

Experiments with Virtual Reality Instruments

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ABSTRACT

In this paper, we introduce and analyze four gesture-controlled musical instruments. We briefly discuss the test platform designed to allow for rapid experimentation of new interfaces and control mappings. We describe our design experiences and discuss the effects of system features such as latency, resolution and lack of tactile feedback. The instruments use virtual reality hardware and computer vision for user input, and three-dimensional stereo vision as well as simple desktop displays for providing visual feedback. The instrument sounds are synthesized in real-time using physical sound modeling.

Keywords

Musical instrument design, virtual instrument, gesture, widgets, physical sound modeling, control mapping.

1. INTRODUCTION

Physical sound modeling is an active research area. Real-time implementations of these models make it possible to alter any parameter of the model while playing, offering more freedom for lively performances. This creates a need for controllers whose input flexibility matches the control complexity of the sound models. Virtual reality (VR) input technology, such as data gloves and location/orientation trackers with gesture analysis, is one way of offering several natural degrees of freedom. We have created several musical instruments that use this approach. See our project web site for additional information and videos [20].

An article by Paradiso [13] and a book edited by Wanderley and Battier [17] offer a good introduction to existing electronic interfaces and gestural controllers. Many of them have been created during the last few decades, even a few commercial ones [23], [26]. However, there has been little research on virtual reality interfaces for sound control [1], [8], [10]. The interfaces presented in this paper are perhaps more “instrument-like” than most of the other virtual reality interfaces, which have been more of the type of interactive sound environments or interactive filters.

There are few quantitative studies that compare sound control interfaces [16], [19]. Also, the importance of parameter mappings

has only lately become a topic of active study [3], [4]. On the other hand, there is a lot of literature on how to design musical interfaces [2], [5], [9], [10], [18]. However, more research on the effects of individual interface properties is needed. For instance, virtual reality interfaces are bound to differ from classical instruments, as the medium and its properties are fundamentally different. VR technology introduces some latency, cannot easily simulate tactile feedback, and is limited in both spatial and temporal resolution. For instrument design in VR, it is important to know the effects of these properties. Only then can we find out the strengths and weaknesses of the approach, and give suggestions on the kinds of interfaces it is well-suited for.

Our analyses of the presented instruments have two emphases. First, we state our design experiences and research on the above concepts. Second, we use Sergi Jorda’s theoretical framework [6] to evaluate the potential and expressiveness of the instruments.

The presented instruments utilize two interaction approaches: gestural control, and interaction with virtual objects called widgets. In this context, gestural control means control by body motion without directly interacting with any physical or virtual objects. Virtual widgets are computer graphic objects the users can interact with. For example, a Virtual Xylophone instrument includes mallet and plate widgets.

2. HARDWARE

Most of the instruments were created in a Cave-like virtual room, called EVE, in our laboratory [22]. Visualization of the virtual environment is back projected onto three walls and a floor of a three-by-three meters large cube-shaped room. The users perceive the visualization three-dimensionally through active stereo shutter glasses. Virtual objects can be created to be perceived at any distance around the user. The rendering is done by an SGI InfiniteReality Onyx2 running an IRIX 6.5 operating system.

User input comes from data gloves (5DT) and a magnetic motion tracker (Ascension Technologies MotionStar). MIDI devices can also be used. The motion tracker has six sensors. It samples the three-dimensional location and orientation of each sensor at a rate of 100Hz. The spatial resolution is about 1cm/2 degrees. Both gloves measure the user’s finger flexure and return one integer number for each finger defining how much the finger is bent. The gloves are not able to simulate tactile feedback.

EVE’s sound system consists of 15 loudspeakers surrounding the cube-shaped room, behind the screen walls. Vector Based Amplitude Panning [14] is used to make the sounds originate from any desired direction.

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Two of the instruments were also implemented in a desktop environment. Their user interface is based on a web camera and computer vision technology, and they run on a typical Linux PC.

3. INSTRUMENT INTERFACE SYSTEM

The main goal of the instrument interface system was to make prototyping quick and easy. Any input from any interface can be easily mapped to any parameter(s) of the controlled sound model(s). Next, we describe the main components of the system.

- *Input devices.* The system can use a variety of input devices, such as data gloves, magnetic trackers, computer vision and MIDI controllers. Input is acquired from input devices at a high and constant rate, allowing for precise rhythmic control of sound.

- *Input processing.* The user interface components can access all collected input data, and process it in any way to extract desirable features, such as gestures, and produce any number of new output values/events. For instance, a xylophone plate component may send its distance from a mallet, collision speed with the mallet, location of the collision in 3D space, and so on.

- *Control parameter mapping module.* The parameters from the interface components control the parameters of the sound models through a mapping module. The mappings can be created using a visual mapping editor application.

- *Control language.* We developed an expressive control language that contains MIDI as a subset. As physical sound models can be computationally heavy, controlling was made possible over a network.

- *Visual feedback.* The performer is surrounded by a 270 degree virtual reality view, able to produce any kind of stereoscopic computer graphics.

- *Collision detection and other object interaction.* We now use a simple collision detection library [21] but we are in the process of integrating a more physically realistic one [25] to the system.

- *Sound models or MIDI synthesizer.* A plug-in based software called Mustajuuri [24] is used as a DSP platform. Each sound synthesis model is converted into a Mustajuuri plug-in. As MIDI is a subset of our control language, MIDI synthesizers can be controlled as well. However, in the instruments presented here, we did not use commercial MIDI devices, but concentrated on VR interfaces and physical sound models instead.

3.1 Mapping the Control Parameters

Control parameter mapping means routing the user interface parameters into the control parameters of the sound model(s). Our configurable mapping module allows any amount of input parameters to influence any amount of output parameters.

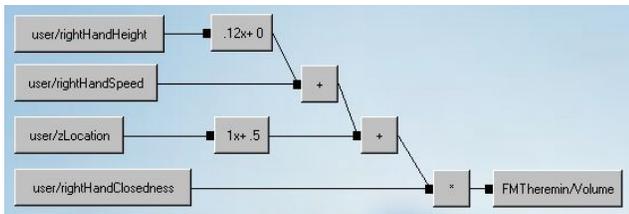


Figure 1. Screen shot of a mapping from the mapping editor. The mappings are created as node trees (the Nx+y node in the figure performs a scaling and offsets the input signal).

For ease of use, we made a graphical editor for creating and editing the control mappings. Its visual node tree gives the user a clear view of each mapping and of the parameters in it.

4. ANALYSIS FRAMEWORK

In Jorda's analysis framework [6], efficiency and learning curve are the main concepts. The framework is aimed at analyzing professional instruments, and does not directly take into account user satisfaction or the appeal of the experience. Our instruments were mostly show cases inspecting possibilities, designed to offer inspiring experiences. Despite this, we use the framework in our analysis, as it offers one useful perspective. We also share our design experiences in the analysis part.

4.1 Efficiency

The efficiency of a musical instrument measures the relation of musical output complexity to control input complexity. This value is scaled with performer freedom, which represents how much control the performer has over the output. Although a CD player produces great music, its performer freedom is low, as the user can do little to influence the music. The equation parameters are not easily quantifiable, and we will only attempt to estimate them in our analysis.

$$\text{instEfficiency} = \frac{\text{outputComplexity} * \text{performerFreedom}}{\text{ControlInputComplexity}} \quad (1) [6]$$

4.2 Learning curve

Learning curve represents the behavior of efficiency as a function of practice time. Simple instruments, such as a Tibetan Singing Bowl, will likely not allow one to find new levels of expression after years of playing in the way a piano or a violin will. A good balance between challenge, boredom and frustration is sought [6].

Classical already established instruments are accepted to have a long learning curve. People are also accustomed to notice subtleties in their playing. However, new instruments are likely to require a shorter learning curve in order to become accepted.

5. INSTRUMENTS

We will now describe four instruments created with the system presented earlier. Each description is followed by design experiences and a short analysis of the instrument in question.

5.1 Virtual Xylophone

The Virtual Xylophone interface consists of a user-definable number of virtual xylophone plates and two virtual mallets. In his hands, the performer holds two magnetic sensors, from which the VR mallet visualizations extend. The mallets inherit the location and orientation of the sensors and cast shadows on the plates.

Collisions are detected between the virtual mallets and the xylophone plates, controlling the corresponding DSP objects accordingly. Hit velocity is mapped to the amplitude of an impulse sent to the sound model. The hit location on each plate affects the decay time of the sound. The instrument allows a polyphony of several sound models.

On the left side of the performer, the interface displays a large piano keyboard. The performer can grab keys with their left data glove. This creates a new xylophone plate of the chosen note,

attached to the user's hand. The note name, such as C5, is also displayed above the plate. The performer can then move the plate to any place and orientation in 3D space. Grabbing and moving existing plates is also possible. The arrangement can be saved and loaded. Figure 2 shows a performer playing a complex layout.

The possibility of moving plates and creating new ones allows the user interface to be customized even for the needs of individual pieces of music. Chords can be constructed by piling plates on top of each other. Short passages can be made by stacking plates further apart, played with one swift motion that goes through them all. Thus, difficult passages can be made easier to play.



Figure 2. A performer playing the Virtual Xylophone. By moving and creating new plates, the performer has created a custom interface for playing a particular musical piece.

5.1.1 Analyses

Because both the mallets and the plates exist only virtually, the mallets can pass through the plates without resistance or recoil. While at first this seemed to bother some users, it elicited a new playing style, where plates could be struck from both sides by moving hands on smooth, elliptical paths. This is markedly different from traditional Xylophone playing, and allows for playing with continuous motion.

Due to the tracker's limited spatial resolution, the motion paths in playing the Virtual Xylophone are larger than with a normal xylophone. There is a latency of approximately 60ms between striking and hearing the sound. Yet, without tactile feedback, the sound and visualization, both delayed, are the only cues of the exact collision time. Thus, the delay is not so noticeable.

The Virtual Xylophone is effectively a different instrument than the traditional xylophone. Plates can fill the entire space around the user, and are relatively large. Moving between them is not as fast as with a traditional xylophone. The sound is more flexible, and the configurable user interface offers possibilities to make playing easier, and for making effects, such as patterns and chords. The instrument is intuitive to anyone familiar with the traditional xylophone.

Based on initial feedback from early user tests, the configurable interface considerably increased the appeal of the instrument. Making chords and short sequences was seen to be very rewarding. The people testing it were excited and inspired.

The efficiency of the Virtual Xylophone can be altered by creating different layouts of plates. The performer has real-time control over three parameters: amplitude, note and decay time. All are controlled by varying the style of striking. The performer can also create chords and sequences and improve the interface by

placing the plates optimally for each musical piece. This increases the efficiency considerably. Yet it also interferes with learning, as each interface is different and usable mostly for a particular piece. We do not yet know if some layout would be a good general solution. Possibly some core of the layout could stay the same.

The learning curve of the instrument is gentle in the beginning. The concepts of playing and modifying the interface are easy to grasp. The instrument is likely to stay interesting for a long time. Unlike with the traditional xylophone, this does not come so much from acquiring kinaesthetic mastery, but from discovering the possibilities of the interface, and from better understanding of how individual interfaces should be designed.

5.2 Gestural FM Synthesizer

The Gestural FM Synthesizer is an evolution of the somewhat famous Theremin instrument [26]. The original Theremin, invented in 1919, is considered to be the first gesture controlled instrument. It is played by moving one's hands in the air near two antennae. The right hand controls the pitch of the instrument's simple sine wave oscillator. Moving the hand closer to the antenna increases pitch, and moving it away decreases it. Amplitude is controlled by moving the left hand relative to a loop-shaped antenna located on the left side of the instrument.

Playing the original Theremin is difficult, and requires perfect pitch hearing, because the only feedback is aural. Finding notes on the instrument requires recognizing them through hearing. The basic sine wave sound also limits expressiveness.

We created the Gestural FM Synthesizer in the spirit of the original Theremin. For a more interesting sound, we replaced the sine wave with a preconfigured FM synthesizer. The sound was set to simulate brass with infinite sustain for a continuous sound.

The instrument is played with data gloves. The pitch of the sound is controlled by moving the right hand up and down, and the amplitude by opening and closing the fingers of the right hand - as if the performer was letting the sound out from his hand. When closed, the left hand's relative position alters the timbre by slight changes in modulation indexes. When the left hand is open, the modulation indexes remain unchanged.

The instrument also offers a visualization of a musical scale as a vertical piano keyboard. A thin line is projected from the performer's hand to the current pitch on the keyboard. The pitch is continuous; the keyboard is only a visual aid.

5.2.1 Analyses

As a result of the visual feedback, users found it much easier to find particular notes on the Gestural FM Synthesizer, compared to the original Theremin. We suspect that the visual feedback is of considerable help in early rehearsal of the instrument. Its importance is likely to lessen as the performer learns the instrument better and comes to rely on their inner presentation.

With continuous sound instruments, system latency is less noticeable than with percussion instruments. We conducted a user test of the just noticeable latency on a normal Theremin [12]. The first latency that the subjects statistically noticed was 30ms. However, they were not certain of their answers until latencies reached the length of 60 to 70ms. We also tested how latency affects playing accuracy, and time to reach desired notes on a Theremin and on a Virtual Reality Theremin [11]. The study

suggested that latencies up to 60ms do not impair playing these instruments. Mostly, this is because the instruments do not offer tactile feedback. As a function of latency, time to reach notes increased roughly five times as much as the introduced latency. In light of these tests, virtual reality interfaces seem feasible for controlling continuous sound, despite the latency. With better hardware the latency can also be considerably reduced.

As mentioned, a traditional Theremin is a difficult instrument. The few virtuoso performers have years of intensive rehearsal behind them. The learning curve of the Gestural FM Synthesizer is likely to be steeper in the beginning as the visual feedback supports learning. Seeing where the absolute notes are makes it possible to play the instrument without perfect pitch hearing.

Vibrato is easy to produce on the traditional Theremin by waving the fingers of the pitch hand. However, because of the low resolution of our tracker, the required motion is slightly larger on our instrument. As a result, it is more tiring to produce vibrato. Thus, we added the option of automatic half-tone vibrato, switched on when the performer moves the right hand away from their body. After a threshold, the distance alters the vibrato speed between 4Hz and 8Hz. This option can be switched off at the performer's preference. The pitch scale can be modified, but because of the limited resolution, should not be too small.

The performer controls four parameters with the hand motions. Pitch and amplitude are controlled more than modulation indexes, which alter the timbre of the sound. However, all of them can be controlled in real-time. Total mastery of controlling all parameters fluently and meaningfully is likely to require a lot of practice. Because of the extra sound parameters, the instrument efficiency is likely to be higher than that of a traditional Theremin.

5.3 Virtual Membrane

The Virtual Membrane is an interface built around a sound model of a rectangular membrane [15], supported at the edges. Its physical properties, such as dimensions, tension, damping and a few other material properties, can be modified in real-time. It is visualized as a simple, textured rectangular plate matching the physical dimension parameters of the sound model.



Figure 3. Playing the Virtual Membrane with a waveform visualization and playing the exhibition version.

The user interacts with the membrane with two mallets, one in each hand. The hit location is mapped to the excitation point of the sound model. Hitting different locations produces a different timbre. Hit velocity is mapped to the amplitude of the impulse given to the excitation location. Plate dimensions, tension and the speed of the sound in the material are controlled by virtual slider widgets. These are mapped directly to the parameters of the sound model. The sliders can be moved by touching them with a virtual mallet held in the performer's left hand. It is possible to quickly "scratch" the sliders even when the sound is playing after a hit.

The membrane allows the user to experiment with a highly flexible sound model. Its sound is realistic, and the material options range from leather to wood, to metal and beyond. The sound propagation can also be visualized as an animated wave grid on the virtual plate (see Figure 3). This visualizes how the impulse propagates on the surface of the membrane.

5.3.1 Analyses

Because of the flexible and realistic sound model the instrument attracts one's interest. Test users remained fascinated with the instrument for a long time. Also, hitting a leather membrane a hundred square feet in size produces a magnificent, thunder-like sound. The user really feels that he is making something happen.

The ability to alter physical parameters while the plate is vibrating opens up interesting possibilities that are not readily available in the real world. The material can be continuously changed while waves are travelling on it. For instance, tension can be low as the user hits the membrane, resulting in a sound of so low a frequency that it is not audible. Increasing the tension after the hit makes the waves faster and creates powerful, rumbling sounds. Thus, the attack can be omitted, and only the decay used for special effects.

Another version of the membrane, based on a web camera and displayed at a science exhibition, uses one slider for interpolating between predefined material sets. The interpolation is also visualized by morphing the drum plate material on screen. Another slider is used for modifying decay length (material friction), and a third one for modifying the size of the plate. Each slider can be "scratched" while playing.

In the VR room version, the performer has simultaneous real-time control over four parameters, impulse amplitude, two-dimensional hit location, and one of four sound model parameters in the form of sliders. Additionally, the other three parameters can be controlled by focusing on a different slider.

It is not clear what a performer could learn to do when practicing the instrument for a long time. In addition for using it as a drum with a large sound scale it offers possibilities for interesting and uncommon sound effects. Currently it could be used as an atmospheric sound generation tool for movies, as an example.

Tactile feedback could be added to the interface by using a MIDI drum set for inputting amplitude and hit location. The MIDI drum could then be expanded with gestural control of the material parameters. Tactile feedback would allow for faster and more accurate playing. Material parameters could be controlled with feet, similar to a kettle drum, or with body location. This would free both hands for drumming. With a MIDI interface the efficiency of the instrument would be that of a normal drum expanded with larger control complexity and performer freedom in the form of additional control of the sound.

5.4 Virtual Air Guitar

Playing an air guitar is to imitate rock guitar gestures along music without the actual physical instrument. It is more showmanship than musical performance and does not require real musical skills. Nevertheless, the musical component is always present. The goal of our Virtual Air Guitar (VAG) project was to create a more interactive version of the experience, something that the users could control instead of just acting along with. The Virtual Air Guitar [7] is actually playable. It has an electric guitar sound and is controlled with guitar playing gestures performed in the air.

We have made two versions of the Virtual Air Guitar. One is implemented in the virtual room, and the other one on a generic desktop Linux PC with a web camera interface. Both versions use the distance between the user's hands to determine pitch, and plucking is done by moving the right hand in a strumming motion. The pitch scale can be either fret-based or continuous. Slides are made by moving the left hand along the imaginary guitar neck, and vibrato is produced by shaking the left hand.

The instrument uses an extended Karplus-Strong sound model, which is tuned to match a Stratocaster guitar. The sound goes through a simulated tube amplifier and effects chain to produce the distorted electric guitar sound.

In order to achieve a realistic result that sounds like real guitar playing, we implemented a guitar control language, and created a software component that is controlled with this language. The component controls the six strings of the sound model, and keeps track of the state of each string and the performer. The controller understands elementary playing techniques such as hammer-ons, pull-offs, vibrato, fret-based slides and mute. The component then modifies the parameters of the sound model accordingly.

The Virtual Air Guitar interface offers different play modes such as free play, pentatonic scale play, strumming and rock solo modes. The desktop version became a major attraction in Finland's largest science exhibition. For more information on the Virtual Air Guitar, see our comprehensive article about it [7].



Figure 4. Left: rocking on with the VR version of the Virtual Air Guitar. Right: computer vision view of the desktop version. A web camera interface tracks the yellow gloves and uses gesture recognition to detect plucks, vibrato, slide and mute.

5.4.1 Analyses

From the selection of instruments we have created, the VAG has proven to be the most popular. It is thrilling for people to produce guitar music out of thin air. Also, the electric guitar is a “cool” performance instrument. Who hasn't dreamed of being a rock star, even for a short while?

The VAG is made so that even an unskilled performer can map his motion intensity into relatively good sounding rock guitar playing. A built in scale quantization makes sure only notes or chords that fit well together are produced.

Naturally, the quantization gets in the way of playing actual songs. However, without quantization, finding specific notes is difficult, because there is only air between the hands. The right hand's motion also causes the distance to fluctuate. Thus, we cannot use too accurate a scale, even though the location of the right hand is lowpass-filtered. On the exhibition version, the two

play modes include the four chords of the intro to *Smoke on the Water*, and a more free solo mode on a pentatonic minor scale.

The performer controls pitch and volume. In most of the modes this control is limited to a predefined scale. Thus, the actual efficiency of the instrument is not near that of a normal guitar. However, the VAG is an entertainment device rather than a professional instrument. And as such it functions well. We have witnessed users of all ages play the instrument. They have been curious and enthusiastic about it and have almost always walked away with a smile on their face.

As the VAG was designed to be playable for a beginner its learning curve is likely to flatten already after a short practice. However, as it supports the playing, even a beginner can have lots of fun with it and experience what it is like to play a rock guitar.

6. DISCUSSION

Virtual reality is a different medium compared to our physical world. Replicating interfaces of traditional instruments in virtual reality may not bring about useful results unless we are extending existing instruments with additional control. Familiarity with a real-world counterpart helps to grasp the concept and supports playing in the beginning. However, it may not be easy to find new ways of playing, which is needed as the instruments are different.

Users of traditional instruments may not even be interested in using virtual replicas, as the original ones work fine. Instead, we should discover the kinds of interfaces that are best suited for the VR medium. For instance, the presented Gestural FM Synthesizer extends the expressiveness of the Theremin, and is not hampered by latency or lack of tactile feedback. For making instruments in a new medium the properties of the medium and their musical effects should be well understood in order to work around the limitations and utilize the strengths.

The efficiency of our instruments is reduced by low spatial and temporal resolution, as well as by latency. Low resolution requires larger motion paths. Together with latency, it makes fast and accurate playing difficult. However, these properties could be improved with existing technology. Lifting the limitations would also allow for faster instruments with vast possibilities.

One of the most promising features of virtual reality interfaces is the potential for visualization. Unlike in physical instruments, where visual feedback can only directly correspond to the physics of sound production, such as vibrating strings, virtual instruments allow for intelligent visual feedback. A physical instrument's appearance is static, but a virtual instrument can modify its visual features in real-time. For example, the Gestural FM Synthesizer includes visualization that helps users reach correct pitches.

In addition to providing visual cues, visualization could be used to teach the user how to play an instrument. For example, the FM Synthesizer could include a scrolling musical score that marks the correct position of the hand in the air.

In addition to teaching music, features of the instrument sound can also be visualized. For example, a virtual widget could change color and texture according to the properties of the sound it is linked to while playing. Visualizing sound has been studied already, but there is little research available on visualizing the interpreted concepts that humans make of sounds. For example, the term “brightness” is subjective. The meanings of these terms

and how to visualize these concepts could offer interesting knowledge for computer instrument design.

In addition to adding to the usability of an instrument, visualization can also affect the entire performance. Playing a musical instrument is not an isolated act, but most often placed in the context of a concert or other performance. The performer is not only producing music, but creating a multimedia show for the audience. By visualizing sounds in an aesthetically appealing way, artists are given more possibilities for engrossing the audience. At the time of writing, music visualization based on audio analysis is gaining increased attention, especially in the music style of electronica. These are most often abstract patterns that change color and shape to the rhythm and spectral content of music. By linking visualization to the instruments that produce the sound, it can be made much more detailed, reacting to changes in individual sounds. Basically, this generalizes the concept of mapping to cover the routing of control parameters also to the visualization as well as to the sound model.

7. CONCLUSIONS

In this paper, we have presented a virtual reality software system designed for making musical instruments. Four instruments created with the system were presented. The instruments were analysed against a framework that considers the learning curve and efficiency of an instrument. Each instrument's analysis was also accompanied with our design experiences. The effects of several interface properties were discussed in relation to design of musical instruments using novel input and output hardware.

8. ACKNOWLEDGMENTS

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