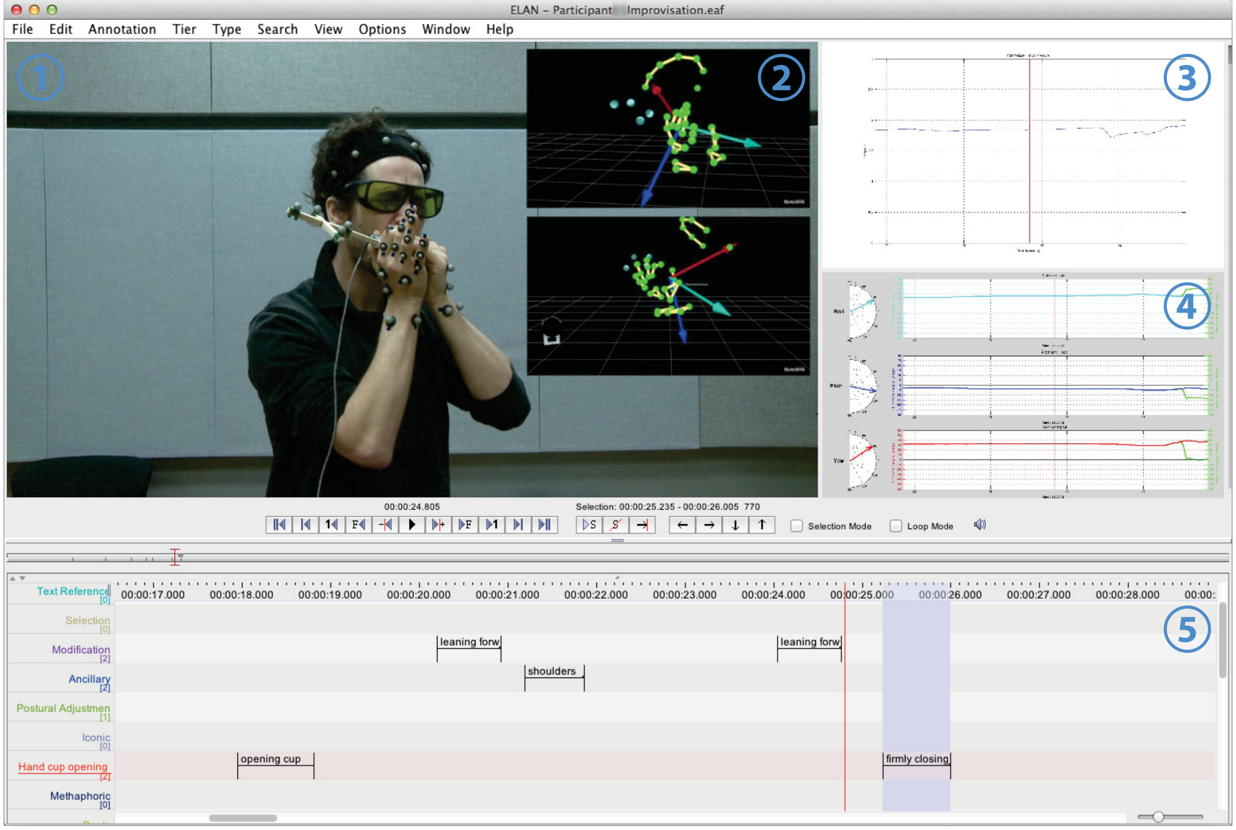

Fig. 4.10 – A screenshot of the ELAN software used for the visualisation and partial annotation of the video files, displaying video footage **1**, acquired Qualisys markers and harmonica rigid body definition **2,** finger pressure data **3**, harmonica inclination **4**, and the annotation area **5**.

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[3] http://social.cs.uiuc.edu/projects/vcode.html
[4] http://anvil-software.de/

Observing finger pressure data

The visual examination of the improvisation sequences yielded no obvious relationship of the finger pressure data with the instrument's inclination data, nor with recurrent gestures. Finger pressure didn't alter specifically with any single playing technique, nor was it a consistent indicator for phrasing and rhythmic sequences.

Observing the hand cupping gesture

The video footage was visually analysed to draw conclusions about the hand cupping technique. Generally, participants opened the cupped hand more often on the bottom, keeping the top hand placed on the harmonica. Other times, the hand's posture was preserved while it was moved to and from the instrument's body. The vertical position of the right cupping hand when touching the instrument remained relatively constant for all participants. When moved away from the instrument's body, the direction of movement was always towards the bottom. This might be related to the way the diatonic harmonica is usually held (cf. sec. 2.2.1), where the thumb supports the instrument from the bottom.

4.3 Conclusion

In this chapter, a motion capture study of harmonica performance gestures was presented. The participant selection process was described, and the course of the study outlined. Qualitative findings related to common playing techniques such as note bending and hand cupping were shown. The relationship between instrument orientational pitch and expressiveness was investigated, and footage of free harmonica improvisation was used to investigate relationships within the captured data.

5 | DMI Evaluation and Jamboxx Augmentation

5.1 Evaluation of harmonica-related DMIs

As a second part of the conducted study, four of the five participants were presented with two harmonica-related DMIs: A *Jamboxx*[1] prototype and the *Millioniser 2000*[2]. Both devices are slide-based harmonica-related DMIs, where the notes are selected by sliding a mouth piece in the associated horizontal position. The devices were discussed informally while examining them together with the performer. The video footage of the discussion was later reviewed and comments were annotated.

When discussing the devices with the participant, a number of research questions were kept in mind.

1. Is the proprioception trained using an acoustic harmonica easily transferred to a slide-based sensing system?
2. Does the slide's movement resistance interfere in the note selection process?
3. Is the up/down tilt movement a good substitute gesture for the note bending technique?
4. Is the visual feedback important?

The comments made by the participants indicate design flaws that are only discernible by expert harmonica players, and thus very interesting to note. The following summary is

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[1] http://www.jamboxx.com

[2] http://www.millioniser.com

a particular case study and not intended to patronize the developments, but to provide constructive criticism applicable to the entire field of harmonica-like DMI design.

5.1.1 Jamboxx

The *Jamboxx* prototype provided by *My Music Machines, Inc.* was presented first. It was mounted on a microphone stand with the original mounting equipment and connected to a PC with an installed version of the *Jamboxx Pro Suite* software (cf. Fig. 3.21).

5.1.1.1 Bypass air

The provided mouthpiece of the device did not include a *bypass channel* for the blown/-drawn air. Three out of four participants reported that they were uncomfortable with the fact that the air does not flow through the mouthpiece. One stated that it felt as if he was not breathing. The fourth participant mentioned that it does not pose a problem, and depends on experience. He also pointed out that this feature enables holding a note while breathing simultaneously.

5.1.1.2 Air pressure controlled intensity

The *air pressure controlled intensity* of the sound output was criticised by two participants: the resolution would be too small and the note-triggering threshold too high. One participant stated that the quietest note he was able to play on the *Jamboxx* was already as loud as a mezzo-forte. Half of the participants did not recognize the device as being gradually pressure-sensitive at all, and thought it was only processing discrete on and off values.

One participant pointed out that he was unable to use the tongue articulation technique. This might also be due to the use of a pressure threshold that needs to be attained in order to trigger a tone. The tongue articulation technique, however, involves fast successive zero-crossings between positive and negative breath pressure, so that a direct translation of breath pressure to amplitude envelope would be more purposeful in this context.

5.1.1.3 Ergonomics

Two participants stated that the mouth piece does not respond to their ergonomic needs. The embouchure around the small mouthpiece nipple would require constant effort, which leads to earlier fatigue during performance.

5.1.1.4 Mouth piece slide friction

None of the participants had problems with the *mouth piece slide friction*, and two reported that it was very fluid and easy to slide. One reported that he was able to quickly jump from one note position to another just like on a standard Richter-tuned harmonica. When asked to perform the diatonic scale on the second octave, all participants showed that it was possible and highly probable that they could adapt quickly. The difficulty of note selection with the slide was rated as being medium-difficult.

5.1.1.5 Note spacing

Two participants mentioned that the spacing between selectable note positions on the slide is too big, so that the way to travel from one note to another is long. This leads to fatigue and slows down the performance speed. Again, two participants reported difficulties in the note selection process due to a difference in spacing between the leftmost and second-to-left note, as well as the second and third note, and suggested that all note positions should be equidistant.

5.1.1.6 Pitch bend

The *Jamboxx* has a pitch bend functionality related to up/down movement of the device when mounted on a stand, or the turning of a knob on the left side when unmounted. The rotary encoder (cf. Fig. 3.10) is used in both settings as the input sensor. The prototype mapping was such that upward tilting bent the pitch downwards, and downward tilting bent the pitch upwards. All of the participants reported this behaviour as being counter-intuitive, and rated the feature as being very unnatural. The *Jamboxx Pro Suite* software includes a calibration wizard that allows the user to choose whether to use the device mounted or free-hand, but this does not reverse the sensor data.

When playing in free-hand mode, one participant stated that he would prefer the knob to be on the right side of the device. Another participant stated that he would generally prefer a lever on the back side of the device for pitch bend gestures, whereas a second participant suggested a pitch bend wheel like those widely used on keyboard synthesisers, as well as the use of a lip pressure or bite pressure sensor.

When asked about the use of a self-centering spring-mounted knob that would enable the instrument to move back to the neutral note bend position, the participants approved.

5.1.1.7 Distribution in Space

Combined up/down tilt movement (when mounted) and mouth piece slide movement was experienced by two participants as resulting in a too-large movement space, whereas one participant found it to be acceptable. Furthermore, one participant mentioned that the hands-free use of the controller significantly facilitates the movement. Not only could a head displacement gesture be used to select a note or pitch bend, but hand movement could also be used to displace and tilt the device. The use of the head and hands to accomplish a task together may improve the speed and accuracy of the gesture, and thus the accuracy of note selection or pitch bend.

Another interesting suggestion was to modify the sliding mechanism from being linear to being somewhat circular. This would therefore better correspond to the angular yaw movement of the head.

5.1.1.8 Feature limitation

One participant spoke out in favour of limiting the pitch bend functionality so that only the notes that are bendable on a Richter-tuned harmonica could be bent using the *Jamboxx*. This demonstrates a point of view that is also discussed in the theory of product design. The first design law of John Maeda's book "The Laws of Simplicity" is that of (methodical) reduction (Maeda 2006). In development, input devices can easily become overcomplicated. Simple removal or masking of features can add to the intuitiveness of the device, which is also improved by enabling the use of a known gestural repertoire.

Another participant argued against this notion and stated that this feature extrapolation is a big plus.

The fact that the pitch bend functionality only bends one semitone up or down, whereas a Richter-tuned harmonica can be bent down up to three semitones depending on the air channel was criticized by two participants.

Furthermore, two other participants remarked that the visual feedback indeed indicates the pitch bend on a virtual pitch wheel, but not on the virtual keyboard displayed as part of the software's graphical user interface. This caused confusion among the participants.

5.1.1.9 Tactile feedback

When asked about the use of a tactile bump strip (which was not available at the time of the study), three participants answered in the affirmative. One of them, however, thought of it as being only useful for the learning stage and pointed out that expert harmonica players are used to playing their instrument "blindly" without tactile cues.

5.1.1.10 Chord functionality

The *Jamboxx Pro Suite* includes a functionality that can add chords to the played note. Participants criticized this as not being useful, as the chords are always in the same mode for all notes. On an acoustic diatonic harmonica, it is possible to play major chords, major seventh chords and single notes interchangeably by letting air flow through one or multiple holes.

In the same way, octave playing and split intervals (cf. sec. 2.2.2) is made impossible on the *Jamboxx*.

5.1.1.11 General interest

While all participants showed great interest in the device, they were all skeptical about whether they would use it personally. One participant stated that even if he can apply his own musical skills, it still feels like learning a completely new instrument. Another participant was skeptical about whether he would be ever able to master the instrument.

5.1.2 Millioniser 2000

The *Millioniser 2000* is not manufactured anymore, and there are only a few used exemplars selling. This is why only the controller, but not the synthesiser unit, could be procured. Thus, the participants could only evaluate the interaction with the controller without any audible feedback.

In order to give an impression of how the Millioniser is played and how it sounds, the original 1983 advertisement video of the *Millioniser 2000* was shown to the participants (millioniser2000 2009). An interesting off-topic comment on the video mentioned that even though it shows someone playing the *Millioniser 2000*, the participants did not perceive him as being a master of the instrument, which inspired skepticism among all the participants about the quality of the device.

As the device was presented second and the study duration was limited to three hours, the device was not examined to the same extent as the *Jamboxx*.

5.1.2.1 Half tone lever

The device's half-tone lever was instantly recognized by all participants as having a similar function to a switch button on a chromatic harmonica. This suggests that if any button or lever is placed on the frontal left side of a harmonica-related DMI, its function is anticipated. This user expectation can be used for an intuitive design.

5.1.2.2 Slide steps

The mouthpiece slider of the *Millioniser 2000* does not slide smoothly, but in increments that stop at small notches for every selectable note position. This can be seen as an amelioration to the note selection task. However, one participant reported that the perceptible bumps would cause discomfort when switching rapidly between two adjacent notes.

5.1.2.3 Size of the instrument

When compared to the small and lightweight diatonic harmonica that becomes an integral part of the performer's hand, one participant said that the sheer size of the *Millioniser 2000* prevents it from becoming easily adapted for proprioception. Of course, engineers today would be able to develop a smaller and lighter device with the same capabilities, but it is interesting to note that small size, weight, and portability are features important to expert harmonica players.

5.2 Instrument Augmentation

The aforementioned *Jamboxx* was chosen as a base model for the creation of a novel digital musical instrument via instrument augmentation.
Building upon an existing DMI offered the possibility to focus on the application and evaluation of the findings from the motion capture study, as well as DMI evaluation instead of reinventing the note selection and excitation gesture sensor systems.

The DMI developers at My Music Machines, Inc., provided a Jamboxx gestural controller used as a base model. The electronics inside the Jamboxx were left untouched. Instead, a separate sensor acquisition system was added to the device. The input from Jamboxx was combined with that from the sensor system in the Jamboxx Augmentation software, written in Max.

The Jamboxx-based augmented prototype is designed to incorporate additional sensors capable of capturing musical gestures that were not considered in the original design, such as hand cupping, finger pressure, and tilting the instrument.

Base model

The features of the base model are described in Chapter 3, and also presented in Whalen, Luther, and DiCesare (2011). They involve a slide-mounted mouth piece that includes a differential pressure sensor, and an infinite turn rotary potentiometer.
No attempt was made to transmit the sensor data wirelessly. As the development was based on the cabled Jamboxx, the increased complexity of a wireless transmission was not justified. Furthermore, many harmonica players are used to playing the harmonica while even holding a microphone at the same time, so the cables seemed to be an acceptable obtrusiveness to performance. Perry Cook shares the opinion that “Wires are not that bad (compared to wireless)”. In his 2001 paper *Principles for Designing Computer Music Controllers* (Cook 2001), he also states that “Programmability is a curse”, advocating for more fixed and simple designs over the continuous addition of new features. This advice was implemented by the use of a fixed mapping, as described in the *Mapping layer* section (5.2.2.3).

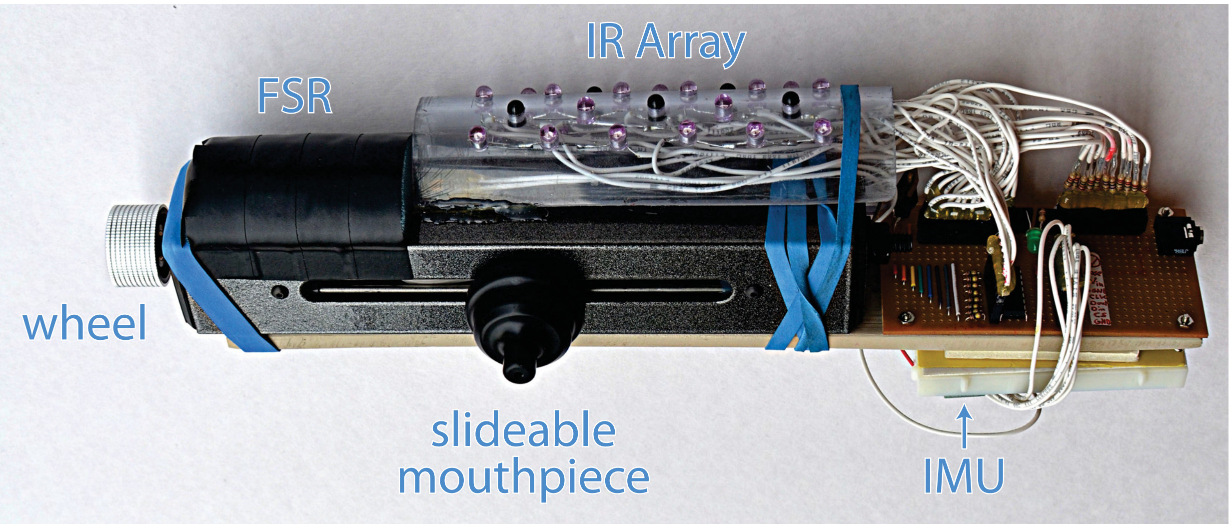


Fig. 5.1 – An overview of the prototype with annotated sensor system features.

5.2.1 Sensor system design

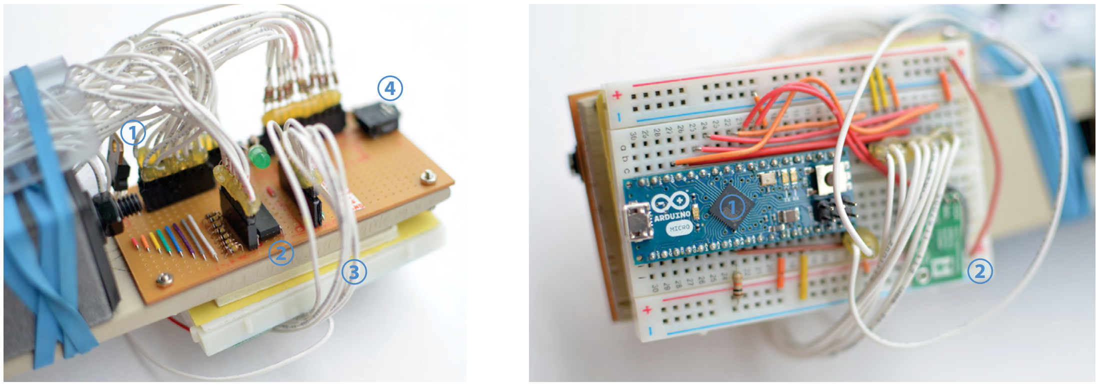
An *Arduino Micro* single-board microcontroller was used to sample and transmit sensor data to the computer. The *Arduino* IDE prototyping platform allows the writing of a firmware script that can be loaded into the EEPROM storage of the microcontroller, so that it can perform various tasks independently from the sound synthesis computer.

An emulated serial connection through USB was created, which operates with call and response communication and sends a packet of sensor readings only when the computer requests it (see appendix B). This way, sensor readings do not pile up in the serial buffer and cause a lag in response time if the computer reads the packets slower than the Arduino sends them.

5.2.1.1 Finger Pressure

The goal of integrating a finger pressure sensor to the Jamboxx design is to provide an alternative to the pitch bend wheel currently used to translate the note bending gesture on the Jamboxx.

While the wheel provides pitch bend functionality in both up and down directions, the note bending technique on an acoustic harmonica only provides a means of lowering the



(a) Top view of the electronics unit, showing the current-switching transistor **1**, the analogue-to-digital converter **2**, the cabelling to the Arduino **3**, and the power supply socket **4**.

(b) Bottom view of the electronics unit, depicting the Arduino **1** and showing the location of the Plolu MinIMU 9 v2 **2**.

Fig. 5.2 – Additional external electronics unit.

pitch (cf. sec. 2.2.3). Some participants of the user study described in section 5.1.1.6 mentioned their preference for this apparent feature limitation over feature extrapolation. They argued that the note bending functionality should resemble that of the acoustic harmonica.

Finger pressure through isometric force is measured in a single direction and might be more suitable as a translation for the note-bending gesture. It has already been proposed for pitch control by Wheaton (1993).
The fingers of the left hand naturally rest on the top of the acoustic harmonica during performance without having any function in the modification of the sound. We could take advantage of this spare bandwidth by placing the gesture acquisition in the same physical space. A finger pressure sensor can be actuated instantly from the natural rest position, which might increase the intuitiveness of the device.

An Interlink Long Force Sensing Resistor (FSR) 408[3] was used in the current design. The FSR is a sensor containing a conductive polymer which changes its electrical resistance proportional to the applied force. The sensor is low-cost and very thin, but only offers lim-

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[3] http://www.interlinkelectronics.com/FSR408.php

ited precision. It may be useful to investigate to which degree the low repeatability impairs the learnability of the pitch bend technique on the device, given the high sensitivity of the human ear to pitch fluctuations.

The FSR was firmly attached to the top left surface of the Jamboxx. Synthetic elastic foam was cut into a semi-cylindrical shape and attached on the top of the FSR by means of electrical tape. This way, a bigger surface area could be used to actuate the sensor. Also, due to its expansion property, the foam contributes proprioceptive feedback, which might facilitate the control of finger pressure by taking away its purely isometric aspect. The addition of foam was inspired by the *T-Stick* (Malloch and Wanderley 2007) and the *Meta Instrument* (Laubier 1998).

5.2.1.2 Hand Cupping

The hand cupping gesture (as described in sec. 2.2.7) is fairly complex. The hand acts as a deflector and floodgate for the air stream. Thus, it is very dynamic in terms of occupied physical space, position in space, distance to the instrument, and solidity, providing different levels of airtightness and deflection.

In order to represent the gesture appropriately, we need to know the approximate angle of the covering hand, as well as the amount of "airtightness" when cupping the hand around the device (which is, of course, not to be taken literally as there is no actual air flow coming out of the back of the *Jamboxx*).
Thus, the most straightforward approach is an array of distance sensors. With a minimum of four distance sensors, the approximate angle of the hand can already be determined by applying trigonometry. The smaller the distance across the array sensors, the higher the assumed "airtightness".

Obvious candidates for sensing distance are capacitance sensors, ultrasonic distance sensors and optical proximity sensors.
However, ultrasonic distance sensors have a narrow beam width, limited resolution, and experience drift and interference from changes in the environment (Paradiso and Gershenfeld 1997). More importantly, the sensor output is saturated if a minimum distance of the

object to the sensor is not kept[4]. This renders the ultrasonic distance sensor unsuitable for the hand cupping application, as the gesture involves movement very close to the instrument's body.

Capacitive sensors are mostly used for touch sensing (for example, in touch screens), but the same principle may be used to measure distance. This technique is then called electric field proximity sensing, based on the principle that the recharge time of a capacitive antenna is proportional to its distance from an object such as the performer's hand. This principle is used by the Theremin to control amplitude and frequency of the output sound with hand (and body) proximity to each antenna. A minimum of three electrode antennas are needed to determine the 3D position of a fixed-size mass such as the hand (Paradiso and Gershenfeld 1997).

Optical proximity sensors are usually pairs of light emitters and receivers, which measure the amount of light reflected by an object. In order to minimize interference of visible ambient light, they usually operate in the infrared light range. As lamps (and especially stage lights) emit infrared light as well, some interference can still occur to the sensor signal.
Due to these interferences, the sensor readings are non-monotonic. A sensor response is called non-monotonic when "[...] a sensor presents the same output in response to multiple different inputs" (Brum Medeiros and Wanderley 2014). In our application, the sensor yields low values if the hand is very close to the photo transistor (lack of reflected light), high values for medium distance, and low values for higher distances. This renders the unfiltered sensor input unusable for the use of a DMI, as the computer cannot determine if the hand is very near or very far away.

However, as the interference can be filtered fairly easily, and the infrared emitters and photo transistors are low-cost and do not require a complex measurement circuit, the optical sensing approach was chosen for the augmented Jamboxx design. In addition, previous work by Tarabella (2000) – the *Twin Towers* DMI – had already proven that an infrared sensor system is suitable for the recognition of certain hand gestures. Here, an array of

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[4] The minimum distance is usually bigger than several inches
(cf. e.g., http://www.maxbotics.com/Ultrasonic_Sensors.htm)

four infrared distance sensors was used to determine the distance and rotation of the hand with respect to a reference frame.
A variety of commercially available IR proximity sensors with on-board signal conditioning exist, some of which were considered in this design. However, the very common Sharp Distance Measuring Sensors either exhibit a too-short or too-high sensor range[5], as do many other reflectance sensors originally designed for line-finding robots (such as the Pololu QTR-1A[6]). Instead, it was found to be more useful to work with more basic electric components, such as IR LEDs and IR photo transistors, and to condition the sensor signal inside the Arduino's ATmega32u4 microcontroller chip.

There are at least two conditioning approaches to minimizing the interference of ambient infrared light to the sensor signal. First, the emitter signal can be modulated at a high frequency (kHz range) and demodulated at the receiver. As the ambient light only fluctuates at a low frequency, it is disregarded by the demodulation process. This filtering approach is used, for example, in infrared remote controls for televisions. However, modulation and demodulation require a higher number of components, including some which are more expensive.

The second filtering approach is the use of difference sensor readings. The emitter is turned on and off in rapid succession, while the photo transistor voltage is read for both stages. At the end of such a cycle, the voltage difference for ambient light only (emitter turned off), and both ambient light and reflection from the object (emitter turned on), is calculated, yielding a one-dimensional set of values. The downside of this filtering method is the resulting loss of sensor resolution.

The only reviewed device showing a means of measuring the hand cupping gesture (as described in sec. 3.4 and Schille (1991)) employed only one single infrared light emitter and receiver pair. Thus, the sensing of a hand cupping gesture was reduced to a simple distance measurement. The hand cupping sensor interface described in this work is capable of representing the gesture more accurately.

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[5] http://www.sharpsme.com/optoelectronics/sensors/distance-measuring-sensors

[6] http://www.pololu.com/product/958

Construction of the sensor interface

A quarter of a transparent PVC tube was cut off lengthwise so that it could be attached to the edge of the Jamboxx. A total of 39 holes were drilled into the surface of the tube, in a pattern shown on Fig. 5.3. The pattern allows for every photo transistor to be surrounded by six to eight emitters. The structure of the pattern and the high number of infrared light emitters are needed to provide a more homogeneous and brighter illumination of the hand, which in turn ameliorates the sensor resolution and facilitates the processing of the hand position over the sensor. For this same reason, emitters with a radiation angle of 30° were used.

The holes fit the diameter of both the infrared emitter diodes and photo transistors exactly, so that the friction is sufficient to hold them in place.

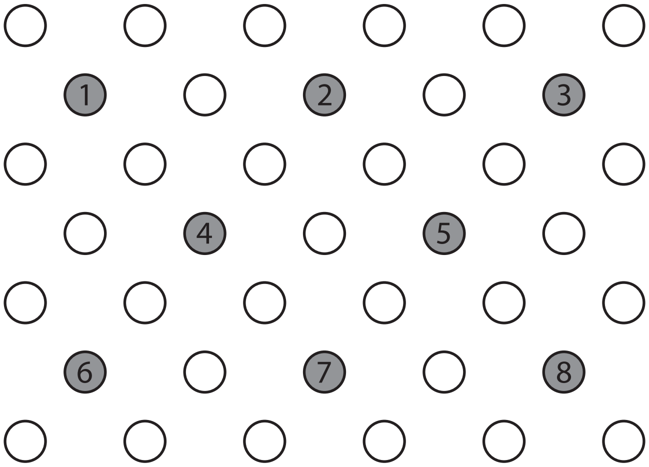

Fig. 5.3 – Pattern layout of the infrared emitter (white) and photo transistor (grey) array.

Circuit design

As the infrared light emitters are only required to be turned on or off all at once, they can be controlled by one single digital out pin on the Arduino. However, the Arduino is only capable of supplying a current of 40 mA[7], which is not enough to power 31 infrared light emitters.

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[7] http://arduino.cc/en/Main/arduinoBoardMicro

A *TIP 120* Darlington transistor was used to create a working circuit controlled by a separate control circuit via the Arduino's aforementioned digital out pin. The working circuit is connected to an external power supply providing a sufficient maximum current. The Arduino then merely switches the transistor, effectively opening or closing the working circuit, turning the infrared LEDs on or off.

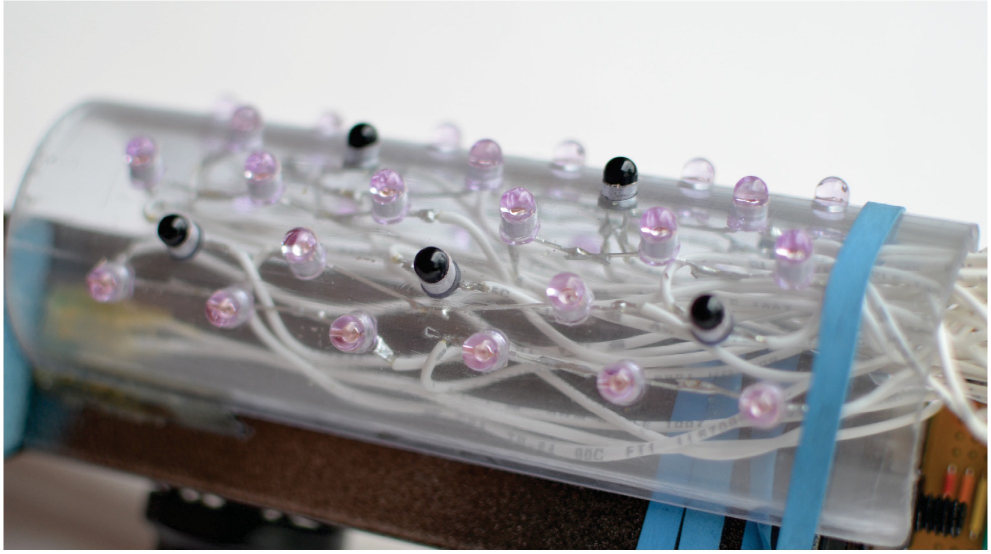

Fig. 5.4 – A close-up view of the infrared emitter and photo transistor sensor array.

In order to reduce the amount of wires going into the PVC tube, the infrared LEDs were connected in series of two or three units, yielding eleven instead of 31 wires. It was not possible to connect more then three (or maximum four) LEDs in series, as they show a voltage drop after every unit, limiting the number of units to $5V - (x \cdot \sim 1.2V) \Leftrightarrow x \approx 4$. The current limiting resistors connected in series with each group of LEDs were calculated as follows:

$$\begin{aligned} \mathbf{V_R} &= \mathbf{V_S - x \cdot V_D}, \text{where} \\ V_R &= \text{series voltage},\ V_S = \text{supply voltage},\ x = \text{number of LEDs},\ V_D = \text{voltage drop} \end{aligned}$$

$$\begin{aligned} \mathbf{R} &= \frac{\mathbf{V_R}}{\mathbf{I_R}},\ \text{where} \\ R &= \text{current limiting resistance},\ I_R = \text{desired supply current} \end{aligned}$$

The photo resistors are connected through a voltage divider with the eight input pins of an *MCP3008* analogue-to-digital converter, which is capable of reading the sensor voltage with a 10 bit resolution.
The Arduino communicates with the *MCP3008* ADC over a Serial Peripheral Interface (SPI) connection by the means of a freely available Arduino library[8].

5.2.1.3 Inclination

A *Pololu MinIMU 9 v2* inertial measurement unit (IMU) was mounted onto the device, and connected to the Arduino over a SPI connection, which is established using freely available Arduino libraries[9].

This IMU uses a combination of accelerometers, gyroscopes, and magnetometers to determine the velocity, orientation, and gravitational forces of the device in all three dimensions.

The current implementation only put the gyroscope raw data in effective use, so that a single 3-axis gyroscope would suit the application as well. However, the IMU was available, and can be used for future work in exploring mappings of accelerometer data.

5.2.2 Software design

The visual programming language and IDE *Max 6* – a common choice for prototyping DMIs, as well as *lingua franca* for computer-based live performance (Place and Lossius 2006) – was chosen for the development of the Jamboxx Augmentation software. The software is comprised of three layers: the input signal processing and visualisation layer, the mapping layer, and the sound synthesis layer, which are described as follows.

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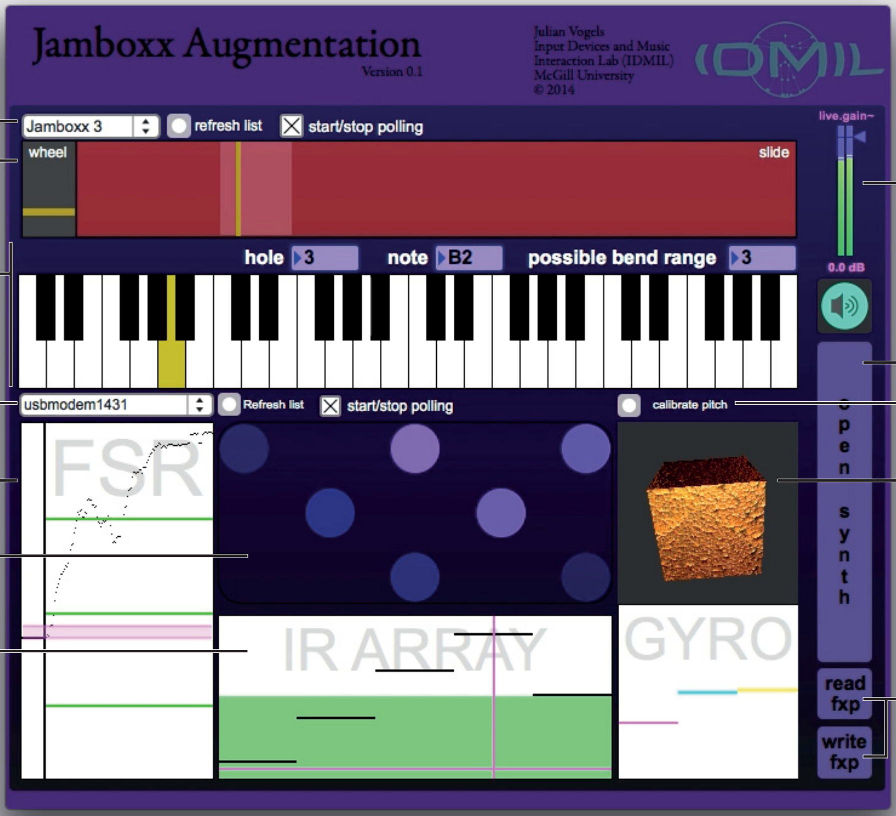
[8] https://github.com/nodesign/MCP3008

[9] https://github.com/pololu/, repositories *l3g-arduino* and *lsm303-arduino*



hole 3
note B2
possible bend range 3

Connection controls for Jamboxx (connected via USB)

Display of slide position, air pressure, and wheel position

Display of hole position, resulting note and its possible bend range (in semitones)

Connection controls for additional sensors (connected via USB)

Display of finger pressure values (FSR), its exponential moving deviation (EMD)

Circle set representation of filtered phototransistor values

Combined display of overall phototransistor intensity, and weighted horizontal and vertical hand position over sensor array

Level meter

Button to open the software synthesiser (NI Massive)

Button to re-set the zero point of the orientational pitch of the device

Rotating cube representation (top) and gyroscope orientation representation (bottom)

Buttons to store and recall synth settings

Fig. 5.5 – The *Jamboxx Augmentation* software, entirely made in Max.

5.2.2.1 Input signal processing and visualisation layer

Jamboxx Human Interface Device

The original Jamboxx implements the USB HID[10] protocol so that it can be recognized by the computer as a Human Interface Device without the need for additional drivers. Max provides a straightforward way to access these devices with the `hid` object. Sensor data can be polled at a desired frequency. The value range is then normalized.

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[10] http://www.usb.org/developers/hidpage

The slide position is visualized with a vertical bar sliding horizontally across a box, as seen in Fig. 5.5. The normalized floating-point slide position value is scaled to a range of 1 to 10 and ceilinged to the nearest integer, according to the number of holes on a Richter-tuned harmonica. The range of the current hole on the slide is displayed by highlighting the area, so that the player can avoid triggering the adjacent holes by accident.

Air pressure values are displayed in the background of the box as a horizontal line moving up or down with positive or negative pressure. Respectively, the background colour of the box changes to green with positive pressure, to red if the pressure is negative, and to grey if the value is very close to zero. As the air pressure values fluctuates near zero when idle, the colour change only occurs if the value passes a low threshold.

The value representing the position of the wheel on the left side of the device is displayed as a horizontal bar moving in a vertical direction, located left of the mouthpiece slider representation.

Additional sensors

The additional sensor data is acquired through a serial call and response connection (cf. sec. 5.2.1) polled every 10 milliseconds at a rate of 115200 baud. The values are parsed into integers, and routed to different groups of processing units. The first eight values, representing the voltage change at the photo transistors' voltage dividers, are filtered with a combined low pass and median filter. This is to smooth out some naturally occurring noise spikes caused by, for example, electromagnetic interference to the longer wires, as well as because of the relatively small resolution of the sensor due to its difference readings. The downside to the filtering is the introduction of latency to the signal. Furthermore, fast hand movements (such as fast hand cupping repetitions) could be completely smoothed out if their time period is smaller than the width of the noise spikes to which the filter is tuned. It might be useful to revisit the filter design for future work.

The IMU and FSR data do not require filtering. All the sensor values are normalized according to empirically determined peak values.

In order to calculate a value that represents the overall distance from the hand to the device, an average value across all photo transistors must first be found. As the hand rarely occupies the entire space of the hand cupping sensor array, an average value of 70% was found to be roughly equivalent to the state where the hand completely occludes the sensor array.

Referring to Fig. 5.3, the approximate angle of the hand to the sensor array (or the occupied space, respectively) is calculated by comparing average values for horizontally and vertically aligned photo transistors. For the vertical direction, transistors *1*, *2*, and *3* are compared to transistors *6*, *7*, and *8*. For the horizontal direction, the values of transistors *1* and *6*, *2* and *7*, and *3* and *8* are first averaged. Together with transistors *4* and *5*, the resulting five values represent horizontal positions. Weighting between values of positions one to three, and three to five (where value three is included in both sets) approximates the horizontal position of the hand over the sensor array.

An alternate method for the representation of the state of the hand above the sensor array was investigated. The *MnM Toolbox* for Max provides objects for gesture mapping (Bevilacqua, Müller, and Schnell 2005), including machine learning methods. A support vector machine (SVM) learning algorithm (*mnm.svm*) was chosen for the creation of a complex many-to-few mapping.
Heretofore, the eight photo transistor values were acquired for different hand postures. Three slider values representing a horizontal position, a vertical position, and the distance from the sensor array, were adjusted for every state. The machine learning algorithm then learned and processed the exemplars. From then on, the algorithm classified all incoming values according to the scheme, essentially providing a way of interpolating between the state of the sliders.
Although this method provides interesting results for many applications, it was found to be an unnecessary over-complication of the problem, and further introduced software instabilities. More stable and reliable results were achieved with the simpler above-stated method of averages and differences.

5.2.2.2 Sound synthesis layer

As the implementation of a custom sound synthesis algorithm is beyond the scope of this thesis, a commercial software synthesiser was chosen for sound production. Native Instruments' Massive[11] was chosen, due to its high number of synthesis parameters, the ability to assign macro controls for easy control of multiple parameters with different ranges, and its subtractive synthesis engine allowing for the direct control of audio filters.

The synthesiser offers up to three oscillators of complex waveforms routed through two filters. Effects and feedback can be added, as well as modulations or noise. The routing can be controlled as well.

5.2.2.3 Mapping layer

True to the model proposed by Hunt and Kirk (2000), the mapping approach taken strives to inspire holistic thinking instead of analytical thinking in musicians. The instrument provides a series of continuous controls mapped to sound synthesis parameters in a complex manner, so that the musician can rather explore the gesture space instead of thinking purely one-parametrically and in unit tasks.
This approach greatly raises the *ceiling on virtuosity* – a term coined by Wessel and Wright (2002) – because the performer can explore the many relationships between the mappings of input positions.
Another important goal is a *low entry fee* for musicians. In our case the entry fee depends on the degree to which an existing gestural harmonica performance repertoire can be applied to the instrument.

Therefore, the note selection mapping and the general functions of techniques are preserved, as on the Richter-tuned harmonica. For example, hand cupping changes the quality of the sound in a filtering manner, and note bending is restricted to a specific note-bending range per hole. However, there are additional continuous control parameters, like hand cupping position and inclination of the instrument, whose inter-connected holistic mappings are also described in the following.

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[11] http://www.native-instruments.com/en/products/komplete/synths/massive/

The mapping was realized by controlling a *VST* object holding an instance of Native Instruments' Massive inside Max. In a first version of the software, the network mapping software *libmapper* (Malloch, Sinclair, and Wanderley 2013) was used, which offers interesting features for building complex mappings, but was later removed due to instabilities in the current version of the Max bindings. We still encourage the use of *libmapper* in future versions of the Jamboxx Augmentation software.

5.2.2.3.1 Slide position

The integer hole position value is used to query two tables. The first table stores a set of note values, which represents a Richter-tuning in the key of C by default. A second table is queried for the possible note bend range of the hole. This way, it is possible to restrict the pitch bend to the natural range of the diatonic harmonica, for example, to three semitones for hole 3 draw, or two semitones for hole 8 blow (cf. sec. 2.2.3 *Note bending*).

5.2.2.3.2 Air pressure

However, the querying of tables according to slide position does not account yet for the two notes per hole. That is why the positive or negative air flow direction is determined from the sensor value sign, which changes the row number of the tables to be queried. As a result, a different set of values is returned, representing either draw or blow notes with their respective bend ranges.

The absolute air pressure value is multiplied by itself and mapped to the amplitudes of the oscillators. As the value is normalized, this results in exponentially smaller values when approaching zero. This way, the performer has more subtle control over low amplitudes and the concerns of the participants in sec. 5.1.1.2 are overcome.

Exponential Moving Deviation

However, the resulting dynamics of the sound were found to be inappropriate when playing rapid successions of fast attack notes, as they were generally too weak. Therefore, a faster attack was mapped in order to result in a higher amplitude.
An exponential moving deviation of the numeric air pressure signal is calculated with the use of the Max MSP extension `dot.emd`, included in the *Digital Orchestra Toolbox* (Malloch,

Sinclair, and Wanderley 2007). More recent data values are given more weight, so that a higher deviation accounts for more abrupt recent data changes. The resulting value is scaled, multiplied with the air pressure value, and then added to the air pressure value in order to achieve the desired effect of stronger attacks, while still allowing the possibility to play subtle notes.

5.2.2.3.3 Finger pressure

The note bending technique is carried out by applying finger pressure to a piece of foam on the FSR placed on the top left surface of the device. The pitch of the resulting sound can be lowered continuously inside a certain range, which is determined by the possible bend range of the selected "hole" on the slide.

The lowest possible bent note can be attained with a comfortable amount of pressure, and the pitch will not lower beyond that point with more pressure. This approach is used in accordance with the note bending technique on a diatonic harmonica, where the lowest point is not passed with more effort either (cf. sec. 2.2.3 *Note bending*).

If it is possible to bend two or more semitones on the selected hole, the high pressure threshold represents the lowest semitone. In other words, the pitch range changes between holes, while the sensor input scaling stays the same. With the same pressure on hole 3 draw and hole 4 draw, a bend of either three or one semitones is achieved. The advantage of this approach is the higher sensor resolution for one-semitone bends. However, it might interfere with the concept of gesture repeatability and proprioception learning processes, which should be investigated in future work.

The exact bend note positions are displayed on top of the finger pressure display as green horizontal lines to provide visual feedback in the learning process.

An exponential moving deviation (cf. sec. 5.2.2.3.2 above) of the finger pressure data was calculated. This signal can be used as an additional input parameter, mapped to the *wetness* of a sine shaping effect unit. The sine shaper adds harmonic distortions to the sound during the process of a note bend, but not when the bent note is held. This approach can distinguish the pitch bend from a common pitch bend wheel sound of a synthesiser, and better approximates the acoustic harmonica bending sound.

5.2.2.3.4 Hand cupping

The proximity of the hand to the sensor array is mapped to the wavetable position of both oscillators, resulting in a subtle timbre change when changing the distance. The amplitude of the second oscillator, whose waveform produces a brighter, more organ-like sound, is coupled to the distance, so that a higher distance results in a louder, brighter sound. Furthermore, the cut-off of a low pass filter and its resonance is subtly controlled, which adds to the effect.

The horizontal hand cupping position controls both the amount of noise added to the signal, as well as the high and low shelf balance of an equalizer. If the hand position is more to the right of the sensor array (from the player's perspective), this results in a darker, more numb sound, whereas a hand position more to the left results in a high pass filtered sound with a noise content.
This feature extrapolation can be controlled by opening the cupped hand to either the left or right side. The technique does not correspond directly to a harmonica performance gesture, but should be easy to discover and learn.

The vertical hand displacement over the sensor array only modifies the sound when the midpoint is passed, so that subtle changes of the natural hand rest position does not continually interfere with the sound. Passing the vertical midpoint to the top, the upper half drives the wetness of a reverb effect. As observed in sec. 4.2.3, this gesture is presumably uncommon during acoustic harmonica performance, so this effect will probably not be triggered by accident. Thus, more drastic effects such as sample and hold, phasing, bit crushing etc. could be used interchangeably.

5.2.2.3.5 Instrument inclination

The instrument inclination is described in terms of pitch, yaw, and roll of the instrument, with pitch being a rotation around its horizontal (longitudinal) axis, yaw being a rotation around its vertical axis, and roll being a rotation around its frontal axis (like a steering wheel).

While the Pololu MinIMU 9 v2 offers sensor signals to represent all nine degrees of freedom that make up an attitude and heading reference system (AHRS), only pitch and yaw data are currently mapped to synthesis parameters. As musicians tend to move and sway their body during performance (Wanderley et al. 2005), using the instrument inclination as an input parameter might restrict the musician's natural movements or introduce unwanted sound modifications. It is thus advisable to consider this ancillary movement with caution in the mapping process.
From observations of the motion capture videos and Fig. 4.2.2 in Chapter 4, it can be suggested that harmonica players have a preferred angle in which they hold the harmonica and generally orient the instrument more towards the ground than to the sky, even when they perform very expressively. Thus, the upper angle of 0°to approximately 60°will not interfere with most of the ancillary movement, and can be used as an input parameter.

The roll of the device is mapped to the panning position of the audio signal. Similarly to the direction of a steering wheel, a left turn pans the audio more to the left.

The pitch of the device is mapped to the resonance of a lowpass filter, such that a inclination towards the ceiling results in timbre change towards a “brighter” sound.

5.2.2.3.6 Wheel

The wheel position was originally mapped to pitch bend. With the finger pressure sensor installed, it has been found to be difficult to use during performance, as the natural finger rest position is far away from the control. However, it can be turned partially with the palm of the hand. It was found to be most suitable for selection gestures rather than sound modification gestures. It is therefore mapped to a digital audio effect unit, more specifically, a variable stereo delay unit.

The normalized raw sensor signal ranges from -1 to 1 and exhibits a sudden change from maximum to minimum, or vice versa, when a certain angle of rotation is passed. As the wheel can be turned indefinitely, there is no way for the performer to know exactly where that point would be, which renders the raw sensor data unsuitable.

Instead of relying on the absolute resistance value of the sensor, an *integrating* approach has been applied. The current sample of sensor data is compared to the past sample, so that the direction of rotational movement can be recognized. Every sample then adds or subtracts a predefined value to a stored variable, up to a specified maximum and minimum (0 to 1). Thus, the wheel can be turned left or right until a maximum or minimum is achieved, linearly changing the variable value and without sudden gaps. The magnitude of the predefined value determines the amount of rotational movement needed to travel from either minimum to maximum or vice versa.

5.3 Conclusion

In this chapter, comments of expert harmonica players on harmonica-related DMI were presented, and the design of an instrument augmentation based on one of the reviewed devices was described. Participants' comments were considered, along with findings of the harmonica performance gesture study (cf. Ch. 4) on the conceptual design and construction.

Underlying goals of the applied sensor signal conditioning techniques, mapping techniques, and visual feedback of the Jamboxx Augmentation software were outlined, along with a description of a custom-built sensor array interface.

6 | Conclusions and Future Work

This chapter presents a summary of the work in this thesis, offers conclusions, and points to future work that will continue after the publication of this work.

6.1 Conclusion

In this thesis, harmonica playing techniques and styles were explained, and with this regard, harmonica-related digital musical instruments were presented based on a patent review. Harmonica performance gestures were studied and analyzed with motion capture. An existing harmonica-related DMI was commented in a qualitative manner by expert harmonica players, and an instrument augmentation based on this device was carried out.

The main achievement of this work is the presentation of harmonica-related DMIs, classified by the ways of interaction they provide. A compendium of this kind provides easily accessible information that can facilitate the work of instrument developers.
It is possible to separate the reviewed devices into two families of harmonica-type digital musical instruments:

- **Multiple hole devices**, where the note is selected by playing the desired hole. This enables techniques such as tongue blocking.
- **Sliding mouthpiece devices**, where a one-hole mouthpiece is slid to the desired note position. This enables the assigning of an arbitrary number of notes to the slide positions.

This example shows that there is no *best* way to design a harmonica-related DMI, but there are important design decisions to be made that affect the entirety of the musical interaction.

The created motion capture data set of harmonica performance and basic playing techniques can further inform the developer about the movements and gestures to which expert harmonica players are accustomed. Applying this knowledge to the design, the device can be made more intuitive and easier adaptable for musicians who are familiar with the diatonic harmonica.

Referring to sec. 4.2.1, different statements about jaw opening during note bends, instrument inclination and expressiveness, speed of the hand cupping gesture, and finger pressure could be made. For example, the maximum hand cupping speed can indicate the minimum sampling frequency that a sensor capturing this gesture needs to exhibit in order to represent the gesture accurately.

In a second part of the study, comments of study participants about two slide-based harmonica-related DMIs were collected, giving insight in the musicians' point of view towards the interaction with a novel instrument.

The design and construction of an instrument augmentation has led some of the aforementioned findings to practice. Design decisions regarding the choice of sensors and placement on the device were explained, and construction and software implementation details were described, providing information about different development approaches.
A custom-built sensor interface enabled a more accurate acquisition of the hand cupping gesture than any of the reviewed devices in Chapter 3. This lead to new possibilities of mapping the gesture to the sound synthesis. The choice of mapping was supported by findings from Chapter 4.

Just before the submission of this thesis, a performance of harmonica player Lévy Bourbonnais on the *Jamboxx Augmentation* was filmed. Along with other additional material, it can be found on my personal website `http://www.julianvogels.de/master-thesis/`.

6.2 Future Work

Although a considerable amount of work has been done in the field of harmonica-type DMI design, the fundamental design questions have rarely been investigated scientifically, and there is still much knowledge to gain about harmonica performance gestures.

6.2.1 Harmonica performance gesture study

Motion capture data is very extensive, as much as its possible analysis methods are manifold. We hope that with the creation of a dataset, we can facilitate work on the subject of harmonica performance gestures, and will be happy to assist in making it accessible to fellow researchers[1].

However, the analysis of the motion capture data of piece excerpts and free improvisation in relation to audio features is limited to some degree, as vocal tract techniques used during performance cannot be known exactly. This includes the degree to which the note is bent, tongue articulation technique, and even the exact hole played. With this amount of undefined factors, no precise statement about the influence of instrument inclination or hand cupping technique on audio features can be given.

A subsequent motion capture study including measurement approaches capable of representing the state of the vocal tract, or a more limited and stricter study definition could do away with these uncertainties and provide a more complete picture.

Certain presented data analysis methods were oversimplified. For example, it is questionable if the distance between the harmonica body centre and one single marker on the back of the hand can represent the hand cupping gesture accurately enough.
It would be constructive to develop a model of the hand's markers in order to be able to use its centre of gravity as a reference point. An even better solution would be to use additional sensors to measure the airtightness of the gesture and obtain more meaningful data through *sensor fusion*, or to apply machine learning methods such as supervised learning to represent and interpolate between different states of the gesture.

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[1] Please refer to `http://www.julianvogels.de/master-thesis/` for up-to-date contact information.

6.2.2 Jamboxx Augmentation

Although the infrared proximity measuring sensor array was found to be useful and appropriate, we hope to improve the sensor resolution in the future by employing stronger infrared light emitters, as well as by tweaking the current throughput by adjusting the limiting resistance. A second version, operating with modulated infrared light, should be conceived in order to weigh the higher cost against its benefits.
The implementation of a sensor array using electric field sensing will also be considered in future work.

Moreover, the device does not yet account for the application of overblow and overdraw technique. Although its direct measurement is most probably as difficult to achieve as that of the note bending gesture, it might prove useful to investigate a means of translating the technique to another gesture or combination of gestures. In a basic example, pressing a button could enable the feature temporarily. Then, if the air pressure range is almost saturated, the pitch could rise along with the air pressure in a similar manner as overblows do, according to the hole's overblow range (cf. sec. 2.2.4 “Overblow and Overdraw”).

As mentioned by one participant of the user study, the possibility of implementing a circular sliding mechanism to the device might be worth investigating.

To make the device more robust for stage performance, the electronic components should be integrated into the device's body, the cabling should be consolidated, and the electrical circuit should be redesigned and etched onto a PCB.
Along with these improvements, whether or not more signal processing and sensor conditioning algorithms can be integrated into the controller should be investigated, up to the point that the device merely outputs “cooked” OSC control messages or even produces the sound internally, eventually becoming an *embedded system*.
Finally, the size and weight of the device should be reduced and its ergonomic qualities should be improved, so that manipulating it exerts less fatigue on the performer. Due to its current size, performers might be inclined to move their heads instead of the device, breaking the learning rule "don't move your head, move the harp" (Baker 1999, p. 30). However, it is not known to which degree this rule applies to harmonica-related DMIs.

A Harmonica Performance Gesture Study appendices

This appendix provides additional material related to the harmonica performance gesture study described in Chapter 4.

A.1 Technical setup

The motion capture study was carried out in a windowless, shock-isolated room using a Qualisys passive optical capture system.

Optical motion capture systems calculate the position of a marker in space by triangulating light ray intersections from captured video frames of different viewing angles. At least two cameras at a minimum angle of 30° to each other are needed to infer a 3D position from the 2D images, although more cameras are often used to minimize errors and increase accuracy.

The special Qualisys Oqus cameras used in the study operate in the infrared range with a high frame rate, such as 240 Hz. In order to enhance the lighting conditions, each camera includes a halo of infrared light-emitting diodes mounted around the camera lens. As the captured frames only contain light in the infrared range, the room lights barely interfere with the marker measurement. However, direct light from a room's light source or a reflecting surface has a significant amount of infrared light, and can lead to phantom marker detection or other errors.

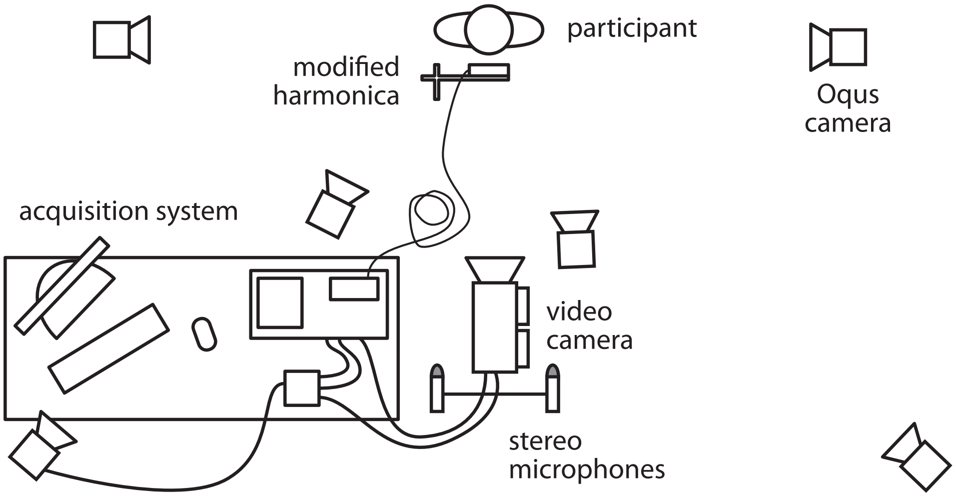

Fig. A.1 – A diagram showing the camera setup in a bird's-eye view perspective.

Reflecting balls are attached to the object of interest at different locations to be investigated. These reflecting balls are called passive markers, as they merely reflect the camera light instead of emitting infrared light themselves. Active markers are bigger and bulkier, as they need a current source to emit infrared light, but they have the advantage of being recognizable under inferior lighting conditions. Furthermore, active markers can emit a pulsed infrared light signal that can be analyzed to identify the marker automatically. Passive markers cannot be distinguished in the capturing process, but must be identified and labelled software-wise (either by a person or a machine-learning algorithm).

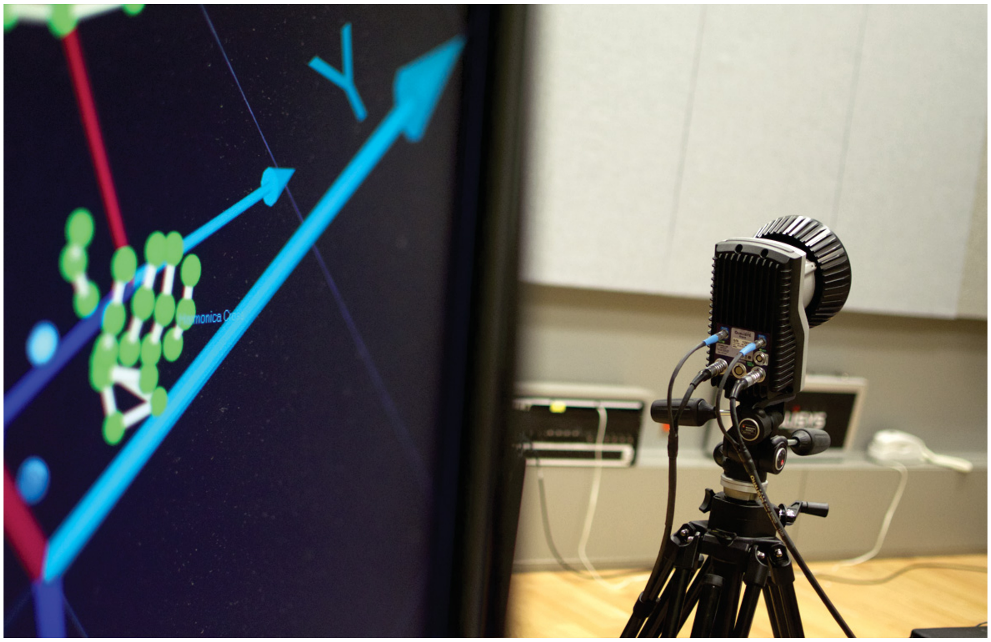

Fig. A.2 – The Oqus cameras are connected to the Qualisys Track Manager, which produces a real-time 3D visualization of the motion capture.

A.1.1 Audio and Video capture

In addition to the motion capture, video footage was captured with a Sony PWM EX-3 professional high definition camera throughout the entire study. That way, none of the participants' comments made in between measurements could be lost.

The audio was recorded with a stereo set of high-quality DPA 4006-TL microphones mounted on a stand above the video camera for AB stereo recording. The microphones were connected to the Sony camera for synced recording with the video footage, and level-adjusted using the camera interface.

Fig. A.3 – Left to right: DPA 4006-TL Stereo Microphone set, Sony PWM EX-3 professional high definition video camera, Qualisys Oqus motion capture camera with high-speed infrared video capture.

A.1.2 Analog Input

In order to measure the finger pressure of the participants' left index finger on the top surface of the harmonica's body, an elongated force sensing resistor (FSR) was glued firmly to the harmonica's body and cabled to an electrical circuit (refer to Fig. A.5). The circuit was supplied with 5V through a laboratory power supply. A voltage divider circuit transformed the FSR resistance to a voltage signal with a range of approximately 0 to 3 V. The circuit output was connected to a Qualisys USB-2355 Analogue Acquisition Board via a BNC connector.

A.1.3 Syncing

In order to sync the Qualisys Track Manager motion capture system with the infrared Oqus cameras, the Qualisys USB-2355 Analogue Acquisition Board, and the Sony PWM EX-3 Video camera with attached DPA stereo microphones, a Rosendahl Nanosyncs HD word clock generator was connected in a cabling as seen in Fig. A.4.

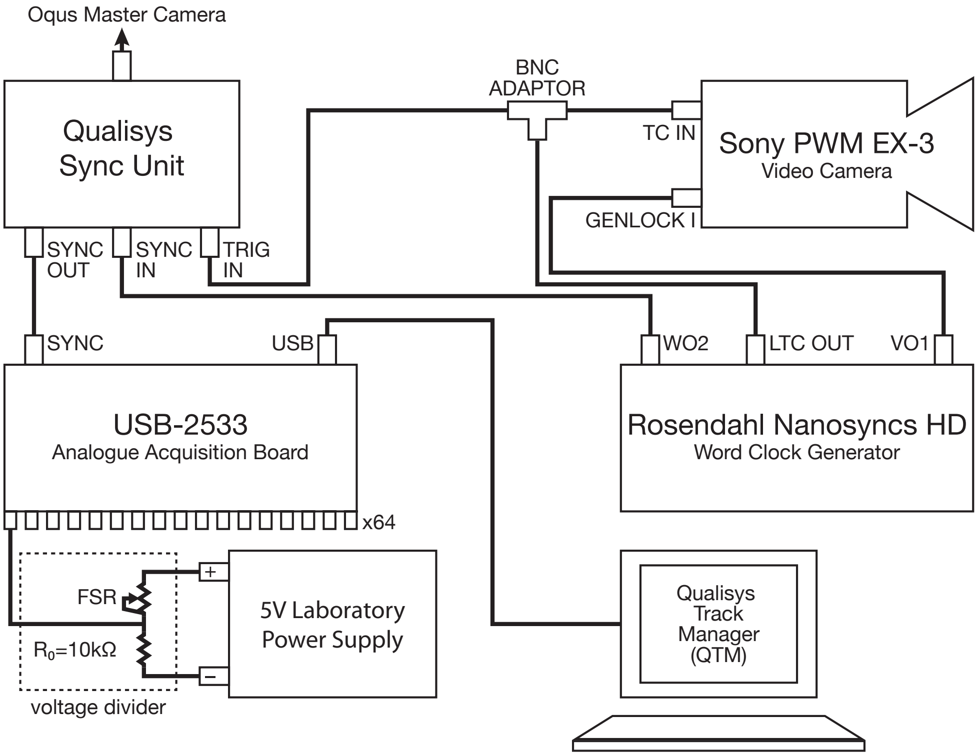

Fig. A.4 – A hardware wiring diagram of the motion capture setup used for the harmonica performance gesture study.

The word clock generator created a LTC or Linear Timecode signal[1] sent to both the video camera and the Oqus master camera sync unit. The latter unit was connected to the master camera, which in turn, further propagated the timecode information to sync all the other Oqus cameras. The actual syncing signal is the digital word clock signal connected to the SYNC IN of the unit. The video camera took two signals as well: The Genlock signal ensured the syncing of every captured frame, while the TC IN (timecode in) was used to

---

[1] an encoding of the SMTPE timecode standard defined by the Society of Motion Picture and Television Engineers

slave the camera to an external timecode reference signal. The acquisition of the finger pressure data was synced by its connection to the sync out of the oqus master camera.

A.1.4 Rigid bodies

The Qualisys Track Manager software allows the specification of “rigid bodies”. Once specified or acquired by capturing an exemplar object, not only is the body position in space available, but also its inclination. As this adds three degrees of freedom, this method is also called “6DOF Tracking”.

A rigid body can be defined from any structure of at least three markers whose in-between distance does not change. The markers should also be mounted asymmetrically on an object in order to minimize the possible errors of marker swapping by the system’s machine learning algorithms.

In order to be able to capture the harmonica body’s inclination, a non-standard solution needed to be found, as any directly attached marker would have been occluded by the performer’s hands during performance. Therefore, an asymmetric wooden cross was constructed and firmly attached to the harmonica’s body by the means of metal strips and screws. Four markers were attached to the wooden cross. The modified instrument was placed in the measurement realm parallel to the global coordinate axes and acquired as rigid body definition. Then, the center of gravity and pivot point were adjusted according to the object dimensions, in order to reflect the centre of the harmonica’s body.

The participants of the study reported the obtrusiveness of the structure to their performance as acceptable. One participant commented that his finger usually lays more on the back of the top surface and that the harmonica is held deeper in his mouth, but as the finger pressure sensor was fixed on the middle of the top surface, he had to adjust his posture. Another participant remarked that the pressure sensor hindered him to a small degree in the note selection process, but only in the beginning of the study.

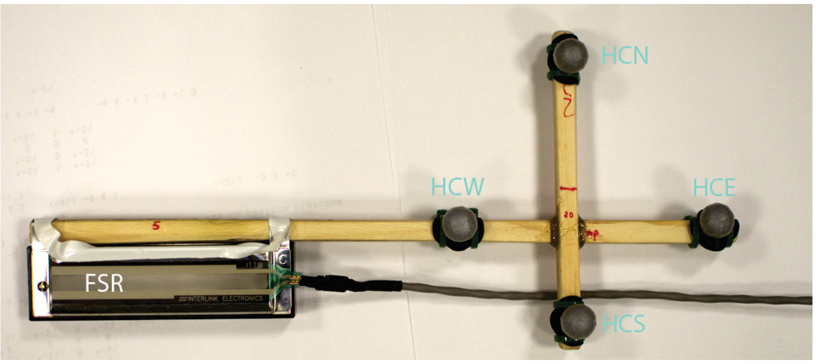

Fig. A.5 – The modified diatonic harmonica with markers mounted on an asymmetrical wooden cross. This enables rigid body definition in the QTM.

Participants were advised to wear a marker headband, consisting of a headband with eight markers attached in equidistance. As the head is a fairly rigid body part, the headband could also be defined as a rigid body, using higher distance change tolerances in the 6DOF Tracking settings. The overall accuracy of the headband inclination is still very good, as the rigid body calculation is based on the high number of eight markers so that inconsistencies of individual marker positions are not crucial.

The rigid body's centre of gravity and pivot point are set to the geometrical centre of gravity of the eight headband markers. The rigid body needed to be acquired by reprocessing the measurement after the capture, as it would have been impractical to ask the participant to align himself with the global coordinate axes and hold still until the body was acquired before every capture. Thus, the orientation vectors of the rigid body needed to be set manually. As the head shape is clearly identifiable by looking at the marker positions in space, the yaw and roll vectors could easily be adjusted. As the headband is not worn in a way that the markers are aligned with the X-Z-plane, the pitch vector had to be adjusted using video and capture footage to match the Y-axis in a frame when the performer's head was looking straight ahead.

A.1.5 Marker labelling

The identification and labelling process of the markers is done entirely in the Qualisys Track Manager software. While playing back or scrubbing through the 3D visualization of the motion capture, markers were identified visually by the user. Ideally, a marker's

virtual trajectory has the length of the entire measurement. However, in practice, markers sometimes get occluded, so that the trajectory is split into multiple trajectories that need to be assigned to the same marker label.
Specifically with markers located very close in space to one another, such as markers attached to the fingers, trajectory swapping can occur. Here, the machine learning algorithm wrongly assigned part of a trajectory to an adjacent marker's trajectory. This incorrect trajectory needs to be split and reassigned manually.

Depending on the quality of the capture, which itself depends on the camera placement, lighting conditions, calibration quality and residual, and tracking settings such as maximum prediction error and maximum residual, the labelling of a 30-second capturing sequence can take between 15 minutes and one hour.

Captured markers should be labelled according to the Plugin-Gait marker labelling convention where applicable. If not, the labelling should still follow an easy to recognize naming convention. For example, the *right hand, second finger, uppermost segment* marker was labelled "RH2U".

A.2 MATLAB code

The MATLAB scripts are available upon request and from `http://www.julianvogels.de/master-thesis/`

A.3 Questionnaire responses

Question	Participant					
	1	**2**	**3**	**4**	**5**	**Mean (Std)**
Mainly played harmonica type	chromatic	diatonic	diatonic	diatonic	diatonic, bass	
Experience						
Years of experience	15	13	30	20	10	17.60 (7.83)
Note Bending (1-10)	10	9	10	10	10	9.80 (0.45)
Overblow / Overdraw (1-10)	7	9	8	10	10	8.80 (1.30)
Hand Cupping (1-10)	10	9	10	10	10	9.80 (0.45)
Tongue Blocking (1-10)	10	7	8	5	10	8.00 (2.12)
Obtrusiveness of measurement setup acceptable?	yes	yes	yes	yes	yes	yes
Quality of performance						
Note Bending (1-10)	10	10	n/a	9	8	9.25 (0.96)
Hand Cupping (1-10)	10	10	9	9	10	9.60 (0.55)
Overdraw / Overblow (1-10)	unknown	10	n/a	8	10	9.33 (1.15)
Room To Move (1-10)	unknown	9	9	8	8	8.50 (0.58)
Summertime (1-10)	unknown	9	9	8	7	8.25 (0.96)
Free Improvisation (1-10)	unknown	8	8	8	10	8.50 (1.00)
Harmonica-type DMI						
Difficulty of note selection on slide (0 not difficult at all, 4 very difficult)	n/a	2	2	4	3	2.75 (0.96)
Obtrusiveness of movement resistance (0 unobtrustiv, 4 very obtrusive)	n/a	4	0	4	0	2.00 (2.31)
Up/Down gesture note bend natural? (0 very unnatural, 4 very natural)	n/a	0	0	1	0	0.25 (0.50)
Necessity of visual feedback (0 not necessary, 4 very necessary)	n/a	2	1	4	3	2.50 (1.29)

Table A.1 – Harmonica performance gesture study questionnaire responses (excerpt without comments).

B | Jamboxx Augmentation appendices

B.1 Arduino code

The Arduino code used to read, process, and send the additional sensor data of the *Jamboxx Augmentation* DMI over a call and response serial connection is shown below.

```
// REFERENCE 1
// Simple Proximity Sensor using Infrared
// Description: Measure the distance to an obstacle using infrared light emitted by IR LED and
//   read the value with a IR photodiode. The accuracy is not perfect, but works great
//   with minor projects.
// Author: Ricardo Ouvina
// Date: 01/10/2012
// Version: 1.0

// REFERENCE 2
/*
  Example for MCP3008 - Library for communicating with MCP3008 Analog to digital converter.
  Created by Uros Petrevski, Nodesign.net 2013
  Released into the public domain.
*/

#include <MCP3008.h>
#include <Wire.h>
#include <L3G.h>
#include <LSM303.h>

// define pin connections
#define CS_PIN 9
#define CLOCK_PIN 8
#define MOSI_PIN 6
#define MISO_PIN 7
#define BASE_PIN 4
#define NO_OF_PHTRANS 8
#define FSRPIN A4

int ambientIR[8];              // variable to store the IR coming from the ambient
int obstacleIR[8];             // variable to store the IR coming from the object
int value[8][10];              // variable to store the IR values
int distance[8];               // variable that represents the distance of the object to the sensor
                    (unit is a scaled voltage difference)

int times = 4;                 // amount of samples to the averaging filter

// Serial communication variables
int serialvalue;               // serial input value

// Gyro & compass
```

```
L3G gyro;
LSM303 compass;

// FSR
int fsrval = 0;

// MCP3008 constructor
MCP3008 adc(CLOCK_PIN, MOSI_PIN, MISO_PIN, CS_PIN);

void setup() {

// open serial port (baud rate)
 Serial.begin(115200);

// Setup IMU with error handling
 Wire.begin();
 if (!gyro.init())
  {
    Serial.println("Failed to autodetect gyro type!");
    while (1);
  }
  if (!compass.init())
  {
    Serial.println("Failed to initialize compass!");
    while (1);
  }
gyro.enableDefault();
compass.enableDefault();

 // Configure Base Pin (IR LEDs) and turn off
 pinMode(BASE_PIN,OUTPUT);       // Transistor Base to turn on all the IR emitter LED on digital pin 4
 digitalWrite(BASE_PIN,LOW);     // Turn IR LEDs off

 establishContact();             // send a byte to establish contact until receiver responds
}


void loop() {

  if(Serial.available() > 0)       // check to see if there's serial data in the buffer
    {
      serialvalue = Serial.read(); // read a byte of serial data

    /*============================================
       IR HANDCUPPING
    ============================================*/
    // READ SENSOR VALUES FOR HAND CUPPING GESTURE
     for(int x=0;x<times;x++){

        // OFF
        digitalWrite(BASE_PIN,LOW);                     //turning the IR LEDs off to read the IR coming
    from the ambient
        delay(1);                                       // minimum delay necessary to read values

        // READ
        for (int i=0; i<NO_OF_PHTRANS; i++) {
          ambientIR[i] = adc.readADC(i);                // storing IR coming from the ambient
        }

        // ON
        digitalWrite(BASE_PIN,HIGH);                    //turning the IR LEDs on to read the IR coming
    from the obstacle
        delay(1);                                       // minimum delay necessary to read values

        // READ
        for (int i=0; i<NO_OF_PHTRANS; i++) {
          obstacleIR[i] = adc.readADC(i);               // storing IR coming from the obstacle
```

```

          // TAKE DIFFERENCE
          value[i][x] = ambientIR[i]-obstacleIR[i];    // calc. IR val. changes, store for average
        }
    }

    for(int x=0;x<times;x++){          // calculating the average based on the "accuracy"
      for (int i=0; i<NO_OF_PHTRANS; i++) {
        distance[i]+=value[i][x];
      }
    }
    for (int i=0; i<NO_OF_PHTRANS; i++) {
      distance[i] = distance[i]/times;        // final mean value
      Serial.print(distance[i]);
      Serial.print(" ");
    }

    /*==================================================
       FORCE SENSING RESISTOR
    ==================================================*/
    fsrval = analogRead(FSRPIN);
    Serial.print(fsrval);
    Serial.print(" ");

    /*==================================================
       INERTIAL MEASUREMENT UNIT
    ==================================================*/
    readGyro();
    Serial.println();

  }
}

void establishContact() {
  while (Serial.available() <= 0) {
    Serial.println("whatevs");   // send an initial string
    delay(300);
  }
}


void readGyro() {
  gyro.read();
  compass.read();

  // X
  Serial.print(((int)gyro.g.x));
  Serial.print(" ");
  // Y
  Serial.print(((int)gyro.g.y));
  Serial.print(" ");
  // Z
  Serial.print(((int)gyro.g.z));
  Serial.print(" ");
  // Yaw
  Serial.print(((int)compass.a.x));
  Serial.print(" ");
  // Pitch
  Serial.print(((int)compass.a.y));
  Serial.print(" ");
  // Roll
  Serial.print(((int)compass.a.z));
  Serial.print(" ");

}
```

B.2 Max patch

The Max/MSP patch is available upon request and from `http://www.julianvogels.de/master-thesis/`.

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