Hyperreal Instruments

Bridging VR and Digital Fabrication to Facilitate New Forms of Musical Expression

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ABSTRACT

Virtual Reality (VR) and digital fabrication technologies today are ushering in a new wave of opportunities in instrument design; the marriage of these two domains, seemingly at odds with each other, can bring impossible instruments to life. In this article, the authors first sample such instruments throughout history. The authors also look at how technology has facilitated the materialization of impossible instruments from the twentieth century on. They then discuss the bridging of VR and fabrication as a new frontier in instrument design, where synthetic sounds can be used to condition an equally synthetic sensory scaffolding upon which the time-varying spectra can be interactively anchored: The result is new instruments that can defy our sense of audiovisual reality while satisfying our proprioceptive and haptic expectations. The authors report on their ongoing work as well as their projections of how emerging technologies in VR and fabrication will shape the design of new musical interfaces.

A SURVEY OF IMPOSSIBLE INSTRUMENTS

The string inspires poetics of the immaterial in its capacity to "hale souls" [1]. In the absence of the musician's touch, however, the instrument is firmly in the material realm, straddling a delicate balance between structural resilience, acoustics and ergonomics [2]. Instrument-making has advanced to ameliorate this balance, making acoustically vibrant materials increasingly amenable to human control of timbre, pitch and dynamics. Evolving fabrication technologies have allowed builders to transition from found forms (e.g. tortoise shell lyres and bone flutes) to geometries fashioned in wood, metal or plastic. The gulf between instrument ideas and opportunities for construction of imagined instruments continues to close as materials are made increasingly malleable through advances in fabrication. With the advent of VR, even the most physically implausible ideas can be reified into an audiovisual scene and made subject to human interaction within a computed space. In this context, what was once an impossible instrument can become a prompt to model its contours and sound in new mediated spaces.

The idea of an instrument may occur centuries before its actual materialization. The viola organista was merely a sketch in Leonardo da Vinci's *Codex Atlanticus* [3] until it was recently constructed by Slawomir Zubrzycki, with playable results. Other musical ideas, however, are bound to remain in the imagined domain, being intentionally implausible. Such specimens may serve as elements within literature and visual arts or become animated within mythopoeic dramas, far from any functional role of producing airborne sound. They are often imbued with "magical" qualities that can range from the divine to the whimsical. Orpheus's lyre, for instance, was famously capable of placating the cantankerous gods, a power that he used to convince them to bring Eurydice back from the underworld.

Orpheus's lyre reminds us that instruments are represented in myth as conduits of knowledge and agency, inseparable from the ontology of their time and place. At the turn of the sixteenth century, for example, instruments became synonymous with human indulgence for early Netherlandish painters. The third panel of Hieronymus Bosch's *Garden of Earthly Delights* conflates musical tools with the infernal condition of the condemned, depicting a riotous scene where instrument hybrids participate in the bondage of human figures. These diabolical chimeras in paint have inspired some to attempt their construction. Yet, having evolved out of the imagination rather than the constraints of acoustics, such endeavors usually amount to one-off sculptural materializations.

The imagined instrument seems to acutely illustrate the human capacity to dream up not only visions of hell but also other forms of auditory cruelty: Athanasius Kircher's cat piano was to sound through tuned feline cries; or, returning to antiquity, the Bull of Phalaris was said to have been a hollow sculpture wherein the cries of the incarcerated were converted into music [4]. A few decades after Bosch created

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his triptych, Johannes Kepler would write of more mellifluous associations in his *Harmonices Mundi*, where the cosmos is conceived as an instrument generating celestial harmonics.

In modern art, Paul Klee's *Instrument for New Music* elides the notation of musical time with physical form, providing a conceptually rich example of an impossible instrument. The object is a visualization of musical information cast within the contours of an otherwise acoustical shape. Using symbols of musical time instead of materially inspired textures, Klee fuses the ideas of music with the tools of its production. Klee's painting replaces the instrument as a vector to bring compositions into sound with one that itself bears the symbolic language of composition. The "composed instrument" is a term that describes this increasingly blurred line between composition and instrument design [5].

Some of the most unlikely musical instruments can be found in science fiction. These instruments often transcend the auditory domain, as with Philip K. Dick's Mood Organ or Isaac Asimov's Visi-Sonor, where the musical performance interfaces directly with the listener's nervous system. J.G. Ballard, in his short story "The Sound-Sweep," describes an anti-instrument that vacuums up sound within the audio range to make way for a superior form of ultrasonic music [6].

Like the made-up technologies of science fiction, developments in technology can redefine what is possible in instrument design. With the advent of twentieth-century sound reproduction and amplification technologies, musical instruments witnessed a significant paradigm shift as amplitude and timbre became liberated from both instrument geometries and performer gestures. Whereas the theremin dispensed with the tactility of the performance, the electric guitar magnified it. Recording technologies helped extract impossible performances out of real instruments, while developments in electronics paved the way for instrumental metamorphoses, where the 300-year-old piano keyboard could be made to emit the sound of a cello.

MODERN PRACTICES IN INSTRUMENT DESIGN

Many modern practices in instrument design subvert the limits of physics to unlock new forms of artistic expression. Digital musical instruments, in particular, expand upon the decoupling of acoustics from performance, a phenomenon we began to observe in twentieth-century amplified instruments. Equipped with a range of sensors from binary buttons to depth cameras, these instruments are designed to sample the performer's actions with varying degrees of freedom. These samples are then translated into virtual excitations of a digitally defined resonator. The mapping between the interface and the sonic output in these instruments is defined arbitrarily in software. Some of these pairings follow the metaphor of an acoustic instrument (e.g. the Eigenharp), while others are more abstract (e.g. the Launchpad).

Advances in physical computing and fabrication have fostered new communities of instrument designers over recent decades. One such community, rooted in the field of human-computer interaction, is NIME (New Interfaces for Musical Expression), which brings together designers and performers of digital musical instruments. In its investigation of musical interaction design, this community is often concerned with the integration of emerging media into novel instruments. As a result, a growing number of researchers in this community are exploring ways of incorporating modern VR and fabrication technologies into new instruments. In an early study of VR instruments, Teemu Mäki-Patola et al. utilize a CAVE-like environment to explore the gestural control of virtual interfaces that are modeled after existing instruments such as the xylophone and the guitar [7].

In another reimagining of existing instruments through technology, Amit Zoran proposes digital fabrication as a means to overcome the "evolutionary impasse" of traditional instruments [8]. In his exploration of new structural properties for future designs, he envisions a four-pipe trumpet that would be impossible to fabricate by any means other than 3D printing. Although Zoran models an intriguing form, it remains a thought experiment that illustrates the potential of 3D printing for instrument design. Whereas acoustic modeling may prove such hypothetical designs to be impractical, a novel rationale for the production of such fanciful objects emerges in VR: The digital model can be coupled with intuitive synthesis schemes in VR, while the fabricated object satisfies tactile expectations.

In a similar reconceptualization of a traditional instrument, Rob Hamilton and Chris Platz bring the carillon into VR [9]. Although the carillon serves as the representational centerpiece of a networked performance, the artist's exploration of the virtual context that surrounds the carillon scales up the instrument to the level of an environment; the performer's virtual navigation of this space is out of proportion to any form of embodied interaction with a musical instrument. Conversely, a digital musical instrument can take the concept of an environment and shrink it to the scale of an instrument. In *Proprius*, Zeynep Özcan compresses a vast artificial ecosystem into the performance area, populating it with interactive agents that display a range of musical behaviors based on the performer's movements in this space [10].

Whereas most traditional instruments are designed for individual performers, virtual instruments—abstracted from physical constraints—can facilitate otherwise impossible participatory approaches. In one such example, Victor Zappi et al. create a virtual performance where the artists' embodied interactions with virtual objects lead to new visual and auditory forms that can then be manipulated by the audience in real time [11]. The networked music platform *Monad* implements a similar shared instrument by employing game mechanics to stimulate a musical collaboration, where multiple performers manipulate a single visual object that functions as a virtual synthesizer [12].

HYPERREAL INSTRUMENTS

In the Hyperreal Instruments Project, we explore the use of digital fabrication and VR to bridge our haptic expectations of physical instruments with the unrestrained audiovisual mechanics of VR. Just as electroacoustics can amplify an instrument far beyond its acoustic capabilities, VR allows

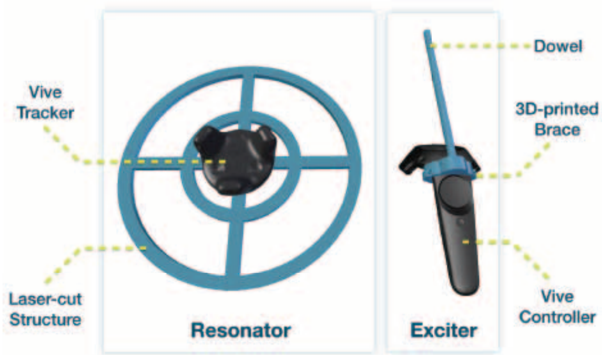

Fig. 1. The digital model of the first Hyperreal Instrument prototype. The resonator on the left is laser-cut from quarter-inch MDF (medium-density fiberboard). A Vive Tracker attached to this structure allows it to be tracked by the VR system. A 3D-printed brace attached to the Vive Controller on the right allows a dowel to be affixed to the controller, which is also tracked. (© Anıl Çamcı)

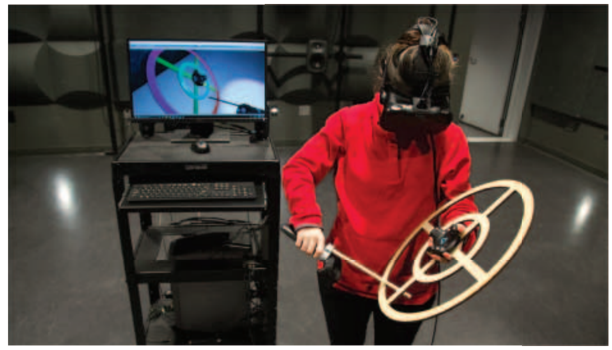

Fig. 2. A performer playing the Hyperreal Instrument prototype. In the background, the Unity Engine displays the performer's view in VR. Each quadrant of the virtual model is given a different color to indicate the tuning of the instrument. (© Anıl Çamcı)

us to amplify mental states associated with how we expect a physical object will resonate. By pairing the fabricated and the virtual manifestations of a digital design, we impart acoustic and other kinds of impossible qualities on musical expressions. In return, the tactility of the instrument, which governs its playability [13], binds the performer's experience of the virtual space with learned sensorimotor functions.

The occlusion of the senses in VR creates a discrepancy between the virtual and the real. The technology leaves the body in a duplicate state, moving conjointly in these parallel and often incongruous domains. However, when the two domains are aligned, the tactility of the real world becomes a part of the virtual experience. This expansion into multimodality is deemed a crucial requirement for the immersive illusion [14]. To explore this alignment between the real and virtual worlds in the context of music performance, we modeled the instrument seen in Fig. 1.

In this prototype, we used the Unity Engine and the HTC Vive VR System to create a room-scale virtual environment. The tracking in this system, often referred to as "outside-in" tracking, is achieved with two base stations that flood the performance area with nonvisible light. The system consists of a head-mounted display that projects a stereoscopic view of the VR scene, a handheld controller for user interactions and a tracker that can be affixed to physical objects. These are outfitted with sensors that respond to the light emitted from the base stations so that they can be tracked in space with six degrees of freedom. This allows a mapping between physical and virtual objects, where, for instance, the controller held by the user can be displayed in VR in a way that perfectly conforms to the object's physical dimensions and orientation. This one-to-one mapping anchors the user's virtual experience in the physical domain: The virtual manifestation of the handheld controller gives the user a sense not only of scale but also of agency and presence in VR.

To fabricate an instrument that is tracked by this system, we integrated the controller and the tracker into the structure of the instrument. This way, we were able to augment these devices both in the physical and the virtual domains. We conceived the Vive Controller as the exciter of the instrument, similar to a bow or a drumstick. The 3D-printed prosthetic extension to the Vive Controller seen in Fig. 1 allows a dowel to be affixed to it. Similarly, the Vive Tracker is mounted onto the laser-cut resonator via a threaded insert. Whereas the fabricated object remains a rigid and nonresonant entity, its virtual counterpart can be subdivided into an arbitrary combination of virtual parts imbued with virtual acoustic properties. This allows us to redefine how the instrument responds to excitations, how it is tuned and even how it should be handled. In our prototype, the four inner and four outer quadrants, as well as the four bridging pieces between the inner and outer circles, are defined with unique colliders, each of which is mapped to changing pitch chroma (Fig. 2).

The sound engine of our prototype is programmed in Max based on an adaptation of the Karplus-Strong physical modeling synthesis algorithm. The collisions detected between the virtual exciter and resonator are used to trigger the transmission of a white noise signal into a feedback system. The velocity vector derived from the movements of the exciter are used to control the amplitude envelope of this signal to articulate the effects of different gestures such as striking and bowing. The trigger button on the Vive Controller is used to activate a constant excitation mode, where the resonator gives out a sustained sound for as long as the exciter is in contact with it. Figure 3 gives an overview of the Hyperreal Instrument system design.

To better understand the affordances of this prototype and to determine future directions for our project, we conducted a pilot study. Ten participants with varying degrees of experience with music performance were tasked with exploring the instrument and providing feedback about their experience. When a participant felt they had exhausted the possibilities of the instrument, they were invited to take part in an informal interview. After the interview, we asked the participants to perform with the instrument again, this time without the fabricated parts attached to the controller and the tracker.

Most participants reported that the response of the instrument was convincing. A few mentioned that they expected the sustain mode to display dynamic variations based on the

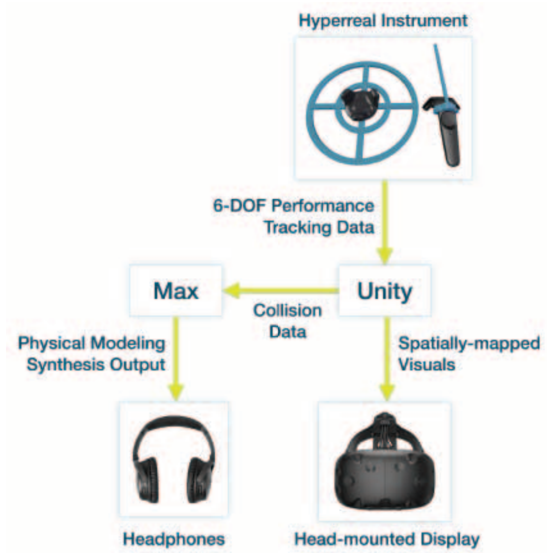

Fig. 3. Information flow across the hardware and software components of the Hyperreal Instrument system. (© Anıl Çamcı)

intensity of their playing, similar to its behavior in the regular mode. The auditory, visual and haptic modalities were reported as primary modes of sensory engagement; all users indicated that stimuli were coordinated across these modalities, although intermittent drifts in the tracking caused moments of haptic-to-visual misalignment. Two participants reported that, due to the occlusion of the physical instrument, they were concerned about breaking it if they struck it hard enough. They therefore used gentler gestures than they might have on an instrument whose real material could be observed. Most participants mentioned feeling that their performance with the instrument might improve with time as they refined their grasp of the dynamic response and the tuning of the instrument. This indicates a level of learnability, which has been previously stressed as an area of improvement for VR instrument design [15].

Participants most commonly likened the prototype to a string instrument, although other instruments—including the hang drum, cymbal and daxophone—were also mentioned. Most participants expressed a preference for the bowing gesture on the physical instrument and the striking gesture in the fully virtual condition. These users reported that the ability to have the exciter pass through the resonator to create percussive sounds was a positive feature of the condition in which the physical parts were removed. One participant mentioned that they enjoyed the lifting of the instrument's weight in the latter condition. Another user reported that this weight imparted a more fulfilling sense of performance.

A GLANCE AT THE FUTURE

Our studies with the first Hyperreal Instrument prototype have helped us to identify several prospective steps for our project. An iteration of our current prototype features additional virtual spokes that the exciter can pass through, affording the user the tactility of the physical object alongside the unobstructed gestures allowed by the virtual model. For the second version of this instrument (Fig. 4a), we created a design that favors continuous surfaces in place of the discrete quadrants of the first prototype. This design facilitates unobstructed bowing and ratcheting gestures, which were deemed favorable by the users. The grooves in this model also enable precise excitations through the physical anchoring of the exciter in the collision zones; such precision is difficult to achieve with a fully virtual instrument.

Finally, in a new design, we are investigating the use of magnets with the same polarity attached to the tracked controllers, as seen in Fig. 4b, to exploit the use of force feedback in a virtual instrument. This can, for instance, be made to function like a theremin, with the repelling force between the two magnets giving the performer a haptic indication of changes in pitch, timbre or volume.

The coupling of VR with fabrication in order to design instruments has other applications for digital instrument design. Building physical computing systems for musical interfaces often requires many iterations. The ability to redefine a physical instrument's topology, as described in this article, creates opportunities for prototyping instruments with virtual sensors in the form of colliders mapped onto the physical object, which can be later substituted with electronic parts. Furthermore, VR systems that use inside-out tracking will open up new possibilities for virtual instrument design. Untethered from a computer and an external tracking system, these systems will facilitate large, room-scale and collaborative VR experiences, enabling Hyperreal Instrument ensembles. With the Hyperreal Instruments Project, we will continue to explore such emerging prospects in the coordination of VR and fabrication for the design of new musical interfaces that synthesize virtual interrelationships between acoustics, visuals and haptics.

Fig. 4. (a) A revision of the resonator from our first prototype with continuous grooves and surfaces. (b) A new Hyperreal Instrument design based on the use of magnets to incorporate force feedback in a virtual instrument. (© Anıl Çamcı)

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