SMART INSTRUMENTS: TOWARDS AN ECOSYSTEM OF INTEROPERABLE DEVICES CONNECTING PERFORMERS AND AUDIENCES

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ABSTRACT

This paper proposes a new class of augmented musical instruments, "Smart Instruments", which are characterized by embedded computational intelligence, bidirectional wireless connectivity, an embedded sound delivery system, and an onboard system for feedback to the player. Smart Instruments bring together separate strands of augmented instrument, networked music and Internet of Things technology, offering direct point-to-point communication between each other and other portable sensor-enabled devices, without need for a central mediator such as a laptop. This technological infrastructure enables an ecosystem of interoperable devices connecting performers as well as performers and audiences, which can support new performer-performer and audience-performer interactions. As an example of the Smart Instruments concept, this paper presents the Sensus Smart Guitar, a guitar augmented with sensors, onboard processing and wireless communication.

1. INTRODUCTION

Digital musical instrument design often involves a balance of seeking artistic and technical novelty while connecting with established musical traditions and playing techniques. Augmented instruments [1, 2] have a long history of extending the creative possibilities of familiar acoustic instruments through sensors, actuators and signal processing techniques.

Communication is fundamental to any musical performance, whether it is amongst performers or between performers and audience. Networked musical performance has an established history [3], but further opportunities exist for networking amongst augmented instruments, many of which are bespoke self-contained systems.

A useful model for interconnected musical instruments comes from the *Internet of Things* (IoT), an umbrella term encompassing the augmentation and interconnection of physical devices [4]. Recent years have seen a substantial expansion in "smart" devices and appliances in the home, office and other environments which connect wirelessly through the internet to other more conventional computing devices. However, IoT integration in musical instruments has thus far received comparatively little attention.

In this paper we propose a novel class of musical instruments, *Smart Instruments*, which are characterized by embedded intelligence, bidirectional wireless connectivity and an embedded sound delivery system. [1] Smart Instruments integrate disparate technologies found in various strands of augmented instrument, networked music and IoT research. They offer a direct point-to-point communication between each other and other portable sensor-enabled devices, without need for a central mediator such as a laptop. In this paper, we suggest that the holistic Smart Instruments approach will enable artistic capabilities beyond current augmented instruments.

Section 2 of this paper examines the component parts of the Smart Instruments concept, including recent developments in sensor-augmented and actuated musical instruments, lutherie techniques, and relevant IoT technologies. Section 3 then argues for the prospect of a holistic integration of these technologies in a new generation of Smart Instruments. An example of this approach, the Sensus Smart Guitar, is presented in Section 4, and future prospects are discussed in Section 5.

2. RELATED WORK

2.1 Augmented Instruments

The augmentation of familiar acoustic instruments with sensor technologies has a long history [2,7]. More recently, interest has grown in electromechanically actuating the vibrating structures of acoustic instruments [8]. Though a comprehensive survey of these efforts is beyond the scope of this paper, this section examines selected recent examples in this space.

2.1.1 Sensor Strategies

The addition of sensors to familiar instruments is well-established, as is the construction of "instrument-like controllers" [9], which replicate the physical form of a famil-

[1] Our use of the term "Smart Instruments" is distinct from the IRCAM *SmartInstruments* active acoustics project (e.g. [5, 6]), though onboard acoustic actuation is one component of a Smart Instrument in our usage. Full details on the IRCAM SmartInstruments can be found at http://instrum.ircam.fr/smartinstruments/

iar instrument to control other sounds. Sensor augmentations exist of nearly every familiar instrument, including violin [10–12], trumpet [13], guitar [14–16] and piano [17], as well as more rare instruments, such as the hurdy-gurdy [18]. Techniques have been proposed for customisable sensor surfaces adaptable to different applications [19] and toolkits for musicians to create their own augmentations [20].

In some cases, sensors are used as extra controls separate from the main playing techniques, while other approaches seek to provide a more detailed picture of playing gesture than audio alone can provide [10, 12]. Other sensor approaches use ancillary gestures to control sonic effects [15] without requiring the performer to explicitly manipulate additional controls.

In many cases, the addition of sensors requires either wired connections to outboard computing, though wireless communication links [14], embedded computing [21] and fixed camera-based sensing [22] are also used to give the performer free movement.

2.1.2 Actuated Acoustic Instruments

Sensor augmentation of instruments often relies on audio post-processing or digital sound synthesis played through external loudspeakers. More recent developments fold the sound synthesis back into the acoustic structure of the instrument. These *actuated instruments* [8] seek to retain the sonic richness of acoustic instruments while expanding their performance possibilities.

Actuation can be applied directly to an instruments vibrating elements: examples include guitar strings [23], piano strings [24,25], drum heads [26], vibraphone bars [27] and metal tines in a Fender Rhodes [28]. Feedback control allows the application of novel effects including active damping [23], changing resonance properties [29], inducing self-sustaining oscillations [5] and creating novel timbre effects [6]. In other cases, speakers or vibration actuators are embedded in the resonant chamber of an instrument to manipulate its sound [16,30,31].

2.2 Digital and Hybrid Lutherie

Lutherie, the technique of building musical instruments, requires artistry, skilled craftsmanship and intimate knowledge of the materials one works with. This is no less true in *digital lutherie* [9] than the acoustic techniques that preceded it. Considerations in the digital domain relate not only to sensors and synthesis techniques but to the mapping strategies between them, a review of which is beyond the scope of this paper.

An emerging practical consideration within digital lutherie is creating entirely self-contained instruments using embedded single-board computers [32]. While self-contained digital instruments once required specialist DSP platforms and significant engineering resources, the rise of embedded computers like Raspberry Pi and BeagleBone Black and associated audio maker platforms [21,33] has increased the accessibility of self-contained instruments.

Digital lutherie does not imply an inattention to physical materials. While 3D printing and other rapid prototyping technologies have been applied to create acoustic instruments [34], materials and physical craft often feature prominently in new hybrid acoustic-electronic instruments such as the Halldorophone by Halldor Ulfarsson [2] and the Overtone Fiddle [35].

2.3 Wireless Sensor Networks

Wireless sensors networks (WSNs) [36] are the essential component of IoT. They are networks of tiny autonomous sensor and actuator nodes that can be embedded in any physical object for control and monitoring via wireless transmission. They are characterized by the scarcity of resources for communication, computation and energy supply. However, despite WSNs are making smarter many devices such as phones, watches, and home electronic appliances, little has been done when it comes to musical instruments manufacturing. The capability to deploy small sensing nodes everywhere, without the need of power supply and cables, makes these networks a most interesting and versatile technology to embed in the musical instruments in a seamless manner and without impeding the traditional interaction with the instruments.

There have been many efforts to design WSNs, both in academia and industry (e.g., [37]). New communication protocols for WSNs have been built around standardized low-power protocols such as IEEE [38], Zigbee [3] , ROLL [4] . The design of WSNs for musical instruments should be grounded in the theory of cross layer design [39] to overcome problems such as message losses, delays and lack of synchronization among sensor nodes. This poses difficult design challenges, especially in the musical domain, where the transmission of messages has to be very reliable and the communication latencies very short.

3. THE SMART INSTRUMENTS

From the analysis of the works reviewed in previous section, it emerges that various systems have been developed to satisfy different needs, but that such systems have not been integrated yet. Musical instruments augmented with sensors for gesture tracking respond to the need of controlling the sound output in novel ways in order to achieve novel types of musical expressions. Instruments augmented with actuation systems satisfy the need of modulating the vibrations of the resonant body. Actuated systems, as well as loudspeakers systems embedded in the instrument, serve the purpose of having the source of the electronically generated sounds placed onto the instruments. IoT technologies satisfy the need of having a bidirectional communication between two or more devices via wireless connectivity. Embedded systems serve the purpose of having the computational unit placed inside the musical instrument. Systems for collaborative networked music respond to the need of exploring novel forms of music creation. Furthermore, current digital audio workstations (DAWs) serve the

[2] https://www.youtube.com/watch?v=uo4Jq-_tysc
[3] http://www.zigbee.org
[4] http://www.ietf.org/dyn/wg/charter/roll-charter.html

purposes of applying effects to audio signals, generate synthesized sounds, as well as mix, record and play audio tracks.

We argue that the integration of all the technologies described in those works will lead to a novel class of musical instruments that we define as "Smart Instruments".

3.1 Features

The class of Smart Instruments that we propose are characterized by the following components:

- a system for capturing the sonic output generated by the instrument (e.g., by means of microphones or pickups embedded in the instrument);
- a system to extract in real-time the musical information related to the player's interaction (e.g., by means of pitch tracker, onset detection, and envelope following algorithms);
- a system for networked, bidirectional, low-latency, and wireless communication of various kinds of data (including audio streams) towards/from connected devices (including other smart instruments). Such a system can leverage both the Internet and ad-hoc communication networks;
- a sensors-based system for tracking a performer's gestures. The tracked interactions with the sensors are used to modulate the instrument sonic output and to deliver control messages to connected external devices;
- a sound delivery system located onto the instrument (for instance via actuation systems or loudspeakers embedded in the instrument);
- an embedded computational unit for sensors data processing, for sound processing and generation including all capabilities of DAWs, as well as for the processing and control of received/transmitted data from/to connected devices;
- an embedded feedback system to display information received from connected devices, for instance by means of visual, auditory, or haptic stimuli.

Smart instruments can be based on conventional acoustic instruments or be totally electronic. However, their features make them different from current augmented instruments or system for interactive performance: to the authors' best knowledge, none of the systems mentioned in Section 2 encompasses all the features listed above in a unique, playable, intelligent musical instrument.

One of the core characteristics that differentiate Smart Instruments from other interactive art systems is that they allow one to explore expressive and networked possibilities which would normally require the involvement of a multitude of equipment pieces: these include a musical instrument, a soundcard, a mixing interface, a computer, microphones, loudspeakers, a DAW and controller interfaces for it, as well as a networking system for local and remote communication. All these components are embedded in the instrument itself. In particular, Smart Instruments technology excludes the involvement of an external computation unit. Throughout many different forms of augmented, interactive or multimodal performance, the constant presence has been indeed a computation unit placed externally to the instrument (e.g., a laptop), which acted as the central hub for all the data to be processed. For example, it is a common setup to have two performers on stage, one playing an amplified acoustic instrument and the other having some sort of sensor apparatus which modulates the sound of that instrument. In this scenario, both performers have their sound go to a central computer which does the processing and then sends the results out of the house PA system. With the introduction of Smart Instruments all such computations and sound delivery are performed on the instrument itself.

In particular, whereas augmented instruments are mostly bespoke standalone systems, Smart Instruments are capable of directly exchanging musically relevant information between each other, not just in one direction and in a passive manner. In addition, Smart Instruments are capable of communicating with a diverse network of external devices connected to them. While augmented instruments capable of delivering multimodal information to external equipment exist (e.g., the augmented violin capable of generating real-time visuals related to bow movements described in [12]), Smart Instruments allow one additionally to receive, process, and display information to the player.

To achieve such a peer-to-peer communication, which is bidirectional and wireless, Smart Instruments can leverage both standard wireless networks technologies (e.g., Bluetooth, Wi-Fi, 4G) and ad-hoc ones (especially those allowing for a ultra-low latency transmission, which is a fundamental requisite for real-time applications in the musical domain).

3.2 Applications

The embedded intelligence of Smart Instruments allows for the delivery of musically relevant information to one or more Smart Instruments such as the notes played, the sensors values and their mappings to some sound effects parameters, or the generated sound. This information, for instance can be delivered in form of MIDI messages, Open Sound Control (OSC) messages, or audio signals. It can then be used to generate sounds that are reproduced directly on the receiving instrument thanks to its embedded DAW and sound delivery system and/or can be displayed by the instrument thanks to the embedded feedback system.

A variety of devices can be connected wirelessly to Smart Instruments, such as wearable technology (e.g., smart bracelets), smart phones, virtual reality headsets, or stage equipment such as lighting systems or smoke machines. Smart Instruments not only can deliver multimodal information to such devices in order to control their behaviour, but can also receive, process and display information coming from them.

The features of bidirectional, low-latency, and wireless communication capabilities offered by Smart Instruments, as well as their embedded system for display feedback and sound delivery, enable an ecosystem of interoperable devices connecting performers as well as performers and audiences. This can take place not only in co-located, but also in remote settings. Such an ecosystem will make possible performer-performer and audience-performer interactions not offered by current augmented instruments. It can be exploited, for instance, for collaborative networked music creation, which has the potential to lead to novel forms of performance. Figure 1 illustrates an example of the data flow enabling such interactions and their human/machine agents.

A first example of the possible use cases implementing such interactions is represented by a novel form of jamming between players of such instruments: multiple players can wirelessly stream between each other and in real-time, audio content or musical messages (e.g., MIDI data) that are then reproduced by the sound delivery system of one or more receiving instruments. This is accomplished while the instruments themselves are being played by their performers. Moreover, each performer can control the mixing of the received audio streams. A second example consists of an enhanced creative content creation and delivery: performers interacting with the sensors embedded on their Smart Instruments not only can modulate the instruments sound production, but also deliver additional multimedia content to audience members in possession of smart devices. Such smart devices can produce multisensory feedback involving, for instance, visual, textual or tactile stimuli. A third example, consists of exploiting the feedback from the audience in a concert settings: information about body movements of each person in the audience are tracked by means of smart wearable devices, forwarded to a Smart Instrument, and used by its performer to modulate various aspects of the performance (e.g., the instrument timbre). Finally, a fourth example concerns remote rehearsals (at relatively close distances): the Smart Instruments of two or more performers can stream and receive in real-time the sounds generated by each of the performers, and the received audio stream is then reproduced and mixed directly by the instrument.

4. THE SENSUS SMART GUITAR

To date, a unique exemplar of musical instrument that encompasses all features of Smart Instruments exists: the Sensus Smart Guitar developed by the company MIND Music Labs [5] (see Figure 2). Such an instrument is based on a conventional acoustic guitar that is augmented with WSNs technologies. It is the result of the tight and interdisciplinary collaboration of instrument makers, software engineers, hardware engineers, sound designers, interaction designers, and IoT experts.

Sensus is built according to the crafting techniques of the most renowned of all the school of instrument making, that of the Stradivaris tradition [6] . All involved materials (wood, varnishes, etc.) are of high quality. Various parts of the instrument are made with a specific wood, carefully selected and naturally well seasoned. In particular, those woods include the special red spruce wood found in the Paneveggio Forest (in the Italian Dolomite mountains). This wood is characterized by a certain elasticity and particular honeycomb structure that allow the efficient transmission of sound waves and amplify sound.

In addition to regular knobs, switches and buttons, Sensus involves several sensors embedded in various parts of the instrument and ergonomically placed in order to not disrupt the natural interaction of the performer with the guitar. Specifically, these sensors include an inertial measurement units, five pressure sensors, two ribbon sensors, and an infrared proximity sensors. They allow for the tracking of a variety of gestures of the guitar player, including fingers pressure and position in various instrument areas (e.g., the neck), the distance of the hand from a specific part of the instrument located on the soundboard, and the position of the instrument (e.g., resulting from tilting up-down or front-back) and its linear acceleration along the three axes. As all augmented instruments, the tracked gestures are used to extend the expressive possibilities of the conventional acoustic guitar. In more detail, such gestures modulate the instrument sound and produce additional sounds thanks to a DAW running on a computation unit.

Such a computation unit is part of an embedded system, which is also responsible for the analog-to-digital conversion of sensors data and for the wireless connectivity. This system includes a multichannel soundcard and is powered by a battery that is also embedded in the instrument. The DAW employs a set of plugins for the processing of the guitar sound with a variety of effects, as well as for the generation of synthesized sounds by means of synthesizers and virtual instruments. It includes a loop station, and recording and playing features. It can be controlled via both MIDI and OSC messages.

Sensus can be connected to a regular PA system via standard jack cable and wirelessly. However, one of its main and peculiar features is that sounds, digitally processed or generated, can also be delivered by the instrument itself without the use of any external loudspeaker. This is achieved by means of a system of multiple actuators that transforms the instrument resonating wooden body into a 360° hi-fi loudspeaker. Such a system coupled with digital signal processing techniques, allows one to alter the timber of the instrument in manifold ways.

Furthermore, Sensus is equipped with bidirectional wireless connectivity leveraging both local networks and the Internet. This makes it possible the delivery and reception of different types of data from the instrument to a variety of smart devices (even including one or more Smart Guitars) and vice versa. Specifically, the connectivity technology includes Bluetooth Low Energy, standard Wi-Fi, and 4G. The data stream includes MIDI messages, OSC messages, and audio signals. The player's gestures tracked by the

[5] http://www.mindmusiclabs.com

[6] The traditional Stradivari's musical instruments craftsmanship in Cremona is inscribed on the Representative List of the Intangible Cultural Heritage of Humanity: http://www.unesco.org/culture/ich/en/lists?RL=00719

Figure 1. A schematic representation of the bidirectional wireless connectivity between Smart Instruments and smart devices enabling new forms of interaction between performers and audience.

embedded sensors are also used to deliver and control such data stream.

The new forms of interaction between performers as well as between audience and performers enabled by this novel technology have started to be explored: MIND Music Labs has developed various applications running on smart devices that implement some of those interactions. One of these allows for novel forms of co-located jamming (i.e., collaborative and spontaneous music making). It runs on both Android- and iOS-based smartphones and tablets that wirelessly stream in real-time to Sensus audio content and/or musical messages (e.g., via MIDI or OSC). Such data are fed into the instrument DAW and then reproduced by its sound delivery system, while the instrument itself is being played by its performer. In turn, the performer acting on the instrument sensors can change the behaviour of the app running on one or more smart devices in possession of as many users (for instance, changing presets or the interface layout).

Thanks to its Internet connectivity feature, Sensus can easily share on various social networks audio content generated by playing on it and recorded in Hi-Fi quality. In addition, it can receive and reproduce audio signals streamed from remote repositories (e.g., songs streamed from Spotify), allowing a smart guitar player to play over them (e.g., for improvisation or rehearsing purposes).

Although Sensus is not yet on the market, to date various guitar players have had the chance to try it, both in public demos and during user experience experiments whose results have informed its ongoing development. In general, guitar players had positive feedback about their interaction with Sensus as far the sound production and modulation is concerned. The novel gesture-to-sound possibilities offered by the embedded sensors have been welcomed although, as one would expect for any augmented instrument, a general comment was that it takes time to learn, master, and incorporate them into the usual playing technique. One of the most appreciated features is the embedded actuation system, which allows one to play a guitar that vibrates like an acoustic instrument while incorporating effects like an electric one. Another feature which users appreciated is the presence of the embedded DAW and its continuous/discrete controls which are embedded in the instrument, since they eliminate the need for external equipment (e.g., footpedals) that a guitar player would usually have to carry, and that force him/her to a specific position in the stage. A more detailed description of the results of studies about the user experience during the interaction with Sensus is planned in another publication.

Videos of Sensus are available on the MIND Music Labs website[5] .

Figure 2. The Sensus Smart Guitar developed by MIND Music Labs.

5. DISCUSSION

Though augmented instrument research is well established, the potential designs and applications of Smart Instruments have only begun to be explored. Just as the transformative developments in mainstream computing have gradually shifted from individual devices to networked services, the most novel frontier to be explored in Smart Instruments is their capability to directly communicate with one another wirelessly and without a laptop as a mediator.

An open question is to what extent the presence of a laptop on stage affects the content of a performance. Many digital musical instruments use the laptop as a convenient source of computation without interacting with it directly in performance. Though this may seem to be aesthetically neutral, we suggest that there may be influences both overt and subtle from its presence. These include the tethering effect of cables, communication or audio processing latency, and questions of performer trust in a complex computer system. Commonly used audio processing languages may also introduce subtle aesthetic biases in that certain musical outcomes are easier to achieve than others.

Therefore, the musical content and forms of interaction supported by direct instrument-to-instrument or instrument-to-audience communication may differ in significant and as-yet unforeseeable ways. To fully achieve this outcome, however, further development is needed on network technologies and protocols.

Current technological barriers that need to be addressed include network latency, which must meet strict requirements for musical performance. Wireless communication of electronic musical instruments has just recently seen an increase in popularity thanks to the use of dedicated communication protocols such as OSC. Nevertheless, such protocols are limited to the simple delivery of musical messages that are used to control the sound production of the receiving instrument. No IoT systems are currently available for the simultaneous, ultra-low latency, and bi-directional delivery of those control messages and of audio streams, which is an essential feature to enable novel forms of collaborative music creation. Existing systems are typically wired, which is in contrast with the seamless and ubiquitous connection needs of modern Internet wireless technologies. The main challenge in exchanging audio signals resides in achieving a low-latency bidirectional communication over wireless networks. This implies the creation of a technological infrastructure that is capable to transmit audio content from one musician to another not only in hi-fi quality, but also with a negligible amount of delay, e.g., in order to allow performers to play in synchronous ways. Current technologies do not satisfy these tight constraints needed for the real-time transmission of audio content both at short and at large distances. Indeed, while the most cutting-edge current networks can deliver very high data rates, they are also restricted by communication delays of the order of 25ms [40]. This delay is unacceptable for real-time collaborative music.

The introduction of the proposed novel class of musical instruments opens questions regarding their standardization. The authors consider the features listed in section 3.1 as the minimum required for a musical instrument to be considered a Smart Instrument. However, as any process related to the development of a technical standard, the standardization of Smart Instruments will ultimately be the result of a community effort. It is the authors' hope that the present work could also serve to foster a discussion towards such a topic.

Finally, it is worth considering the aesthetic opportunities and pitfalls that a new generation of Smart Instruments will produce. Smart Instruments have the potential to add many new dimensions of control and communication onto existing performances. On the other hand, live multimodal and augmented performances have a multi-decade history, and as Tanaka observed in 2000 [41], more is not always better: "Discussions of computer based instruments often tend to focus on the power or capability of the instrument. With sensor instruments the question typically raised is how many synthesis parameters it allows the musician to control.... While this may show off the power of computers to simultaneously control multiple parameters across multiple media, it does little to convey the expression of the performer. Instead, viewing the situations from the standpoint of creative applications of limitations may yield more musical results." Whatever the capabilities of future Smart Instruments, thoughtful applications of them should retain the focus on the expression of the human performer, with an understanding that one or two well-chosen control dimensions may be worth more than the most extensive possible performance environment.

Acknowledgments

The authors wish to thank all MIND Music Labs team members. The work of Carlo Fischione is sponsored by the TNG SRA ICT project "TouCHES".

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