Digital Musical Instruments: A Design Approach Based on Moving Mechanical Systems

Elliot Sinyor

Master of Arts

Music Technology Area
Department of Theory
Schulich School of Music

McGill University

Montreal, Quebec

October 2006

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

ACKNOWLEDGEMENTS

First and foremost, many thanks to my supervisor, Marcelo Wanderley, for continued guidance and encouragement over the course of my research. Thanks to David Birnbaum and Joe Malloch for spirited discussion and argument concerning our work. Thanks to all who have provided valuable feedback and advice on the instruments that comprise this thesis, namely Carmine Casciato, Avrum Hollinger, Mark Marshall, Doug Van Nort and Mark Zadel. Thanks to David Birnbaum and Rodolphe Koehly for their invaluable proofreeding help. Thanks also to Darryl Cameron and Julien Boissinot for their much appreciated support. Many thanks to my family — Rachel, Ernest and Jessica — who have supported me throughout this project and long before it. Finally a special thanks to Sarah Schultz for her constant understanding. Without her, the past months would have been all the more challenging.

ABSTRACT

This thesis describes the design and use of two novel digital musical instruments (DMIs) based on moving mechanical systems. The motivation behind using mechanical devices was threefold: to explore the effect of physical effort on DMIs, to make use of the device's inherent haptic and visual feedback, and to serve as a starting point for sound mappings. It was hoped that their mechanical nature would give the instruments a character that could emerge through each of the mappings. The first DMI built was the Gyrotyre, a hand-held DMI based around a small bicycle wheel outfitted with sensors that measure its speed of rotation and as well as its angle of orientation. The second DMI built was the Springwave, which consists of a loose metal spring stretched to one meter and fixed at both ends to a metal frame. The frame is in turn mounted horizontally on a hi-hat stand so that it can be raised and lowered with the pedal, thus inducing oscillation in the spring. Various mappings were designed to reflect and make use of the physical nature of both instruments. It was found that the nature of interaction with each instrument was very different depending on the mapping used. The use of mechanical devices was found to be a useful starting point for the development of mappings, and made playing the instruments engaging for the performer. by the relationship between DMIs and musical contexts, a framework for characterizing DMIs that takes musical context into account is presented.

ABRÉGÉ

Cette thèse présente le développement de deux instruments de musique numériques (IMN) basés sur des objets mécaniques pouvant être mis en mouvement. L'objectif des instruments mécaniques était multiple: tout d'abord, explorer l'influence de ces phénomñes mécaniques sur la façon de jouer un IMN, puis, exploiter la réaction tactile et visuelle implicite de ces objets mouvants, et enfin, se servir de leur proprieté d'inertie comme point de départ pour diverses stratégies de *mapping*. Le premier instrument construit fut baptisé *Gyrotyre*: c'est un IMN basé sur une roue de vélo de 30 cm de diamètre contenant des capteurs qui mesurent la vitesse de rotation ainsi que son orientation spatiale. L'utilisateur tient l'instrument par une poignée prolongeant l'axe de la roue. Le second instrument construit fut le *Springwave*. Il est composé d'un ressort étiré sur un mètre, ses extrémités étant fixées à un cadre rigide. Celui-ci est monté a l'horizontale sur un pied de charleston, pour que l'utilisateur puisse le faire se mouvoir en actionant la pédale, générant ainsi des oscillations du ressort. Deux capteurs capactifs mesurent le mouvement du ressort. Diverses stratégies de *mappings* ont été créé pour exploiter et refléter la nature mécanique de chaque instrument. Il a été confirmé que chaque IMN a été utilisé de façon très variée suivant le *mapping* utilisé. L'utilisation d'appareils mécaniques a été un bon point de départ pour les *mappings*, ainsi qu'une expérience engageante pour le musicien. Finalement, un cadre conceptuel de caractérisation des IMN est presenté.

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Introduction

1.1 Context and motivation

As means of sound production have shifted from acoustic to electronic and finally to digital, the human interface has become increasingly decoupled from the sound-producing mechanism. While most traditional instruments have a direct physical link between the performer and the acoustic resonator, no such coupling naturally exists for electronic and digital means of sound production. From the most rudimentary analog electronic oscillators to the most sophisticated digital synthesis techniques, the designer must define a way in which the various parameters of sound generation are controlled by the user. Put simply, "Each link between performer and computer has to be invented before anything can be played. " [21].

For the vast majority of people, the piano keyboard is the physical interface that comes to mind when considering electronic musical instruments. This is by no means a recent development, as the first three electronic instruments, the Musical Telegraph (1876), the Telharmonium (1897) and the Singing Arc (1899) all use keyboards as their interface, despite having different sound-producing mechanisms [17]. The keyboard's dominance was reasserted in the 1960s with the first commercial synthesizers, manufactured by Moog.

A notable exception to early keyboard-based electronic instruments is the theremin (1919), which relied on a performer changing the electric field in proximity to an antenna. This varied the frequency of an oscillator, which would audibly beat against a reference oscillator. The Ondes Martenot (1928), also used this sound-generation technique, known as heterodyning, but it used a keyboard for control [3].

Beginning in the 1960s, digital synthesis became more accessible on room-sized computers and specialized hardware. This decoupled interface from sound-production even further than analog electronic instruments such as the theremin. Sound could now be described in code and programmed in precise sequences. The need for interfaces was downplayed, since most digital synthesis techniques required time-consuming computation, making real-time performance a distant possibility. The arrival of MIDI-controllable hardware in the 1980s brought new possibilites. With a standardized control protocol, computer musicians could now easily separate the sound-producing hardware from the contoller. The 1990s brought real-time digital synthesis and processing to general-purpose computers, precipitating even more interest in the development of new ways to control real-time software sound-generation processes.

In recent years, the number of commercial and experimental controllers has been steadily increasing. Most can be classified as either *instrument-like controllers* or *alternate controllers* [27]. In the realm of instrument-like controllers, the keyboard has remained the most common option, however a wide variety of other instrument-like controllers have been developed and commercialized. Controllers have been designed that either directly mimic or are inspired by string instruments, valve instruments, percussion instruments and wind instruments.

Alternate controllers, on the other hand, may share little in common with each other, aside from the fact that they generally do not seek to imitate the design of existing musical instruments. The theremin's interface can perhaps be thought of as the first alternate controller. We refer to something as a digital musical instrument (DMI) if it contains both the controller and the sound-producing mechanism. We refer to the relationship between the input gestures and the sound produced as the mapping. A mapping can range from a one-to-one relationship between a physical control parameter and a particular sonic parameter to a many-to-many relationship in which multiple streams of gestural input data control multiple sonic parameters.

The sound-generating capabilities of modern audio hardware and software means that most DMIs can be made to turn a wide number of input gestures into an even wider range of sounds. This is both a blessing and a curse.The oft-touted advantage of "immense timbral freedom" [8] can be seen in another light as a "nauseating infinity of possibilities." [22]. The fact remains that once a controller is built, it still has no inherent 'sound', and in fact the same controller can have a radically different 'sound' and 'feel' if the mapping is changed. In contrast with acoustic instruments, the majority of controllers have no inherent relationship between their physical characteristics and the sounds they produce.

This thesis concerns the building of two alternate DMIs in an attempt to address this issue, as well as to explore some other related issues. The DMIs that comprise this thesis are based on simple moving mechanical devices that can be put into sustained motion by a user. This approach is motivated by three main reasons: to leverage everyday experiences with physical objects by means of the inherent passive feedback involved in the systems; to explore the use of an interface that requires some physical effort in order to play; and to give the instrument a physical character that can manifest itself in the various mappings. This is somewhat akin to the idea of "idiomatic expression" [29]. The mechanical characteristics of the DMI can serve as a starting point for mappings in which the character of the sound reflects the energy used to create it.

The first device built was the Gyrotyre [23], a hand-held bicycle wheel outfitted with various sensors that can measure both continuous and discrete rotation of the wheel, including both the rotational velocity as well as the absolute position of the wheel's rotation. In addition to this, a dual-axis accelerometer can measure the orientation and acceleration of the whole instrument. The initial idea for the Gyrotyre came from a desire to build a DMI based on a moving mechanical system, and to explore mappings such that the musical output somehow mirrors the motion of the wheel. The Gyrotyre's most pertinent physical phenomena are gyroscopic precession and rotational inertia. Gyroscopic precession refers to the wobbling motion of a spinning object along its axis of rotation. A common example is the way the tilt axis of a spinning top slowly oscillates counter to the direction in which it spins. Rotational inertia refers to the tendency of the wheel to keep spinning once it is set in motion, which is useful for maintaining a relatively constant angular velocity. The absolute position measurement of the wheel, provided by the infra-red emitters and detectors, was used to implement a physical sequencer track such that one rotation of the wheel corresponds to one musical measure, and the movable sensors placed around the track can trigger repeating musical events such as drum hits.

The second device built was the Springwave, which is based on a loose metal spring stretched to roughly one meter long and fixed at both ends on a metal frame. The frame is mounted horizontally on a standard hi-hat stand, allowing the pedal to move it up and down. The spring can be put into sustained oscillation by using the pedal or by manually grasping and shaking it at one or more points. To transduce the motion of the spring, two capacitive pickups are mounted on the stationary base of the stand. When the spring is in motion, the pickups measure the time-varying distance between the spring and each of the pickups. The signals from the pickups can then be treated as control signals for sound synthesis.

This thesis discusses the motivation and design of these instruments. Chapter 2 examines work that informed their design. Chapter 3 and 4 describe the Gyrotyre and Springwave respectively. Following the design discussions, Chapter 5 is devoted to examining the issues encountered in using the two prototypes and presents a conceptual framework for DMIs. Finally, Chapter 6 contains concluding remarks.

CHAPTER 2
Background

This chapter examines the literature related to various aspects of DMI design. The first publications discussed are general overviews of DMIs, and raise some of the issues that this thesis addresses. The issue of mapping is a central one, and various viewpoints on the topic are then presented. Finally, other DMIs that are mechanical in nature are presented.

2.1 Effort and expression

One of the core aims of this thesis was to explore the role of physical effort in using a DMI to perform music. An idea shared by some instrument designers is that an interface that requires physical effort to play is more satisfying to the performer, and can possibly afford virtuosic performance. Granted, using a standard keyboard and mouse can be considered "physical effort" but here the phrase is used to describe an interaction that more closely resembles the physical effort required by acoustic instruments, which itself varies greatly.

A central theme of both [21] and [22] is diminishing the gap between composers/performers and computer-music systems. To contrast this idea, the author begins the discussion by referencing early twentieth century serialism as an example of an attempt to *widen* the gap between musical impulse and execution in order to avoid traditional forms. Early computer-based music fit this approach well, as there was necessarily a wider distance between the composer and the music. Because it took considerable time between programming a sound and hearing the result, early methods emphasized careful refinement over immediacy. Now, following the advent of inexpensive and widespread computing, there is newfound emphasis on immediacy and on integrating a performative element into computer-music making. From [22]:

> "But despite the obvious advantage afforded by afterthought and the chance to rework ideas, the fact is we all yearn for the fluency and grace which traditional music achieves via performance. Though these qualities are not exclusive to live music, they are greatly amplified by the circumstances of performance and greatly frustrated by most of the tools we have so far provided for the studio. The point is not that all composers must jump into the limelight, but that in computer music as in traditional music, there is much to be gained from a direct relation to the material."

Another attraction of real-time performance is that it can act as a constraint against the unwanted tendency to overwork ideas, which for some is a pitfall of computer-music to this day.

> "For other composers, any limitation is disagreeable, the attraction of computers is partly a taste for infinite possibility, infinite refinement. But for many composes real time is simply a healthy constraint imposed on a nauseating infinity of possibilities." [21]

The author goes on to present the view that adding a physical element to a computer synthesis model affords the performer a more immediate grasp of the intricacies of a model. Physical interfaces, then, are not simply for performance, but for the exploration and experimentation during the initial stages of composition. This emphasis on instrumentation seeks to bring the focus away from "music" as an untouchable final product, as it is often viewed, and towards the process of experimentation.

Contrary to the "ease-of-use" objective valued in computer hardware and software design, the author makes the case that effort and experimentation are necessary to producing expressive music.

> "Too often, controllers are selected to minimize the physical, selected because they are effortless. Effortlessness is in fact one of the cardinal virtues in the mythology of the computer. [...] Though the principle of effortlessness may guide good word processor design, it may have no comparable utility in the design of a musical instrument. Physical effort is a characteristic of the playing of all musical instruments. Though traditional instruments have been greatly refined over the centuries the main motivation has been to increase ranges, accuracy and subtlety of sound and not to minimize the physical. Effort is so closely related to expression in the playing of traditional instruments. It is the element of energy and desire, of attraction and repulsion in the movement of music." [21]

A similar view is expressed in [12], although not necessarily pertaining to physical effort, but rather the effort required to learn an instrument. The authors write:

> “However, it is notable that nobody questions the need to practice an instrument, yet in the same breath everybody demands easy-to-use computer interfaces. Much of the HCI literature concentrates on making interfaces more direct, and less hard to learn. At first glance this would seem a laudable goal, even an obvious one. But are we perhaps throwing out the proverbial baby with the bathwater (in this case the bathwater represents interface complexity and learning time, and the baby represents the rewards of a flexible interface)?”

In contrast, one of the design goals raised in [8] is a “Low ‘entry fee’ with no ceiling on virtuosity”. This implies that the interface should be relatively easy for a novice to use, but should allow for repeated use and advancement of skill. The authors themselves raise the possibility that this might be an impossible dream, but they argue that by appropriate gesture-to-sound mappings, low latency and jitter, and control metaphors, musicians will be inclined to develop skills on new instruments.

2.2 Mapping and transparency

The issue of mapping is of great importance to DMIs and it has been argued that the mapping is the *essence* of the instrument [12]. There are different views on how gestures should be linked to sounds, and how mappings affect the playing of a digital musical instrument. One viewpoint is expressed as follows:

> “Although any gesture can be mapped to any sound, instruments are most satisfying both to the performer and the audience when subtle control gestures result in subtle changes to the computer’s sound and

> larger, more forceful gestures result in dramatic changes to the computer's sound." [8]

This idea is analogous to the one expressed in [11], which the author terms "gestural coherence". He divides gestures into the categories "Current control", which are sustained and can be changed, and "Balistic Control", which are short and energetic. Similarly, he proposes two categories for sound-generating devices, including traditional instruments — ones with sustaining capability and ones without. Gestural coherence, then, means matching the the type of sounds with the type of gestures. The author illustrates his views by providing counterexamples, for instance: " ... an electric keyboard does not adequately control a violin sound, nor does a wind contoller appear a convincing way to play a drumset."

In [9] the authors discuss the *transparency* of the relationship between gesture and sound. Due to the physical nature and cultural history of acoustic instruments, they are transparent to both player and audience. That is, both the player and audience understand how gesture translates to sound. The authors contend that this makes expressive performance more likely than if the mapping is opaque. They contend that with novel DMIs, thought must be put into making the instrument transparent to the player and the audience. One way suggested is using metaphors for the relationship between gesture and sound.

Metaphors can be seen as a way to patch the mental separation of gesture and sound that can arise from the fact that these are physically separated in DMIs. For instance, in Sound Sculpting, metaphors are used to provide the user with a mental model for various sound design tasks. In this case, methods of changing physical shape of objects was used, namely claying, carving, chiselling and assembly. Depending on the type of synthesis used, these metaphors help the user develop an appropriate mental model for control of synthesis parameters. Some similar ideas were used by the gyrotyre for some of the mappings, as will further be discussed in Chapter 3.

2.3 Related DMI design reports

A number of related publications are design reports by DMI builders, as well as surveys of DMIs associated with certain institutions. These are useful in that they can serve as inspiration for new instruments, as well as technical references for common DMI-building issues. There are several DMI and/or controllers that relate directly to the two that comprise this thesis. All are moving mechanical systems, yet only certain ones can be put into sustained motion by a user.

In [25], the authors discuss several haptic devices used to browse and manipulate audio and video data. They discuss the tendency for consumer products to use buttons due to their low cost, while continuous controls such as knobs and sliders would be more useful. Several devices were built that use dynamic mechanical systems and haptic feedback to control media. Two that are related to the Gyrotyre are the *Big Wheel* and the *Haptic Clutch*. The *Big Wheel* is a motorized wheel that can sense hand pressure both parallel to the axle (pushing down on a turntable) as well as normal to the axle (pushing on the rim of a turntable). The *Haptic Clutch* virtually models a set of wheels, one inside the other. By pushing down on the outer one, the inner wheel is engaged by a set of virtual "teeth" and moves with the outer wheel. Then, by removing pressure, the outer wheel can be disengaged while the

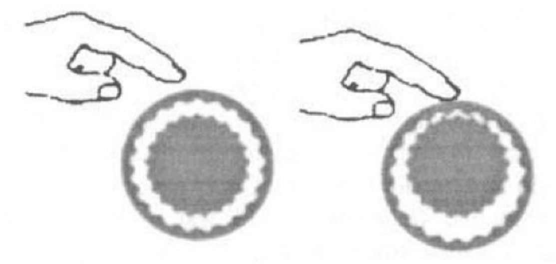

Figure 2–1: The Haptic Clutch [25]

inner wheel keeps spinning due to momentum or continuous energy input (Figure 2–1). This controller can then be used by always applying pressure and moving the two wheels together slowly, or by setting the inner wheel in motion and then quickly releasing pressure. The angular velocity of the inner wheel can then be used to control the playback position and rate of audio or video data. One of the mappings used by the Gyrotyre implements a similar idea.

In [24] the authors discuss the design of the *Tymbalimba*, a controller that imitates the rib-buckling mechanism that cicadas use to create sound (Figure 2–2). Unlike the cicada, the buckling ribs on the *Tymbalimba* do not sustain motion. Rather, the user pushes down on the ribs, and each rib's velocity is sensed and then used to calculate an energy level. The energy level is in turn used as a parameter for physical modeling synthesis. In addition to discussing the physical model, the authors assert the importance of having a mechanical user interface in terms of visual and haptic feedback for the user controlling the synthesis.

In [13] the author discusses the motivation and construction of the *Strimidilator*, a 4-string MIDI controller that uses the motion of the strings as control parameters

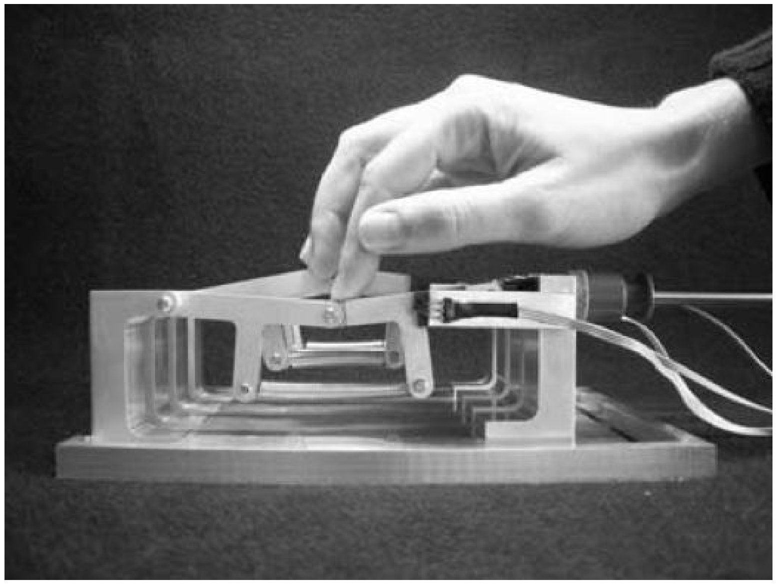

Figure 2–2: The Tymbalimba [24]

(Figure 2–3). As for the motivation, she writes, "The objective for the development of the Strimidilator was to create an interface between the mechanical and electronic world, which has an intuitive feel to it, which allows the musician to use subtle hand movements for control and gives the musician tactile force feedback of the instrument parameter with one hand."

The output of the Strimidilator is MIDI control messages suitable for use with various MIDI sound-producing modules. To transduce the motion, two strings use electric-guitar coils, and the other two use linear potentiometers attached to the string. The author notes that these affect the motion of the string such that it returns to the rest state after being plucked, meaning that those particular strings must be pushed or pulled, similar to a standard modulation or pitch-bend wheel on

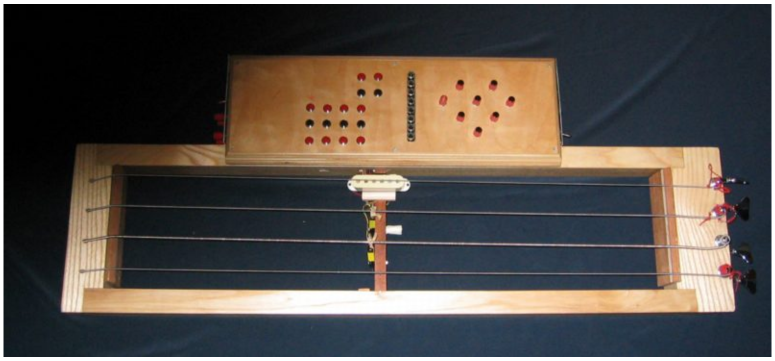

Figure 2–3: The Strimidilator [13]

some synthesizers. While the signal from the guitar coils is audio, it is extremely low in frequency and is better used as a control parameter according to the author.

The most similar known interface to the Springwave is *Boing Boing* (Figure 2–4)interface, briefly discussed in [16]. In the author's words:

> "BoingBoing is a new musical performance interface built by the author that provides the musician with four sensor-equipped ping-pong balls. The springs vibrate at frequencies less than 20Hz, thereby lending unusual qualities to the music, such as collisions, bounces, trembles, shudders and shakes. The performer can adjust the spring constants of each ball by raising or lowering the corresponding rod. A 2- axis accelerometer is contained inside each ball, and there are simple knobs above each of the balls to adjust other parameters of the synthesis."

Like the Springwave it uses the motion caused by oscillating springs as control signals. While the sound-generating techniques of each of the three aforementioned interfaces is different, the common aspect to all three is their mechanical nature. The first two contain moving mechanical parts, but cannot be put into sustained motion.

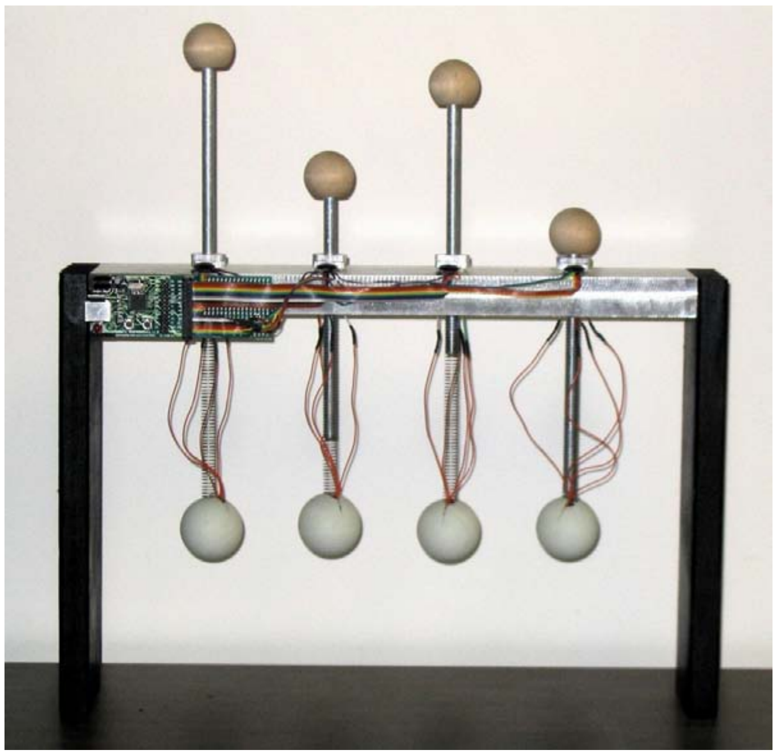

Figure 2–4: Boing Boing [16]

In that respect *Boing Boing*, is more closely related to the DMIs that comprise this thesis.

CHAPTER 3
The Gyrotyre

This chapter describes the design of two versions of the Gyrotyre, describing their mechanical, electronic and software components. The hardware issues will be discussed separately for each version, while the software component, which remains the same for both hardware versions, will be discussed toward the end of the chapter.

3.1 First prototype

Two versions of the Gyrotyre were built, although their fundamental form is the same. Both share the three main components, namely the wheel, the handle, and the circular optical sequencer track. The first version can be seen in Figure 3–1

3.1.1 Mechanical construction

Wheel

The Gyrotyre is built around the 30 cm (12 in) front wheel of a child's bicycle. The tire is included as it increases the rotational inertia when the wheel is spun. Its size was chosen to be large enough so that the gyroscopic effects of its spinning would be enough to be clearly felt by the performer, but small enough so that it could be comfortably held.

Handle

The handle is a three cm wide metal L-bracket with a hole to receive the wheel's axle. Due to its shape, holding the handle for extended periods would be uncomfortable, so it was covered by an 11 cm section of ABS pipe with a diameter of 5 cm.

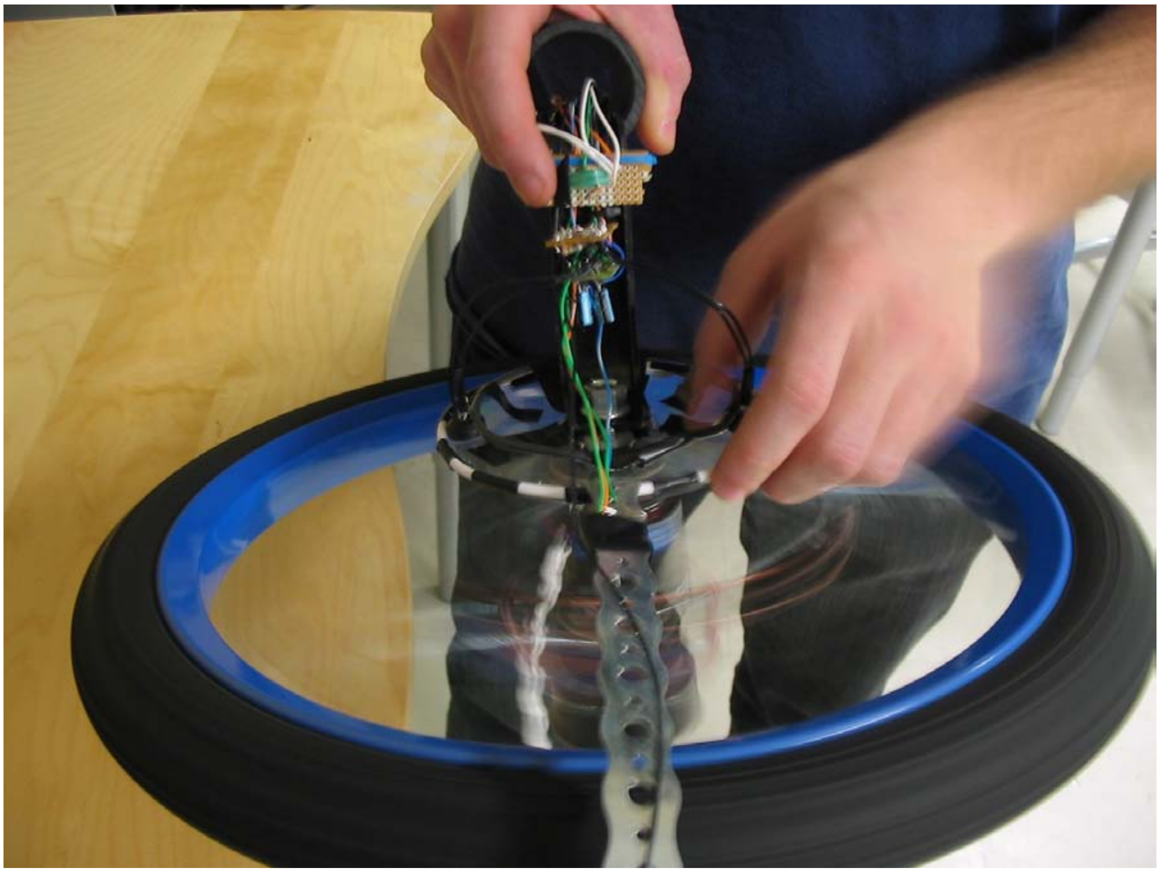

Figure 3–1: The Gyrotye in use

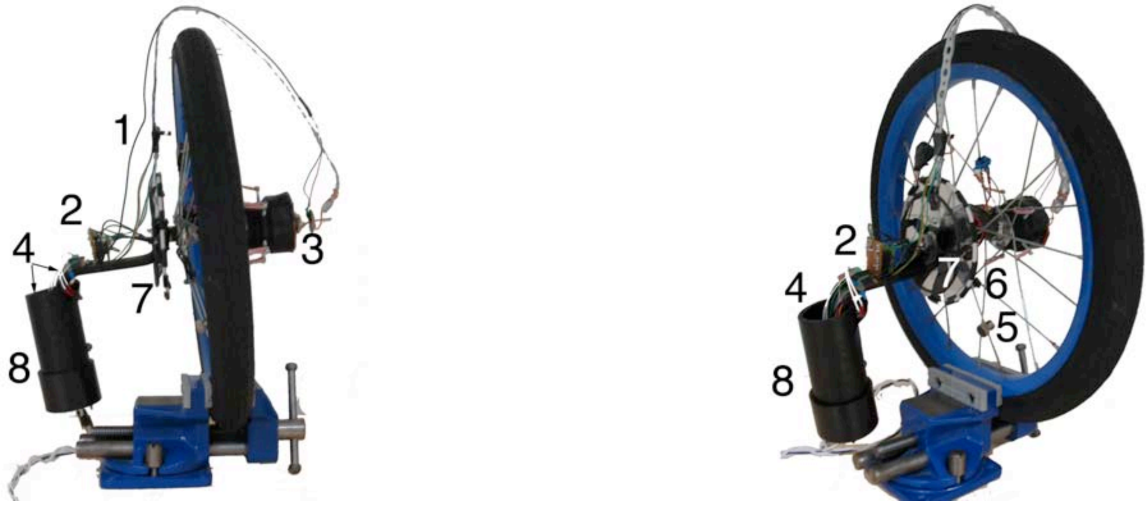

Figure 3–2: 1. Hall-effect sensor 2. Two-axis accelerometer 3. Gyroscope sensor 4. Force-sensing resistors 5. Magnet 6. Photodiode 7. Optical Sequencer Track 8. Handle

The handle also holds some of the touch sensors, to be further described in the next section.

Gyroscope Sensor Contact Arm

To receive signals from gyroscope sensor, which spins with the wheel, it was necessary to connect an arm that extends from the handle. A 50 cm strip of pliable aluminum was secured between the handle and the axle of the wheel and bent over the rim of the tire. This strip serves two purposes: to hold the hall effect sensor in place so that it is aligned with the magnets on the spokes and to hold the contact with the gyroscope sensor on the other side of the wheel. The strip can be seen going over the wheel in figure 3–2.

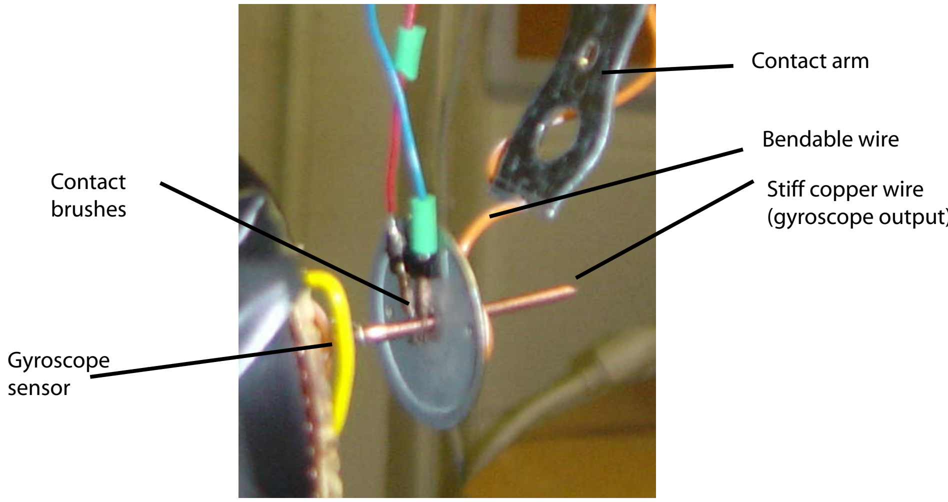

Figure 3–3: Gyroscope sensor contact. The contact brushes from a dismantled CD player motor are used as they offer an extremely low amount of friction.

Gyroscope Sensor Mounting

The PCB containing the gyroscope circuit is attached to a 5 cm section of ABS pipe which is attached to the spokes by elastic bands. The gyroscope circuit thus rotates with the wheel but does not touch the axle. The main challenge was mounting the gyroscope PCB such that it is completely centered on the axis of rotation, thus minimizing off-center oscillations. For this purpose, elastic bands work well since they allow some movement, such that if the axis is slightly off center, the elastic bands tend to pull it towards the center. The gyroscope contact, pictured in Figure 3–3, is attached to the metal arm via a piece of copper wire. This allows it to move with the gyroscope contact rod due to any off-center oscillations.

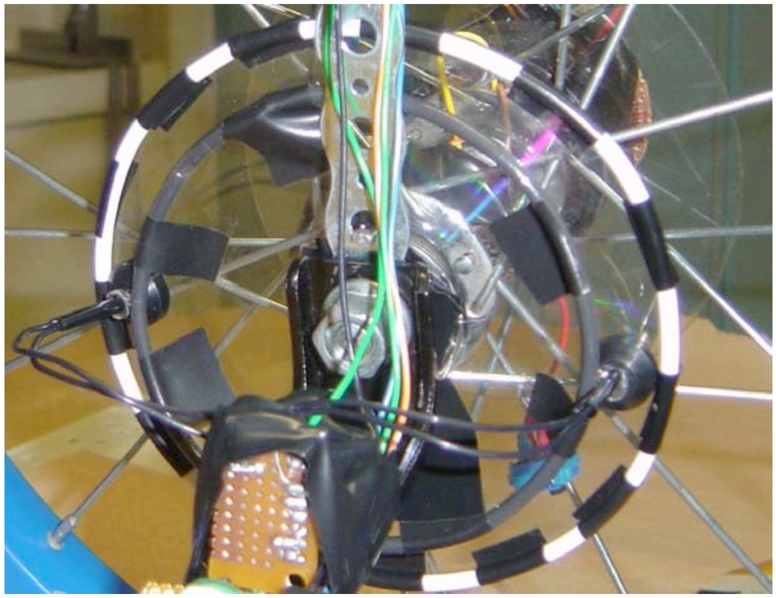

Figure 3–4: The optical sensor track. The circular track guides two IR receivers that align with an IR emitter mounted on the spokes.

3.1.2 Optical sequencer track

On the handle side of the wheel, a clear compact disc is attached to the axle so that it stays in place while the wheel turns. Two circular tracks of insulated heavy-gauge copper wire are affixed to the disc serving as a track for the infra-red recievers, which are placed inside plastic washers. The washers are held in place by the wires, but can be moved around the track so that they are triggered at different points by a spoke-mounted infra-red photodiode. Their physical spacing then corresponds directly to their temporal spacing when they are used to trigger audio events. This is akin to a *structural modification gesture*, as defined by Cadoz and Wanderley in [**?**]. The track can be seen in Figure 3–4, and in again in Figure 3–5.

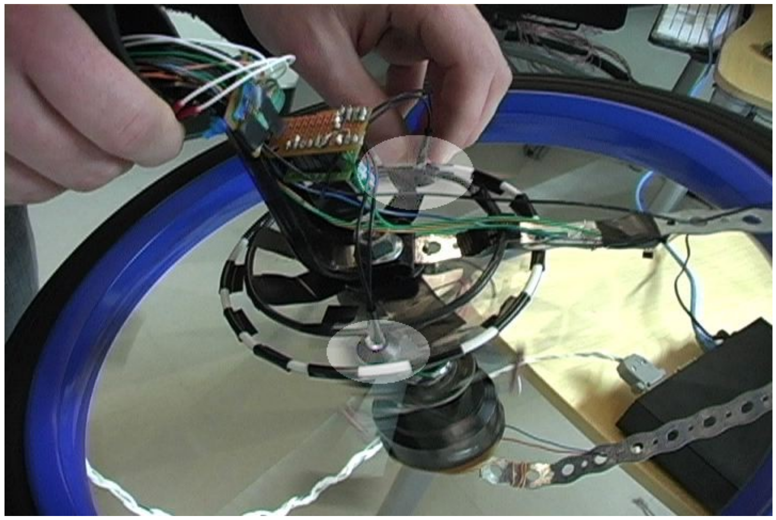

Figure 3–5: The optical sensor track in use

3.1.3 Sensors and Electronics

As previously mentioned, the main goal of the project was to exploit the dynamic behaviour of the spinning wheel in both continuous and discrete ways. The choice of sensor types was done after consulting various sources, including [4], and the internal Music Technology sensor documents that would later contribute to [1] and [15].

The following table summarizes the four functional categories for the sensors:

Table 3–1: Sensing types

Sensing quantity	**Sensor type**	**Information type**
Angular velocity	Gyroscope sensor	Continuous
Angular position	Infrared emitter/receiver pairs, Hall effect sensors	Discrete
Tilt and acceleration	Inertial 2D accelerometer	Continuous
Touch	FSRs and buttons	Continuous and discrete

Angular Velocity Sensing: Gyroscope Sensor

The gyroscope used is the Analog Devices ADXRS300 along with the ADXRS300EB evaluation board. It measures angular velocity in two directions, from zero degrees per second up to 300 degrees per second.[1] When the wheel is stopped and the velocity is zero, the gyroscope outputs a voltage of 2.5 Volts. When the wheel is spinning at the maxium sensable velocity, (for instance 300 degrees per sec) the voltage rises to approximately 4.5 Volts, and when it spins at the maximum velocity in the opposite direction, the voltage output is at approximately 0.5 Volts.

Just as mounting the gyroscope posed a technical challenge, so did connecting the wheel-mounted circuits to those on the handle. The solution was to use two separate power sources connected to the same ground. The power and ground for the stationary sensors (accelerometer, hall-effect, FSRs and IR detectors) are provided by an external power source, while a 9 Volt battery mounted inside the wheel provides power to the spinning circuit, comprised of the gyroscope and the infra-red emitter. The ground is shared through the spokes and hub themselves, which connect to the stationary circuit through the bearings and axle. The output signal from the gyroscope sensor is connected to a 1.3 mm-thick copper wire, which touches two motor brushes extracted from a CD-player motor, as seen in Figure **??** above.

[1] By adding an external capacitor, the range can be extended to 900 degrees per second, which entails a decrease in resolution.

Angular position sensing: Infrared LEDs, hall effect sensors

In order to sense when the wheel is passing certain points, hall effect and IR emitter/reciever pairs were used. The hall effect sensor was mounted on the gyroscope sensor contact arm, on the same side as the handle. One or more spoke-mounted magnets pass by the sensor with every revolution of the wheel, causing a pulse to be output by the sensor. This pulse could then be used to count the number of revolutions in a given time frame, thus calculating the velocity. This was especially useful for measuring velocity at a rate higher than the limit of the gyroscope sensor. The downside to this method is that at least two readings are required for the first calculation, so if the velocity is too slow or the wheel stops spinning, then the calculated velocity is inaccurate.

Furthermore, since the magnet always passes the hall-effect sensor at the same phase of the wheel's rotation, one can assign the pulse to trigger a musical event. This aspect of rotation is impossible to measure with the gyroscope sensor alone, since it offers no information of absolute position. Of course the position information offered by the hall effect sensor is of an extremely low resolution, and although adding more magnets would be an improvement, the sensor still has no way of differentiating one magnet from another. A possible solution would be to mount the magnet on the handle, and use multiple hall-effect sensors mounted around the wheel, thus being able to identify which spoke-mounted sensor had just passed the magnet. The downside is that this would require more electrical channels between the wheel and the handle, while implementing only two (ground and gyroscope signal) proved difficult.

Along similar lines, an infrared emitter is mounted on the spokes of the wheel, and 2 infrared detectors align with it around a circular track, as seen in figure 3–4 above. Unlike the magnets, which spin with the wheel and are mounted on specific spokes, these detectors are movable around a stationary track, which allows the performer to alter the physical and thus temporal spacing while the wheel is in motion. By keeping the detectors stationary and the emitter spinning, it is possible to determine which detector has been triggered, which would not be possible if there was a single detector and multiple emitters. It is useful to be able to distinguish among the detectors, as will be seen in the mapping discussion below.

Tilt and acceleration: Two-dimensional inertial accelerometer

An important aspect of the Gyrotyre is the precession effect which occurs when the wheel is spun quickly. In order to measure the overall spatial movement that results, a two-dimensional accelerometer was mounted to the handle. It is centered on the same axis as the axle, so that both axes are zero when the Gyrotyre is aimed downward, and its range is symmetrical in both directions. The accelerometer used is the Analog Devices ADXL202 with the ADXL202EB evaluation board. Since the output is pulse-width modulated (PWM), it is necessary to usea 0.1 μF capacitor at the output which acts as an integrator and converts the PWM output to an analog voltage suitable for the analog-to-digital (A/D) converter. A larger capacitor size minimizes ripple on the output signal, but increases the time delay between a motion and a change in signal.

Table 3–2: Sensing Ranges

	Sensor	**Usable Range**
Continuous	Accelerometer	-90 deg to 90 deg from horizontal
	Gyroscope	0 to 0.83 revolutions/sec (300 deg/sec)
	FSR	30g to 10kg
Discrete	Hall effect	> 0.83 rev/sec
	IR	N/A

Touch sensing: Force-sensing resistors

The handle contains two circular FSRs, one measuring 1.5 cm to be activated by the user's thumb and the other measuring 0.7 cm and activated by the index finger. They change resistance under force, so they can be used as finger pressure sensors. Each FSR is wired in series with a 68 kΩ resistor acting as a voltage divider. Depending on their desired use, finger pressure can be mapped to a scalable parameter, or a threshold can be set in software so that the FSRs can function simply as two-state switches.

3.2 Second prototype

The first prototype was successful in terms of exploring the use of a spinning wheel to create and control sounds. Some issues were encountered during its use that warranted improvement in a second version. They are as follows

1. The spinning circuit requires a battery to be mounted inside the wheel, which causes a weight imbalance. Additionally, the battery needs to be replaced quite often [6].
2. The gyroscope sensor contact arm is delicate, and if the wheel is spun too quickly, the contact can become unseated.

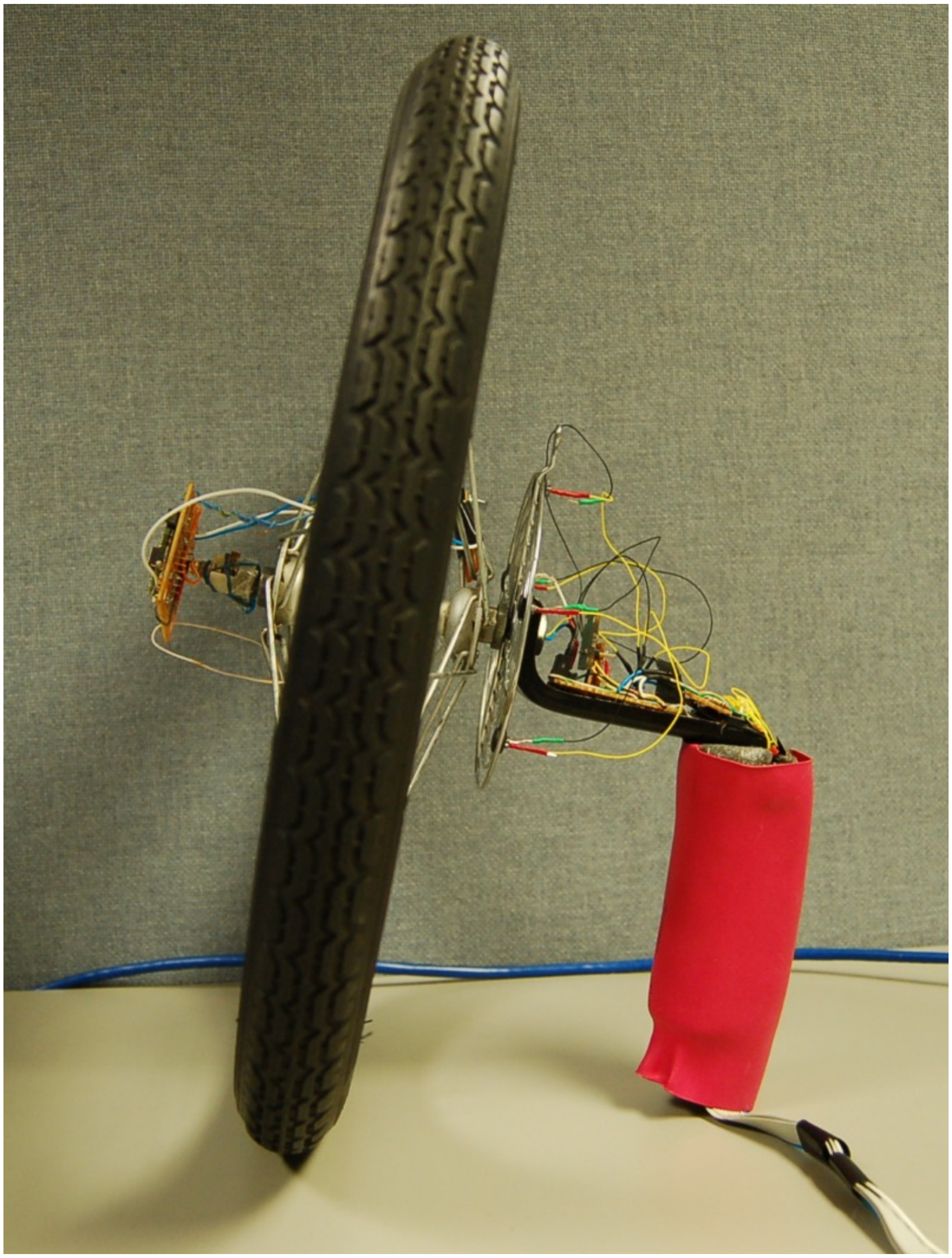

Figure 3–6: The second Gyrotyre prototype

3. There are only two sequencer triggers, and the track is not robust enough to hold them in place.
4. When in use, the FSR sensors are difficult to fully control, and due to their placement, they tend to get pushed unintentionally. In fact, during some manuevers, the user must take care *not* to press them.

For the first and second issues, the solution was to drill a trench in the axle of the wheel so that two thin wires could be threaded through it. On the other side of the axle, a two-channel 1/8th-inch headphone jack was connected to these wires. The spinning circuit could then make contact with these wires through the headphone jack. Using these two channels as well as the conductivity of the axle itself, power, ground, and the gyroscope sensor signal could be shared between both circuits. The axle and headphone jack can be seen in Figure 3–8. The interfacing spinning circuit can be seen in figure 3–7.

The second version also contains a more robust sequencer track, with four triggers instead of two. It was constructed using a power-supply fan-grill, which supplied circular tracks for the triggers. A rubber grommet was used to affix the IR detectors onto the grille (Figure 3–9). The improved track can be seen in figure 3–10.

Finally, the handle was outfitted with more sensors and buttons, so that the user can control more parameters. It also holds the accelerometer and interface circuits for the infrared detectors. The new handle is covered in foam padding, under which there are the two FSRs, which respond to the user squeezing the handle in the front and in back. In addition, there are five microswitch-style buttons on the handle. The handle can be seen in figure 3–11 before the foam padding has been added.

Figure 3–7: The axle, gyroscope sensor contact, and gyroscope sensors

Figure 3–8: Gyroscope Sensor Contact (Second Version) mounted on the axle

Figure 3–9: Infrared detector with rubber grommet for mounting on track

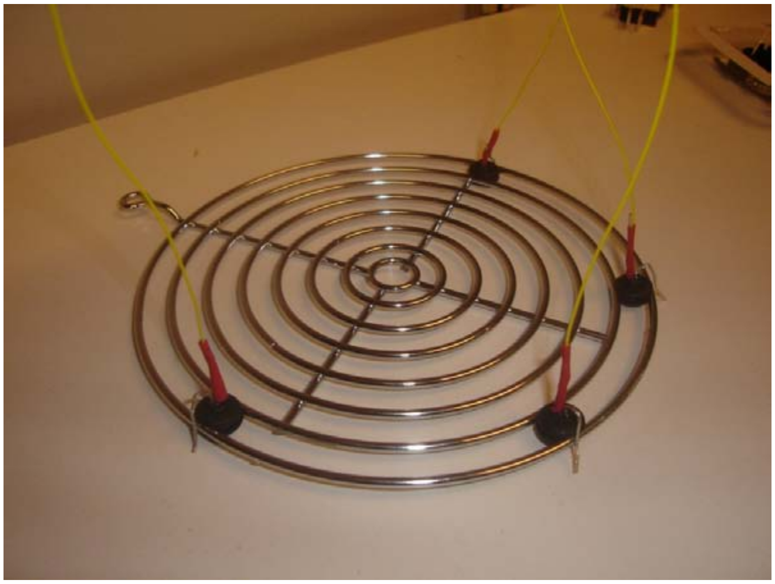

Figure 3–10: Improved optical sequencer track

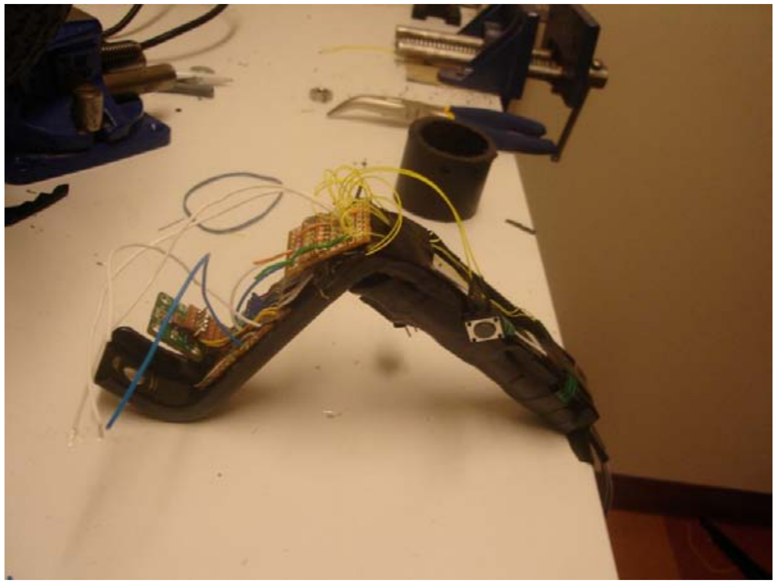

Figure 3–11: Improved handle. Note the FSRs on the underside and button on the side. The accelerometer can be seen close to the axle's hole.

3.3 Analog to digital converter

As an interface between the analog electronics and the software component, both versions use the Ethersense [10], an analog-to-digital converter manufactured by IRCAM. In its basic version, the Ethersense is capable of digitizing up to 16 channels of analog signals at a sampling rate of up to 1000Hz. For some sensors, such as the gyroscope and accelerometer, a lower sampling rate would suffice. For others, such as the IR receivers, the sampling rate needs to be fast enough to sample to register the passing of the IR emitter. At a rotation speed of 1 revolution per second, the IR emitter and receiver align for roughly 16 milliseconds.

The Ethersense transmits the sampled data over ethernet using the Open Sound Control (OSC) protocol [30]. Max/MSP OSC objects are used to receive the data from the sensors, at a rate of 250 Hz.

Figure 3–12: The Ethersense A/D interface by IRCAM [10]

3.4 Software

3.4.1 Sensor data receiving and processing layer

The software layer was built in Max/MSP. The guiding principle was to develop a layer that receives the incoming data and conditions it so that it can be easily used by successive layers. This involved parsing the OSC data coming from the Ethersense, smoothing it if necessary, normalizing it, and extracting pertinent information. For the gyroscope data, this consisted of taking a moving-average over five values to counter noise due to bouncing. The first-order difference was calculated so that angular acceleration could be used as a parameter if desired. For the hall effect sensor, an object was developed that outputs a bang when a magnet passes, as well as the width of the pulse, the time since the last pass and the angular frequency in degrees per second. A similar object was used for the IR receivers.

Unlike the hall effect sensor, which outputs either zero or one, the IR receiver output signal varies with distance from the emitter. As the emitter approaches, the signal level increases, peaking when the emitter is directly with the receiver. This allows the sensors to be used as more than triggers, as mentioned in the scanned synthesis mapping below.

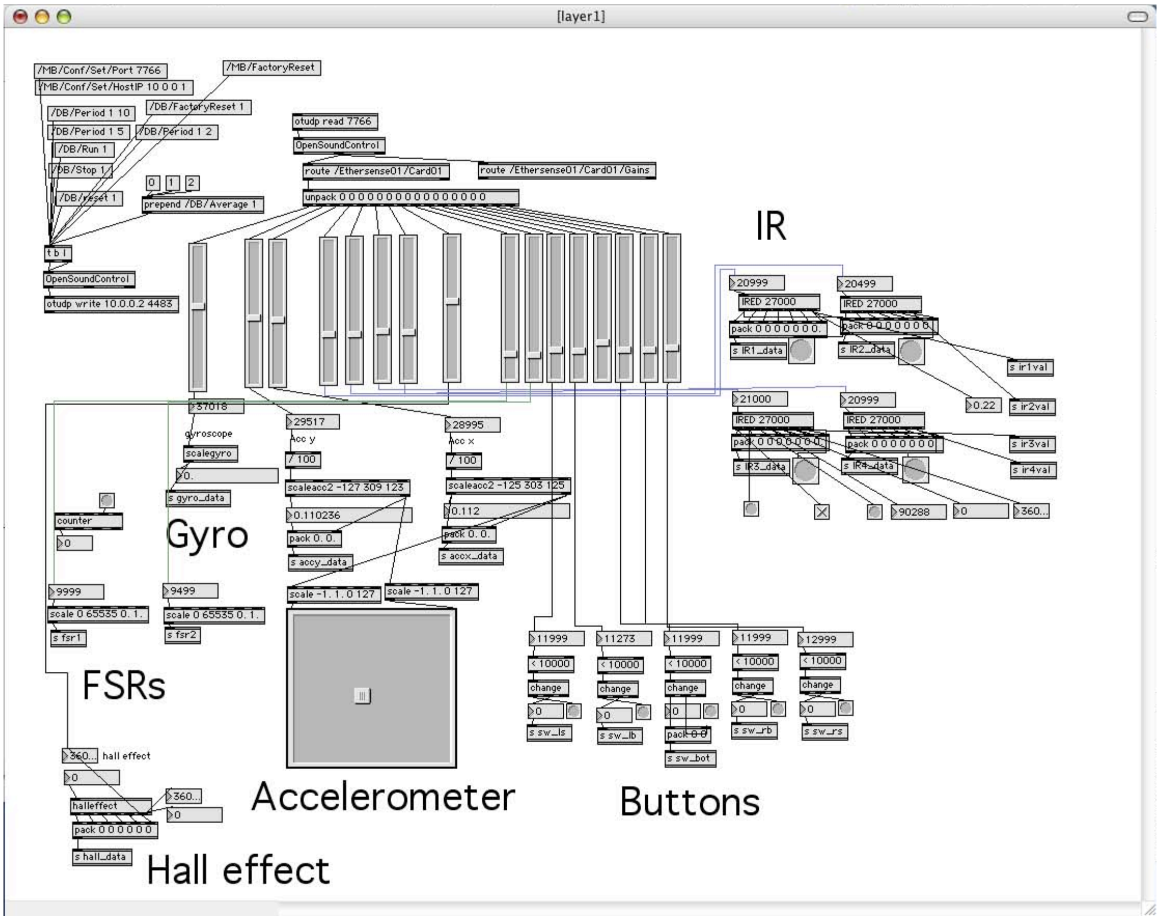

Figure 3–13: The sensor receiving and processing patch. Raw (unprocessed) and cooked (processed) data is sent to other patches using *send* and *receive* objects.

The usable range of the accelerometer was scaled to map to [0, 1] using the `scale` object. Using the `send` and `receive` objects in Max/MSP allows for easy expansion and re-mappings. Also, each sub-patch has a on/off toggle that is controllable by the Gyrotyre. The sensor layer can be seen in the figure 3–13.

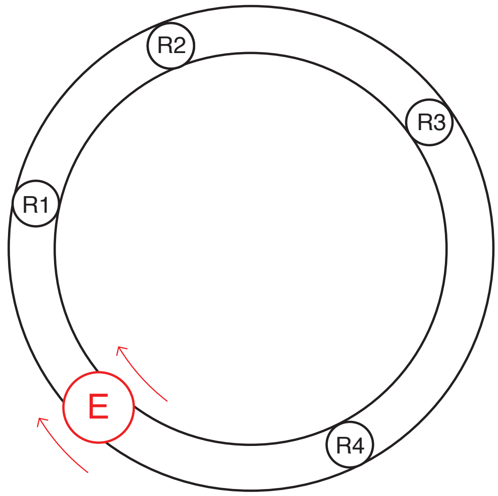

Figure 3–14: The four IR receivers (R1-R4) are triggered by the rotating emitter (E). Each receiver can be assigned to a different sound sample.

3.4.2 Mappings

Sampler

The IR receivers and hall effect sensor trigger short samples. For instance, in one configuration the hall effect sensor triggers a bass drum while one infra-red receiver triggers a hi-hat and the other a snare drum. The second prototype allows two additional triggers. By moving the receivers around, different beats can be created. The x-axis tilt angle controls sample playback speed while the y-axis changes the set of samples played. The thumb FSR controls volume. An illustration of this mapping can be seen in Figure 3–14.

Noisy Synth

The gyroscope controls the main oscillator frequency, while the x-axis tilt signal increases the range of its control. In other words, for small tilt angles the maximum gyroscope velocity corresponds to several hundred Hertz, while for large tilt angles it corresponds to several thousand Hertz. This is somewhat analogous to “fine” control versus “coarse” control. The index-finger FSR controls volume.

Omnichord/Arpeggiator

This was inspired by a 1980’s musical toy from Suzuki in Japan that generates major/minor/7th arpeggios in various keys [2]. The device has buttons for choosing the key and a linear “strumplate” (a small ribbon-controller) that plays the arpeggios in four octaves as the user strums her finger along it. The Gyrotyre adaptation uses the gyroscope to determine how fast the arpeggios are played and the y-axis tilt angle to determine the octave. The index finger FSR acts as a “clutch” [25] such that when it is pressed down, the gyroscope speed controls the arpeggio speed. When the FSR is released, the speed stays constant until it is pressed down again, and the new arpeggio speed is determined by the new angular frequency. The key can be chosen from C, G, D, A, E, B or F, depending on the x-axis tilt angle. The direction of the rotation determines whether major or minor arpeggios are played.

Scrubber

This patch is useful for “scrubbing” long segments of audio, similar to using a turntable or jogwheel. Here, the “clutch” concept was used again in that when the finger FSR is pressed, the gyroscope determines the speed and direction, and when it is released, the chosen speed and direction are held constant. The “coarse” control concept is also used the playback speed is scaled by a factor of 1, 2, 3 or 4 depending on the y-axis tilt angle. The thumb FSR controls volume.

Effects

This sub-patch is connected in series with the others in the signal chain so that it can be used to affect the output of any unit. X-axis tilt controls stereo panning; y-axis tilt controls bandpass filter cutoff frequency;, index finger FSR controls filter Q; value, thumb FSR controls delay length; and gyroscope speed controls reverb time.

Scanned Synthesis

This mapping uses the scanned synthesis patch by Couturier [7]. The IR emitter acts as a trigger and each receiver excites the mass-spring model at a different point. The intensity of the signal from the IR receiver determines the excitation force. One of the receivers acts as a mute, quickly damping the oscillation of the mass-spring model. Moving the gyrotyre along the y-axis causes the spring-mass model to be excited with more force.

3.4.3 Performance issues

It was found that the physical mode of interaction with the Gyrotyre varies greatly depending on the mapping used. Certain mappings, such as the noisy synth, encourage users to try to find the extremes of the sensor range in order to produce feedback-like squeals. The arpeggio mapping, on the other hand, encourages more subtle gestures, as the user attempts to remain in the position for a particular number of arpeggios before switching key or octave.

Table 3–3: Physical modes of use

Mode	**Physical property**	**Relevant sensors** (in order of importance)	**Musical application**
Fast spinning (> 300 deg/sec)	Precession	Accelerometer, IR, hall effect	Envelope generation, spatialization, dynamic control
Medium Spinning (between 100 and 300 deg/sec)	Rotational Inertia	Gyroscope, Accelerometer, IR, hall effect	Long sample playback
Slow	Repetition	IR, hall-effect, FSR, Gyroscope	loop triggering, short sample triggering, long sample scrubbing

The use of the hall effect and optical sensors to trigger samples was also successful. In addition to moving the receivers to change the rhythm, the performer can also cover them or remove them from the track entirely in order to silence them. Changing the tempo is simply a matter of spinning the wheel at a different speed. With practice, it is possible to keep a steady tempo by gently tapping the wheel along for each revolution. Some users didnt even spin the wheel, but rather positioned the IR sensors close to each other and moved the wheel back and forth to trigger them in quick succession. Table 3–3 summarizes the three main physical modes of use.

CHAPTER 4
The Springwave

4.1 Concept and motivation

The motivation behind the springwave was to build and examine a second interface that made use of a moving mechanical system in which the sound produced was more tightly coupled to the motion of the instrument. To recap, the instrument consists of a four cm diameter metal spring, similar to the Slinky Jr.$^{\text{TM}}$. Both ends are fixed to a 1.15 m metal rod which is in turn mounted on a 1.1 m hi-hat stand. Two movable capacitive pickups transduce the motion of the spring. The oscillatory motion can then be used as a parameter for sound synthesis. To drive the system, the user can use the hi-hat pedal to move the entire spring up and down, thus inducing vibrations. A string tied to one end allows the user to add tension to the spring, thus increasing the rate of oscillation. The Springwave prototype can be seen in Figure 4–1.

4.2 Mechanical construction

Compared to the electrical component of the prototype, the mechanical component is relatively simple. The prototype was built using primarily off-the-shelf parts. The heart of the instrument is the spring, a smaller version of the familiar metal slinky. The spring is mounted horizontally on a curtain-rod frame, fixed at both ends. The spring holder is in turn mounted on a hi-hat stand. The small version

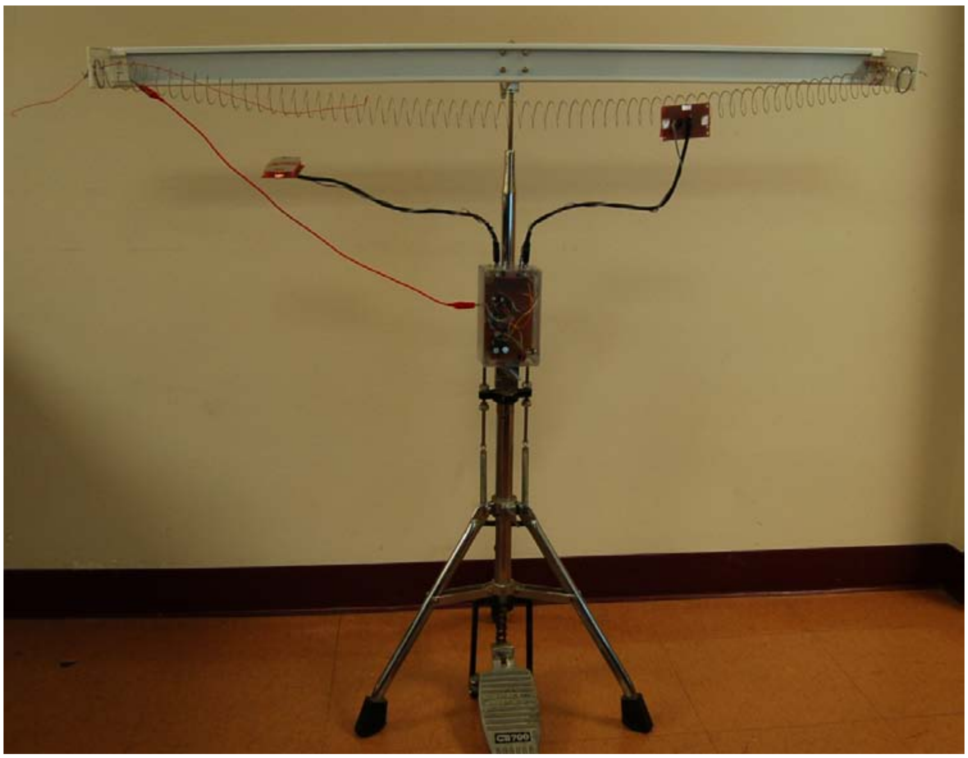

Figure 4–1: The Springwave prototype

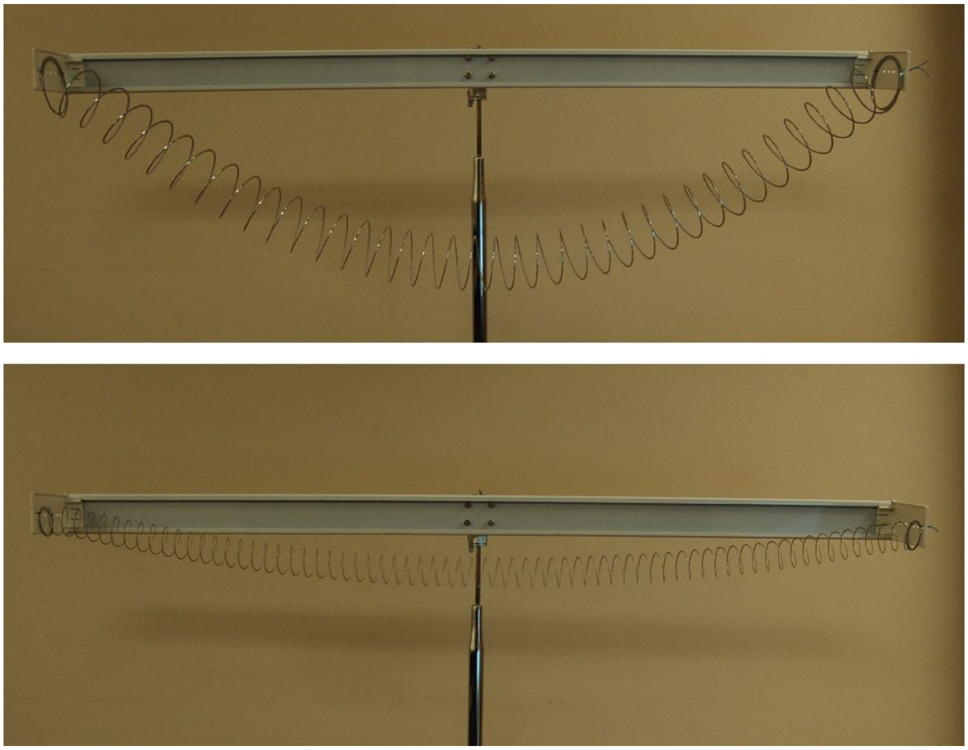

Figure 4–2: Two different-sized springs.

was chosen as it was more tense when stretched and fixed to the frame, whereas the larger version sagged down, as can be seen in Figure 4–2.

The ends of the spring are fixed 1.1 m apart. At normal tension, the fundamental frequency of oscillation is roughly 4.5 Hz. This can be changed by using a wire to shorten the coils at one end of the frame, as seen in Figure 4–3. The wire was chosen to be light enough to minimally affect the motion of the spring.

The electronic components are located in a box mounted on the shaft of the hi-hat stand, below the spring-holder. Two aluminum foil pickups extend from the electronics box via flexible necks, taken from gooseneck-style USB lamps. These necks allow the location of the pickups to be changed according to the performer's

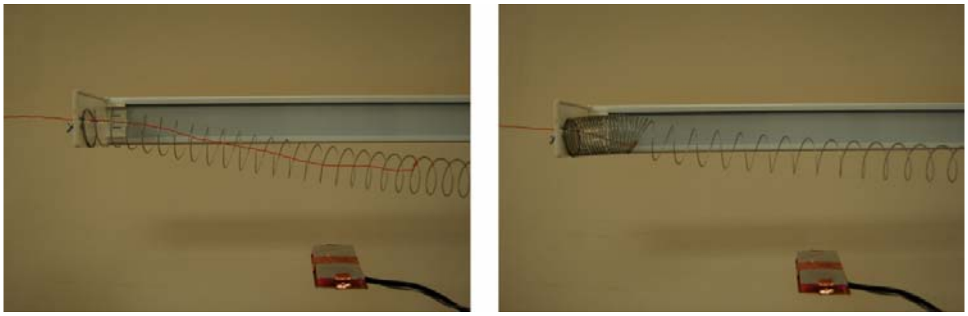

Figure 4–3: The spring tensioner

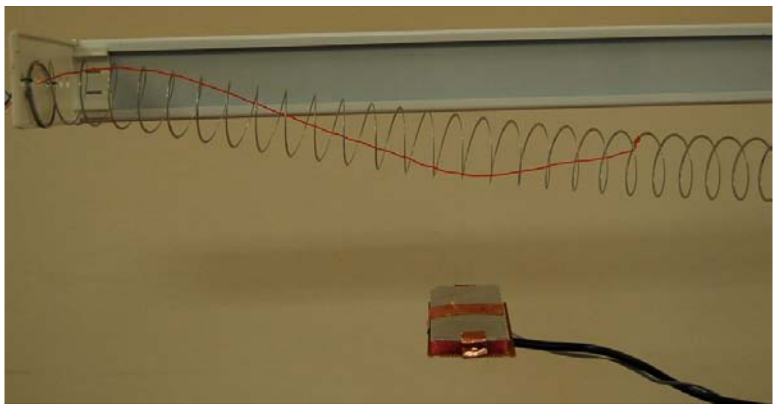

Figure 4–4: Movable capacitive pickup

wishes. The necks that were used contained only two conductors, so it was necessary to use an extra two-conductor wire for the required four conductors. The foil pickup can be seen in Figure 4–4.

4.3 Electrical construction

The basic circuit and reasoning was largely based on [18]. Essentially, the spring acts as an antenna and two pickups produce signals that vary according to their distance from the antenna. The functional block diagram can be seen in Figure 4–5.

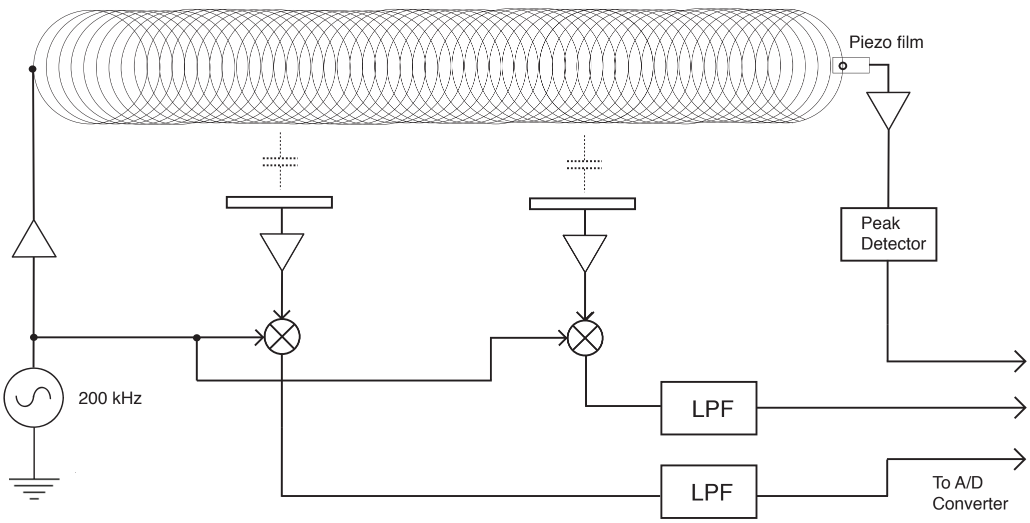

Figure 4–5: Springwave functional block diagram

4.3.1 Transmitter

The oscillations of the spring are transduced by measuring the capacitive coupling between the foil pickups and the spring itself. The spring acts as an antenna and is driven by a 30-Volt, 200 Khz sinusoidal signal. The XR-2206 oscillator is used to generate a roughly 6 Volt peak-to-peak sinusoid, which is then amplified to 30 Volts in order to increase the amount of current induced on the pickups, thereby increasing the range.

4.3.2 Receivers

The foil pickups capacitively couple with the spring, meaning that the AC voltage going though the spring induces a proportional AC current in the foil pickups. In practice, this current is roughly proportional to 1/d, d being the distance between the pickup and the spring. [18]. The induced current is put though a transimpedance amplifier to provide a buffered low-impedance voltage output. The amplifier is physically located immediately being the pickups to reduce parasitic capacitance due to long cable lengths, and to provide a buffered low-impedance signal for the demodulation stage [18].

The signals coming from the pickup are then demodulated by being multiplied by the antenna/carrier signal and then lowpass-filtered to remove the components at nf_C. The AD663 4-quadrant multiplier was used for this purpose. By using this method, noise at any frequency other than the carrier frequency is greatly reduced. After the multiplication and lowpass filter stage, the signals are fed through a first-order active bandpass filter with cutoff frequencies at roughly 1 Hz and 2000 Hz. This serves to remove the DC component of the signal and to smooth out any high-frequency noise so that it can be fed into an audio input. Should one wish to use a traditional A/D interface the signal can be output before this stage. An example of the pickup outputs can be seen in Figure 4–6.

4.3.3 Transient Sensing

In addition to outputting the distance of the pickups to the spring, a small piece of piezoelectic film is coupled to the string at one end (Figure 4–7). When a high-frequency shock is sent though the string, the stretching of the piezo film induces a voltage at its terminals. This is amplified, buffered and then fed though a peak detector circuit so that it may be used to sense percussion on the string as a control input. The signal trace can be seen in Figure 4–8

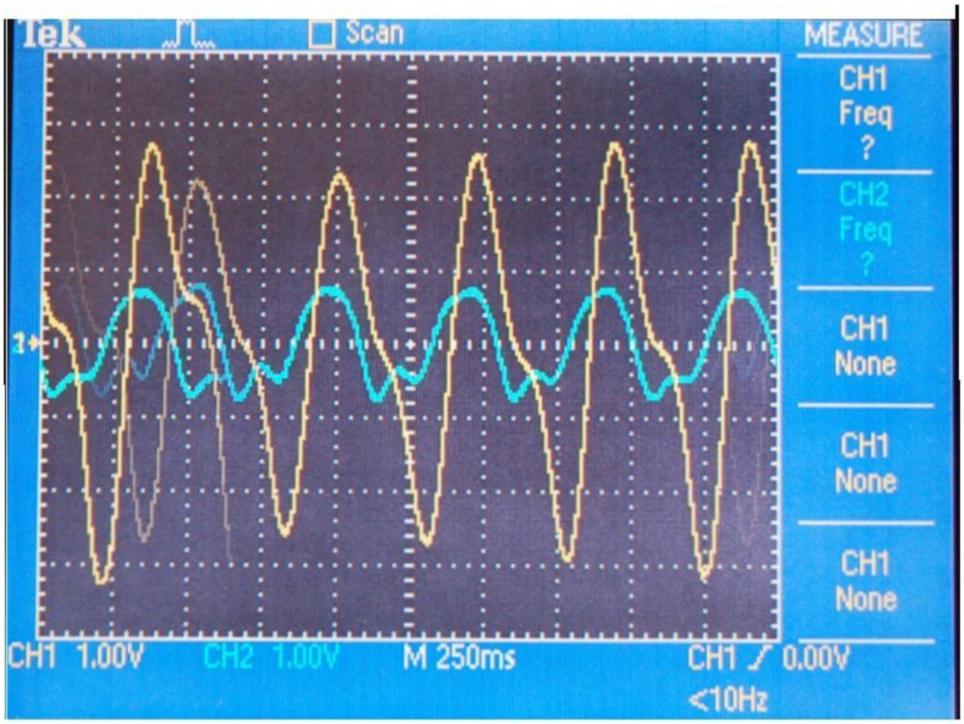

Figure 4–6: Signals produced by driving the spring. Yellow and blue traces represent the left- and right-hand pickups.

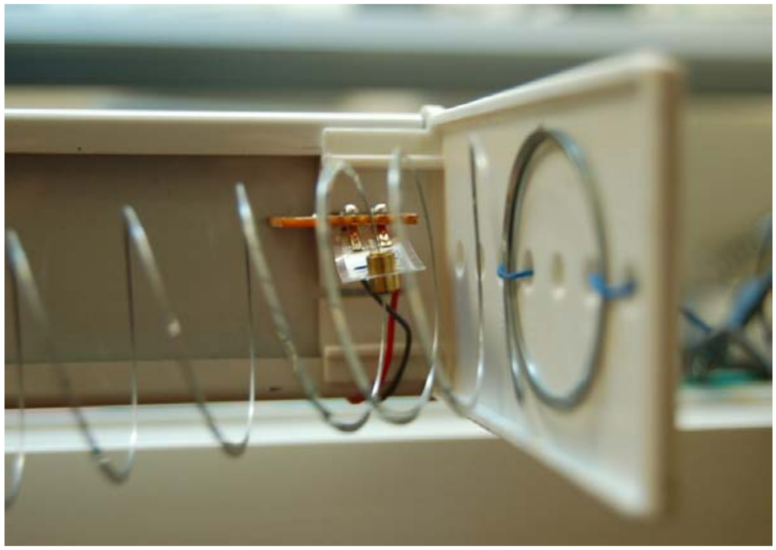

Figure 4–7: The piezo-film element is coupled to one end of the spring to measure percussion on the spring.

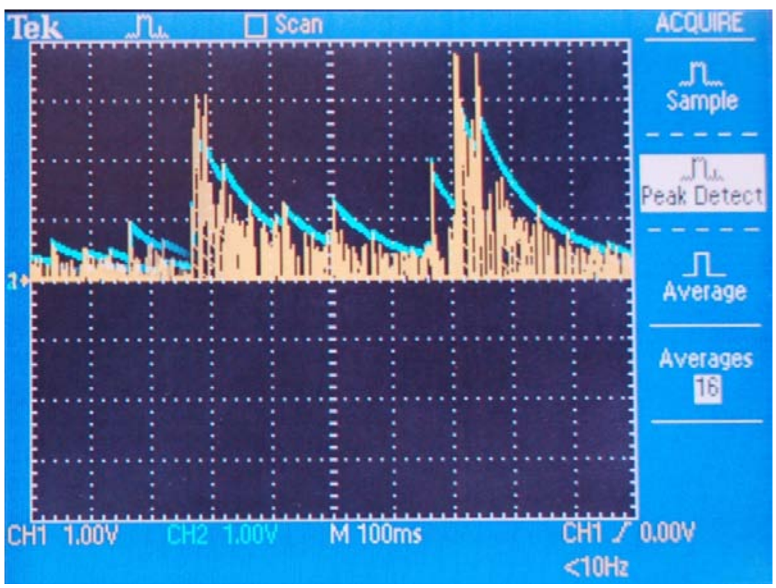

Figure 4–8: Signal from piezo sensor after string has been struck. The yellow trace is the signal after being amplified while the blue trace is the output of the peak detector.

4.4 Software

The primary mapping used for the Springwave is an implementation of scanned synthesis [26]. This entails scanning a sub-audio signal at audio rate so that it can be sonified. It can be thought of as wavetable synthesis with a dynamic wavetable. In some cases, the signal is a physically modelled mass-string system, as in [7]. In the case of the Springwave it is an actual physical signal.

Due to the lack of an intermediate interface and the reduced number of input channels as compared to the Gyrotyre, the data-acquisition layer is also simpler. The signals from the capacitive pickups are simply input though an `adc~` object. They are further lowpass filtered and then scaled up. Using the `poke~` object, they are fed into a `buffer~` of 10 seconds. The `groove~` object is used to play back a portion of the buffer, the size and scan-rate being up to the performer. The current patch includes the `fiddle~` [19] object which allows the performer to set the playback frequency by singing into a microphone.

Since there are two separate channels, two separate buffers are used, and they can be played back at arbitrary rates. There are presets for playing the buffers at specific intervals so that two-part harmonies can be created. Another interesting effect is created by playing the buffers back at slightly different frequencies to cause beating. An example of the playback buffer can be seen in Figure **??**.

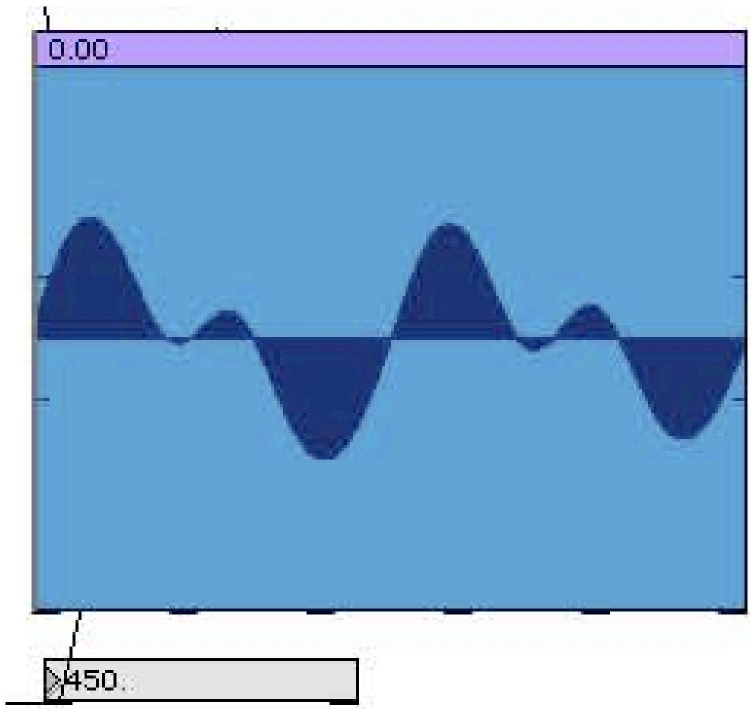

Figure 4–9: The portion of the buffer which is played back at audio rate for scanned synthesis.

CHAPTER 5
Discussion

While the instruments that comprise this thesis are both mechanical in nature, there are perhaps more differences than similarities between them. The Gyrotyre is hand-held and due to its weight of 1.5 kg, it requires considerable physical effort by the user in order simply hold it up. Furthermore, most mappings use the spinning of the wheel as well as its motion in space as parameters. It can be played either sitting or standing, but it encourages standing in order to make the most use of space (Figure **??**).

The Springwave, on the other hand, is mounted on a stand and features a pedal. It can be played either sitting or standing, though there are few, if any, advantages to standing. It actually takes very little physical effort compared to the Gyrotyre, and depending on the desired sound the player can simply hit the spring to cause it to oscillate and then let it decay. Alternately, she can push down on the pedal

Figure 5–1: Gyrotyre being played using the noisy synth patch

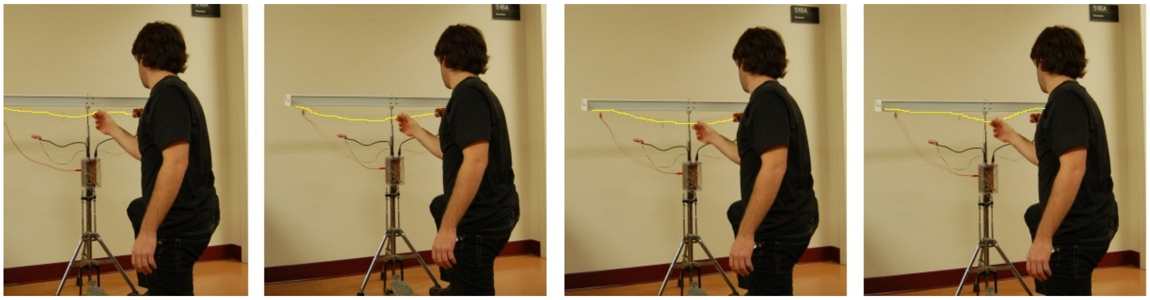

Figure 5–2: Driving the spring by hand. The spring is outlined in yellow.

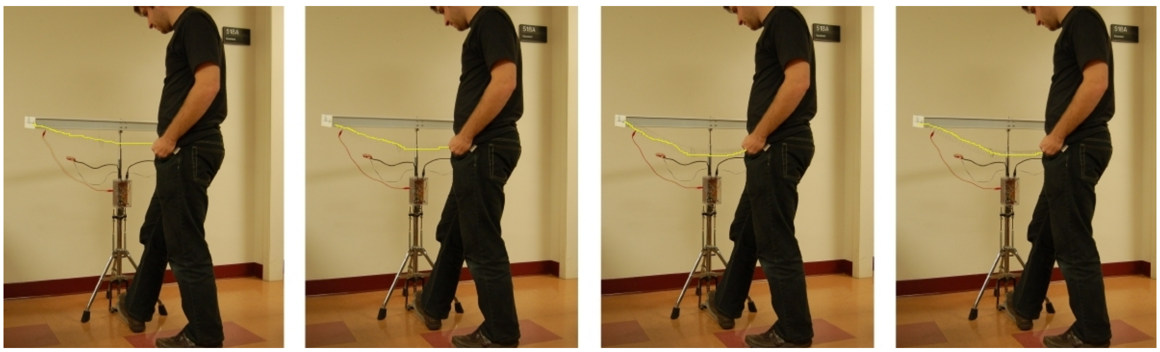

Figure 5–3: Driving the spring by foot-pedal. The spring is outlined in yellow.

one or more times to set the spring into motion, or carefully time her foot motion to to create an unchanging drone (Figure 5–3). At the other extreme, the user can grasp the spring with both hands and actively and continuously drive the oscillations (Figure 5–2). If the performer then doubles the speed of the pedalling and the buffer is kept at a constant size, it is possible excite a higher mode of oscillation and introduce higher harmonics to the sound. This too can also be done by manually driving the spring with one's hands.

The degree of interaction with the physical system is also quite different from one system to the other. With the Gyrotyre, the user moves the handle around, yet the wheel can be stationary when doing so. The spinning wheel provides proprioceptive feedback and its speed can be used as a synthesis parameter, but it is possible to play the Gyrotyre without the wheel spinning. With the Springwave, if the spring isn't moving, then no sound *can* be made. An interesting aspect to the Gyrotyre is that as mentioned, the passive force-feedback of the wheel causes it to behave differently when the wheel is spinning as opposed to when it is stopped, or spinning in the opposite direction. Due to the phenomenon of gyroscopic precession, the axis of the wheel tends to rotate in in opposite direction in which it is spinning. This favours certain performer motions and makes others very difficult. When the difficult motions are mapped to 'extreme' sounds [1] , or when the change caused by these motions is amplified, it makes for a satisfying experience in trying to push against the forces being induced by the spinning wheel.

5.1 Strengths and weaknesses

5.1.1 Gyrotyre

The strengths of both systems have been alluded to in previous sections, and will be summarized here. The Gyrotyre is definitely novel and it is interesting to watch it being used in a performance. The spinning of the wheel is a suitable metaphor for certain computer music tasks, namely scrubbing audio back and forth at various speeds, repetition of phrases or rhythms, speeding up and slowing down of tempo as well as increase and decrease in loudness. The size and mass of the wheel was large and heavy enough for the wheel to spin on its own momentum, but light enough for it to be stopped quickly should the user wish to do so. Also, the combined mass of

[1] Extreme in the sense of being louder or harsher.

the wheel and tire contribute to the precession effect, which provides proprioceptive feedback to the user while the wheel is spinning. Finally, due to the combination of the the gyroscope sensor, pressure sensors and dual-axis accelerometer, any gesture that requires physical effort (such as spinning the wheel, squeezing the handle, or changing its spatial orientation) is reflected by the sensor data.

The two prototypes of the Gyrotyre are not without their weaknesses. Due to the electrical interconnection between the spinning and stationary components, the Gyrotyre is delicate. With the first prototype, spinning the wheel too forcefully threatens to unseat the connector. The second prototype is more rugged then the first, but this fundamental issue still exists. The optical sequencer track also has an issue that should be improved, namely that the IR detectors can sometimes aim off-axis rather than directly at the passing emitter. It is not a severe problem, and simply requires aligning them by hand (figure 5–4). Finally, the mass of the Gyrotyre can be seen as both a positive and a negative feature: positive because of the precession effect described above, but negative because it can cause arm fatigue if held for a long period of time. In connection with this, some of the buttons require stretching one's fingers, which can further contribute to fatigue.

The final weakness is not related to the Gyrotyre itself, but rather to the interface between its sensor outputs and the computer. While the Ethersense is a fast and reliable sensor interface that allows for rapid prototyping, it requires setup and sometimes troubleshooting before the Gyrotyre can be used. In the future a less conspicuous embedded wireless interface would be a significant improvement.

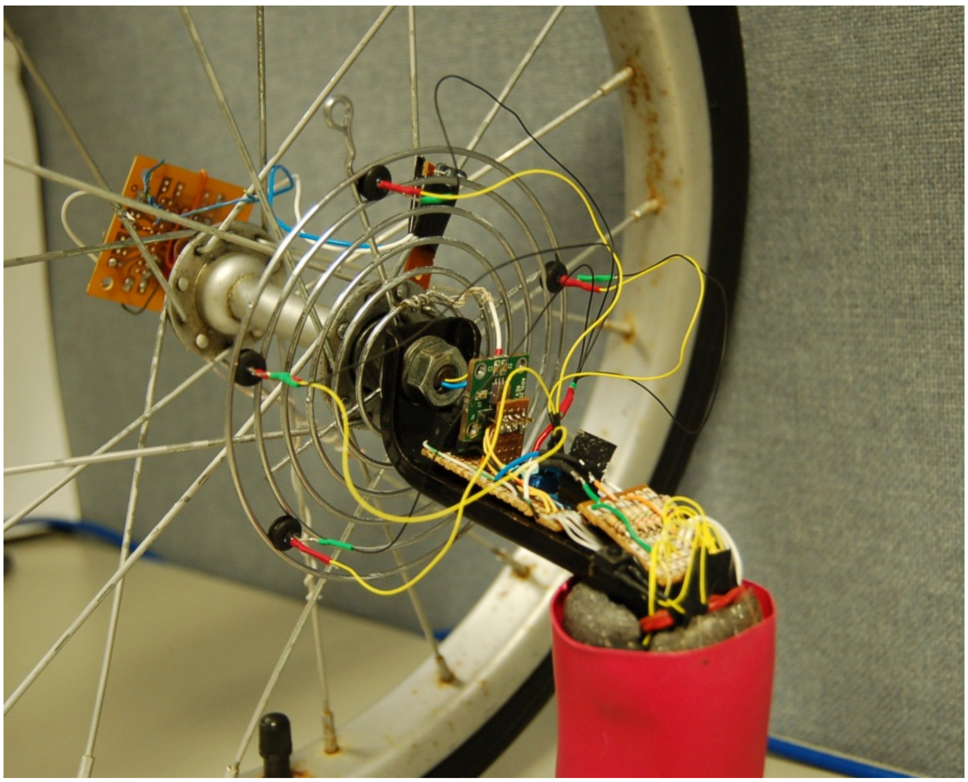

Figure 5–4: The IR detectors sometimes require realignment.

5.1.2 Springwave

The Springwave has not been as thoroughly tested as the Gyrotyre, but it has been tested enough to reveal some of its strengths and weaknesses. During one of the first tests, a fellow lab user remarked that the interface "Sounds like it looks", which was taken as a positive comment. The tight coupling between the motion and the sound is more pronounced than the Gyrotyre. There is an immediate and obvious connection between the motion and the sound so first time users had an idea of how to play it. The interface itself is simpler, with two sensing types, as opposed the the "mixed-bag" approach of the Gyrotyre. Consequently, its range of sound is narrower than that of the Gyrotyre, which can be seen as a weakness by some. Due to the barely adjustable spring constant of the fixed spring, the approximate speed of the spring is constrained to a range of roughly 4.5 Hz to 8 Hz. This dictates the speed of the music produced, in that it is harder to quickly stop the motion. This can be somewhat compensated by the software, for instance by adding a "silencer" mechanism to the patch [8].

5.2 A conceptual framework for digital musical instruments

The issue of a DMI's range as mentioned above was part of a larger discussion between the author of this thesis and two lab colleagues. The outcome of these discussions is presented in [14]. The paper began as an attempt to devise a framework of musical interaction contexts that could encompass computer-based as well as traditional ways of performing music. Since the range of musical interaction contexts ranges from virtuosic acoustic performance to triggering multiple temporal events at the push of a button, it was necessary to find an approach that could be useful in describing as many performance contexts as possible. We have adapted Jens Rasmussen's research on human information processing [20] since it offered a promising approach and had been previously used by another DMI designer [5].

Rasmussen's research is based in human-machine interaction and has applications to industrial machine design. However his model of human information processing was found to be useful with regards to musical interaction. While our framework is based on Rasmussen's work, we found it neccessary to qualify and alter some of his ideas as they relate to musical interaction. Broadly speaking, he categorizes interaction behaviours as being either skill-, rule- or knowledge-based. Skill-based behaviour is characterized by continuous real-time response to a perceived signal. By skill, we refer to a an "automatic" response, where the performer is focused on the outcome rather than the action itself. Rule-based behaviour involves responding to cues from the system by executing learned procedures. Knowledge- or model-based behaviour is characterized by an active problem-solving approach toward a conceptual goal. Each of these behaviours has an information-type counterpart, namely: signals for skill-based behaviour, signs for rule-based behaviour and symbols for model-based behaviour. In terms of musical interaction, acoustic playing falls almost completely into the skill-based domain whereas many traditional computer-music interfaces fall into the rule-based domain. Figure 5–5 shows a visualization of the framework. A basic rule of thumb is that as one moves toward the skill-based side of the diagram, time plays a greater role, or put another way, the interaction is less tolerant of interruption.

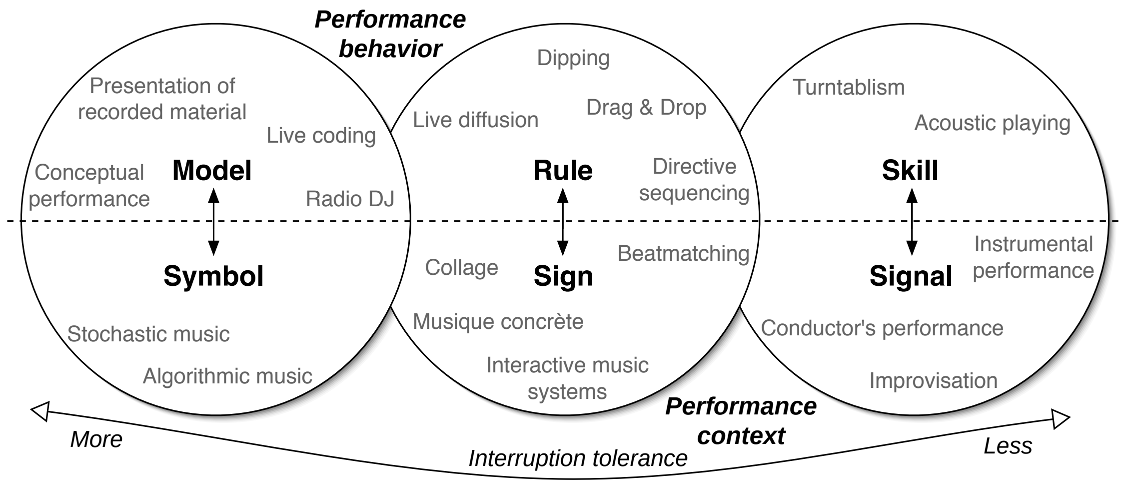

Figure 5–5: A visualization of the framework [14]

An example that illustrates the difference between the three modes of interaction is that of performing a drum rhythm. Consider a drum machine, such as the Roland TR-808. To create a rhythm, the user selects a drum type using a knob, and then places the drum in a 16-note sequence by pressing the corresponding buttons. When the start button is pressed, the sequence is played automatically at the selected tempo. This would be a rule-based way of performing a rhythm. A skill-based example in a similar vein would be using a drum machine controlled by trigger pads that require the performer to strike the pads in real-time. Of course, an acoustic drum kit would be another obvious skill-based example. Using the same musical interaction but on the opposite end of the diagram we can consider using the live coding tool Chuck [28] to create the same rhythm. Here the performer would take a model-based approach; playing a beat would require breaking the task into programming sub-tasks, namely creating a loop and deciding on an appropriate rest interval based on the desired tempo. This is even less immediate than the rule-based context, and the performer's timing of his actions is of considerably less importance than in the skill-based approach, where timing is crucial.

This framework can be used to think about specific mappings for DMIs and as well as to characterize DMIs based on what type of musical interaction they afford. To illustrate, let us consider two mappings of the Gyrotyre, the scrubber and the arpeggiator. In the first mapping, the interface controls playback of a sound file scrubbed backwards and forwards by spinning the wheel, evoking a turntable interface. The wheel may be spun very fast and then damped to achieve a descending glissando effect, or it may be kept spinning at a constant speed. This particular mapping of the Gyrotyre controller fits in the skill-based domain of the framework. To make a particular sound, the performer must control the speed of the wheel and listen to the sound for guidance. Any movement of the wheel, intentional or not, is audible in the sound produced.

In the arpeggiator mapping, spinning the wheel while pressing one of the keys on the handle repeatedly cycles through a three note arpeggio whose playback speed is directly correlated to the speed of the wheel. The performer changes the root note and the octave by tilting the Gyrotyre. In this case, performance behaviour is predominantly rule-based. The musician reacts to signs, such as the current root note and the speed of the playback. The skill-based aspect of performance is the sustaining of a constant speed of rotation while holding a steady root-note position. Ostensibly, a performer could practice to develop these skills, but this would offer little advantage as the instrument's output is discrete, predetermined pitches. Considering our framework we can determine two possible changes: the mapping could be altered to reflect the required skill in the musical output, and/or the root-note selection method could be mapped to a gesture more appropriate for a rule-based behaviour.

In addition to discussing individual mappings of a controller, the framework can be used to broadly characterize what types of interactions a particular DMI affords. Of course, the DMI and its mappings are inextricably linked, and in fact each mapping is considered its own instrument. With that in mind, each mapping can be roughly placed as a point on the visualization of the framework, and thus an aggregate characterization of the controller can be seen.

Considering the current mappings of the Gyrotyre and the Springwave, it can be concluded that the Gyrotyre affords a greater variety of playing contexts, mostly due to its variety of continuous and discrete sensing types. The Springwave generally affords more skill-based playing, and in fact its current mappings only support this type of interaction. Also, as was discovered during multiple improvisational sessions, skill-based mappings are generally more suitable for multi-performer improvisation, largely due to the more intimate control of timing.

CHAPTER 6
Conclusions

Computers and music now meet at many stages of the creative process and will continue to do so. Consequently, many new interfaces have been built in an attempt to widen the channel between performer and instrument. The standard keyboard and mouse are quite limiting as performance interfaces considering both the range of sounds possible with modern hardware and the range of gestures in the human repertoire. Controllers based on traditional instruments can be useful to trained musicians and in certain contexts, but they too impose restrictions and suggest implicit modes of playing. What suits one person may be cumbersome to someone else; what works in one context may be limiting in another. For playing a piece of classical repertoire an instrument-like controller may be ideal, but for navigating through a multi-parameter synthesis model it can fall short. There is certainly no general controller ideal for every situation and context, and in the author's opinion such an objective is misguided. Just as there are many approaches to making music, there are many approaches to DMI design and this thesis presents but one such approach.

While theoretical considerations are important and useful when designing a digital musical instrument, unforeseen insights are gained from building and using one. The goal of this thesis was to build and examine two digital musical instruments that make use of moving mechanical systems. The underlying intention was to explore the use of such systems to leverage the user's previous experience with physical objects in the hopes that they could have a more satisfying interaction with the interface. This proved to be a worthwhile approach, as both instruments afforded physical modes of use that were not anticipated by the designer. During an improvisation, one user played the Gyrotyre by holding the wheel stationary and sweeping the handle across the closely-arranged IR detectors. Similarly, shortly after building the Springwave, it was discovered that it could be silenced by placing one's hands between the pickups and the spring.

The multi-faceted, physical nature of each instrument served as fertile ground for sound-generating techniques, and different aspects of their physical behaviour were exploited by different mappings. Indeed the controllers are hard to imagine without their mappings, and it's equally hard to imagine these mappings controlled by another interface. While using the Gyrotyre's Omnichord mapping, the slowly turning spokes serve as a fitting visual counterpart to the harp-like arpeggios they drive, and as the wheel tilts higher, the notes follow upward. At the other sonic extreme, the screaming noisy synth patch howls as the wheel is spun faster. At a certain speed the precession effect is perceived, and if the performer gives in to the favoured trajectory, the control signals from the accelerometer sonify the trajectory as howls. As for the Springwave, the tight coupling between sound and motion make for a satisfying experience. A steady and repetitive driving of the spring with the pedal produces a hypnotic drone while a vigorous shaking of the spring wells up a bloom of harmonics. The flow from one human excitation to another is smoothed by the residual motion of the spring and its natural decay.

Music evokes motion, and motion evokes music. The Gyrotyre was originally conceived on a train while listening to the sounds being made by the steel wheels against the rails. The physical properties of a wheel seemed an interesting starting point for sound generation on a computer. The use of mechanical devices was done in an attempt to integrate the physical with the virtual. It was perceived as a way of injecting a physical nature into the control signals ultimately being used to generate sounds. Of course this could also be done computationally, but doing it physically has the added advantage of providing a tangible interface for the performer and visual feedback for the performer and audience alike. Digital musical instruments have been termed "physical handles on phantom models" [21]. However the Gyrotyre and Springwave can be used the other way around. While both were designed with specific sound-generating ideas in mind, a large part of the appeal was to devise new phantom models for the physical handles, as a way to generate sound that reflects the energy used to create it.

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