Smart Mandolin: autobiographical design, implementation, use cases, and lessons learned*

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ABSTRACT

This paper presents the Smart Mandolin, an exemplar of the family of the so-called smart instruments. Developed according to the paradigms of autobiographical design, it consists of a conventional acoustic mandolin enhanced with different types of sensors, a microphone, a loudspeaker, wireless connectivity to both local networks and the Internet, and a low-latency audio processing board. Various implemented use cases are presented, which leverage the smart qualities of the instrument. These include the programming of the instrument via applications for smartphones and desktop computer, as well as the wireless control of devices enabling multimodal performances such as screen projecting visuals, smartphones, and tactile devices used by the audience. The paper concludes with an evaluation conducted by the author himself after extensive use, which pinpointed pros and cons of the instrument and provided a comparison with the Hyper-Mandolin, an instance of augmented instruments previously developed by the author.

CCS CONCEPTS

• **Hardware** → **Sensors and actuators**; • **Human-centered computing** → *Sound-based input / output*; • **Computer systems organization** → *Real-time system architecture*;

KEYWORDS

smart instruments, Internet of Musical Things, digital musical instruments

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1 INTRODUCTION

An emerging area of research in the field of new interfaces for musical expression [6] is that of the so-called *smart instruments*. This novel family of musical instruments proposed in [29], is characterized by embedded computational intelligence, wireless connectivity, an embedded sound delivery system, and an onboard system for feedback to the player. Smart instruments bring together separate strands of technologies, including augmented instruments [11], networked music [18], semantic audio [3, 19], and Internet of Things [1]. They offer direct point-to-point communication between each other and other portable sensor-enabled devices connected to local networks and to the Internet.

Smart instruments are a key component of an ecosystem of interoperable musical devices that has been recently termed as "Internet of Musical Things" (IoMusT) [7, 26]. In the IoMusT, smart instruments are "Musical Things", that is interoperable devices dedicated to the production and/or reception of musical content, which can support novel forms of interactions between performers and audience members. Examples of smart instruments are the Sensus Smart Guitar developed by MIND Music Labs[1]) [25, 29] and the Smart Cajón reported in [27] and [28]. Other examples of Musical Things are the Musical Haptic Wearables (MHWs) recently proposed in [23]. These are IoT devices conceived for musical purposes, which are capable of delivering tactile stimuli to the wearer.

This paper presents the Smart Mandolin, which is the result of the enhancement of a mandolin with all the smart qualities characterizing the theorized smart instruments. Such an instrument aims to represent a milestone in the long developmental path of the mandolin, which originated in Italy during the 17th and 18th centuries as an evolution from the lute family [20, 30]. Various shapes, characteristics, and construction techniques were developed by luthiers along the centuries (e.g., flat/round back or number, position, and shape of the holes), and starting from the 1920s the electronics made inroad into the instrument so that it could be amplified. Following the paradigm of the autobiographical design of HCI research (were the designer and the user are one and the same) [15], in 2017 the author proposed the the Hyper-Mandolin (see Figure 1) [22]. This is a conventional acoustic mandolin enhanced with sensor technology and ad-hoc digital signal processing techniques to achieve, during the performer's act of playing, real-time control of effects processing the strings sounds, as well as the generation of additional sounds (e.g., via synthesizers).

The Hyper-Mandolin, which belongs to the family of the so-called *augmented instruments* [11], was conceived to unlock new degrees of expressivity beyond those offered by the plucked/strummed nature of the mandolin or by the use of conventional external equipment for sound effects (e.g., stompboxes), while at the same time avoiding the disruption of the natural interaction occurring between the player and the instrument. The proposed augmentation also aimed to enable composers to explore novel pathways for

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[1] www.mindmusiclabs.com

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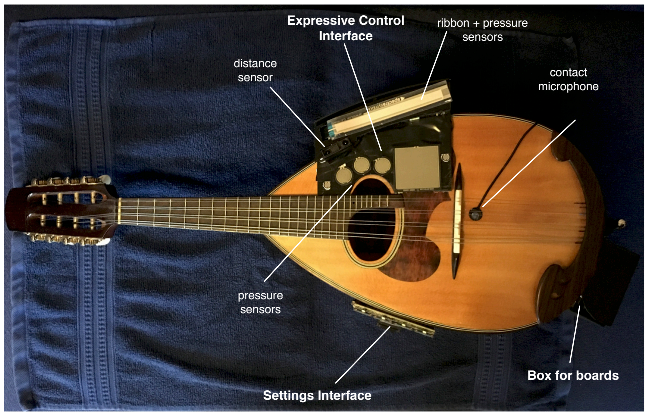

Figure 1: The Hyper-Mandolin [22] and indication of its augmentation components.

musical creation with a new instrument. The design reflected trade-offs among high level of expressive control, low cost, and ease of installation.

In more detail, the overall setup of the Hyper-Mandolin consisted of a contact microphone and a set of removable plastic supports for different layout of sensors, which connect, in a modular architecture, to a central microcontroller. Audio and sensors processing were achieved by means of an external computer running Max/MSP connected to an audio interface. The microcontroller placed on the mandolin was connected to the computer via a cable, and additional cables connected first the microphone to a dedicated pre-amplifier and subsequently the pre-amplifier to the audio interface.

A practical lesson learned by the author during the extensive and long lasting use of this instrument for both composing, rehearsing, and performing, was that such a setup was rather cumbersome, time consuming to setup, and difficult to carry to the performance venues. These issues are typically common to many augmented instruments, where the player (who is usually the designer of the instrument itself [13, 14]) has to setup not only the augmented components of the instrument but also all the required external equipment (including audio interface and computer).

One of the motivations at the basis of the development of the Smart Mandolin was the author's concrete need of an instrument having all the benefits of the Hyper-Mandolin while being at the same time capable of saving space, time and effort of setup, as well as easy to carry. Another author's rationale for this work was to investigate use cases leveraging the smart qualities of the instrument during artistic practice in order to research how to progress the possibilities for music creation and interaction with the audience. Therefore, this work, based on an autobiographical design approach [15], follows the strand of designers on new interfaces for musical expression that primarily build new instruments for personal needs, as emerged from recent analyses reported in [13] and [14]. Nevertheless, in an effort to make this study more useful to the community of designers of smart instruments, performers, and composers, the paper also reports the author's experience of using such a novel instrument for composition and performance. More importantly, it provides a comparison of such an experience with that of playing the Hyper-Mandolin reporting the lessons learned. Such a comparison is offered under a peculiar perspective, which is that of a designer, composer, and performer of both augmented and smart instruments.

2 DESIGN

The design of the "smartification" [4] of the mandolin was conceived as result of a long-lasting research on using the Hyper-Mandolin. Such a research was entirely based on the author's personal needs as a performer to avail himself of a novel interface for musical expression that, leveraging the novel smart qualities, could enable unexplored paths for composition, improvisation, performance, as well as interactions with other performers and the audience. On the one hand, these needs led to the adoption of the same design choices underlying the development of the Hyper-Mandolin reported in [22] (see Figure 1):

- Use of easily removable supports holding sensors interfaces, to be placed onto the instrument without entailing physical modifications of the instrument with holes or carvings;
- Use of a modular architecture for connecting sensors interfaces (to be placed in various parts of the instrument) to a unique microcontroller board for the analog to digital conversion of the sensors data;
- Use of two sensors interfaces, the first dedicated to the expressive control, the second to settings (e.g., bank select and preset select);
- Placement of the expressive control interface at the bottom side of the soundboard, between the bridge and the point where the neck is attached, with minimal impact on the soundboard vibrations;
- Placement of the settings interface in the region of the top side of the soundboard;
- Placement of the microcontroller board at the back of the soundboard in the region opposite to the neck.

On the other hand, those design choices were complemented by the following ones, which were conceived having in mind the use cases reported in Section 2.1:

- Creation of a self-contained instrument where not only sensors interfaces are embedded, but also audio processing, sensor processing, wireless connectivity (to local networks and to the Internet), sound diffusion, and power supply;
- Lightness and relatively small dimensions of the added technology;
- Use of a small loudspeaker capable of delivering sounds with an intensity similar to that generated by the concurrent acoustic sounds, and placement of it in a position facing the audience;
- Extendability with an optional system of wireless transmission of audio signals;
- Interoperability exploiting standard communication protocols;
- Capability of supporting mapping strategies based on data gathered not only from sensors but also from acoustic features extracted in real-time;
- Easiness of software upgradeability, easiness of programming of the sound engine, and use of open source software;

2.1 Designed use cases

The following use cases were designed in order to satisfy practical needs of programming the Smart Mandolin and to support multimodal performances leveraging the features of the instrument:
Programming. Use of applications for both smartphone and desktop PC to easily create or modify the sound engine (e.g., effects chains) and to modify its parameters for sound design and compositional purposes;
Jamming and audience participation. Enabling of an external performer in the generation of concurrent sounds computed and delivered by the instrument, as well as empowering of audience members with the control of parameters of sound effects applied to the instrument;
Local and distributed visualizations. Control of visuals projected on a screen placed in a concert hall or displayed on remote computers connected via the Internet;
Distributed lights. Control of apps running on smartphones in possession of audience members, which display different blinking colors in reaction to data received from the Smart Mandolin;
Touch the audience. Control of MHWs in possession of audience members, which deliver different tactile sensations in reaction to data received from the Smart Mandolin;
Record and transfer. Recording of all data related to a performance, the sensors values, and the reception and transmission of messages from/to connected devices, along with the transfer of such data on both a local computer and to a remote server connected via Internet.

3 IMPLEMENTATION

3.1 Hardware

Figure 2 shows the developed prototype of Smart Mandolin. The designed smartification was composed by the following components. An high quality contact microphone (HotSpot by K&K Sound) placed next to the instrument's bridge. The sensor interface was similar to that of the Hyper-Mandolin, consisting of a settings interface and an expressive control interface, which both leveraged 3-D printed plastic supports and techniques for attachments to the mandolin described in [22]. The settings interface consisted of six Standalone Toggle Capacitive Touch Sensors manufactured by Adafruit, where four adjacent capacitive sensors were dedicated to preset selection, while the other two to bank selection. The expressive control interface consisted of six Force Sensing Resistors of various sizes and types manufactured by Interlink Electronics (precisely, one squared FSR 406, three rounded FSR 402, one small-rounded FSR 400, and one strip FSR 408), one Soft Pot ribbon sensor manufactured by Spectra Symbol, the BNO055 inertial measurement unit (IMU) manufactured by Bosh, and one Sharp GP2Y0A41SK0F Infrared Proximity Sensor Short Range manufactured by Sharp. The ribbon sensor was attached, thanks to its adhesive film, on top of the strip pressure sensor in order to create a unique device capable of providing simultaneous information about position and pressure of the finger interacting with it. The IMU, used for tracking the instrument movements in the tridimensional space, was placed into a box containing the unit responsible for processing and wireless connectivity.

Such a unit consisted of the Bela board for low-latency audio processing [9, 10], based on a Beaglebone Black board, which in its basic version features 8 analog inputs, 8 analog outputs, and 16 digital GPIO, besides one audio stereo input and audio stereo output. A small wireless router was connected to it for use as a server, and was attached to the front external side of the box. The used model (TL-WR902AC by TP-Link) features the IEEE 802.11.ac Wi-Fi standard as well as a USB port for 4G dongles enabling direct Internet connectivity. When the instrument was configured as a client in presence of another router providing Internet connectivity and/or a local network, a Wi-Fi USB dongle was utilized (A6100-100PES by NETGEAR), which also features the IEEE 802.11.ac standard.

As far as the audio diffusion is concerned, the Micro II by JBL portable speaker was chosen because it represented the best tradeoff between size, weight, shape, sound quality, integrated and rechargeable battery, and also featured Bluetooth connectivity. It was attached to the top part of the box in order to face the audience. In presence of a diffusion system composed by external loudspeakers, the instrument was setup in such a way to substitute the embedded speaker with a wireless audio transmitter having an integrated and rechargeable battery (Relay G10 by Line6). Power supply to the overall system was provided by means of a lightweight power bank (5V/2A) selected for size, weight, shape, and endurance, which was attached to the bottom of the box.

An important aspect of the design was that battery, router, speaker, and wireless audio transmitter were all attachable and removable by means of velcro. All involved wires were shortened to the minimum to not be cumbersome and reduce weight. The total weight of the most heavy configuration was 320 g for the components placed into and onto the box, and about 50 g for sensor interface support.

3.2 Software

The Bela board is based on the Linux operative system, and its booting time amounts to about one minute and a half. For audio and sensors processing Pure Data (PD) applications were coded along with a dedicated C++ program capable of handling both IMU and wireless communication. The designed interoperability feature was achieved leveraging not only the Wi-Fi standard, but also Open Sound Control (OSC) messages: data reception and forwarding over Wi-Fi were achieved by leveraging OSC messages over UDP. Following the recommendations reported in [12] to optimize the components of a Wi-Fi system for live performance scenarios in order to reduce latency and increase throughput, we configured the router in access point mode, disabled security, and limited it to support "IEEE 802.11.ac" only.

Mostly adapting the research conducted for the Hyper-Mandolin (which leveraged Max/MSP), a variety of ad-hoc sound effects were implemented in PD (collected in the "PD Sound Effects Library for Smart Mandolin"), as well as mapping strategies to control them from the data gathered from the sensors. Another set of mappings was based on the real-time extraction of features from the audio signal captured by the microphone. The mandolin is an instrument with an intrinsic high level of affordances as far as the features suitable for the control of the digital sound production are concerned. It can be used as a percussive, melodic and accompanying instrument, and from all of these characteristics it is possible to

Figure 2: Front, side, and bottom views of the developed Smart Mandolin in the configuration as a server.

find a variety of potential controls by extracting different acoustic features. In more detail, for strumming (especially using stopped or palm-muting techniques) the onset, amplitude, and spectral centroid of each strummed hit was detected by or computed from the bonk~ object reported in [17]. Another extracted feature was the pitch of each note, which was achieved by means of the aubiopitch~ object reported in [2].

Figure 3: Side view of the developed Smart Mandolin in the configuration of client of a wireless local network and involving the wireless audio transmitter.

3.3 Implementation of the designed use cases

The designed use cases were implemented as follows.

Programming. Firstly, a PD application running on macbook pro laptop was created to wirelessly control and monitor all aspects of the developed sound engine by leveraging OSC messages. Data transmitted were: enable/disable each sensor, switch bank and preset, enable/disable of sound effects, control of each parameter of the sound effects, triggering of backing tracks. Data received were: values of the sensors and data related to the extracted audio features. Secondly, an app for smartphone was created by using the TouchOSC[2] environment, which allows one to rapidly build modular control surfaces for mobile applications leveraging OSC messages. The app displayed the current bank and preset controlled from the settings interface on the Smart Mandolin, the status of the sensors, as well as widgets to enable/disable each sensor and control a subset of the parameters of the sound effects.

Jamming and audience participation. In order to enable a jamming with another performer by means of a controller for instrument's sound engine, a TouchOSC-based app for smartphone was created to wirelessly control a sampler delivering sounds from a drums kit. Another app was created to enable audience members to control some of the parameters of the sound effects in each chain of effects developed.

Local and distributed visualizations. An application running on a laptop was coded in Processing[3] to display visuals controlled from the Smart Mandolin. Specifically, the application displayed abstract elements placed at the center, whose color was controlled by the extracted pitch and whose dimension was controlled by the related amplitude. The eight sensors instead controlled other abstract elements appearing at the sides and corners of the screen, whose brightness was proportional to the sensor value.

Distributed lights. By leveraging the TouchOSC environment a simple app for smartphones was created, which consisted of three circles of different colors whose brightness and blinking patterns

[2] www.hexler.net/software/touchosc
[3] www.processing.org

varied according to data sent from the Smart Mandolin. Various mappings were created, leveraging both discrete and continuous controls from both sensors data and data extracted from the acoustic feature pitch, amplitude, and onset.

Touch the audience. The engine of four prototypes of an armband-based MHW was configured to respond with tactile stimuli to messages delivered by the Smart Mandolin (see Figure 4) [24]. Specifically, the temporal happening as well as amplitude of the notes detected in real-time (via the $fiddle \sim$ object [17]) were wirelessly transmitted and mapped in a haptic stimulation whose duration was proportional to the amplitude of the note. The hypothesis, currently under investigation and based on other findings in the literature (e.g., [8]), is that the felt vibrations (e.g. related to rhythmic patterns) would enhance arousal in the audience wearing MHWs.

Record and transfer. The engine of the Smart Mandolin was configured in such a way to record in separated files various signals: the two channels of the overall electronically generated sound; the raw sound detected by the contact microphone; the strings sound processed with effects; the sound generated by synthesizers, samplers, and backing tracks triggered and modified by sensors; the temporal evolution of the values of each sensor; all the messages sent and received to/from connected devices. Moreover, a Python script was created to encode the signals in mp3, compress all files in a unique zip file, transfer it to a connected local computer as well as upload it to a remote server via FTP. The commands to start and stop the recording, as well as to transfer or upload the recorded files were sent by an app running on a smartphone, coded with TouchOSC.

4 SELF EVALUATION: LESSONS LEARNED

During the whole development process, the Smart Mandolin and the technology to implement the described use cases were subjected to extensive tests to validate the implemented smartification from the technological and artistic standpoints. Such tests were conducted exclusively by the author, since the initial "target user" of this instrument was the author himself. However, an evaluation with other mandolin players is planned and will be reported in future works.

The following presents observations of the author's own tests conducted to investigate to what extent the smartification allowed him to explore new artistic pathways. Following the guidelines of autobiographical design a non-user of the instrument was also involved in the design process for getting criticism from a different point of view. The same non-user simulated the role of audience member and jamming performer to assess the experience of playing in such situations. Moreover, in the reported self assessment a comparison is conducted between the experience of using the Smart Mandolin with that of using the Hyper-Mandolin. The perspective here reported is that of a performer who is also the composer of the music he plays, as well as the designer of both the instruments. Inspired by O'Modhrain's framework for the evaluation of digital musical instruments [16], observations are reported according to the standpoints of three roles: designer, performer, and composer.

Designer's standpoint. The prototype was found to be robust and reliable in all its aspects at a level comparable to that found for the Hyper-Mandolin. Notably, the evolution of hardware and software design went hand-in-hand with the development of the envisioned use cases and a dedicated Smart Mandolin repertoire. Eleven months of usage with the final version of the prototype revealed the effectiveness of its design in supporting creativity, expressivity, and virtuosity. The usage of the prototype and systems for use cases revealed the effectiveness of its design in supporting creativity, expressivity, and virtuosity. Compared to the Hyper-Mandolin, the Smart Mandolin actually reduced time and effort of setup, as well as it avoided to carry to performance venues additional equipment such as soundcard, cables, preamp, and laptop. Nevertheless, the augmentation technology for the Hyper-Mandolin was smaller and lighter than the one for the Smart Mandolin. Despite the size and weight of the smartification hardware were manageable in the short and medium term, a smaller and lighter setup was felt needed after two hours of continuous practice, especially to make it easy the tilting of the instrument along pitch, yaw, and roll axes. However, this desirable requirement poses technological challenges due to the miniaturization of the technology as well as would entail a sophisticated design of a PCB with integrated processing board and router. A major issue was found for battery duration, which lasted up to two hours and a half of continuous use, thus requiring the substitution with another battery for prolonged use.

As far as sound design is concerned, in the configuration involving the embedded speaker, the electronically generated sounds were carefully designed to accomplish a good integration with the sound acoustically generated. The possibility of differently balancing the volume of the electronic sounds with the acoustic ones, both of them coming basically from the same spot, led to interesting results about timbral nuances not achievable with the Hyper-Mandolin where the loudspeaker is not embedded into the instrument.

The tuning of the sound effects by means of the PD application on the laptop was found useful. The easiness of the tuning process via this application was comparable to that of using the software for the Hyper-Mandolin. In its current version the app allowed a less accurate level of fine-tuning compared to the desktop application, nevertheless its benefit of being portable and avoiding the use of a laptop was found valuable. In particular, the use of the app was preferred during rehearsals to display the names of the banks and presets as well as the effects and components present in each of them.

Performer's standpoint. The developed instrument and technology for use cases were found to be effectively capable of responding to the author's expressive needs. The accuracy, resolution, response time, and placement of the sensors, as well as the intuitiveness of the defined mapping strategies, were all factors that contributed to achieve such a goal. These aspects were comparable to those present in the Hyper-Mandolin. However, the quality of the produced sounds was not as good as that achieved with the software used Hyper-Mandolin, which run on an external laptop. This made arise the need of an embedded system not only more powerful than the used Bela board, but also capable of supporting commercial software such as Max/MSP or plugins.

The involvement of connected devices controlled by the instrument according to the described use cases involving the audience, was basically transparent when performing and was an aspect totally relying on the structure of the performed multimodal compositions. Conversely, the shared control of the sound effects from

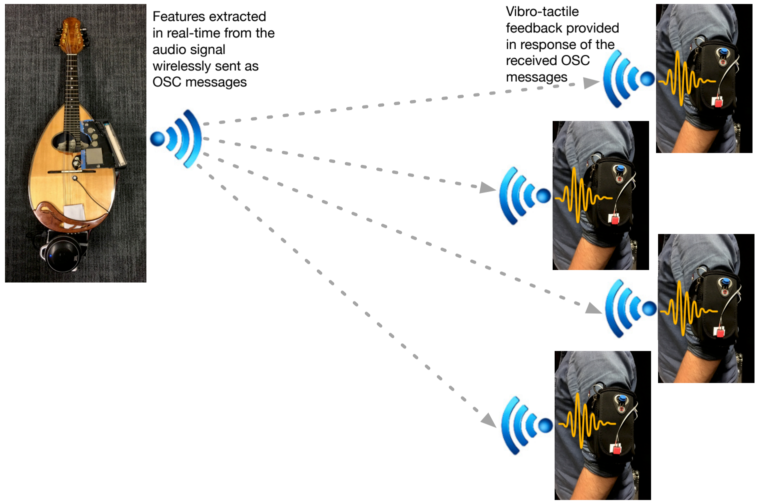

Figure 4: Interaction between a Smart Mandolin player and audience members wearing an armband-based musical haptic wearable.

an external user using the app to simulate audience participation was found most of the times detrimental for the author's expressive needs, even when the information about which parameter of the effect would have been changed was known in advance. The controlled effects that worked best were equalization and reverberation. On the other hand, the jamming with a virtual drum kit controlled by the app in possession of a user was found an interesting avenue, provided an appropriate balance between the volumes generated by the parties.

Notably, the author noticed that the the additional hardware affected the acoustic quality of the sound. Specifically, the instrument timbre was perceived to be less rich in high frequencies compared to the acoustic sound produced in absence of the hardware enhancements. This is likely to be due to the fact that the vibrations of the soundboard are in part blocked by the plastic support placed on top of it.

Composer's standpoint. The instrument enabled a novel language based not only on a variety of gestures trackable by the sensors to be incorporated in the usual playing technique like for the case of the Hyper-Mandolin, but also on multimodality. Composing for this smart instrument and the connected systems was found more challenging than composing for the corresponding augmented instrument since it entailed a radical rethinking of the instrument and its affordances: it basically shifted the focus of the composition from the music alone to the multimodal experience of the audience (e.g., involving "tactile composition" practices [5]). Moreover, the time taken to compose with the tools at hand was much longer than that required by the Hyper-Mandolin also because the use of an embedded system is more difficult than that of desktop solutions. This is due to the fact that working with the adopted embedded system required the coding of the sound engine in PD on a desktop computer, the uploading of the files into the board, and to perform compilation of the uploaded files. A factor limiting the creativity of the sounds generated by the Smart Mandolin was the restricted set of tools offered by PD compared to the larger variety offered by Max/MSP and other plugins, and above all the power of computation much limited than that of a desktop computer.

To date, four composition for solo Smart Mandolin have been produced by the author. One of these is "Dialogues with Folk-Rnn" premiered on the 20th of November 2017 at the "Being Human Festival" in London, which involves the playback of tunes generated by artificial intelligence algorithms [21]. In this composition the instrument is used in the configuration with the embedded speaker, and all the features extracted were used in conjunction with those resulting from the interaction with sensors as controls for effects, synthesizers, and backing tracks. The same composition was performed at the International Conference on New Interfaces for Musical Expression 2018[4].

Finally, as suggested by O'Modhrain regarding the design of a digital musical instrument *"a measure of the success can be seen as the audience response"* [16]. Based on audience members' comments and response, the author reports that the live performances held so far have been welcomed by audiences.

5 CONCLUSIONS

The goal of this study was to implement a prototype of Smart Mandolin starting from the lessons learned from the development of the Hyper-Mandolin [22], as well as to investigate applications relying on the smart qualities of the instrument. This research resulted in a novel interface suitable for the use in both live performance, improvisation, and composition contexts. The smartification of the mandolin was achieved by enhancing it with a microphone, a speaker, sensors, onboard processing, and wireless connectivity. Depending on the use case at hand the instrument can be configured in different ways thanks to a modular architecture that allows components to be easily attached and removed.

[4]A video of the performance is available at https://www.youtube.com/watch?v=VmJdLqejb-E

Various examples of applications exploiting the potentialities of having an embedded intelligence were presented including the real-time extraction of features from the acoustic signal, the real-time control of various ad-hoc and standard effects processing the strings sound, as well as the generation of additional sounds (i.e., via synthesizers, samplers, or backing tracks player). Its interoperability feature also allowed for the control of a variety of applications running on connected devices, which enable forms of performer-audience interactions not achievable with the Hyper-Mandolin.

On the one hand, the design of the Smart Mandolin was conceived to improve some the limitations of the Hyper-Mandolin, namely the time of setup and effort of carrying a multitude of equipment. On the other hand, it was conceived to enable novel compositional pathways leveraging multimodality and distributed processing over both local and remote networks. However, if the mentioned limitations were solved the current prototype showed to be limited in other aspects such as computational power, sound quality, variety and easiness of use of tools for composition.

The reported self evaluation pinpointed pros and cons of the instrument, especially in comparison with the Hyper-Mandolin previously developed by the author. This information, which might be useful for designers of smart instruments, will be used as a benchmark for future iterations of in the design process of subsequent prototypes. Future work will focus on the improvement of the current prototype, on the assessment with mandolin players other than the author, and on the evaluation of the audience response.

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