ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF ARTS AND SOCIAL SCIENCES

EXPLORING HAND INTERFACES WITHIN NEW DIGITAL MUSICAL INSTRUMENTS RESEARCH

Ph.D. THESIS

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ SOSYAL BİLİMLER ENSTİTÜSÜ

EL ARAYÜZLERİNİN YENİ SAYISAL MÜZİK ÇALGILARI ARAŞTIRMASI KAPSAMINDA İNCELENMESİ

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Sair Sinan KESTELLİ, a Ph.D. student of ITU Graduate School of Arts and Social Sciences student ID 409122006, successfully defended the dissertation entitled "EXPLORING HAND INTERFACES WITHIN NEW DIGITAL MUSICAL INSTRUMENTS RESEARCH", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Canım Annem Nur AR KESTELLİ' ye…

FOREWORD

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September 2019 Sair Sinan KESTELLİ

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ABBREVIATIONS

AI	: Artifical Intelligence
DMI	: Digital Musical Instrument
FFT	: Fast Fourier Transform
FSR	: Force Sensitive Resistors
HCI	: Human Computer Interaction
MIDI	: Musical Instrument Digital Interface
NIME	: New Interfaces for Musical Expression
OSC	: Open Sound Control
PD	: Pure Data
STEIM	: Studio for Electro-Instrumental Music
VR	: Virtual Reality
VST	: Virtual Studio Technology

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EXPLORING HAND INTERFACES WITHIN NEW DIGITAL MUSICAL INSTRUMENTS RESEARCH

SUMMARY

Increasing accessibility to hardware and software components such as powerful programmable microprocessors, industrial sensors and various programming platforms favours personal and institutional efforts for new digital musical instruments (DMI) research leading to many new DMIs being designed, developed, protoyped and even commercialized.

Like their acoustic counterparts, most DMIs using hand gestures have their own 'specifically designed physical surfaces the performer is acting upon' such as those of well known commercialized examples like Roli's Seaboard or Artiphon's The Instrument 1. The physical interaction between the performer and such instruments happens mostly between the performer's hand gestures and a spatially limited 'musical surface' designed and manufactured specifically as part of the instrument. One of the ways to overcome this limitation and extend performance possibilities beyond a limited surface and space is to use on-body technologies such as hand wearables or hand interfaces.

This study explores hand interfaces and wearables within new DMI research by presenting a general overview of DMI research with various approaches and discussions, reviewing prominent examples of data gloves with their use for both non-musical and musical purposes as well as musical gloves specifically designed and used for electronic music performance and focusing on hand interfaces with their unique dynamics, structure and taxonomy.

As the main output of the study, a new DMI named 'Grain Harvester' was developed, which transforms the interaction between hand gestures and any physical surface or object into digital signal and uses the representing signal to generate sound without loosing tactile feedback. The design offers a new DMI approach, based on the idea that any physical surface and object could be used as a 'musical surface' as part of a new DMI. While the instrument does not include a separate physical control device commonly used to explain DMI instrument chain, it allows any physical object or surface to be used 'to harvest sonic grains' with its surface-specific signal generation capabilities, sound generation mechanisms and extended spatial accessibility. With its key features, components and design decisions, the instrument is described detailedly and discussed within new DMI research and related work.

The developed instrument proposes an innovative musical instrument approach towards electronic music practice as well as general music practice with its currently available features and design. This approach could enable extension of scope of objects and surfaces described as 'musical instrument' and use of any object or physical surface as a characteristic component of a musical instrument similar to the extension of 'musical sounds' beyond those generated only by traditional acoustic instruments in 20th century by practices such as musique concrete or elektronische

musik. Another innovation brought with this approach is the extension of the commonly limited proprioceptive relationship of the body with the physical surface of the musical instrument. As the representative signal originates from body with the transducer attached to the finger nail, any physical surface or object interacted with the finger could become the physical interface of the instrument and could be changed any time by changing the interacted physical surface or object. Therefore, the instrument incorporates any available physical surface at the performance space into music performance and also extends commonly limited mobility of the performer.

With its currently available features and capabilities, design approach and additional features and capabilibities to be built as part of future work, the new DMI developed as part of this study offers a great potential for innovation in DMI design, practice, as well as context of electronic music performance.

EL ARAYÜZLERİNİN YENİ SAYISAL MÜZİK ÇALGILARI ARAŞTIRMASI KAPSAMINDA İNCELENMESİ

ÖZET

Programlanabilir güçlü mikro işlemciler, endüstriyel algılayıcılar veya farklı programlama platformları gibi farklı donanımsal ve yazılımsal bileşenlere artan ulaşılabilirlik, kişisel ve kurumsal ölçekte yeni sayısal müzik çalgıları araştırmalarını kolaylaştırmakta, bu araştırmalar sonucu birçok yeni sayısal müzik çalgısı tasarımı, prototipi ve hatta ürünü ortaya çıkmaktadır.

Akustik benzerlerinde olduğu gibi, el jestleri kullanan çoğu sayısal müzik çalgısının, Roli firmasının Seaboard veya Artiphon firmasının The Instrument 1 ürünlerindeki gibi 'özel olarak tasarlanmış, icracının üzerinde etki ettiği fiziksel yüzeyleri' bulunmaktadır. İcracı ve bu tip çalgılar arasındaki fiziksel etkileşim de çoğunlukla icracının el jestleri ile çalgının bir parçası olarak özel tasarlanan ve üretilen, uzamsal olarak kısıtlı 'müzikal yüzeyler' arasında gerçekleşmektedir. Bu kısıtlılığı aşmak ve icra olasılıklarını belirli bir yüzey ve uzamın ötesine taşıyabilmek için başvurulan yöntemlerden biri, ele giyilebilir araçlar ve el arayüzleri gibi vücut üstü teknolojileri kullanmaktır.

Bu çalışma, yeni sayısal müzik çalgıları araştırmalarında giyilebilir el araçları ve el arayüzlerini araştırmaktadır. Çalışma kapsamında sayısal müzik çalgıları araştırmasındaki temel kavram ve tartışmalar hakkında genel bir gözden geçirme yapılmış, özellikle bilgisayar çevre birimi olarak kullanılan veri eldivenlerinin müzikal ve müzikal olmayan amaçlarla kullanımı ve baştan müzikal amaçlarla tasarlanmış ve kullanılmış araçlarla ilgili bazı önemli örneklere yer verilmiş ve kendine özgü dinamikleri, yapısı ve sınıflandırmalarıyla el arayüzlerine odaklanılmıştır.

Tez çalışması, çalışmanın araştırma alanı, amacı ve ilk elektrikli müzik çalgıları, elektronik müzik pratikleri ve yeni sayısal müzik çalgılara geniş bir tasarım alanı yaratan teknolojik gelişmelerden oluşan tarihsel bir arkaplandan oluşan giriş bölümüyle başlamaktadır.

İkinci bölümde, yeni sayısal çalgıları araştırmasıyla ilgili tanımlar, akustik çalgılarla karşılaştırmalar, farklı akış modelleri, temel kavram ve paradigmalar ve yeni sayısal müzik çalgılarında sınıflandırmalar gibi araştırma alanı hakkında literatürden bilgilere yer verilmektedir.

Bir sonraki bölümde ele giyilebilir araçlar ve el arayüzleri daha yakından incelenmiş, el jestlerinin temsili, giyilebilirlik gibi ilişkili kavramlarla ilgili bilgi verilmiş, veri eldivenlerinin ortaya çıkışı, müzikal amaçlarla kullanımı ve müzikal pratikte kullanım amacıyla geliştirilmiş müzikal eldivenler ve önemli örneklerin çalışma prensiplerine yer verilmektedir.

Dördüncü bölümde, bu çalışmanın ana çıktısı olarak geliştirilen ve 'Grain Harvester' olarak adlandırılan, herhangi bir fiziksel yüzey ve objenin 'müzikal bir yüzey' olarak kullanılma potansiyelini ortaya koyan yeni bir sayısal müzik çalgısı sunulmaktadır.

Çalışma esnasındaki tasarım süreciyle ilgili kısa bir özetin yanı sıra, çalgının detaylı açıklaması, bileşenleri, kilit özellikleri verilmekte ve literatür ve ilişkili işler üzerinden değerlendirilmesi yapılmaktadır.

Tez çalışması, son bölümde çalışmanın genel bir değerlendirmesi, gelecekte yapılması planlanan çalışmalar ve nihai değerlendirmelerle tamamlanmaktadır.

Bu çalışmanın ana çıktısı olarak, el jestleriyle herhangi bir nesne veya yüzey arasındaki fiziksel etkileşimi bir sinyale dönüştüren ve bu temsil edici sinyali doğrudan dokunsal geribildirimi kaybetmeden ses oluşturmak için kullanan yeni bir sayısal müzik çalgısı, 'Grain Harvester', geliştirilmiştir. Çalgının tasarımı, herhangi bir fiziksel yüzey veya nesnenin yeni bir sayısal müzik çalgısının bir parçası olarak 'müzikal yüzey' olarak kullanılabileceği fikrine dayanan yeni bir yaklaşım önermektedir. Çalgı, sayısal müzik çalgıları zincirini açıklarken sıklıkla kullanılan ayrı bir fiziksel kontrol aracı içermemekle birlikte, yüzeye özgü sinyal oluşturma yetenekleri, ses oluşturma mekanizmaları ve genişletilmiş uzamsal ulaşılabilirlik özellikleriyle herhangi bir fiziksel nesne veya yüzeyin 'ses zerreleri hasat etmek' için kullanılabilmesine izin vermektedir.

Çalgıda temel olarak el parmak tırnağı üzerine yerleştirilmiş transdüser kullanılarak, fiziksel bir yüzey veya objeyle el jestleri arasındaki arasındaki etkileşim elektrik sinyaline dönüştürülür. Daha sonra bu sinyal, bilgisayar ortamında sayısal olarak örneklenerek ve Fast Fourier Transform (FFT) yöntemi ve istenirse farklı FFT işlemleri uygulanarak frekans bileşenleri ve ilgili şiddetlerine dönüştürülür. Bu işlemler sonucu elde edilen veriler, ses zerreleri oluşturmak için geliştirilen algoritmanın temel parametreleri olarak kullanılmaktadır. Bu parametreler dışında, ses zerrelerinin süreleri ve bu sürelerin olası aralıkları da kontrol edilebilmektedir.

Çalgının mevcut halinde arttırmalı ve eksiltmeli sentez yöntemlerinin yanı sıra ters FFT (iFFT) yöntemiyle elde edilen üç ayrı ses sinyali çıktısı bulunmakta ve bu ses çıktıları birbirleriyle karıştırılabilmektedir. Çalgıda bu ses çıktılarının yanı sıra, halihazırda geliştirilmiş ve Musical Instrument Digital Interface (MIDI) nota mesajları kabul eden farklı platformlardaki yazılımlarla (örn. Virtual Studio Technology (VST)) birlikte çalışmaya imkan veren MIDI çıktısı da bulunmaktadır.

Çalgı bu özellikleriyle elektronik müzik pratiği ve genel olarak müzik pratiği için yenilikçi bir müzik çalgısı anlayışı önermektedir. Bu anlayış, aynı 20. yüzyılda ortaya çıkan 'müzikal sesler' olarak nitelendirilen seslerin kapsamının musique concrete veya elektronische musik pratikleriyle genişlemesi gibi 'müzik çalgısı' olarak nitelendirilen nesne ve yüzeylerin de kapsamının genişlemesi ve herhangi bir nesne veya fiziksel yüzeyin müzik çalgısının karakterini veren bir parçası olarak kullanılabilmesinin önünü açabilir. Bu anlayışın getirdiği bir başka yenilik ise çoğunlukla icra esnasında bedenle propipriyoseptif ilişkisi sabit olduğu varsayılan müzik çalgısının fiziksel yüzeyinin uzamsal olarak da genişlemesi ve icracının icranın gerçekleştirildiği herhangi bir yüzeyi icra edebilmesi, bir başka deyişle mekanın müzikal çalgının bir parçası olarak icra içine dahil edilebilmesidir.

Ayrıca, çalışma kapsamında geliştirilen algoritma, yan ürün olarak canlı veya kayıtlı herhangi bir ses sinyalinin gerçek zamanlı olarak işlenebilmesine imkan vermektedir. Böylece, çalışmada geliştirilen çalgının yazılımsal bileşeni, fiziksel yüzeylerle etkileşime dayalı olarak kullanılabilmesinin dışında farklı ses kaynaklarını işleyebilen bir araç olarak da kullanabilmektedir.

Çalgının tüm bu özelliklerinin ve yeteneklerinin gelecekte yapılacak çalışmalarla genişletilmesi planlanmaktadır. Örneğin, şuan için tek parmakla kullanılan çalgının daha ulaşılabilir mikrofon ve algılayıcılar kullanılması ve algoritmanın daha az işlemci yüküne yol açacak şekillendirilmesiyle çoklu parmakla kullanılabilmesi araştırılacaktır. Halihazırda yüzeye dokunma durumunu ve yüzeye uygulanan basıncı tespit edemeyen çalgı, eklenecek farklı algılayıcılar ve algoritmalarla bu anlamda geliştirilecektir. Halihazırda arttırmalı ve eksiltmeli ses sentezi yöntemleriyle gerçekleşen ses oluşturma süreçleri, farklı ses sentezleme yöntemlerinin eklenmesine yönelik çalışmalarla çeşitlendirilecektir. Çalgının kontrol parametrelerinin ele yerleştirilecek bir kontrol yüzeyiyle değiştirilmesi sağlanacaktır. Bir yüzey üzerinde parmağın konumunun belirlenebilmesi herhangi bir yüzeyin müzikal kontrol yüzeyi olarak kullanılabilmesi olanaklarını da arttıracağından, bu alanda yapılacak araştırmalarla çalgının yetenekleri arttırılacaktır.

Çalgı, halihazırdaki özellikleri, tasarım anlayışı ve gelecekte yapılacak çalışmalarda geliştirilecek yetenek ve özellikleriyle, mevcut 'müzik çalgısı' anlayışını ve müzik üretim süreçlerini dönüştürecek bir potansiyele sahiptir.

1. INTRODUCTION

This study explores hand interfaces within new digital musical instruments (DMI) practice by presenting a general overview on DMI research with various approaches and discussions, focusing on hand interfaces with their specific dynamics, classifications and reviewing prominent examples of data gloves with their design and use for both non-musical and musical purposes as well as musical gloves specifically designed and used for electronic music performance. As the main output of this study, it presents a new DMI, ‘Grain Harvester’, developed as part of this study which is based on the idea that any physical surface and object could be used for musical purposes as part of a new DMI and finally evaluates and discusses the developed instrument considering the DMI practice and available literature.

1.1 Motivation of the Study and Purpose of Thesis

When I applied for Music Master’s Degree program with the speciality field of sound engineering and design after an environmental engineering undergraduate degree, I thought my main motivation was achieving progress in making my own music. While I was not fully conscious where such an education might lead my music, after 15 years, I realize that the aim of ‘making my own music’ was more specifically about ‘forming my own music practice’ by learning the possibilities offered by technology on different parts of the music practice, be it composition, performance, production as well as the concept of a musical instrument which is closely related with the former components.

After seeing and exploring different means and platforms for designing new instruments which could exploit diverse musical possibilities from different sound generation and control methods, I decided to focus on development of new musical instruments and as most of the means and platforms accessible for me was on digital domain, I focused more and more on new DMI research.

Like the electronics domain, DMIs have hardware and software components and the relationship between these components is a major part of the design process. In the beginning, I was working more on the software side where my first DMI design studies were based on designing sound generation processes with the capabilities of the laptop computer components and control of these processes by using body gestures was a secondary functional element.

I remember that I was using an external mouse to control my DMI in my first live electronics performance back in 2007, mainly looking at the laptop screen monitoring the parameters, correlating them with the generated sound to check where I was at the composition, as shown in Figure 1.1.

Figure 1.1 : First live performance with developed software instrument in 2007 with the physical controller as mouse.

The limitations of such an approach emerged soon as it was almost excluding a major part of music practice, the body and its gesture space. So, I started to explore the gesture space starting from the available technologies and tools to capture body gestures and found out clearly that while many implications of the new digital world leads to virtuality, at the same time it develops many tools to capture the human gestures and use them to design and control this virtuality. In a era where the machine is becoming able to replace human labor with many body gestures in different fields of industrial production, understanding and sensing human gesture space as well actuating the machine based on this knowledge becomes an indispensable part of the research process. Right now, there are many different types of technologies to capture, learn, process and imitate human body gestures in the forms of sensors, algorithms, microprocessors and actuators.

During this exploration, it became clear to me if I want to include human body gestures in DMI design, the design process will not be like designing sound generation processes and finding out tools to control these processes.

My first output of including gesture space as a core element of DMI design was the instrument named as ‘Ensample’. Consisting of three linear force sensitive resistors (FSR) measuring the distance of the pressed fingertip linearly and two infrared sensors measuring the proximity of the obstruction, which is a hand mostly in this case, the instrument enables hand gestures to become bodily part of the musical expression. The linear position of the FSR sensor was mapped to the position of a sound event extracted from a sound recording and the proximity of the obstructing gestures to the infrared sensors was mapped to the pitchshift of the sound events through time stretch and pitch of the grains synthesized from the sound recording. Pictures of the physical control interface of the Ensample could be found in Figure 1.2.

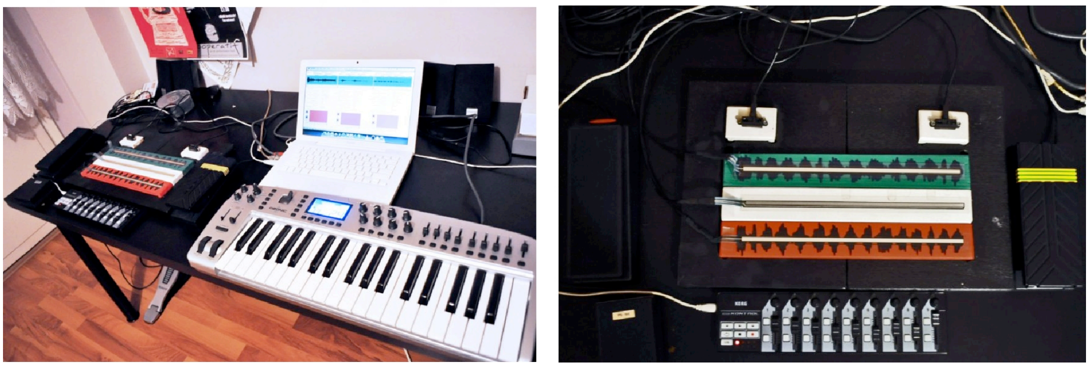

Figure 1.2 : Physical control interface of the ‘Ensample’ instrument.

The other side of the instrument chain, sound generation process, was based on my previous DMI designs developed at Cycling 74’ s Max platform and I adapted later versions of this instrument to Novation LaunchPad and LaunchControl XL control interfaces and still use at my performances.

Design process of this instrument showed me that hand gestures, which are very common in musical instrument design, are very versatile and have great potential for new DMI design and research. The diversity of available technologies to capture and process data acquired from hand gestures is very promising for new DMI practice as well. While these promising technologies also come with their problematics as in many other DMIs in terms of lack of feedback and poor ways of interaction, different application options of these technologies also enable many ergonomic and interactive solutions to the current problems of new DMI design.

However, instruments like Ensample and many other well-known commercialized ones such as Roli Seaboard or Artiphon The Instrument 1, mostly have their own designed physical surface the performer is acting upon. In such instruments, the physical interaction between the performer and instrument happens mostly between performer's hand gestures and a designed, manufactured and spatially limited 'musical surface', which could be defined as 'a physical surface designed and manufactured specifically for musical interaction' as part of a musical instrument. One of the ways to overcome this limitation and extend performance possibilities beyond a limited surface and space is to use on-body technologies such as hand wearables or hand interfaces. So, I decided to explore how such 'musical surfaces' could be extended with a new DMI design approach.

With these motivations, I determined main research field of the this study as 'Exploration of Hand Interfaces within New Digital Musical Instruments Research', where a general overview of DMI research is given and a closer look at hand wearables and hand interfaces is taken. As the main output of this exploration, a new DMI named 'Grain Harvester' was developed, which transforms the interaction between hand gestures and any physical surface or object into digital signal and uses the representing signal to generate sound without loosing tactile feedback. The developed approach mainly explores the usability of any physical surface and object as a 'musical surface'. The instrument is described detailedly with its key features, components and design decisions, and discussed within new DMI research and related work.

1.2 Contents of Dissertiation

The thesis starts with an introduction chapter giving the main research field with the motivations of the study and purpose of thesis and a preliminary historical background including first electric music instruments, their practice, rise of new technologies enabling a versatile design space in DMIs before the following chapters.

The thesis continues with a chapter about DMI research giving definition and conception of DMIs, various flow models, basic concepts and paradigms in DMI research and taxonomy of DMIs with different approaches.

The following chapter looks more closely at hand wearables with related subjects such as hand gesture recognition, wearability, data gloves, music gloves, continues with some important examples of hand wearables and ends with a closer look at hand interfaces with a fundamental taxonomy and their relationship with wearability.

The fourth chapter introduces a new DMI developed as the main output of this study, 'Grain Harvester', which explores the potential of any physical surface and object to be used as a 'musical surface'. It gives a brief summary of the design process during the study, a detailed description and key components of the instrument, details about the modules and processes and finally evaluation of the instrument with related work and literature.

The final chapter concludes the thesis with a general evaluation and summary of the study and statement of future work and final remarks.

1.3 A Historical Background

Use of electricity and electronics in musical instrument design has its roots from 1700s, with first examples such as Denis D' Or and Clavecin Electrique. At the end of 1800s, with rapid developments in technology, rise of inventor-entreprenuers in the field of tele communication through sound and business ideas involving new ways of producing and transmitting music beyond the acoustic medium, new electronic instruments have been built.

An important example, Telharmonium was made mainly for the production of traditional acoustic music in electronic environment and its commercial distribution through a network. While the business plan failed because of interruption by telephone signals, it has been an inspiration for the upcoming instrument ideas. The invention of diode tubes in the beginning of 1900s enabled less electricity demand, less space requirement and lighter structure for the production of sound and the same principles were used in later versions such as Hammond Organ.

Theremin was another significant example of early electronic instruments which was invented accidentally while generating an alarm sound to indicate exceeding level of a chemical in a research laboratory. It uses heterodyning effect and radio frequencies and it was a major innovation with its ability to generate sound without contacting the instrument. Unlike Telharmonium with a keyboard control interface, its physical control interface was first of its kind as a musical instrument without the need to contact with the instrument for sound generation.

Such examples of early electronic music instruments could be extended. However, the main practice of these instruments was performing traditional music pieces and their limited use has been criticised by avantgarde artists such as John Cage who described thereminists of that time as ‘censorists’.

There were other examples of emerging music practices in the 21st century such as phonograph, gramophone and magnetic tape, all of which enabled sound recording and generation of sounds from these recordings on different surfaces. While Edison and Berliner competed to become the prominent recording and playing medium of music until the end of 1920s with their inventions, cylinders and discs, respectively, Berliner discs with its complementary gramophone device became a major medium for music production and distribution.

On the other hand, magnetic tape, which is a major invention in the field of telecommunication, added new features for sound and music production such as ease of editing, processing. It was firstly used in production at radios and its experimental use at different electronic music studios across the world lead to rise of electroacoustic music and its golden age.

While there is a rapid development in sound and music production by analog technologies, development and mass production of integrated circuits enabled processing capabilities required for common use of computers. Max Matthews is frequently called as ‘the father of computer music’ with his efforts at Bell Laboratories to develop new platforms for computer-assisted sound generation devices. He and his collaborators such as Jean Claude Risset, Jon Appleton and many more explored sound synthesis on digital domain and made a major contribution to make up the huge difference between sonic possibilities generated at analog and digital domains.

Another important stage concerning new digital musical instruments was the use of digital technology at music production. With the widespread use of computers and shift from analog devices to digital devices because of their flexibility and practicality, music production has been most commonly made in digital domain starting from 1990s.

After the widespread use of computers, the next step towards the dominance of digital technologies in media production and distribution of sound and music, was development of ‘intelligent devices’ with their higher portability with the most visible ones, intelligent phones. These devices offer many different interaction possibilities between people and other devices. Such developments gets people prepared to be open to new interaction ways to come as well.

The ambitious research and development efforts as well increasing use of intelligent devices in today’s modern society enabled development and easier accessibility to sensors which enabled new means of acquiring gesture data. The use of such sensors is wide open for DMI design and enables realization of many ideas which were technically and logistically impossible short time ago.

Right now, increasing accessibility to hardware and software components such as powerful programmable microprocessors, industrial sensors and various programming platforms favours personal and institutional efforts for new digital musical instruments (DMI) research leading to many new DMIs being designed, developed, protoyped and even commercialized.

2. GENERAL OVERVIEW OF NEW DIGITAL MUSICAL INSTRUMENTS RESEARCH

This chapter takes a general look at DMI research including definition and conception of DMIs, models, basic concepts and paradigms in DMI research, and taxonomy of DMIs.

2.1 Definition and Conception of New DMIs

The concept of 'musical instrument' may be a useful starting point for the definition and conception of new DMIs. A musical instrument could be defined with different perspectives. One of the pioneers of music organology, Von Hornbostel (1933), states that for music research, a musical instrument could be generally defined as "everything with which sound could be produced intentionally". He put intentionality at the core of the definition. Another definition at Encyclopedia Britannica (2019) defines musical instrument as "any device for producing a 'musical sound'" where the musicality of the produced sound is at the center of the definition. Longman Dictionary of Contemporary English (2019) approaches musical instrument as "something used for playing music such as a piano or guitar" which takes traditional acoustic music and performance as the key element.

Another definition by Kim and Seifert (2017) approaches a musical instrument as "a sound-generating tool used explicitly for making music". They also take the traditional definition of musical instrument "being a device that has the function of generating sounds" as their starting point and state that this definition implies the intentionality of the performer acting upon the instrument. They comment that this reactivity forms the fundamentals of instrumentality based on the properties of an object which is acted upon to generate sounds, such as material resistance, tactile feedback, etc.

Depending on the perspective, the definition of a musical instrument focuses on elements of intentionality, musicality of a sound, exclusivity to traditional acoustic instrument practice, its explicit use for making music or being a reactive apparatus.

Hardjowirogo (2017) states that musical instruments of the 21st century could be differentiated from earlier ones in many aspects such as their appearance, technical functions, performing techniques and their sound generation processes. As so many features of musical instruments have differed, the concept and understanding of 'a musical instrument' in the 21st century have changed as well. After including DMIs in a sub-category of 21st century musical instruments, Hardjowirogo asks how DMIs could be defined and conceived.

The definition of a digital musical intrument was made by Miranda and Wanderley (2006) as "an instrument using computer generated sound and consisting of a control surface or gestural controller driving the musical parameters of a sound synthesizer in real time". This definition leads to a strict separation between the sound production and control processes with the mediating mapping strategies. Bennett (2010) refers to the digital musical instrument with its use of digital technology such as computers or microprocessors and adds that use of such digital systems enables separation of gestural input fed to the system from the musical output. This separation allows the instrument designer to use vast of possibilities about how to 'map' the input gestures into sound generation processes. Malloch et al (2006) define DMIs as "instruments whose sound generators are digital and separable from their control interfaces". There, they make an important emphasis on the difference between 'separate' and 'separable' which could be critical for the approach towards new DMIs.

While conceptualizing DMIs, it may be also essential to focus on differences between the dynamics of acoustic and digital musical instruments.

Magnusson (2017) compares DMI practice with that of acoustic counterparts with its components such as accelerometers, photocells, face detection algorithms and states that DMI design originates primarily from technological knowledge and gives computer, mostly at the core of DMI design as a components, being not a musical instrument but adopted for such a use. He also references Jorda (2005) stating that DMI design expertise does not come from acoustic properties of materials but from factors of human-machine ergonomics. He then mentions the need for "a new type of knowledge" to build, test, perform, analyse and understand these new instruments which do not follow the long tradition of acoustic musical instruments. He then compares this knowledge to traditional lutherie practice characterizing it by the typical relationship between composers and performers, knowledge, experience on physical materials and the acoustics of architectural performance spaces and gives product design, human computer interaction (HCI), electronic game design, network design, ergonomics and virtual reality (VR) as examples of this new type of knowledge, commonly involved in DMI design.

Bevilacqua and Schnell (2016) argues that DMI practice challenges the classical role of instrumental gestures and the instrument in different aspects. They state relationship between effort and output is changed significantly by mapping simple gestures controlling complex music processes without requiring any virtuosic motor control, which contradicts the common traditional notions of musical virtuosity, giving a simple example of non-contact interfaces or physiological sensors that have no equivalent counterparts in acoustic instruments.

A unique perspective about musical instruments was by Enders (2017) who approaches the subject from technical development to the virtual musical instrument at the paper with the same title. He looks at the history of music as increasing digitalization and representation and processing of musical information as notes and sounds. He identifies ten developmental stages with regard to construction and usage of musical instruments and multimedia performances, which are named as instrumentalization, mechanization, automatization, electronification, modularization, digitalization, virtualization, globalization, informatization and hybridization. While one instrument may be characterized by more than one stage, each of these stages lead building of instrumentality in 21st century from different aspects.

2.2 Models of DMIs

Another tool to better understand the dynamics of DMIs other than their definition and conception could be to give a closer look at different DMI models. O'Modhrain (2011) defines a model as "representations of systems or artifacts that provides a means of reflecting upon the design or behavior of a system" which could be in the forms of mathematical formulae describing the structure to flow diagrams explaining system behavior. This section gives different models given for DMIs with varying perspectives, some of which are updated from previous ones.

A basic and well-known DMI model was given by Miranda and Wanderley (2006) according to the basic definition of DMIs with its instrument chain as control and sound generation components with the mediating mapping process and shown in Figure 2.1.

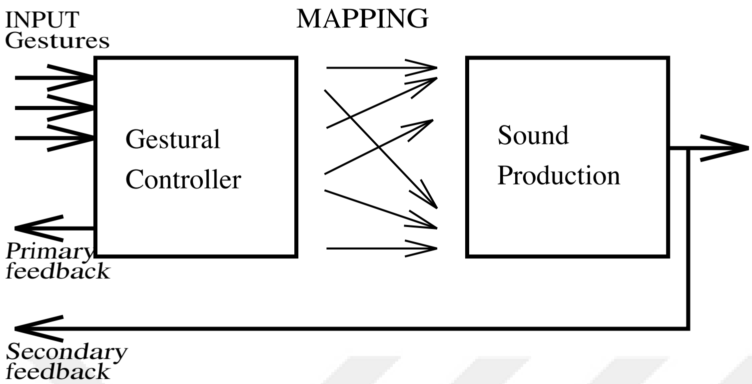

Figure 2.1 : A Basic DMI model by Miranda and Wanderley (2006).

Another DMI model, given in Figure 2.2, was made by Birnbaum (2007) where he recontextualizes the DMI model given above as ‘gestural control of musical feedback’ where ‘gestural controller’ is replaced with ‘gestural interface’, to better accomodate the likelihood that sensors and actuators are both present in the device. There is a bi-directional process around the mapping stage to emphasize the interaction between the two stages generated by mapping. The ‘sound production’ stage has been renamed as ‘feedback generator’ to consider the sonic output as an auditory feedback for the following gestural processes as well the concrete output of the DMI, giving a stronger emphasis to the action-perception cycle.

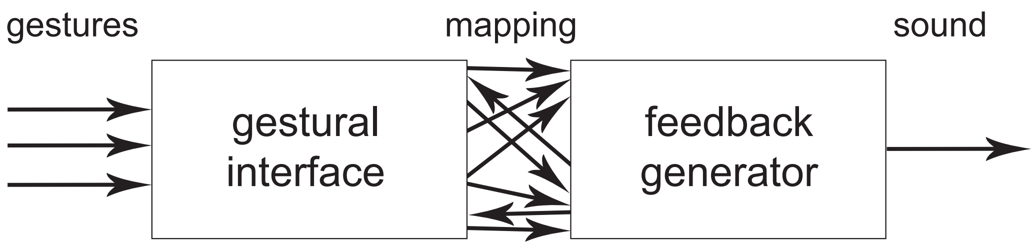

Figure 2.2 : A model based on the idea of DMI as ‘gestural control of musical feedback’ by Birnbaum (2007).

The components of the instrument were detailed in another combined model by Marshall (2008) based on the work of Bongers (2000), Wanderley (2001) and Birnbaum (2007) given in Figure 2.3.

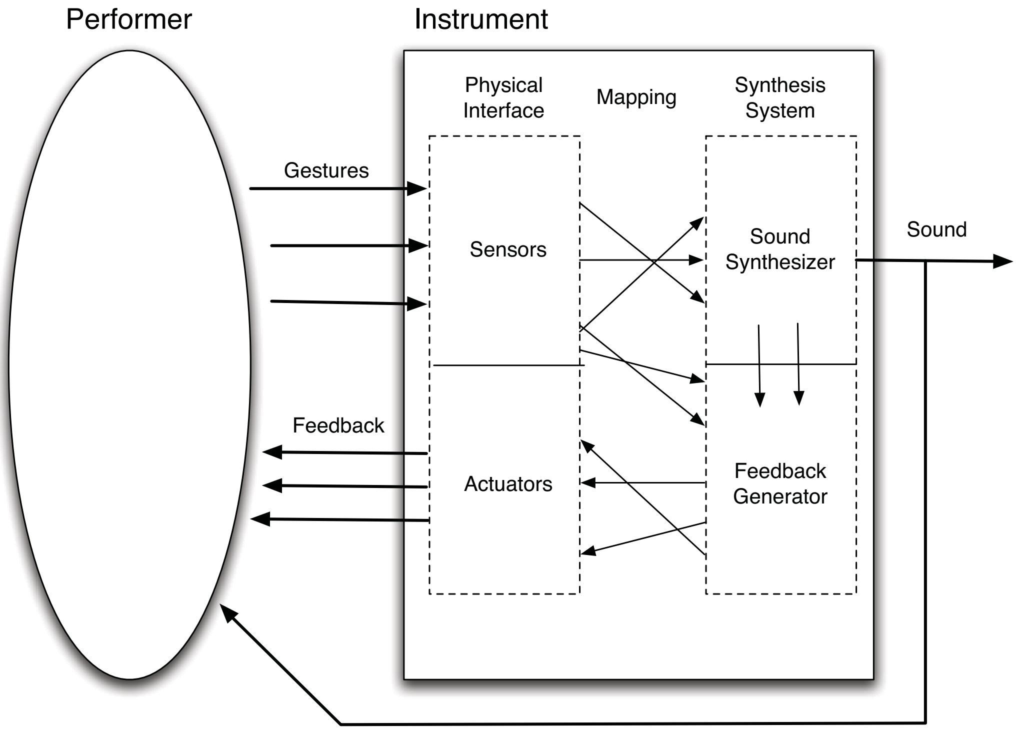

Figure 2.3 : Combined DMI model by Marshall (2008) based on the work of Bongers (2000), Wanderley (2001) and Birnbaum (2007).

In his combined model based on the work of Bongers (2000), Wanderley (2001) and Birnbaum (2007), Marshall (2008) adds the performer component into the DMI flow in addition to the instrument which comprises of the physical interface, synthesis system and the mapping process. He divides the physical interface into sensors and actuators with which the performer is interacting and notes that the physical interfaces of some DMIs does not include all of these parts and the interaction between the performer and the instrument changes accordingly.

Wessel and Wright (2001) focused on the performer side of the DMI model given in Figure 2.4.

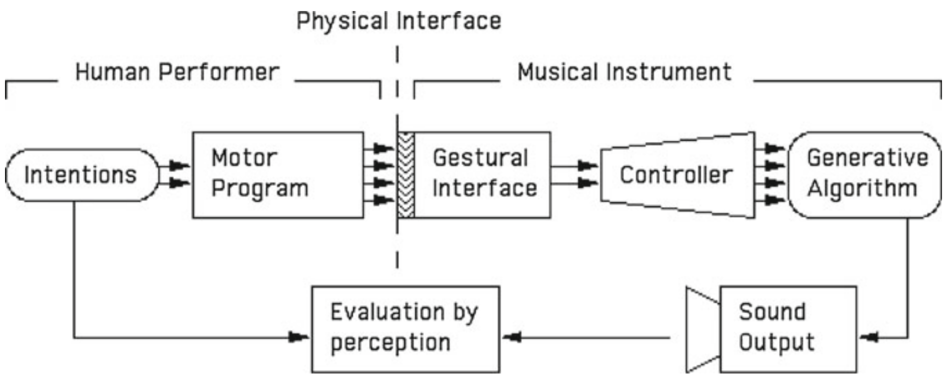

Figure 2.4 : The DMI model by Wessel and Wright (2001).

A DMI model adapted from Wessel and Wright (2001) is given by Bennett (2010) shown below in Figure 2.5. Bennett puts the sound output on the musical instrument side while moving evaluation by perception onto human performer side adding its relationship with the intentions of the human performer.

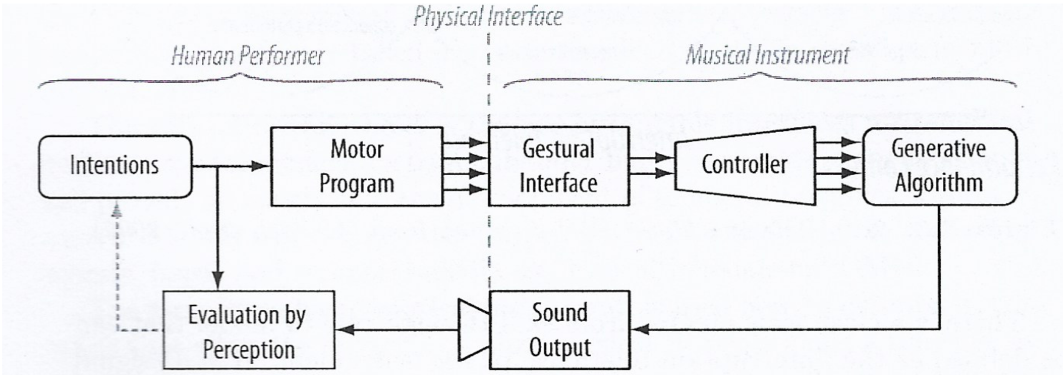

Figure 2.5 : The DMI model by Bennett (2010) adapted from Wessel and Wright (2001).

Another DMI model by MyGlynn (2014) includes all the above models with both the performer and instrument components and is given in Figure 2.6.

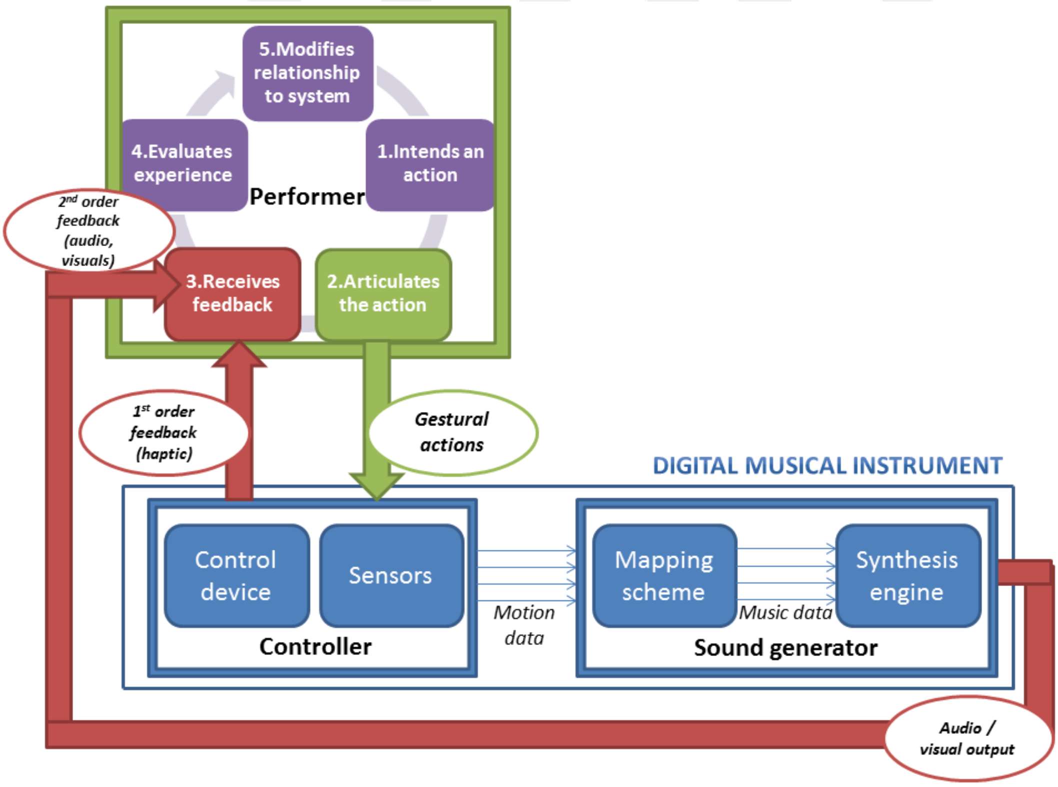

Figure 2.6 : The DMI model by McGlynn (2014) with performer and instrument components.

McGlynn (2014) notes that this DMI model may need some modifications in different cases such as in instruments where feedback is part of the controller and there may be many more components to be added to this model, but notes that it is compatible with most of the designs.

These models help one to understand and review a DMI better in terms of the relationships and interactions between its components and performers.

2.3 Basic Concepts and Paradigms in DMI Research

After giving different DMI model propositions, this section will include the basic concepts and paradigms in DMI research such as interface, interaction, feedback and mapping.

2.3.1 Designing instruments, interfaces, interaction

Does the strong emphasis on the separate or separable structure of DMIs imply that design process should be taken separately as well? Does a physical interface constitute most of the controller design? Where does sound generation process start in a DMI? What is the difference between interaction design and mapping? What kind of approaches could there be? While such questions may seem to have concrete answers, the versatile dynamics of DMIs leads us to think about these in a variety of ways.

An interface could be defined as ‘the access or communication port where the user interacts with a design’. This definition implies that the interface is not related with only control processes but with interaction as well. The name ‘New Interfaces for Musical Expression’ (NIME), one of the leading events on DMI research, implies that interfaces are the ultimate outputs of creation process of tools for musical expression. However, it should be noted that the outputs at the conferences do not include only those on interface design.

DMI design process could also be seen as an interaction design process involving the concept of musical instrument with its control and sound generation components. However, there are different views on the interpretation of the interaction concept influencing the approach towards instrumentality.

Kim and Seifert (2017) compare the approaches towards the concept of interaction from social sciences/humanities and computer science/human computer interaction (HCI) research areas. They state that according to social sciences and humanities practice, the subjects of interaction processes are limited to humans excluding machines and animals, while in HCI research these terms generally refer to technological capabilities offered by the computational artifacts to the user.

At their work, Kim and Seifert (2017) also criticise the approach given by Thoben (2014) in investigating interactive musical instruments where he puts three components: an interface, a mapping scheme, and a sound-generating component. Thoben formulates the dynamics of the components as an interface provides haptic and visual feedback and a sound-generating component provides acoustic feedback. He also uses the term ‘interact’ as a relationship between the performer and interface in relation to the (human) performer and the interface, with statements such as “The performer interacts with a musical interface”. Kim and Seinfert (2017) criticise the use of the terms by Thoben (2014). They discuss that Thoben uses the term ‘interaction’ synonymously with the term ‘feedback’, the interface provides haptic and visual feedback and the user “interacts” with the interface.

In his well-known paper about the relationship between interaction and interface design, Beaudouin-Lafon (2004) argues that in order to achieve significant developments in user interfaces, the focal point of the research must shift from interface design to interaction design. He compares the increasing computing power of the computers with the same components of the input/output devices throughout the years and asks the question why this increase in computational power has not led to a compatible development in input/output devices. He argues that a shift from individiual point designs to a more holistic approach could be the main difference resulting in next generation of interactive environments. He emphasizes that the goal of such research should be interaction design where user interfaces are means to achieve it, not designing user interfaces as final products to be used on different interactive environments.

In order to explain previously discussed subject of how interaction could be conceived; Beaudouin-Lafon (2004) gives three primary interaction paradigms: computer-as-tool, computer-as-partner and computer-as-medium.

He explains that the computer-as-tool paradigm proposes extension of human capabilities through tools as in the example of wheel enabling more efficient transport systems over long distances. He gives use of natural language to delegate tasks to a computer as an example of computer-as-partner paradigm. Finally, he examplifies the use of computer as a medium for communication between humans for computer-as-medium paradigm with outputs such as email, chat and videoconferencing.

Giving research area examples of HCI, Artificial Intelligence (AI) and Computer-Supported Cooperative Work for computer-as-tool, computer-as-partner and computer-as-medium paradigms, respectively, Beaudouin-Lafon adds that none of these paradigms should be considered superiour against others and a holistic approach with all these paradigms must be developed.

In his work, he approaches instrumental interaction, which is also the key element in this study, with a model based on computer-as-tool paradigm. He considers instruments as mediators between users and objects. He gives examples such as pens easing writing and fins making swimming more efficient. However, compared to the field of HCI, it should be noted that DMI design has its unique characteristics that the best designs are not always the most comfortable, functional and effortless ones.

In his paper, he illustrates instrumental interaction with the example of scrollbar, given in Figure 2.7.

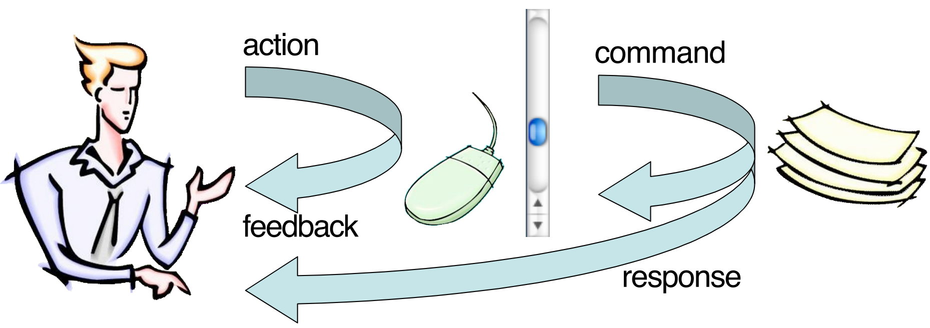

Figure 2.7 : The Scrollbar Example by Beaudouin-Lafon (2004) to illustrate instrumental interaction.

In this example, the instrument is composed of the physical mouse and on-screen scrollbar. The user interacts with the hardware interface, mouse, and interface at the software program, the scrollbar on the screen and receives direct tactile feedback from the mouse and visual feedback from the scrollbar as highlight. The scrollbar transforms user actions into scrolling commands. The thumb of the scrollbar is updated as a response towards the instrument and the contents of the document are updated as a response towards the user. With this process, interaction between the user and the document is mediated by the instrument. Beaudouin-Lafon (2004) also describes a paradox of HCI, based on the idea that the best interface designs are invisible with a accompanied 'natural' interaction. So, new systems which disappear as a result of the design process are created.

Giving an example from another discipline, he mentions that as astronomy is not the science of telescopes, HCI is not the science of user interfaces and concludes that while developing interfaces to create interaction, the focal point should be describing, evaluating and generating interaction, not interfaces.

2.3.2 Developing mapping strategies

Mapping has been an important part of DMI research and literature where an extensive review of the related literature until the 20th century could be found in Hunt and Kirk (2000), Wanderley (2001) and Hunt and Wanderley (2002) as given by Hunt et al (2003).

In their paper on the importance of parameter mapping in electronic instrument design, Hunt et al (2003) describe mapping in DMIs as "the art of connecting the two traditionally inseparable components of a real-time musical system, sound generator and controller". According to Birnbaum (2007), mapping strategies in DMIs are developed to replace the role of the dynamics of physical laws in acoustic instruments at digital domain.

Hunt et al (2003) emphasize the effect of mapping on an instrument which can directly effect the interaction process with an example they named as 'accidental theremin'. In this example, a wiring 'mistake' lead the volume antenna of a theremin-based instrument to work only when the hand is moving. According to observations of the authors, this mapping 'mistake' led users to spend much more time and have a much more engaged experience compared to the classical mapping of the theremin. They added that ironically the mapping mistake was corrected the next week despite its increased engagament with the instrument which could be given as an example of 'conservative mapping'.

Van Nort et al (2014) gives three perspectives to mapping, systems point of view, functional point of view and perceptual point of view.

They state that Chadabe (2002) describes a hierarchical point of view where a unidirectional control of many low-level parameters is made by a few high-level parameters. He also describes a network point of view, where all parameters are hierarchially equal in sending and receiving control information in a non-deterministic manner. Van Nort et al (2014) refer to this approach as a *systems* point of view on mapping. They differentiate this from a *functional* point of view, defined by the operations that focus on the functionality of different sets of variables, such as between control and sound synthesis parameters. They also describe a *perceptual* point of view focusing on the human intention leading to representative sonic output.

A representation of systems point of view is given at Van Nort et al' s work (2014), shown in Figure 2.8. It considers the number of degrees of freedom afforded by a physical controller or synthesizer, and uses many different layers to define how each of these degrees or parameters can be associated.

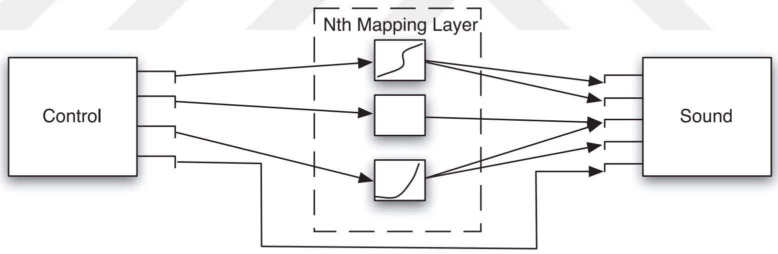

Figure 2.8 : A generalized systems-oriented view of mapping from control to sound parameters (Van Nort et al, 2014).

The direction arrows in Figure 2.8 describe the given control-to-sound parameter association or "what to map where" through mapping layers.

A functional point of view is interested in the functionality of the mapping process as well as its structure. In addition to the control and sound synthesis components including control sets given in Figure 2.9 as X,Y, the functional relationships between the components are defined through functions, given in Figure 2.9 as f,g which could also define additional control sets given as X'. Such an approach considers the action-perception cycle of the user and generation of new subsets at the control components.

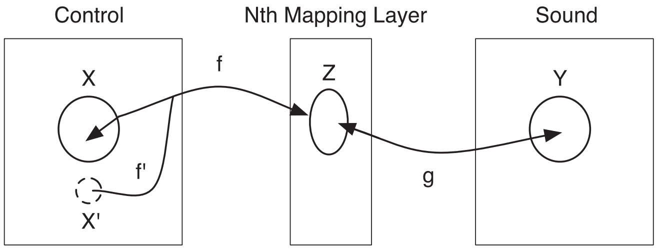

Figure 2.9 : A generalized functional view of mapping from control to sound parameters (Van Nort et al, 2014).

While the focus of Van Nort et al' s work (2014) was on the functional view of mapping, they also emphasize that sometimes systems point of view needs to be integrated in order to understand and explain design process. In addition, a perceptual point of view could be added to this holistic approach focusing on the intention of the performer.

Birnbaum (2007) states that the abstraction of mapping parameters leads interruption in the interaction component of instrumental music experience and proposes that DMIs could solve this problem by 'freezing' the mapping structure as he notes an instrument could be characterized by its mapping decisions. He summarizes this approach with a phrase, "Change the mapping, you have a new instrument".

2.3.3 Different forms of feedback

Feedback is defined by Hartveld and Hegarty (1996) as "sensory information received back by the appropriate control centers in the brain on the resultant movement during or after a task".

Marshall (2008) discusses the concept of feedback in musical applications both metaphorically and literally. Especially in HCI research related to gestural control systems, 'feedback' is used as a metaphor for any information produced by the system being perceived by the user no matter if the information is used to control the state of the system and stabilize the sound output, or not. On the other hand, it is used literally directly related to the music output of the instrument. The significant difference between the context of both uses needs us to elaborate and categorize feedback more detailedly.

Birnbaum (2007) summarizes 3 different categorizations of feedback reviewing the available literature:

• primary/secondary (Vertegaal et al, 1996)

• passive/active (Bongers, 2000)

• inherent/augmented (Schmidt, 2005)

Primary feedback originates from the physical control interface with its visual appearance, haptic feeling it gives, sounds it generates with its moving components during performance. Secondary feedback comes from the digital mechanisms of the instrument such as synthesized sounds generated from sound generation mechanisms. Birnbaum (2007) discusses that digital vibrotactile feedback could not be included precisely in one category of primary/secondary categorization as it is related with the mapping process as well as part of the physical interaction with the interface.

Passive/active feedback categorization is described by Bongers (2000) with its relationship to the intrinsic qualities of the physical interface while active feedback is described to be generated by the system itself. During the pluck of the string on a acoustic guitar, Bongers gives the tension of the string as the main component of the passive feedback, while the sound output of the acoustic guitar was given as an example of active feedback generated by the gestures of the performer. Such a categorization could also explain digital vibrotactile feedback more clearly as an example of active feedback.

A third categorization by Schmidt (2005) focuses on the relationship between the user and the task. Feedback directly related to the task is categorized as 'inherent' while feedback related more closely to external information is 'augmented'. This categorization mostly leads generation of inherent feedback during performance of an acoustic musical instrument, but for DMIs where different components could be mapped to different gestures, it may be very useful to think about the relationship between the gestures and the task. It also brings a new task-oriented perspective instead of a sonic output-centred perspective.

An alternative approach for feedback categorization is proposed by Birnbaum (2007) focusing on the origin of the feedback being either on the control signal side, named 'collateral feedback', or output signal side, named 'derivative feedback'. Collateral feedback implies a parallel structure with gesture mapped to sonic output as well as to another mode. On the other hand, derivative feedback is generated in a serial structure where the first feedback synthesis leads to another signal synthesis. This approach analyzes feedback signals in terms of their location within instrument chain instead of their function, agency or modality.

2.4 Taxonomy of DMIs

It may be challenging to organize and classify DMIs as they may be different than their acoustic counterparts in a variety of ways. Despite these differences, traditional organology may be a good starting point for DMI organology.

Kim and Seifert (2017) take the context presented by von Hornbostel and Sachs (1914), where they describe musical instruments at their work about traditional musicological studies on the classification of musical instruments as "physical-mechanical devices manufactured to generate sounds are foregrounded, with focus on the mechanism of a sound generator, including its material and the ways of vibrating it."

In the first Hornbostel and Sachs (HS) classification in 1914 where electrophones were not included, the main parameter for classification of musical instrument which is the material of the sound generator was deviated with the inclusion of aerophones. Unlike idiophones, membranophones and chordophones which were named by the material vibrating to generate sound, aerophones were named for their way of sound generation by air. Therefore, even in the first HS classification, the consistency was questioned by Simon (2004) as given by Kim and Seifert (2017).

In 1940, electrophones are added in the HS classification system as "musical instruments using forms of electrical energy". Davies (2000) further detailed electrophones and classified them into electroacoustic, electromechanical and electronic musical instruments.

Thinking about DMI taxonomy, Magnusson (2017) claims that the physical materiality of the DMIs is not a main concern as the material DMIs made of does not produce the emitted sound. Instead of the materiality, algorithms, performer gestures, perceived modalities of sensors or mapping strategies are the main determinants for DMI classification. He adds that taking the traditional musical instrument classification guidelines while working on DMI taxonomy could lead to limiting difficulties for this new kind of musical instrument class. As an example of these difficulties, he states that the works which make effort to adapt DMIs to existing organology approaches frequently use the word ‘towards’ at their titles, which often does not get any closer at the further studies. He proposes that design process, performance dynamics and sound control/generation dynamics are too diverse to be used with traditional organology guidelines.

McGlynn (2014) gives the categorization approach of Tanaka (2000), who uses bioelectric signals generated by the human body for music and visual control, focusing on the relationship between the user body and the system. Tanaka uses the mode of interaction (physical or non-physical) and type of manipulation (mechanical or nonmechanical) for his categorization. McGlynn (2014) gives an extreme example of “turning a knob”, which could be categorized as physical and mechanical and use of biosignals through electroencephalogram, as physical and non-mechanical according to Tanaka’ s categorization. It involves both the type of transducers transforming performer gestures as well as the way of interaction of the performer.

Miranda and Wanderley (2006) categorized DMIs in four groups according to their acoustic similarity as shown in Figure 2.10.

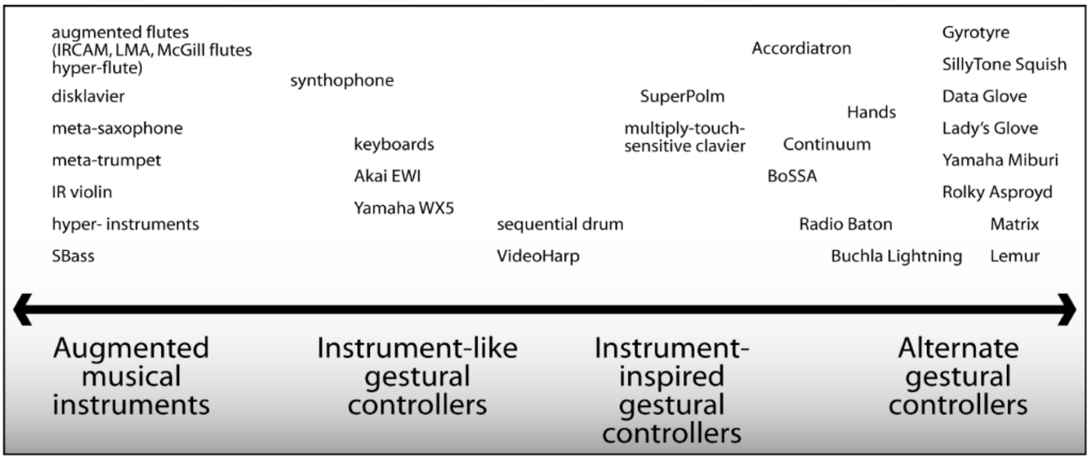

Figure 2.10 : Categorization of DMIs according to acoustic similarity (Miranda and Wanderley, 2006).

McGlynn (2014) notes that their categorization presents a continuum reflecting the development of DMIs in the last decades.

1. Augmented Musical Instruments: Based on the extension of existing acoustic instruments with some transducers, the basic performing techniques of these instruments remain mostly the same and the added sonic output capabilities

support the instrument with increased musical expression. They are also called ‘hybrid instruments’, ‘hyperinstruments’ or ‘extended instruments’.

2. Instrument-like Gestural Controllers: As the name implies, these are called as controllers instead of instruments, where the control interface ise designed based on the working principles of existing acoustic or electronic instruments with the aim of emulation of the instrument. The design motivation mostly comes from expansion of sound generation mechanisms of the existing instrument.
3. Instrument-inspired Gestural Controllers: Similar to instrument-like gestural controllers with the idea of using existing instrument as the starting point of the design process, instrument-inspired gestural controllers also seek to overcome physical limitations of the instrument and articulation possibilities.
4. Alternate Gestural Controllers: Unlike previous ones, these instruments do not have a direct connection with the existing instruments in terms of their control interface or sound generation capabilities. As the diversity of these instruments could vary significantly based on the design, some further categorizations have been proposed such as one given by Mulder (2000) with three main categories, touch controllers, expanded-range controllers, and immersive controllers.

A catalogue of prominent examples for each of the categories above could be found in McGlynn (2014).

Another approach for categorizing DMIs is based on technique and practice proposed by Bandesnaci at controllerism.com (2019), an online community of electronic musicians using various generic controllers. He proposes four main categories based on personal audio creation practice and techniques: instrument, transfiguration, conjuration and hybrid. It is important to note that depending on the performance practice, the same physical interface could be categorized differently.

1. Instrument: This performance practice is based on an external audio source such as an electric guitar or a hardware synth and it could be combined any of the following practice categories.
2. Transfiguration: This practice mainly manipulates an existing audio material to create new structures out of it using tools such as loopers or effects.

3. Conjuration: There is no pre-recorded or existing material at this practice. External samples of virtual instruments are used to generate sound out of nothing and process it live during the performance.
4. Hybrid: As the name implies, this performance practice uses more than one of the above, especially techniques from Transfiguration and Conjuration.

McGlynn (2014) comments that while this categorization approach includes an approach based on individual choices and uses, at the same time it is very useful to think about DMIs in terms of personalized performance practices and analyze them accordingly. Th’s approach also implies that a physical interface does not have to be used as offered or designed and different DMI practice categories could be developed with the same interface based on individual artistic decisions.

3. REVIEW OF HAND WEARABLES

3.1 Definition and Conception of On-Body Technologies

Wearability is defined by Gemperle et al (1998) as "the interaction between the human body and the wearable object" and adds the term 'dynamic wearability' to specify the human body in motion. At his work, he defines various guidelines with different topics such as 'placement' discussing where the object should be placed on body, 'form language' about the object's shape, 'human movement' about its dynamic structure in motion, 'sizing' about the relationship between the object's size and body, and 'attachment' considering different fixing methods to the body.

Liu et al (2016) proposed a taxonomy about 'on body technologies' based on its location on body surface which they adapted from Ranck (2012), given in Figure 3.1.

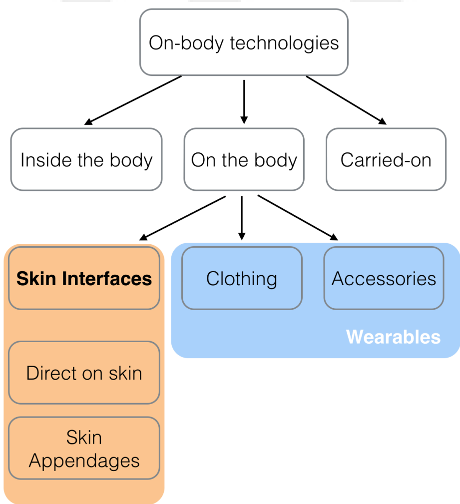

Figure 3.1 : An on-body technologies taxonomy by Liu et al (2016) adapted from Ranck (2012).

As seen in Figure 3.1, on-body technologies are classified to be inside the body, on the body and carried-on, with examples such as wearables, implants and smartphones, respectively. On-body technologies which are on the body are further classified as skin interfaces, clothing and accessories. Wearables are defined as the group including clothing and accessories. Skin interfaces could be directly on skin or on skin appendages such as nail.

3.2 Data Gloves

In his book on ‘HCI Using Hand Gestures’ with a particular focus on visual recognition technologies, Premarante (2014) gives a review on data gloves as part of a review on historical development of hand gesture recognition.

Premarante (2014) describes a data glove as “a wired or wireless interface with certain tactile or other sensory units that were attached to the fingers or joints of the glove, worn by the user” and states that even in 1990s where the processing power capacities of the computers were very limited, data gloves showed great potential to function as a promising control interface connected to a computer.

In his work focusing musical gloves, Torre (2013) also gives prominent examples of data gloves developed throughout history. As given in his work, the first glove-based input device, ‘Communication Device’, was developed in 1962 by IBM engineers Robert Seibel and Nathaniel Rochester to assist computer operators to write in high acceleration aircraft, where a computer keyboard was fitted inside a glove, as shown in Figure 3.2.

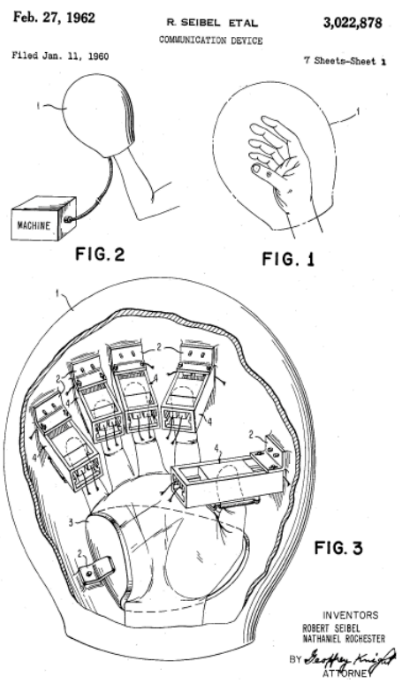

Figure 3.2 : Communication Device by Robert Seibel and Nathaniel Rochester (1962).

Sayre Glove, shown in Figure 3.3, was the first data glove controller giving continous data, developed in 1977 at the University of Illinois. It used a light source and a photocell to detect the amount of finger bending of the user. The first data glove using multiple sensors was ‘Digital Entry Data Glove’ developed in 1983. The glove included flex sensors, tilt sensors and inertial sensors in order to create alphanumeric characters from hand positions.

Figure 3.3 : An archive image of the Sayre Glove taken from Sturman and Zeltzer (1994).

However, as commented by Torre (2013), these first examples of gloves had limited accuracy, were considered experimental and were never commercialized. The first commercially available glove product is ‘DataGlove’, launched in 1987. Despite working with similar technology to the one used in Sayre Glove, there were more sensors and fibre optics were used instead of light tubes to increase its sensitivity to distinguish gestures. Popularity of DataGlove with its multiple sensors and high accuracy lead to development of Power Glove, which was commercialized by Mattel Intellivision as a control device for the Nintendo video game console in 1989. Resistive ink technology was used in Power Glove to measure flexion of finger joints. P5 Glove, which is an updated version of Power Glove, was launched in 2002 by Essential Reality.

The next section will give information about some commercialized data glove examples, as given in Premaratne’ s work (2014).

3.2.1 MIT Data Glove

The first protoype of MIT Data Glove was developed in early 1980s and different models have been produced for different purposes. AcceleGlove, one of the models produced by MIT company, AnthroTronix, is a user programmable data glove which could record hand and finger movements in 3D setting. It is primarily designed to be used in video games, sports training and physical rehabilitation applications.

An accelerometer below each fingertip and on the back of the hand were placed on the glove to detect hand gestures in terms of three dimensional orientation of the fingers with respect to gravity. The finger tips are not closed so that the glove allows to do other actions such as typing or writing while wearing. The structure of the glove is given in Figure 3.4.

Figure 3.4 : MIT Acceleglove with its multiple sensors.

3.2.2 CyberGlove II

CyberGlove aims to detect joint motion by using data from eighteen sensors including bend sensors on each finger, sensors measuring thumb crossover, palm arch and wrist abduction. There is also another version with more sensors. Each sensor is very thin and flexible making it almost invisible in lightweight glove, as shown in Figure 3.5. The glove is used in various fields such as digital prototype evaluation, virtual reality and animation.

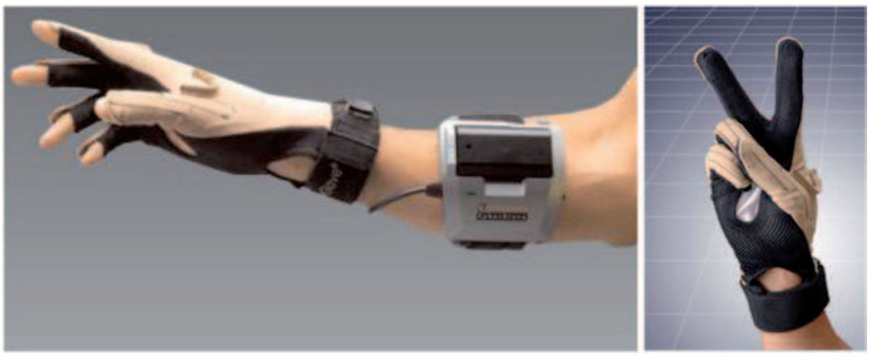

Figure 3.5 : CyberGlove II.

3.2.3 CyberGlove III

CyberGlove III, also known as MoCap Glove, was developed by CyberGlove Systems to record gestures for motion capture, movie and graphic animation industries. The device has twentytwo sensors creating data representing hand gestures. It could transmit data wirelessly with WiFi within 30 m distance and could also use secure digital (SD) memory card to store motion recordings for motion capture and animation purposes. A photo of the CyberGlove III is given in Figure 3.6.

Figure 3.6 : CyberGlove III for motion capture.

3.2.4 Fifth Dimension Sensor Glove Ultra

5DT Data Glove Ultra is a glove based hand gesture recognition device with high accuracy and resolution. It aims to capture high resolution motion data for movie industry. Figure 3.7 shows early and current version of Sensor Glove by Fifth Dimension.

Figure 3.7 : 5DT Motion Capture Glove and Sensor Glove Ultra.
(*left*) Current version, (*right*) early version.

3.2.5 X-IST Data Glove

X-IST Data Glove from Inition is a motion capture tool with finger tip touch sensors. It is wired to an usb interface and each finger joint flex is measured with the tilt of the hand, as shown in Figure 3.8.

Figure 3.8 : X-IST data glove.

3.2.6 P5 Glove

P5 Glove was developed by MindFlux in 2002 for gaming industry as a cheaper alternative. As shown in Figure 3.9, the device consists of bend sensors and remote tracking technology to enable users to interact with 3D and virtual environments. Another significant feature of the device is that it was one of the rare technologies at that time able to be used as a control peripheral like mouse, joystick or keyboard.

Figure 3.9 : P5 glove.

Hand wearables given above as significant examples of their time, are today no longer developed only for HCI. They are also used in health industry or ergonomics as well as for musical purposes. Torre (2013) included a section for data gloves used for musical purposes.

Scanglove was one of the examples which explores sound synthesis manipulation with two hands. The instrument was developed by Kessous and Arfib in 2003 and consists of a 5DT data glove for the right hand and custom built data glove for the left hand, as shown in Figure 3.10.

(a) (b)

Figure 3.10 : Data Glove - (a) the 5DT glove for the right hand;
(b) the ‘home made’ glove for the left hand (Kessous and Arfib, 2003).

ForTouch by Sydney Fels, Robert Pritchard and Allison Lenters, uses also data gloves, a Cyberglove II at the performer’ s left hand and a TouchGlove at the right hand (Fels et al, 2009). The instrument uses Glove Talk II system, which transforms hand gestures into speech components such as letters, vowels, consonants, syllables and manipulate them to to simulate speech. So, the gloves interface Glove Talk II system with hand gestures.

Figure 3.11 : Marguerite Witvoet performing with ForTouch.

There are also many examples where data gloves were used for spatial control as well as sound control and generation. Naef and Collicott (2006) used a Polhemus Fasttrack 6DOF magnetic tracking system and an Immersion CyberTouch glove to develop a VR interface for collaborative 3D audio performance. As another example, Schacher (2007) also developed some tools to map a hand gesture to a sound source location with the use of a data glove.

3.3 Hand Wearable Examples Designed and Built Specifically for Musical Purposes

Besides using data gloves which are mainly built for other purposes, there are many hand wearables designed and built specifically for musical purposes. This section gives some examples of such tools, which were included in Torre (2013) and Bongers (2006). While it does not offer an exhaustive list and detailed description about the examples, it aims to give an idea about major design decisions about hardware and software components of the developed instruments.

3.3.1 SoniMime

SoniMime by Fox and Carlile (2005) consists of two custom built gloves with one 3D accelerometer sensor in each glove measuring acceleration in three dimensions, as shown in Figure 3.12. The data is then transmitted through Open Sound Control (OSC) to the visual programming platform Pure Data (PD) with an ATMEL microprocessor.

Figure 3.12 : SoniMime by Fox and Carlile (2005).

The control data acquired with the sensors are used as input to a synthesizer generating vowel-like sounds. The mapping model of SoniMime is summarized in Figure 3.13 where left and right hand gloves have different mapping arrangemenrs. For example, X and Z axis tilt values of the right hand control the weight of the partials of the given sound, while X axis tilt value of the left hand controls the fundamental frequency in the range of 50-615 Hz and Z axis tilt value controls the the overall amplitude.

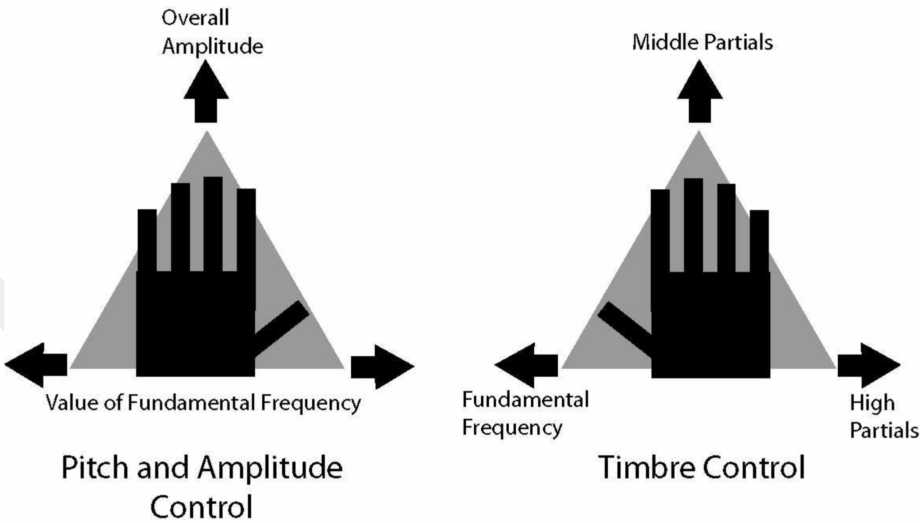

Figure 3.13 : Mapping model of SoniMime (Fox and Carlile, 2005).

3.3.2 The MusicGlove

The MusicGlove developed by Hayafuchi and Suzuki (2008) uses one three dimensional accelerometer and four bending sensors to capture hand gestures and transmits data wirelessly through a bluetooth module as shown in Figure 3.14.

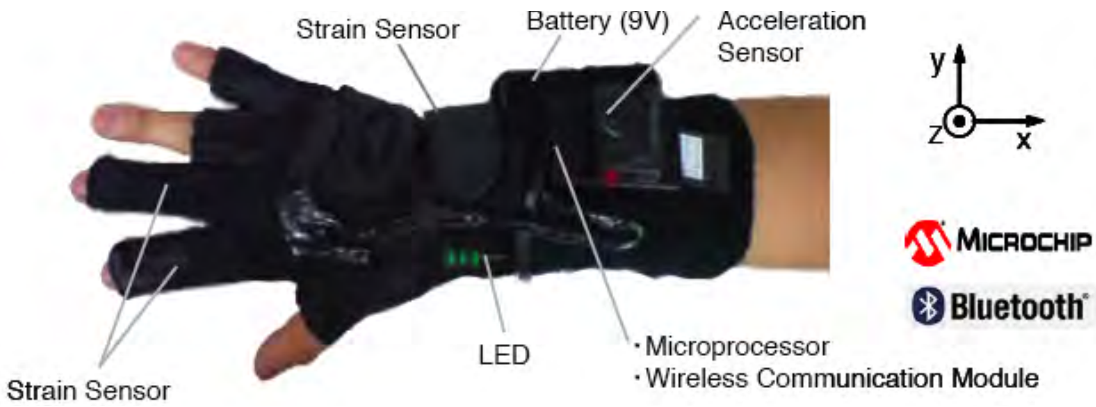

Figure 3.14 : MusicGlove (Hayafuchi and Suzuki, 2008).

The instrument was mainly designed to play and control audio and video files and make simple processing such as increasing/decreasing tempo, fast forward/rewind as well as a scratch function by making simple hand gestures such bending index finger, rotating wrist, pointing left/right, etc.

3.3.3 The Hands

The Hands is probably one of the most well-known new DMIs within the literature because of the highly expressive performance possibilities as well as its advanced and detailed sound generation and control capabilities offered by the instrument. It is also remarkable that the development of the instrument by Michel Waisvisz at Studio for Electro Instrumental Music (STEIM) Laboratory dates back to 1984, just after the MIDI protocol has been started to be used.

The instrument consists of a small keyboard on the performer's hands, accelerometers measuring tilt of the hands, pressure sensors activated by the thumbs, an ultrasound sensor measuring the distance between two hands and a microphone at the left hand to record sound during the performance. It uses the SensorLab microcomputer, which is also developed at STEIM, which converts the analog sensor data into Musical Instrument Digital Interface (MIDI) messages and sends them to the host computer. The microcomputer is attached to the back of the performer. A photo from a live performance of The Hands by Michel Waisvisz is shown in Figure 3.15.

Figure 3.15 : Live performance of Michel Vaiswisz with the Hands at NIME 2003.

In addition to its inventor, Michel Vaiswisz, the instrument has been used many times by other performers and after its invention in 1980s and refinement over time , it is still one of the main icons representing the potential and promise of new DMIs.

3.3.4 The Lady's Glove

Lady's Glove developed by Letitia Sonami and DeMarinis in 1991 was first presented in Ars Electronica Festival in Linz. The first version of the instrument consists of a pair of rubber kitchen gloves housing five hall effect transducers and a magnet on the right hand, as shown in Figure 3.19.

Figure 3.16 : Lady' s Glove by Letitia Sonami (Torre, 2013).

Many other versions have been developed after the first version, a significant upgrade of the instrument was developed with the contribution of Bert Bongers from STEIM Lab in 2001. Like The Hands instrument, the sensors are connected to a STEIM Sensor Lab microcomputer outputting MIDI signals to the sound generation tools.

3.3.5 Mi.Mu

Mi.Mu, which is the final product name of an ongoing collaborative project involving different engineers, artists and specialists, is commonly known with its creative director and artist, Imogen Heap. The first protoype of the instrument was developed by Thomas Mitchell controlling an ad hoc application, SoniGrasp (Mitchell and Heap, 2011).

Using a 5DT 14 Ultra dataglove with a lavalier microphone, the instrument is based on recording loops and manipulating them via instrument. The instrument could be used in two modes, where continous data is transmitted from the sensors to the host application as well as a switch mode enabling selection different functions available. There is also the Glover software which arrange gesture and mapping settings working in conjunction with the hardware interface. A photo from a live performance by Imogen Heap could be seen in Figure 3.20.

Figure 3.17 : Performance with Mi.Mu by Imogen Heap (Torre, 2013).

3.4 Characterization and Taxonomy of Hand Interfaces

At their work on wearable haptic systems for the fingertip and the hand, Pacchierotti et al (2017) explored taxonomy, review and perspectives of hand interfaces. While they focused mostly on haptic systems and application of vibrotactile feedback at their study with categories, classes and approach, it is also strongly related with the scope of this study.

Chronologically, haptic devices have been mechanically grounded and their portability has been extended using batteries and wireless communication methods. Recently, especially in the last two decades, more sophisticated devices focusing on their wearability have been designed and manufactured which have led to a new class of devices, 'wearables' such as Apple Watch, Samsung Gear Live, Google Moto 360.

There are different type of devices based on their relationship with the body and the environment. Interfaces whose base is fixed to a ground are commonly referred as ‘grounded’. Devices that are connected to the body from different connection points such as bones or joints are called ‘exoskeletons’. There are also ‘fingertip devices’ which are attached to fingertips. While grounded haptic interfaces such as Phantom Premium provide highly detailed and precise control in virtual and remote environments with its structure, other solutions such as exoskeletons like Cyber Grasp or fingertip devices like Ring allow more comfort, yet higher portability and wearability. So, there is a trade-off between more precise control and realistic feeling provided more by grounded devices and more comfort, wearability and portability achieved by exoskeletons and finger tip devices.

Figure 3.18 shows examples of grounded haptic devices, exoskeletons and fingertip devices. As given by Pacchioretti et al (2017), the systems become more wearable at the expense of loss of kinesthetic interaction.

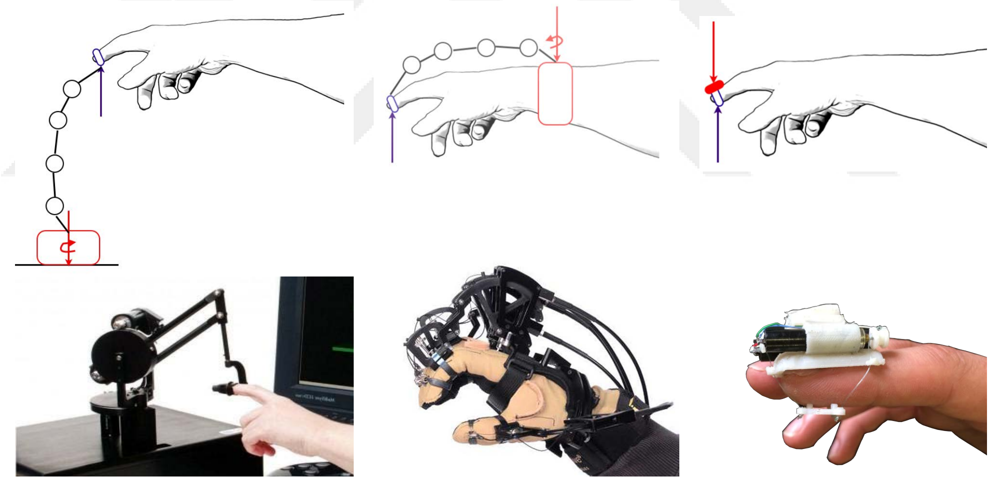

Figure 3.18 : From grounded haptics to more wearable and portable designs (Pacchioretti et al, 2017).

Pacchioretti (2017) commented that while exoskeletons are considered more wearable according to their connection to the body, they are usually heavy and inefficient to operate deteriorating its wearability, which could not be evaluated only with its suitability to be worn. It becomes more wearable as it gets smaller, easier to be carried while not limiting the motion of the user. They defined another parameter for increasing wearability, the distance of the grounding of the system to the application of the stimulus. Finger tip devices could clearly be considered more wearable in this respect. They also noted that as the grounding point of the system gets closer to the point of stimulus, the kinesthetic interaction with the system is significantly lost.

Pacchioretti et al (2017) also evaluated the extreme case where the grounding of the interface is at the point of application of the stimulus and the interface could only provide cutaneous feedback as it is the case in Figure 3.18 (right). They commented that cutaneous feedback could simplify design of wearable haptic interfaces because of the high density of mechanoreceptors in the skin and their low activation thresholds and high resolution. They finally added that cutaneous feedback is proven to enhance the performance and efficiency of immersive systems and cutaneous cues are more informative than kinesthetic cues for differentiation of different surfaces and fine control.

4. GRAIN HARVESTER

As part of the practical output of this study, a new DMI, named ‘Grain Harvester’, has been developed and a basic demonstration has been prepared. This chapter introduces ‘Grain Harvester’, which explores the potential of any physical surface and object to be used as a ‘musical surface’. It gives a brief summary of the design process during the study, a description and key components of the instrument, details about the modules and processes and finally evaluation of the instrument with related work and literature.

4.1 A Brief Summary of the Research and Design Process During the Study

Before giving details about the final design of the developed instrument with its description, key components, modules and processes and evaluation, it may be useful to give a summary of the research process during the study, which may give clues about design process, decisions and final output.

The general scope the practical output of the thesis study was already determined in the beginning of the thesis proposal period as development of a new DMI based on hand gestures. However, the focus and conceptual framework of the design process was not clear as there are a lot of possibilities available, both technologically and conceptually. After a general literature review on DMIs based on hand gestures, some preliminary design decisions were determined such as development of a new DMI which could generate surface-specific control data based on characterictics of physical surface such as roughness/smoothness, hardness/softness and use of any surface within the performance space as part of the DMI. Available technologies and tools were also searched to have an idea about applicability and practicality of preliminary design decisions, where some options such as grid-type FSR sensors, piezo-electric 3-axis force sensors were demonstrated.

In order to see such tools and technologies on site, Sensors Expo and Conference 2016 held in the city of San Jose at California in June 2016 was visited and some information, catalogues and samples were taken.

Also, the optic sensor technology was experimented as a possible way of generating data representing the interaction between the physical surface and hand gestures. While initial informal experiment results showed that there is a potential in the use of optic technology to generate real-time surface-specific data, the generated data at the experiments did not show enough dynamic resolution and accuracy and left for future work. A photo of the setup with use of optical sensor is given in Figure 4.1.

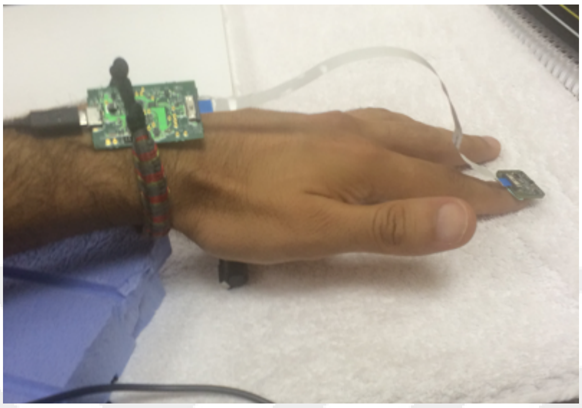

Figure 4.1 : Experimentation with optical sensor to generate surface-specific data.

Also, some modules named ‘envelope-scale mixer’, ‘dynamic amplitude envelope’, ‘motion generator’, ‘spatial gesture generator’ were designed and demonstrated to have potential use in the final design, but were not used because of their incompatibility with the transducer system at the final design.

Among the available technologies having the potential to capture hand gestures on physical surfaces, tiny FSR sensors were explored in more detail. As they have a very small surface-are and they are very cheap, they may be mounted on the fingertip and have great use to measure force exerted on a surface as well as determining whether the finger is contacting the surface or not. However, FSRs were also not used, because they prevent contact with physical surface despite their small size and minimize direct tactile feedback.

Another sensor that was explored as part of this study was an multi-sensor breakout board, BNO055 by Bosch, which includes a three axis accelerometer, gyroscope and magnetometer and basically measures the orientation of the hand in three dimensions as well as three dimensional acceleration data generated by hand gestures. While it presented great potential for use of articulated hand gestures as a source for musical expression, it was also not included in order not to disperse focus on surface-specificity.

While these tools, technologies and module designs were not used at the final design, they offer great potential to be used in future work, which will be discussed in the conclusion section.

4.2 Description of the DMI

Grain Harvester could be described as a new DMI capturing hand gestures on a physical surface and using this signal to generate sound without loosing tactile feedback. The instrument basically uses a microphone placed on the finger nail to capture the signal generated by the movement of the hand on a physical surface, which could be considered as a representation of the interaction between the hand gesture and the physical surface. This signal is then converted into its frequency bin/amplitude components via Fast Fourier Transform (FFT) with additional optional FFT bin processing, gate and feedback and output these components as the main parameters of the sound grains to be synthesized. Their durations are determined with a minimum duration and a diversity parameter. With these parameters, three different sound generation methods are used to synthesize sound grains and they could be mixed with eachother. To sum up, Grain Harvester is a new DMI to generate sound with the hand gestures made on a physical surface with its sound control and generation capabilities.

4.3 Description of the Processes

This section details the processes of the instrument to describe the designed instrument with its modules more detailedly. The software interface of the instrument which includes all the modules to be described is given below in Figure 4.2.

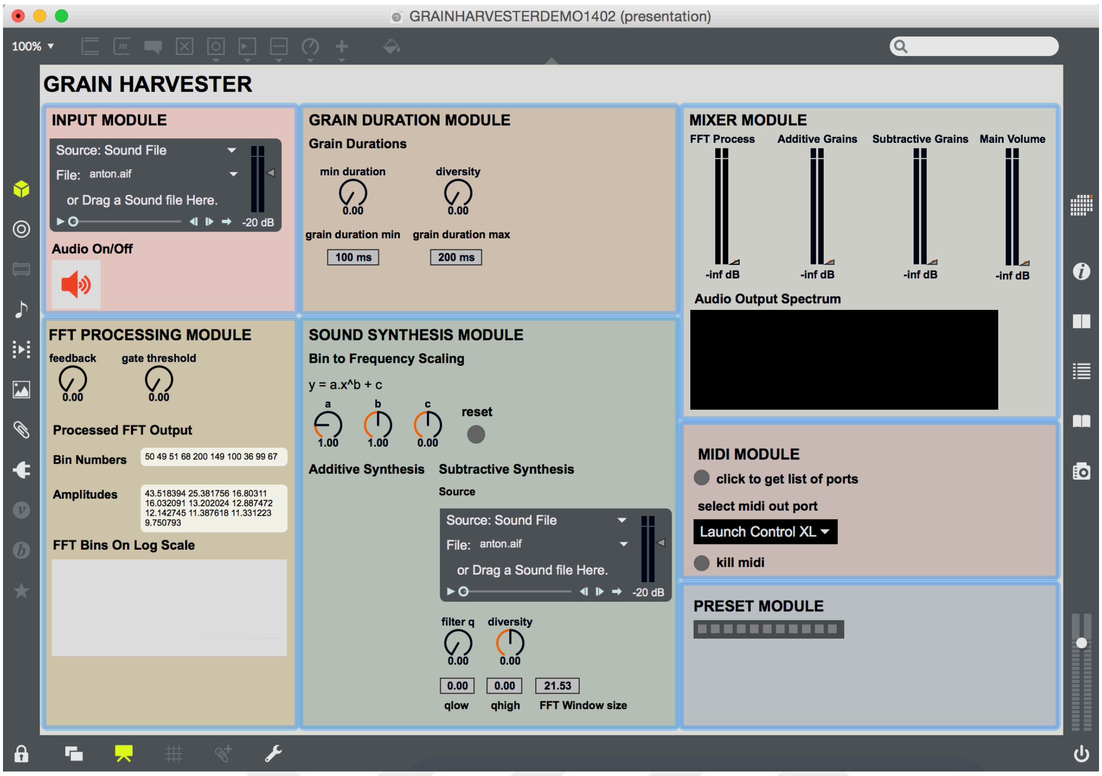

Figure 4.2 : Software interface of the Grain Harvester instrument.

The processes of the instrument could be described in six sections:

- Capturing Live Input Signal
- FFT Processing of the Input Signal
- Generating Control Data Out of the Processed Signal
- Generating Sound from Control Data
- Generating MIDI Messages from Control Data
- Storing Presets of Instrument Parameters

4.3.1 Capturing live input signal

In this instrument, live input signal is captured with a transducer which is a AKG C411 PP, a miniature condenser microphone placed on the index finger nail, as shown in Figure 4.2. It was preferred because of its low noise and high dynamic headroom level. The microphone could be replaced with contact microphone as long as low noise and high dynamic headroom levels are achieved. Also, its built-in cable is 6 m long which allows a large space to be accessible to the performer. It should be also noted that while the microphone captures the signals of interaction between the surface and the gesture, it also acts as a filter attenuating some spectral components of the signal reflecting the interaction between the gesture and the surface.

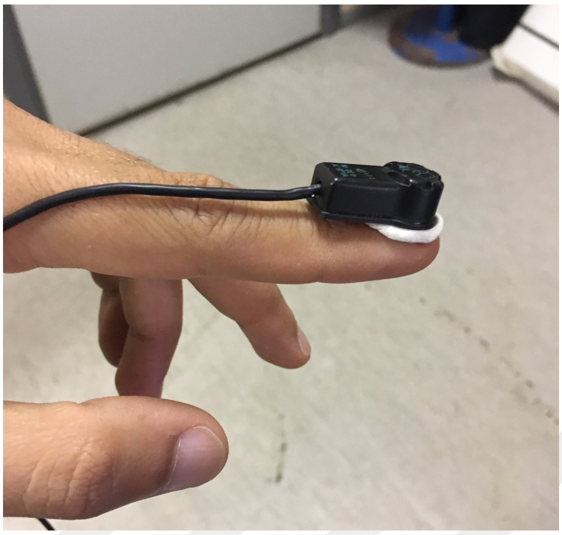

Figure 4.3 : AKG C411 PP condenser microphone attached to the index finger nail.

With the condenser microphone attached on the finger nail, the performer could generate sound on any physical surface and in a way 'perform the space'. Figure 4.3 shows a screenshot from an example performance video with Grain Harvester.

Figure 4.4 : A live performance example of Grain Harvester on different physical surfaces.

While the microphone seems to be the most basic and direct way of capturing the interaction, there may be other tools and methods to capture the interaction between the hand gesture and the physical surface. It could be replaced with any compatible alternative such as an optical sensor, ultrasound sensor or a piezoelectric contact microphone as long as representative output are achieved.

Input Module:

This module selects the source input to be processed such as live input, sound recording, synthesized noise, etc. and sets the volume of the input, as shown in Figure 4.5.

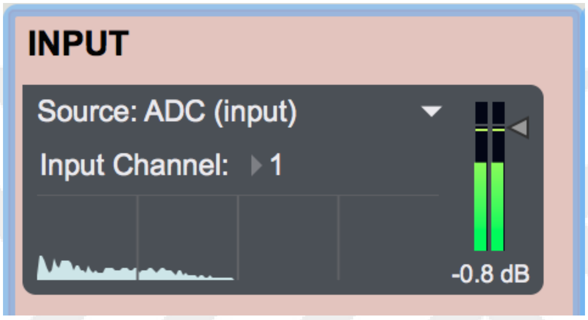

Figure 4.5 : Input module of Grain Harvester.

4.3.2 FFT processing of the input signal

Captured input signal is processed to generate control parameters for the sound generation stage. FFT processing is used to convert audio signal into FFT bins and their corresponding amplitude data and this pack of data could also be processed further with gate and feedback modules within FFT processing.

FFT Processing Module:

Gate: As the typical gate process, this module basically sets the amplitude values of frequency bins to zero practically removing the representation of the frequency content below a threshold value.

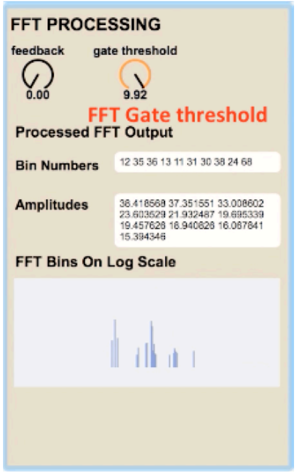

Figure 4.6 : Gate threshold parameter in FFT processing module.

Feedback: As the typical feedback process, this module adds some portion of the amplitude values of the previous FFT frame based on the value between zero and one in real time, zero meaning no portion, one meaning all of amplitude value consisting of the values of the previous portion, practically a spectral freeze.

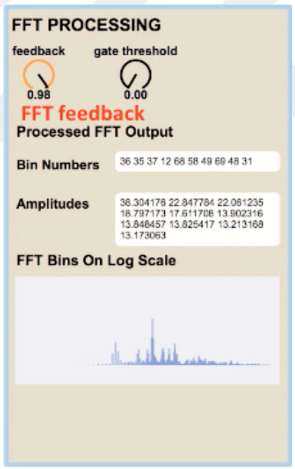

Figure 4.7 : Feedback parameter in FFT processing module.

FFT processed signal is output as frequency bin numbers and their corresponding amplitude values to be used at the different stages of different sound generation processes.

4.3.3 Generating sound from control data

Grain Duration Module: As part of the sound generation process, this module determines the durational structure of the sound grains to be synthesized. While the minimum duration parameter sets the minimum duration of the grains, diversity parameter enables a grain duration range which could be mapped to any parameter of the sound synthesis module.

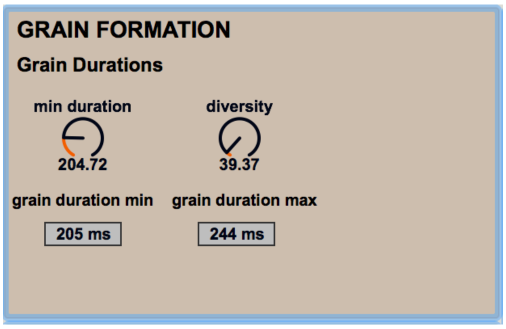

Figure 4.8 : Grain formation module of Grain Harvester.

Scaling Module: Before sound synthesis, a scaling module enables change of spectral distribution according to a generic formula so that the spectral distribution character of the synthesized sound could be changed in real time.

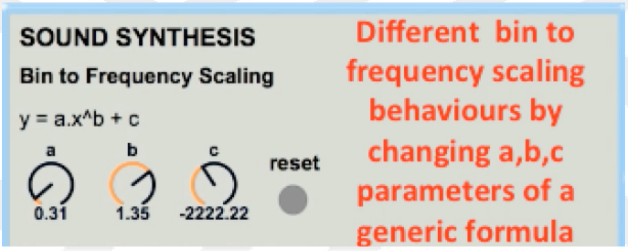

Figure 4.9 : Scaling module of Grain Harvester.

Sound Synthesis Module: With all the parameters generated at the instrument, a sound synthesis module with three sound synthesis techniques -inverse FFT, additive synthesis and subtractive synthesis- outputs synthesized grains where each of the method works its own mapping strategy.

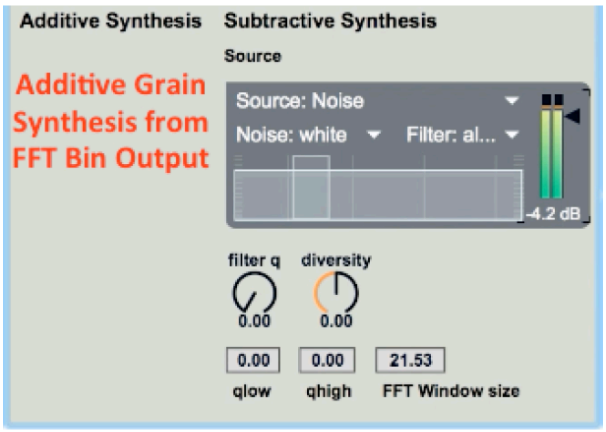

Figure 4.10 : Additive and subtractive sound synthesis modules of Grain Harvester.

Mixer Module: The Mixer module enables live mixing of the generated sound with different synthesis techniques.

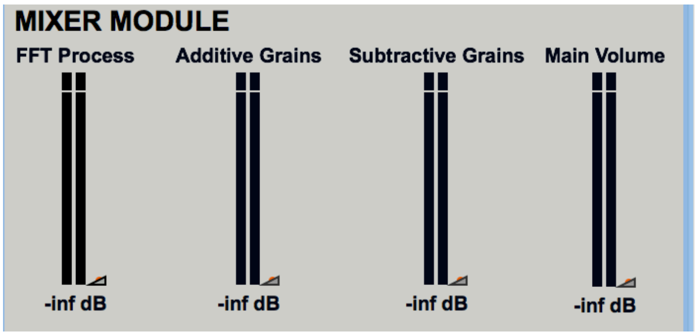

Figure 4.11 : Mixer module of Grain Harvester.

4.3.4 Generating MIDI messages from control data

MIDI Module:_Apart from sound output, the instrument is able to send MIDI note on and note off messages based on the other modules except Sound Synthesis and Mixer modules. With MIDI module, the instrument could also be used with other software and hardware devices accepting MIDI messages.

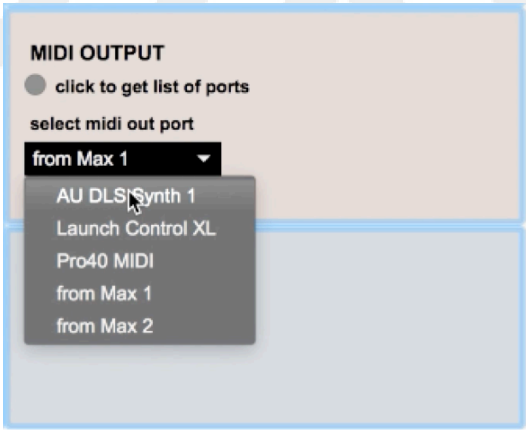

Figure 4.12 : MIDI Output module of Grain Harvester.

4.3.5 Storing presets of instrument parameters

Preset Module: Preset module enables all parameters of the instrument to be recalled to make sudden transitions between sonic outputs.

4.4 Signal and Process Flow

In order to give more detailed information about the designed sound generation and control processes of Grain Harvester, a signal and process flow chart has been prepared, given in Figure 4.13.

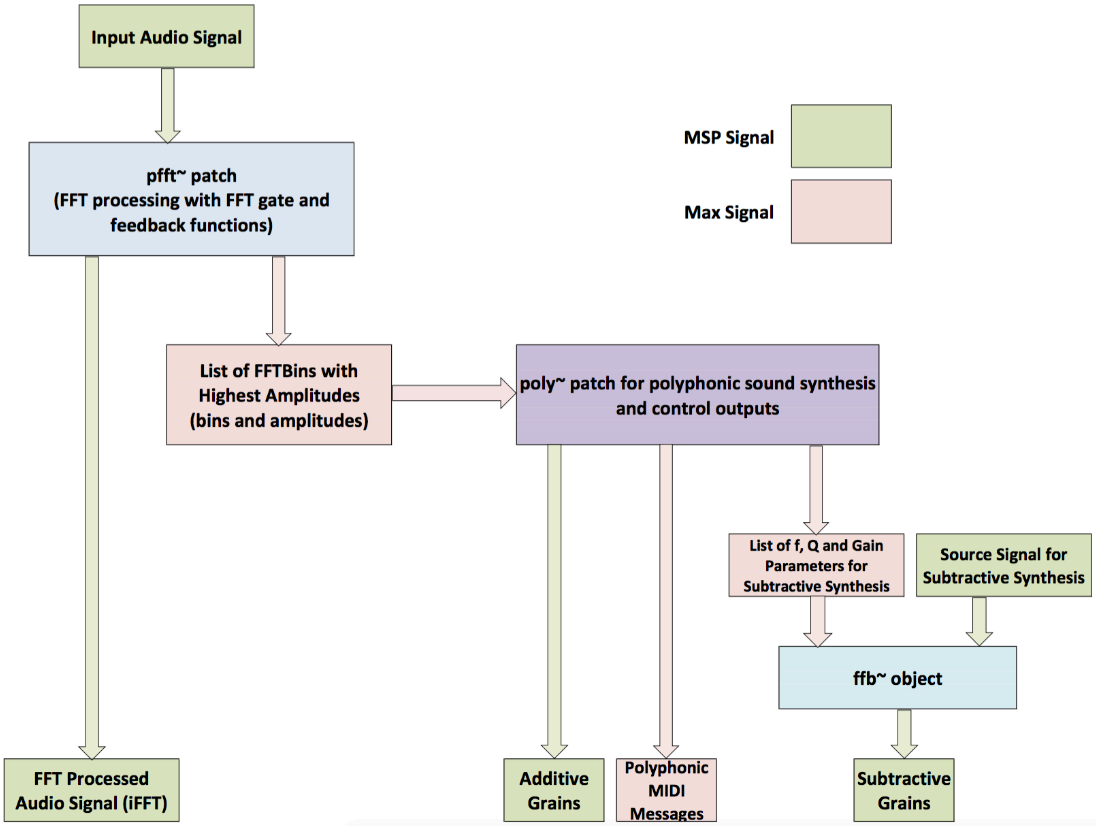

Figure 4.13 : Signal and process flow of Grain Harvester.

As seen in the signal and process flow, input audio signal from the transducer is taken and sent to a pfft~ patch for FFT processing with gate and feedback functions. FFT processing is made with a window size of 2048 samples, but could be changed from the attributes of pfft~ patch. The pfft~ patch sends a MSP output with FFT processing while another Max output sends list of FFT bins with the 8 highest amplitudes to the following poly~ patch.

The list of FFT bins is then sent to poly~ patch in lists with two items to create polyphonic voice instances, durations of which are determined at the grain duration module. Additive grains are synthesized within each poly~ voice separately with the cycle~ object. Additionally, MIDI messages are output from each poly~ instance, allowing polyphonic MIDI output from the instrument based on the input signal.

Third output of the poly~ sends a list consisting of f, Q and gain parameters for the ffb~ object, which generates substractive grains as the third audio output.

4.5 Related Work

4.5.1 Re-midi

Re-midi is a wearable musical instrument designed for expressive musical control with eight pressure sensors and three axis accelerometer in a glove casing. It offers to use any physical surface and as well air gestures for musical control and outputs MIDI messages. The hardware comes with its MIDI editor software, ReRoute, and mobile application, ReMix, to remix tracks and songs with the ReMidi community.

While the instrument is unique in terms of allowing any surface to be used as an interface for musical control, it does not offer any surface specificity as it only measures pressure applied on a surface by a finger and also not provide tactile feedback because of its closed structure on fingertips. The instrument was first marketed focusing on the possibility to perform on any physical surface, but then shifted more towards the air gesture possilibities.

A screenshot of an informative video by Next Media youtube channel could be found in Figure 4.14 where the Re-Midi instrument was introduced as a device turning the hand a musical instrument.

Figure 4.14 : A screenshot from an information video about Re-Midi musical instrument.

4.5.2 Mogees Pro

Mogees Pro is another device with the slogan “Transform anything into a musical instrument”. There is an acoustic transducer attached to a physical surface through a removable adhesive pad which could detect characteristic gestures, mostly impulsive gestures, to generate trigger messages for the following sound generation processing, be it independent sound generation processes or those of the Re-Midi software.

In addition to the acoustic transducer, another key component of the device is the machine learning algorithm, which analyzes spectrum generated by the gesture in real time and match it with a gesture space formed by multiple training sessions. After matching the gesture, a predetermined control message is either output in the form of MIDI message or sent internally to the sound generation algorithm of Mogees Software.

An advertorial photo of Mogees Pro is given in Figure 4.15 where the main idea presented is to play music with different gestures on any physical surface.

Figure 4.15 : An advertorial photo of Mogees Pro.

4.5.3 SSS Shore Scene Soundtrack

Another artwork related with the developed DMI is Shore Scene Soundtrack by Cevdet Erek where physical surface characteristics of different type of carpets are used at live performances for acoustic sound generation and control to mimic sonic spaces at a shore. Also there is a published book about the work with instructions, notations and title “SSS – Shore Scene Soundtrack / Themes and Variations for Carpet” (2008). A photo from a performance of SSS is given in Figure 4.16.

Figure 4.16 : A photo from a performance of Shore Scene Soundtrack.

4.5.4 The Sound of Touch

Another example related with the developed instrument could be given as 'The Sound of Touch' project by Raffle et al (2007) where surface-specificity is a key element of the project. Different wands and surfaces were designed to enrich physical possibilities between the components. The project is described by the project group as follows:

"The Sound of Touch permits real time exploitation of the sonic properties of a physical environment, to achieve a rich and expressive control of digital sound that is not typically possible in electronic sound synthesis and control systems."

A photo showing the setup of 'The Sound of Touch' project is given in Figure 4.17.

Figure 4.17 : A photo from the website of 'The Sound of Touch' project.

4.6 Evaluation and Discussion of the Instrument within DMI Literature and Related Work

Grain Harvester could be categorized as a hand interface according to the categorization given by Liu et al (2016) attached on skin appendages, and as a fingertip device according to the categorization given by Pacchierotti et al (2017). It offers a new instrumental approach for new DMIs from different perspectives with its structure. It is a new DMI which does not include a separate physical controller commonly described to explain DMI instrument chain. With this characteristic, it is one of the rare musical instrument examples that does not impose its physical control surface and does not limit the performance to a predesigned and predetermined performance space and interface. So, any physical surface could be considered as a potential 'musical surface' with its physical characteristics such as roughness/flatness, hardness/softness, etc. In addition to being performable on any physical surface, physical surfaces designed specifically for this instrument could also be integrated to the practice of the instrument.

On the other hand, as it is the case for most acoustic instruments and most unlikely for most of DMIs, Grain Harvester has an inherent relationship with the control data involved in the sound generation process while allowing use of any physical surface as a musical interface. Representative level of the information about the interaction between hand gestures and physical surface captured by the instrument is very close to an acoustic instrument recorded by a microphone. This feature presents a major advantage for mapping processes compared to most DMIs where the relationship between control gestures, physical control interfaces and generated sounds has to be defined from scratch while providing direct haptic feedback which is also not available for most DMIs. The common assumption on DMIs being not able to offer haptic feedback and given as one of their disadvantages is also not valid for this instrument.

Surface specificity is another key component of the instrument. As Pacchioretti et al (2017) emphasized that cutaneous feedback is proven to enhance the performance and efficiency of immersive systems and cutaneous cues are more informative than kinesthetic cues for differentiation of different surfaces and fine control, Grain Harvester offers a great advantage with its direct tactile feedback which would help in differentiating physical surfaces as well as generating surface specific signal. The instrument also allows articulations on the physical surface leading to diversity in gesture and sound space.

The instrument outputs surface-specific information about the interaction between the physical surface and hand gestures which could be reflected at the sonic output of the instrument. A spectral comparison of example surfaces and signals is given in Figure 4.18.

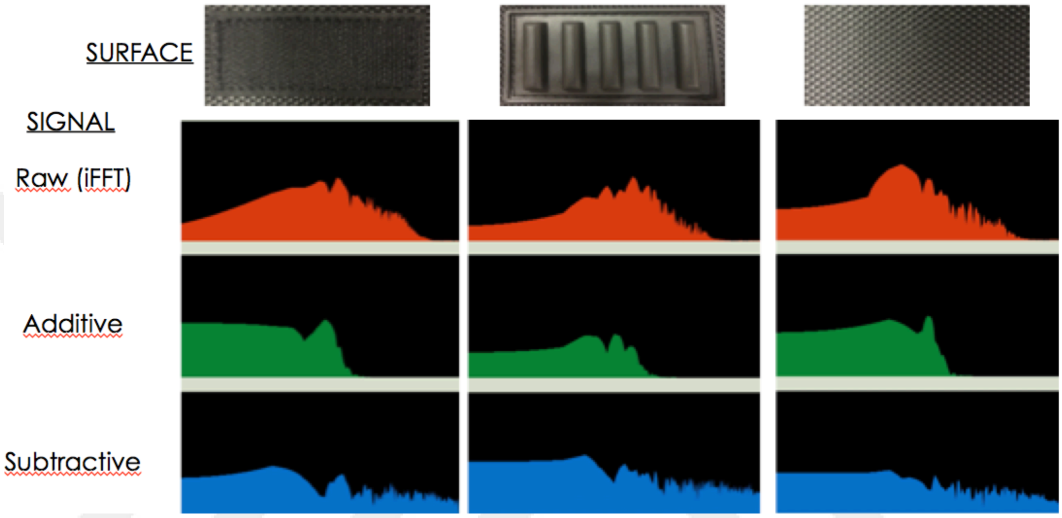

Figure 4.18 : Spectral comparison of example surfaces and signals.

The spectra given Figure 4.18 were created by applying gestures as similar as possible on different surfaces in terms of velocity of the gesture and exerted force on the surface. As can be seen in the figure, similar gestures applied on different surfaces created sound spectra with different active frequency bands and these bands were reflected on spectra of additive and subtractive grains as well. However, it should be noted that the spectra does not reflect solely the differences in the physical characteristics of different surfaces as it is strongly dependent on the interaction between the applied gesture and the surface. While the gestures applied on surfaces were tried to be as similar as possible, there may be slight differences between the gestures. Therefore, a more standardized and scientific approach, which is beyond the scope of this study, could be essential for a more detailed analysis.

Considering different DMI models given in Section 2.2, a flow model from McGlynn' s work (2014) is adapted to Grain Harvester instrument and given in Figure 4.19.

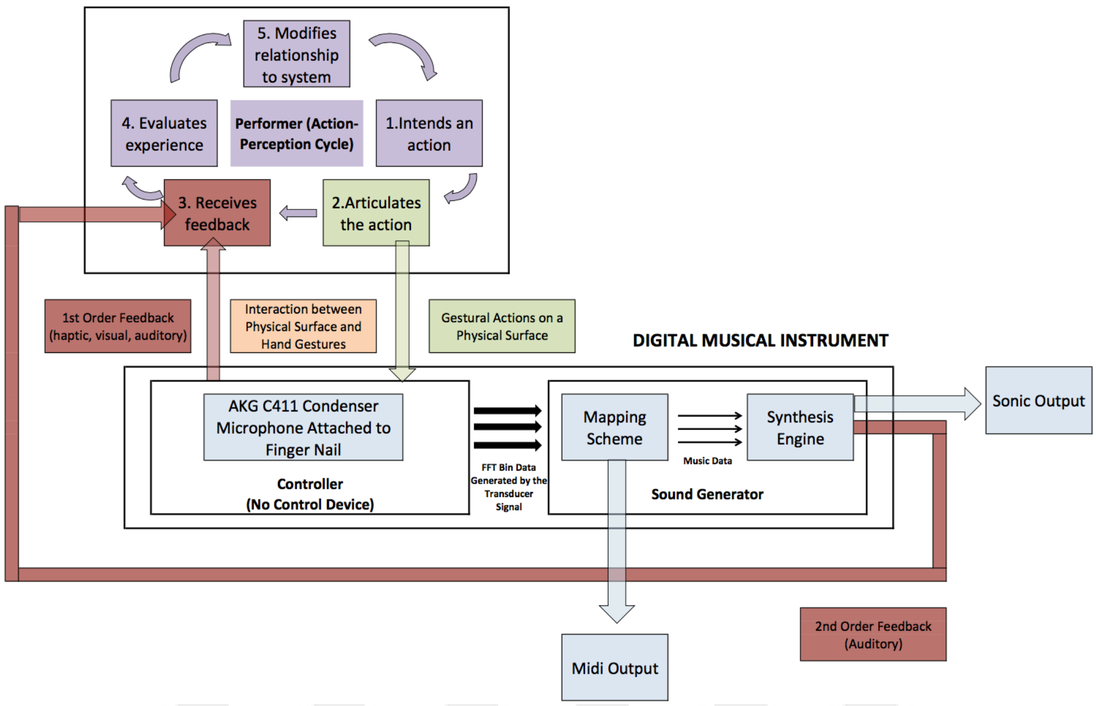

Figure 4.19 : DMI model of Grain Harvester adapted from McGlynn' s work (2014).

As seen in Figure 4.19, the gestural space of the instrument is based on the interaction between physical surface and hand gestures acting on the physical surface which creates first order feedback on haptic, visual and auditory domains. This interaction is captured by the AKG C411 microphone at the controller component of the DMI chain with no control device and generates a signal at audio sample rate. This signal is then transformed into pack of FFT bins and corresponding amplitudes and sent to the mapping algorithms. Out of these packs, these algorithms form grains with different densities, durations and musical parameters which are then fed to the sound synthesis engine where different sound synthesis techniques are used to generate sonic output. This sonic output acts also as a second order feedback on auditory domain. Meanwhile, a midi output stream is continously generated as well which could be sent to any polyphonic sound generator receiving MIDI messages.

As part of this study, three example synthesis techniques, additive, subtractive and inverse FFT have been given to present different timbral possibilities achievable with the instrument. Each real time synthesis technique allows formation of soundscapes with different characteristics and other synthesis techniques could also be added to extend the sound space of the instrument. With the use of FFT processes and other digital processes, there is also a significant space for design of other control processes and adaptation of different sound synthesis techniques to the instrument. Continous generation of MIDI output extends use of the instrument with other available sound generators receiving polyphonic MIDI note messages.

The FFT window size was determined as 2048 samples at the given demonstration. However, it could be changed from the attributes of the pfft~ patch and provide less latency while decreasing the number of frequency bins in the patch and resolution of fft bin frequencies.

The innovative sound generation algorithms developed during this study could be used for any sound input in addition to hand gestures on a physical surface. Therefore, the study outputs some byproducts other than the designed DMI with the developed sound generation algorithms which could be used for live electronic processing of any acoustic or electronic musical instrument as well as live processing of any sound recording. A recent live performance of the sound generation algorithm of Grain Harvester with the live electric guitar performance by the advisor of this study Can Karadoğan at Maçka Electric Music Days IV on 17 May 2019, could be given as an example, shown in Figure 4.20.

Figure 4.20 : Live performance with Can Karadoğan at Maçka Electric Music Days IV (2019).

The instrument offers also unique possibilities compared to related work given above. Mogees Pro is a close example to Grain Harvester as it preserves tactile feedback during performance and still achieves surface specificity based on machine learning algorithms using preconducted training sessions. However, the approach towards formation of gesture space is significantly different. While Grain Harvester could work on any surface without any preparations, machine learning algorithms of Mogees Pro should be trained beforehand in order to detect the hand gestures made on physical surfaces. Also, the sound control and generation processes of Mogees Pro, which require a pre-defined duration for the teaching of the gesture to the algorithm, mostly work with transient gestures while Grain Harvester could work with any gesture. Sound generation algorithms of Mogees Pro are also not as closely related to control processes as they are in Grain Harvester.

Grain Harvester differs significantly from another example, Re-Midi. Re-Midi is a glove-based instrument working with sensors on wrist and fingertips. The sensors on the fingertips and closed structure of the glove do not allow direct haptic feedback from the contacted physical surface. Use of different wands and brushes at the Sound of Touch project by Raffle et al (2007) instead of direct contact of the hand with the physical surface is the main difference between the two DMI designs. Also, use of digital convolution as the only sound generation process in the Sound of Touch project leads to a limited sound space.

Grain Harvester is also closely related to the work of Cevdet Erek's work SSS which is based on performance of different carpets to imitate a scene at a sea shore with its soundscape. While the conceptual framework of Cevdet Erek's work is completely different with its imitation purposes, Grain Harvester is also based on the interaction between hand gestures and physical surfaces and generates surface-specific sonic output and it has been a great inspiration with its approach.

5. CONCLUSION

Like their acoustic counterparts, most DMIs using hand gestures have their own 'specifically designed physical surfaces the performer is acting upon' such as those of well known commercialized examples like Roli's Seaboard or Artiphon's The Instrument 1. The physical interaction between the performer and such instruments happens mostly between the performer's hand gestures and a spatially limited 'musical surface' designed and manufactured specifically as part of the instrument. One of the ways to overcome this limitation and extend performance possibilities beyond a limited surface and space is to use on-body technologies such as hand wearables or hand interfaces.

This study explores hand interfaces within new DMIs by presenting a general overview on DMI research with various approaches and discussions, focusing on hand interfaces with their specific dynamics, classifications and reviewing prominent examples of data gloves with their use for both non-musical and musical purposes as well as musical gloves specifically designed and used for electronic music performance.

As the main output of the study, a new DMI named 'Grain Harvester' was developed, which tranforms the interaction between hand gestures and any physical surface or object into digital signal and uses the representing signal to generate sound without loosing tactile feedback. The design offers a new DMI approach, based on the idea that any physical surface and object could be used as a 'musical surface' as part of a new DMI. While the instrument does not include a separate physical control device commonly used to explain DMI instrument chain, it allows any physical object or surface to be used 'to harvest sonic grains' with its surface specific signal generation capabilities, sound generation mechanisms and extended spatial accessibility. With such key features, components and design decisions, the instrument is described detailedly and discussed within new DMI research and related work.

The developed instrument proposes an innovative musical instrument approach towards electronic music practice as well as general music practice with its currently avilable feautres and design. This approach could enable extension of scope of objects and surfaces described as ‘musical instrument’ and use of any object or physical surface as a characteristic component of a musical instrument similar to the extension of ‘musical sounds’ beyond those generated only by traditional acoustic instruments in 20^{th} century by practices such musique concrete or elektronische musik. Another innovation brought with this approach is the extension of the commonly limited proprioceptive relationship of the body with the physical surface of the musical instrument. As the representative signal originates from body with the transducer attached to the finger nail, any physical surface or object interacted with the finger becomes the physical interface of the instrument and could be changed any time by changing the interacted physical surface or object. Therefore, the instrument incorporates any available physical surface at the performance space into music performance and also extends commonly limited mobility of instrument performer.

The innovative sound generation algorithms developed during this study could be used for any sound input in addition to hand gestures on a physical surface. Therefore, the study output some by-products other than the designed DMI with the developed sound generation algorithms which could be used for live electronic processing of any acoustic or electronic musical instrument as well as live processing of any sound recording.

The features and capabilities of the developed instrument are planned to be extended after the Ph.D. study with future work, given below:

- Use of multiple transducers simultanesouly could provide possibilities for a more expressive performance as well as for an extended sound space.

- Relatedly, more affordable transducers such as piezo contact microphones will be explored as an alternative for live signal capturing.

- Right now, the instrument does not output information about whether the hand or finger does contact or not the interacted physical. This information could be acquired with different sensor technologies such as optic sensor, which showed a great potential during the research and design process of this study. Other technologies or tools could also be explored.

- Parameters of sound control and generation processes could be changed from a custom built controller grounded on the hand and a casing including this custom built controller as well as the connection cable of the transducer could be built.

- An automatic gain reduction/increase tool for gain management may prevent live gain control required to regulate the amplitudes of signals generated from different surfaces.

- Pressure applied on a physical surface could be measured with different sensors such as optic sensors and used as an additional control parameter.

- Other sound synthesis techniques such as wavetable synthesis or granular synthesis based on sound recordings could be adapted to the sound generation algorithms of the instrument.

- New ways for an open source and inexpensive work environment as well as a collaborative user community could be established for the instrument.

With its currently available features and capabilities, design approach and additional features and capabilibities to be built as part of the future work, the new DMI developed as part of this study offers a great potential for innovation in DMI practice, electronic music performance as well as the whole music practice.

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