Digital Music Performance for Mobile Devices Based on Magnetic Interaction

Hamed Ketabdar, Amin Haji-Abolhassani, Kamer Ali Yuksel, Ihsan Kehribar, and Aytul Ercil

***Abstract*—Digital music performance requires a high degree of interaction with input controllers that can provide fast feedback on the user's action. One of the primary considerations of professional artists is a powerful and creative tool that minimizes the number of steps required for the speed-demanding processes. Nowadays, mobile devices have become popular digital instruments for musical performance. Most of the applications designed for mobile devices use touch screen, keypad, or accelerometer as interaction modalities. In this paper, we present a novel interface for musical performance that is based on a magnetic interaction between a user and a device. The proposed method constitutes a touchless interaction modality that is based on the mutual effect between the magnetic field surrounding a device and that of a properly shaped magnet. Extending the interaction space beyond the physical boundary of a device provides the user with higher degree of flexibility for musical performance which, in turn, can open doors to a wide spectrum of new functionalities in digital music performance and production.**

***Index Terms*—Digital music performance, electronic instruments, magnetic field sensor, multimodal interaction.**

I. Introduction

Along with the ongoing development of innovative technologies, audio production as a concept is in constant progress, through which artists are given unique opportunities to compose music and perform their artwork to the masses. Trendsetting functions and capabilities become available with a perpetual motion, inspired from the tendency of constructing audio through new and creative approaches. Specifically, diverse methods focused on new input technologies are being introduced that all aim to provide options untried before to artists' process of music creation and performance.

By far, magnetic field has been used in several applications such as orientation estimation [1] and pitch estimation [2]. Recently, we have proposed a magnetic interaction framework (MagiTact) [3] that uses magnetic field sensors for general-purpose interaction with mobile devices and has achieved an accuracy over 90% for gesture recognition. Similarly, in this work, we propose to use the magnetic field sensor (magnetometer) embedded in the new generation of mobile devices, such as Apple's iPhone 3GS/4G and Google's Nexus one, for musical performance on mobile devices. The embedded magnetometer provides a measure of magnetic field strength along the X-, Y-, and Z-axes (see Fig. 1). In this method, the user takes a magnet (that can be in the shape of a rod, pen, or ring) in his hand and draws coarse gestures in the 3-D space around the device (see Fig. 2). In comparison with touch-screen or keypad input, the proposed technique provides higher degree of flexibility for musical performance because the interaction space extends beyond the physical boundary of the device. Also, when using accelerometer-based interaction [4], the user has to repeatedly rotate the device to launch certain actions. This makes the user to loose direct eye contact with the screen, whereas in our proposed method, device orientation can be maintained and adapted to the user's natural behavior.

Several characteristics of an audio signal (such as frequency, equalization, filtering, etc.) can be altered based on changes in the magnetic field caused by the gestures. The position, movement, shape, and orientation of the magnet can also be used as an input modality to alter parameters of the music being played or being adjusted. We have employed these modalities to either emulate tuning and synthesizing tools or simulate some instruments (guitar, drum, harmonica, and theremin) by mapping gesture-based parameters to the specific audio characteristics of those instruments. Moving a tiny magnet around a device can resemble playing an instrument, and the phonation intentions of the user can be simulated on the mobile device by capturing his gestural pattern. In this way, we can design a natural means of digital music playing without entailing any change in the hardware or physical specification of the device [5].

Moreover, musical performance requires the manipulation of several interdependent parameters simultaneously; thus, its gestural interfaces need to be compatible with motor capabilities of users. The use of natural, intuitive, and touchless gestures performed around the device reduces the motor and cognitive load of the performer. The proposed method enables an innovative way of audio production and performance that can be utilized for different types of target groups, including both professional artists and leisure-oriented hobbyists. Furthermore, the use of natural and intuitive gestures is consistent with the mobile music technology challenges regarding the action–sound relationship and music–movement correspondence.

This paper extends the idea presented in [6] with the study of the state-of-the-art digital music synthesis principles in the context of magnetic interaction and the study of other modalities used for music interaction and finally presents some instrument prototypes. In this paper, we have done a thorough

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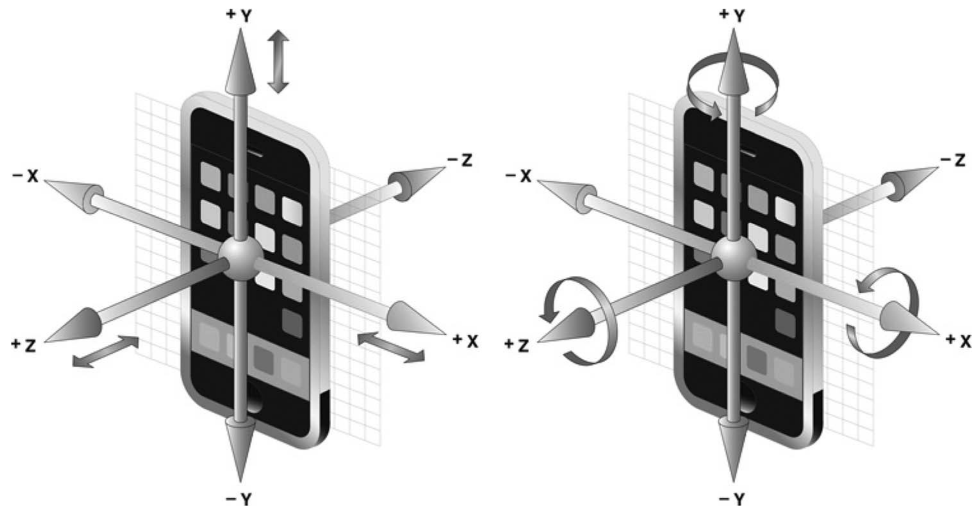

Fig. 1. X-, Y-, and Z-axes of the magnetic field sensor that can detect linear and rotational motion during digital music performance.

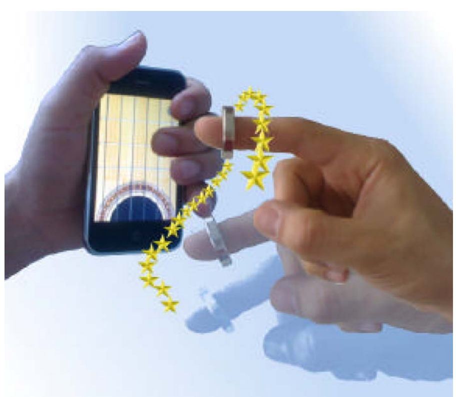

Fig. 2. Magnetic-interaction-based digital music performance developed on iPhone 3GS.

study in state-of-the-art techniques in digital music performance. Section II explains a wide variety of musical interfaces developed in this area. In Section V, we have put all these different modalities together and have studied their pros and cons comparing to our proposed magnetic interface. Proximity and motion sensors, for instance, are two important modalities that are currently used in music performance literature. Therefore, we have added these modalities along with optical-based and touch-screen-based interactions to provide a comprehensive set of modalities. In that way, we were able to compare our method with state-of-the-art techniques and highlight the advantages and disadvantages of our proposed method.

In order to gain sufficient knowledge for bringing together the engineering and the musical aspects of this interdisciplinary project, we need some background in the field of music. Thus, in this paper, we have devoted some parts to elaborate more on technical details of music generation. In Sections VI and VII, thus, we have explained some necessary information for music generation and modulation. By that means, we were able to properly explain different mappings between the magnetic modalities and audio features of music. This will give us an insight in the generation of music and sound effects by using our framework that is explained in the following sections.

II. Related Works

Series of previous works have been established so far to develop new methods to provide control on a digital audio creation environment [7]. Lots of researchers have already attempted to propose different mappings of action to the audio synthesis. The mappings can be explored in two fields in terms of their excitation type: sustained and impulsive. The sustained mappings are based on continuous energy transfer such as the 3-D motion data that are captured using different types of sensors, whereas the impulsive mappings are discontinuous and generally triggered using gestural interfaces.

In an early work, Campo *et al.* [8] proposed a design for generalized sonification environment to deal with experimental data analysis and exploration. Then, Klein and Staadt [9] described a technique for the sonification of 3-D vector fields to map vectors in a listener's local neighborhood into aerodynamic sound. Afterward, Pelletier [10] described another motion-based framework for the generation of large musical control fields from imaging data using granular and microsonic algorithms, additive synthesis, and micropolyphonic orchestration. Bevilacqua *et al.* [11] extended 3-D optical motion capture sonification through gestural analysis via segmentation and pattern recognition. The impulsive mapping has been also widely investigated by designing gesture-based instruments. Wanderley *et al.* [12], [13] thoroughly investigated the gestural control of music and defined different aspects that should be taken into consideration for developing gesture-based digital instruments. Fenza *et al.* [14] presented a multilayer controller with three stages of mapping that explore the analogies between sound and 3-D movement spaces using Laban's theory.

Couturier [15] and Jensenius [16] defined the requirements for using mobile devices as digital instruments. Some researchers experimented sound generation using striking, shaking, and sweeping as natural gestures using an accelerometer. Kayali *et al.* [17] described a number of suitable gestures for musical expression with mobile and tangible devices. Malloch [18] provides the design and construction of a family of novel hardware input devices, a collaborative mapping system, and modal synthesizer software for gesture-based performance.

Bencina *et al.* [19] described a technique for developing gesture-sound mappings using a three-axis accelerometer of a Wii Remote controller. Dekel *et al.* [20] also used accelerometer-based gestures as input to musical instrument digital interface (MIDI) instruments. Gillian *et al.* [21] presented a gesture-based disk jockey (DJ)-effecting mobile game having vibrotactile feedback. Geiger [22] explains the efficiency of using touch screen as an input controller.

Similar designs of touchless instruments based on an electric field sensor (cathode relays) [23] and infrared (IR) proximity sensors [24] are also investigated for musical performance on portable devices. Usakli and Gurkan have also designed a touchless interaction environment by using an electrooculagram-based framework [25]. Essl and Rohs [26] analyzed a wide range of available sensors for their suitability in typical western musical performance practices. However, they did not mention the possibility of a multimodal interaction, and they have evaluated the magnetometer as only capable of sensing rotational motions with respect to magnetic field rather than employing an additional magnet to interfere the magnetic field to sense linear motions. Then, they explained the challenges for turning the devices into performance platforms [27] and discussed new ways for interactive music through sensors [28]. Finally, there have been works that demonstrate the importance of mobile musical performance via real-time collaborative (orchestral) approaches. Tanaka [29] presented the collaborative composing with mobile devices using MaxMSP music environment and open sound control (OSC) messages. Afterward, Wang *et al.* [30], [31] implemented an orchestral ancient flutelike instrument designed for the iPhone using a microphone for breath control and multitouch to represent the holes.

III. Methodology

In this paper, we propose different mappings to various sound characteristics for the sonification of a 3-D data vector provided by the magnetometer. Aside from the mappings, we explain how such a digital instrument can be realized using gesture-based and multimodal interaction. The magnetic field sensor provides a notion of magnetic field strength along the X-, Y-, and Z-axes. The vector of the Earth's magnetic field can be subtracted from the raw output to have the device orientation as the absolute reference frame. Furthermore, using the derivative of the raw data allows us to alter sound characteristics using the velocity of the generated motion and to remove the effect of static magnetic interference of the environment from the positional data.

The mapping of sound characteristics to the 3-D vector set provided by the magnetometer can be explored in two fields in terms of their excitation types: sustained and impulsive. The sustained mappings are based on continuous energy transfer such as the 3-D motion data that are captured using typical sensors, whereas the impulsive mappings are discontinuous and are generally triggered using predefined gestures. In other words, there are two distinct methods to employ the magnetic interaction in playing a musical instrument. The first method is to directly use the projection of the sensor's raw values, time derivative, or normalized value on XYZ-axes to provide three different modalities; these modalities can be directly mapped to various sound generation or modulation parameters. Thus, the resulting audio signal is a function of strength, position, polarity, and orientation of the magnet in the hand of the user. In the second approach, a sequence of sensor values shapes a 3-D gesture pattern. This pattern can be matched against a model to realize their corresponding gesture class.

Regarding practical options for the utilization of the proposed technology in audio production and performance, three incremental levels of application are considered: sound generation, modulation, and effecting. Using mobile devices as digital instruments, a group of users collaboratively controls the event-generating musical algorithms that trigger sound generation for sound synthesizers by providing parameters with the highest level of abstraction. Once these parameters are mapped to the predefined synthesizers, subtler parameters of the synthesizers are modulated afterward by the same group or simultaneously by another group of users. Finally, users can apply different sound effects onto the performance using gestures.

In order to experiment the proposed method, we have implemented several digital instrument prototypes on iPhone 3GS based on magnetic interaction. They offer some simple music composition options using predefined pitch intervals, a set of instruments, and popular sound effects. Along with these music composition emulators, a vinyl-scratching prototype is also realized on the same device using the same technique.

To do so, we have ported SuperCollider (SC) server [32], a real-time sound synthesis environment, to the iPhone operating system. The SC server supports a simple C plugin application programming interface (API) making it easy to write efficient sound algorithms that can then be combined into graphs for further analysis. Each prototype consists of a client-side application, which sends the raw XYZ data and recognized gestures to the server through the OSC protocol. On the server side, there is another SC patch that receives data from one or multiple clients and synthesizes the output parameterized sound. Using client-side application of the digital instruments, the user is able to connect to any SC server using wireless network and stream out the audio signal from any mobile or desktop device to the server side.

IV. Instrumentation

In order to practice the proposed method, we have benefited from the magnetometer integrated within the iPhone 3GS (AK8973N) that is a cheap small IC unit capable of producing 8-b digital output along the three axes with a range of 2000 T [33].

As for the magnets, we have used cylindrical and ring-shape permanent magnets in our experiments which indeed do not require any additional power source. The ring-shape magnet can be worn by the user, and the cylindrical one should be held in the gesture-making hand. The coating of both magnets is Ni–Cu–Ni, and the maximum operational temperature is 80 °C. Based on its physical characteristics, each magnet has an operational region which is a confined region of the 3-D space around the magnetometer sensor. The operational region can be defined by an inner and an outer sphere around the sensor where the magnet's presence can be sensed while it does not saturate the

TABLE I
CHARACTERISTICS OF THE MAGNETS

PARAMETER	CYLINDER	RING
COATING	NI-CU-NI	NI-CU-NI
MAX. OPERATIONAL TEMPERATURE (^{o}C)	80	80
INNER SPHERE'S RADIUS (cm)	0.5	1.7
OUTER SPHERE'S RADIUS (cm)	7.0	13.0
STRENGTH ($grams$)	610	11000
INNER DIAMETER (mm)	5.0	16.0
OUTER DIAMETER (mm)	5.0	26.8
HEIGHT (mm)	14.0	5.0

magnetometer. According to our measurements, for the ring-shape magnet, a 236-G magnetic power at a distance of 2.5 cm from the sensor was obtained which confines the operational region between 1.7 and 13.0 cm. For the cylindrical magnet, we obtained a 49-G power at the same distance to the sensor (2.5 cm) which limits the operational region between 0.5 and 7.0 cm. The inner and outer diameters of the ring are 16.0 and 26.8 mm, and its thickness is 5.0 mm ($+/-0.1$ mm) with the strength of approximately 11 kg. The length of the cylindrical shaped magnet is 14.0 mm ($+/-0.1$ mm), the diameter of its base is 5.0 mm, and its strength is approximately 610 g (Table I summarizes the characteristics of the magnets).

V. MULTIMODAL INTERACTION

Aside from the magnetometer, current mobile phones are equipped with quite a few number of other sensors. The magnetometer provides a touchless interaction framework in the 3-D space around the device by measuring static position, orientation, velocity, and acceleration caused by linear and rotational movements of a magnet. In this section, we have studied some of these other sensors that are already embedded in recent mobile phones. In each section, we will emphasize the advantages of our proposed magnet-based modality over the studied modality by explaining its characteristics and limitations in the application of digital music performance. We also propose some ideas on how using some of these sensors can enhance information obtained by the magnetic sensor. Obviously, different modalities presented in this section can be used in conjunction with the magnetic interaction framework. For instance, as presented in Section IX-A, we have developed an Air Guitar instrument for iPhone which uses both magnetic and touch modalities. The note is held on screen by a finger using touch screen, and it is triggered (played) in the air using a magnet.

A. Touch Screen

Touch screens have recently replaced the keypads and have become the most popular interaction method in mobile devices. Being capable of sensing touches made on the 2-D space of the screen, it can give users more flexibility and realizes a more natural experience. A resistive-type touch screen measures the location of the point where maximum force is applied and gives an average result if there are multiple sources, whereas the capacitive type can further provide multitouch information of each pixel by measuring the capacitance change of each pixel due to the proximity of the human skin. In general, they have quite high-resolution output in relation with their highly limited interaction space; however, they suffer from ergonomic problems, including hand fatigue. Moreover, playing musical instruments on the surface of a mobile device is not natural enough and usually requires both the user's hands on a single small surface of the mobile phone.

B. Motion Sensors

Aside from the magnetometer, there are two other sensors capable of measuring motion-related properties of the device within the 3-D space: the accelerometer and the gyroscope. An accelerometer is a sensor that measures the acceleration experienced by the device relative to free fall. The gyroscope, which is recently integrated to mobile devices, is able to measure the orientation of the device using the principles of the conservation of the angular momentum.

When using these motion sensors, the performer should shake or tilt the device in order to send a command to the device. Tilting the device would result in loosing the direct eye contact with the screen of the device. As a solution, one can use an external sensor and send the commands to the phone via this sensor; however, using a sensor node would reduce the mobility and usability of the device and would result in more power consumption.

Furthermore, both accelerometers and gyroscopes are not able to sense the absolute motion of a device. Also, the application of the gyroscope is only limited to the estimation of rotational gestures, whereas the magnetometer is used to sense both linear and rotational motions of the magnet with respect to the motion of the device. Enabling the user to estimate the absolute motion of the magnet, instead of the device, is also an important advantage of magnetometers as it provides more flexibility regarding ergonomics and the loosing of visual feedback in performing music by the device.

Motion sensor information can be combined with magnetometer output in order to remove the natural noise due to the performer's hand or the environment. This means that motion sensors can be used to make the output of the magnetometer independent of the orientation and movement of the mobile device, and this combination would let uncorrelated mapping of the motion of the device and the magnet to a different set of parameters separately.

C. Proximity Sensors

Proximity sensors measure the distance of an object to the sensor and can be classified into two types, depending on their working principle: reflective and capacitive. Reflective sensors emit a directional wave signal (e.g., ultrasonic or IR) and calculate the distance of an occlusion by measuring the time interval before the reflection is bounced back to the device. Although their maximum sensing range is typically higher than that of a magnetometer, they require the object to maintain a direct line of sight with the device in order to be sensed.

Capacitive sensors, however, are not directional, but they are subject to several noises, including air humidity, skin conductivity, etc. Although proximity sensors do not require any special equipment to interact with the 3-D space around the device, they provide limited interaction space to the performer and particularly are not reliable without calibration.

D. Optical Sensors

Cameras integrated in current mobile phones have fairly good resolution and can potentially be applied to digital music performance through optical tracking and motion flow estimation. Tracking a visual marker would lead to absolute positioning through a frame of reference and can be expanded by using a grid of markers. The main advantage of optical methods is that the performer is able to control multiple visual markers on the same reference frame; thus, collaborative digital performance is possible without requiring multiple devices. Optical flows estimate the relative movements using the correlations of the successive images, but the accuracy is dependent on the distance and lighting conditions of the background.

On the other hand, optical sensors consume lots of resources (both power and memory), their sampling rate is limited, their accuracy is highly dependent on illumination, and they are algorithmically more difficult to implement. The computational complexity of optical-based methods particularly renders this method impractical in the context of music performance where high-speed hand movements are inseparable part of it. Moreover, the interaction entails a direct line of sight, and extending the interaction framework to the 3-D space around the device requires even more resources, suggesting that optical sensors are not good candidates in the context of music performance on mobile phones.

The combination of the camera with the magnetometer in an augmented reality fashion would enable the abstraction of the semantics of the performance and would be very helpful for composition. In other words, the magnet can be used as a visual marker in the same time to give better visual feedback and compositional abstraction to the performer.

VI. Sound Generation

Generation of sound entails tweaking various audio components for composing a certain piece of music. Fundamental elements of music are various, and different categorizations can be considered, depending on the type of classification. Primary characteristics of a musical sound can be defined as pitch, harmony, timbre, dynamics, and duration. In order to generate a musical sound, several methods could be employed for practical use. Subtractive synthesis, additive synthesis, sample-based synthesis, and physical modeling are extensively applied in synthesizing sounds to model instruments. However, in addition to the acoustical aspects of sound generation, when conducting a musical performance, gesture signifies as an indispensable factor for naturally creating musical expressions.

Among the given elements, melody and rhythm are the directly audible elements of a music piece, while all other parameters determine the values for different qualities of audio. Several attempts have been made to design apparatus for imitating traditional instruments such as breath controllers for MIDI implementations. As one can assert that imitating an existing traditional musical instrument is a troublesome act, the use of a singular point interaction drives us to create singular musical events at a single moment in our approach. In our implementations, we have used the X coordinate of the raw data for the selection of notes defined with their pitch/frequency, and the Y and Z coordinates are mapped to major and minor chords, respectively (see Fig. 3). These parameters, which comprise information about the pitch, velocity, and rhythm (the tempo) of the sound, are routed to predefined synthesizers to create sounds of desired types. We believe that, by realizing such a mapping between the gestures and the key features of a sound, not only we are able to create a new modality for digital music performance but also possibilities for creative composition of musical pieces can significantly increase when using gestures to compose music, for it allows the user to adjust the parameters more naturally by giving him an impression as if he is playing the real instrument.

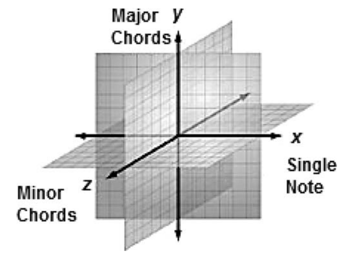

Fig. 3. Axes of the magnetic field data are mapped to notes in a subtractive synthesizer defined with their pitch and major and minor chords.

Here, the challenge is to map the sound parameters to the axes of the magnetic field in the way that the whole setup gives the user the impression of using the real instrument. Since the means of interaction between the user and the device is a magnet held (or worn) by the user, in the implementation of different instruments, the magnet should represent a realistic part of the instrument. For instance, when simulating a guitar, the effect of the magnet should resemble that of a pick when hitting the strings. Mapping of the coordinates of the magnetic field to sound properties can be carried out in a straightforward manner. That being said, invoking different sounds by the magnet in the way that different notes and chords can be distinguished by the user is a major issue that can give the user a natural feeling of playing the instrument. In our example of the guitar, for instance, the challenge is to map the effect of moving the magnet in the surrounding area of the phone so that it simulates hitting different strings when the user reaches different parts of the magnetic field. The recognition of the hitting pattern and localizing the target of the hit, then, are two challenges toward simulating the guitar.

VII. Sound Modulation

After the creation of a certain type of sound, it is possible to modify its characteristics with a subtractive sound synthesizer through a high number of parameters, including but not limited to amplitude, resonance, pan, stereo spread, envelope, and vibrato [34]. The aforementioned sound generation model determines what is to be played, and controlling these subtle details enables us to give the generated sound different expressions.

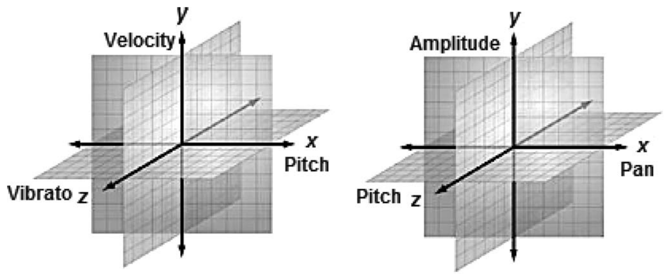

Fig. 4. Different combinations of sound characteristics mappings that are considered for the sound modulation.

In addition to the pitch-based sound generation functionalities of a magnetic interaction, different allocations of axes to modifiers of sound characteristics will enlarge the scope of this modality in sound production and effecting (see Fig. 4). The overall effect will resemble a magnetic music synthesizer that can operate on top of the proposed music generation scheme.

The application of the magnetic synthesizer on a sound track can be done in real time (e.g., collaboratively) and offline. In the real-time mode, two operators (nodes) can work together to generate and modulate a sound track. This is possible since both the sensors send commands to a unified PC-based sound generating server (SC), where the final sound is generated and modulated according to the commands from the corresponding sensors. The modulating node can assign different functionalities, such as amplitude, vibrato, velocity, pan, and pitch (see Fig. 4), to each coordinate of the sensor. The resulting commands obtained via spotting the location of the magnet in the magnetic field of the modulating sensor, then, will be used in the server to modify the corresponding properties of the output sound.

Another way of modulating a sound track (offline mode) is to play a pregenerated sound in the background on the server and modify its properties according to the coordinates of a magnet in the vicinity of the modulating node. In both modes, the passage between different mappings of sound effects in the modulating node can be indicated using magnetic gestures, as an alternative to the touch-screen interface.

VIII. Sound Effecting

Sound effect can be shortly defined as an enhancement brought to a certain sound with alterations applied to the signals. Sound effects can create dramatic changes on any parameter of a sound and enable a number of opportunities for shifting musical components to various forms. Hence, it supplies advanced sound processing capabilities to any audio performance software. With the unique freedom given by the proposed method to utilize the three axes of the magnetic sensor for altering different parameters of a sound, modification and effecting, various combinations can be considered for the desired type of music scoring performance, each with a potential to deliver diverse qualities.

While it is possible to reach further results with combinations of parameters, a brief list of possible sound effects is as follows: equalizer, pitch bend–pitch shift, reverb, delay/multitap, compressor, chorus, limiter, fuzz, distortion–overdrive, flanger, phaser, de-esser, noise gate, and ring modulation. For that reason, we have proposed several mappings of sound effect to the axes of the magnetic field sensor. The sound effects can be applied collaboratively or simultaneously to enhance the digital music performance. The passage between different mappings of sound effects can be performed using magnetic gestures, as an alternative to the touch-screen interface.

IX. Magnetic Instruments

In the following sections, we present the mobile music applications that we have implemented based on the magnetic field interaction. The applications are developed for Apple iPhone 3GS. In order to facilitate the actual implementation of music applications in the trial, magnetic signals captured by the mobile device (iPhone) are sent to a PC-based SC server [32]. Sending data to the SC server is only to simplify the sound synthesis part, and the magnetic interaction is fully implemented through the mobile device. Therefore, there are two components for each application: a client on iPhone 3GS and an SC server on PC. The client sends the data related to the magnetic field surrounding the mobile device to the server over wireless network. The SC server takes the data from one or multiple clients and synthesizes the parameterized sound.

In order to simulate sustained instruments, we have used the raw output of the magnetic sensor as well as its time derivative to constitute a feature vector to be used for tuning certain parameters of the sound being generated, whereas for impulsive instruments, we check for a certain gesture pattern in the data provided by the magnetic sensor. Depending on the application, sometimes, a transformation of magnetic sensor output can be more useful than raw signals. The transformation can be time derivative or calculating norm of magnetic signals. Time derivative operation can be particularly important when there is a need to remove the effect of the Earth's magnetic field on the sensor. In this case, time derivative operation acts as a high-pass filter and removes the effect of the Earth's magnetic field. For instance, in a guitar application, a triggering like gesture in the air (by magnet) can be easily highlighted in time derivatives of magnetic sensor output [3]. A demonstration video of some of the implemented instruments can be checked at http://www.deutsche-telekom-laboratories.de/~ketabdar.hamed/MagiThings/MagiSoundclear.m4v

A. Guitar

A guitar is a musical instrument belonging to the chordophone family which has six attached strings. Playing a guitar is performed by two distinct actions: strumming and holding (locking). In a normal guitar, strumming comes along with periodically scratching the instrument strings with the right hand fingers. The left hand presses different pitches on different strings alongside the neck of the guitar to generate different tones. In touch-screen-based guitar applications offered recently on mobile phones, one can pluck the simulated guitar by scratching the touch screen. The action of holding a note is also done on the same screen (three different areas for each string). Such arrangement for playing the guitar can be to some extent unnatural and inconvenient since it requires using both hands on a small screen of the mobile device.

In our guitar application (Air Guitar), we have replaced the touch-screen-based strumming action with a 3-D gesture-based action in the space around the device. We let the holding (locking) action to be remained on the touch pad. However, the strumming is implemented with magnetic interaction to imitate the natural action. For string triggering (strumming), values obtained by the X-axis component of the magnetometer determine the string which should be triggered. The range of values is divided into six intervals, each representing a particular string. The key factor to detect the triggering gesture (action) is a rapid change in the magnetic field sensed by the magnetic sensor, which corresponds to the rapid movement of the fingers with the magnet in a gesture similar to strumming. This can be detected by comparing the variance of magnetic field (estimated over an interval/window) with respect to a predefined threshold. The rapid movement of fingers (with magnet) in the air creates a rapid temporal change in the magnetic field around the device, and makes the variance of sensed magnetic field exceed the threshold. To avoid stepping changes from one string interval to another, we have considered a gap between these intervals (X component values) in which no tone will be played.

The combinations of pitches (selected by touch screen) and strings (six strings triggered in the air) result in 24 different states that are sent to the server for playing the corresponding sound.

B. Drum Kit

The drum is a cylindrical shaped instrument from the percussion family of musical instruments. Normally, in percussion instruments, the head of the cylinder is covered by some sort of elastic skin that one can hit by hands or by some special sticks. In playing a drum, two main factors are taken into account: the strength of the hit and the radios of the hitting point to the center of the surface. In our method, to simulate the hand gesture on the instrument, the Z component of the magnetic sensor output is mapped to the vertical movement of the hand toward the surface. The second time derivative of the Z component signal is interpreted as the strength or energy of hitting. The greater the strength (energy) is, the louder the sound will be generated. The X component of magnetic sensor output represents the radial distance to the center of the instrument, indicating the tone to be played. Having a magnet in hand, one can magically play a drum by hitting back and forth in the air toward the surface of the device, and right and left with respect to the center, to obtain different tones. The tone is played only if the strength (second derivative of the Z component) exceeds a threshold. If the tone is played, the strength (loudness) of the tone would be proportional to the second derivative of the Z component. Using touchless magnetic interaction in our drum kit for detecting the hit action can be superior to the use of the touch screen, as the strength of the hit cannot be easily calculated based on touch screen. In addition, in our drum kit, we are using a hitting gesture similar to the real drum, which can be more natural than hitting on a rigid screen surface.

C. Harmonics

Sound harmonics are integer multiplicands of a base sound frequency. In some instruments such as metallophones or xylophones, on any consecutive pitch of the instrument, an individual harmonic can be produced. In a metallophone, different metal bars with different sizes are mounted to an oscillating frame. With a mallet, one can strike on different bars to generate different harmonics. To play one particular metallophone, two factors determine the type and quality of the output: the metal bar that is stricken and the strength of the strike. In our method, the X value of the magnetic field (sensed by the magnetic sensor) is dedicated to represent the bars on the instrument. We have split up the X-axis value range of the magnetic sensor into 24 different intervals. Depending on the value of the X component, the index of its corresponding interval $(1:24)$ represents the bar which should be stricken on the simulated metallophone. The strength of the strike can also be obtained in the same way as the drum kit.

D. Theremin

The theremin is a touchless electronic instrument that is controlled by two different shape antennas. The task of the antennas is to detect the distance of the player's hands to the antennas and to track the oscillations of the player's hands. The distance of players' hand to one antenna is used to change the frequency (pitch) of the sound and the distance of the other hand to the second antenna is used to adjust the amplitude (volume) of the sound. In order to simulate the theremin based on our framework, we have assigned the X-axis of the magnetic sensor to control the frequency of the sound. The Y-axis value is also used to control the volume of the sound. Forwarding these settings to the SC server, we can play the appropriate sound resembling the original theremin.

E. Sound Modulation and Effecting

After the creation of a certain type of sound, it is possible to modify its characteristics through a high number of parameters, including amplitude, resonance, pan and spread, velocity, attack/decay/sustain/release, legato, and vibrato. Modifications on the characteristics of an already created sound enable different expressions to be obtained. Sound effecting is enhancement brought to a certain sound with alterations and diversifications applied on signals. Sound effects can create dramatic changes on any possible parameter of sound and enable a number of opportunities for shifting musical components to various forms. The value of the magnetic signals registered by the magnetic sensor can be used as a basis for altering different sound parameters. As a sample for sound effecting, we briefly mention a DJ application developed based on the concept of magnetic interaction.

F. DJ

DJ is the title of a person who plays and synthesizes different types of recorded music for the audience. To simulate a DJ medium, we developed an application on a mobile device that enables the DJ to tune and combine music by means of magnetic field interaction. For a demonstration, we have implemented two standard effects that a DJ can control: crossfading and scratching. Crossfading is the way to interlace two playing sounds. In a simpler sense, crossfading means to increase the power of one sound and decrease the power of the other. On a DJ desk, there is a fader slider that overlaps music with another. How smooth or fast two songs can be faded depends on the DJ's technique. If V_1 is the volume of the first sound, V_2 is the volume of the second sound, and C_1 and C_2 are their corresponding coefficients, the volume of the output sound V_o can be defined as

$$V_o = (V_1 \times C_1) + (V_2 \times C_2) \text{ and } C_1 + C_2 = 1. \quad (1)$$

Scratching is a technique to play a part of previously recorded music back and forth. The effect of doing such an action is hearing a cutting sound. Naturally, scratching is the act of moving, stopping, and reversing a disk on a music turntable. It is known as scratching since the DJ's finger acts like he/she is drawing some scratches. In our work, we have assigned the X-axis values of the magnetic sensor to the crossfading action and the Y-axis to the scratching action. C_1 and C_2 coefficients are calculated based on the X component of magnetic sensor output, hence the relative position of the hand with magnet on the X-axis. In this way, the DJ can obtain different mixtures of two sounds by moving his hand left and right with respect to the device. Scratching effect is produced when a sharp movement of the magnet in the Y-direction is detected. The tuning data obtained by the mobile-phone–DJ interface will be sent through wireless network to an SC server to synthesize the output sound based on the user settings. The advantage of such a setting is that the DJ can keep his natural gesture to tune the sound output while he can freely move through the audience. DJ pooling can also be imagined when several mobile DJ terminals join to a central server.

X. Collaborative Performance

The SC server can be used with other languages or applications having any number of input/output channels because all external control in the server happens via OSC. Furthermore, it gives access to an ordered tree structure of synthesis nodes, which define the order of execution with a bus system dynamically restructuring the signal flow. Thus, any SC server is able to receive data from multiple clients simultaneously through the wireless network. The SC server does not send or receive sound because it is expected that clients will send all control commands for the synthesis. Patching between modules is done locally through global audio and control buses.

In order to perform collaboratively, a group of users can simultaneously generate sounds of different types of digital instruments. Then, the characteristics of the generated sound are modulated afterward by the same group or simultaneously by another group of users. For instance, one performer can alter various characteristics of sounds that are generated from the control data of another performer. Finally, users can apply different sound effects onto the output of this collaborative performance using gestures.

In case of collaborative performance, the system requires the central server to be the only audio output source due to latency and synchronization issues that might occur. Therefore, it requires all of the users to be in the same place and able to get audio feedback at the same time from the central server. This assumption removes synchronization concerns and ensures suitable latency because it reduces the amount of data that needs to be sent, as it only requires the raw or derivative sensor datum and user interface input specific to the digital instruments. Each user selects the appropriate SC patch, which belongs to the digital instrument that he wants to play. SC patches interpret the received data in real time to collaboratively produce the sound output using shared buffers for writing and reading.

Accordingly, we have implemented a final prototype similar to the Mobile Electronic Orchestra [31] where multiple mobile devices play the role of various instruments to form a philharmonic orchestra. In a real orchestra, strings, brass, and percussion sections are collaborating to compose an intertwining music. This instrumental ensemble can also be leaded by a constructor to keep the overall playing process organized. In order to establish such an orchestra, we have installed each client implementations described earlier on different mobile devices to perform the music collaboratively. The prototype is able to perform without any problems while manipulating the same music sample simultaneously.

XI. User Feedback and Studies

The presented prototypes of instruments in this paper should be considered in the context of entertainment for mobile devices. In this section, we reflect the feedback that we obtained from different users (mainly attendees of conferences, some music experts, and students) when they are exposed to the prototypes as an initial user study. Clearly, as the methodology extends to professional music synthesis, a more systematic user study with music expert participants should be conducted.

The users exposed to the prototypes found the methodology interesting in general and a new concept in the field of digital music synthesis. Based on user feedback, we have learned that magnetic instruments based on the sustained mappings, which generate tones of any pitch throughout its entire range, are very easy to use due to the flexible, natural, and intuitive interaction. Directional movements of the magnet allow producing small and reliably reproducible changes in tone quickly and even were able to create tremolo or vibrato effects by themselves.

On the other hand, they were difficult to specialize due to the control of the instrument's pitch with no guidance, as it does not have physical feedback (except audio feedback), such as string tension or the tactile fingerboard for strings. Moreover, users found it difficult for composing to repeat their absolute sonification intents after an interval, as it is hard to represent semantics of a touchless performance. Furthermore, professional performers sometimes experienced a vocal slide between two pitches. Consequently, touchless sustained instruments are more suitable to perform legato on continuously variable pitch instruments.

Performers agreed that several opportunities arise from binding any possible sound generator or modifier to the axes of magnetic based interaction. They also agree that multimodal interaction increased the ability and wealth of their performance. Moreover, they suggested using more complex forms of magnetic modalities such as electromagnets, where the strength is controlled through haptic interaction with respect to, e.g., user's squeezing gesture, as multiple motion-dependent mappings may increase the cognitive load of the performer.

XII. Conclusion and Future Work

In this paper, we have proposed a novel interface for musical performance that is based on the magnetic sensor integrated in the new generation of mobile devices. Moreover, we have proposed different mappings of sound characteristics for the sonification of the 3-D vector datum of the magnetic field. Aside from the mappings, we have explained how such a digital instrument can be realized using gesture-based interaction. The proposed interface allows the digital imitation of a broad number of instruments while still being able to sense musical hits and relative plectrum gestures. It provides a framework for extending interaction space with music applications beyond physical boundaries of small mobile devices, and to 3-D space around the device, which allows for a more natural, comfortable, and flexible interaction. Finally, we have presented several mobile digital instruments developed based on the proposed method on the iPhone operating system. Through trained motions of a professional artist or a leisure-oriented hobbyist, the proposed technology is very likely to bring a new and effective trend to the concept of digital music performance in mobile devices.

This paper extends the idea presented in [6] with the study of the state-of-the-art digital music synthesis principles in the context of magnetic interaction and the study of other modalities used for music interaction and finally presents some instrument prototypes. An initial user study and feedback is also supplied which is generally based on comments of different users when they were exposed to the prototypes. This paper presents the prototypes as demonstration of the idea in the context of "entertainment" on mobile devices. However, the proposed idea can be further extended for designing professional instruments. A user study in professional cases should be planned with digital music synthesis experts.

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