Some reflections on the relation between augmented and smart musical instruments*

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ABSTRACT

Augmented musical instruments (AMIs) consist of the augmentation of conventional instruments by means of sensor or actuator technologies. Smart musical instruments (SMIs) are instruments embedding not only sensor and actuator technology, but also wireless connectivity, on-board processing, and possibly systems delivering electronically produced sounds, haptic stimuli, and visuals. This paper attempts to disambiguate the concept of SMIs from that of AMIs on the basis of existing instances of the two families. We counterpose the features of these two families of musical instruments, the processes to build them (i.e., augmentation and smartification), and the respective supported practices. From the analysis it emerges that SMIs are not a subcategory of AMIs, rather they share some of their features. It is suggested that smartification is a process that encompasses augmentation, as well as that the artistic and pedagogical practices supported by SMIs may extend those offered by AMIs. These comparisons suggest that SMIs have the potential to bring more benefits to musicians and composers than AMIs, but also that they may be much more difficult to create in terms of resources and competences to be involved. Shedding light on these differences is useful to avoid confusing the two families and the respective terms, as well as for organological classifications.

CCS CONCEPTS

• **Applied computing → Sound and music computing**; • **Human-centered computing →** *Human computer interaction (HCI)*; *Sound-based input / output*;

KEYWORDS

Smart instruments, augmented instruments, smartification, augmentation, Internet of Musical Things

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1 INTRODUCTION

In the last three decades, the application of engineering and computer technology to the musical domain has introduced new possibilities to invent digital musical instruments (DMIs). Within the field of New Interfaces for Musical Expression (NIME) [17], a prominent position of such interfaces is taken by the so-called "augmented musical instruments" (AMIs), which are also referred to as "augmented instruments" or "hyper-instruments" [36]. These are conventional acoustic or electric instruments whose capabilities have been electronically extended by means of sensor or actuator technology. Sensors enhancements allow for the tracking of the performers' gestures in order to control the sound production in novel ways: by interacting with the sensors, the players control additional digital audio effects or sound synthesis processes. Builders of such instruments are motivated by the extension of the sonic possibilities of the instrument in its original version, using digital luthierie techniques [18].

Recently, Turchet et al. proposed the "Smart Musical Instruments" (SMIs), or simply "Smart Instruments"[1] [58]. This family of musical instruments is characterized by the use of sensors and actuators, as well as by wireless connectivity, embedded intelligence, and on-board processing. SMIs result from the integration of various technologies that were developed for different purposes: sensor- and actuator-based AMIs (e.g., [29, 41]), Internet of Things [1], embedded acoustic and electronic instruments [3, 23], networked music performance systems [14, 44], as well as methods for sensor fusion [43], audio pattern recognition [10], semantic audio [45], and machine learning [12].

Thanks to their features, SMIs have the potential to support novel forms of interaction of the musician with his/her instrument, between musicians or between musicians and audience members, in both co-located and remote settings. These are the result of the creation of a paradigm that has been termed as "Internet of Musical Things" (IoMusT) [19, 55], which relates to the network of objects (Musical Things) dedicated to the production, experience of, and interaction with musical content. Within this context, SMIs are instances of Musical Things.

This paper reflects on the relation between the concept of smart instruments and that of augmented instruments. We attempt to counterpose the features of these two families of musical instruments, as well as we compare the processes to create them, i.e., augmentation and smartification. Shedding light on such differences contributes to not confuse the two terms and achieve a correct use

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[1] The term "Smart Instruments" here utilized differs from the *SmartInstruments* active acoustics project of IRCAM (e.g., [34, 35]), 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/

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of the terminology, which is in particular useful for organological classifications (e.g., [26]).

2 RELATED WORKS

This section provides a non-exhaustive list of examples of augmented and smart instruments. This review provides the basis for the comparative analysis performed in Sections 3, 4, and 5.

2.1 Augmented Instruments

There are two main types of enhancements of conventional instruments: by sensors and by actuators (e.g., [41]). The former consists of the integration in the instrument of an interface composed by sensors dedicated to the tracking of performer's gestures. The latter consists of the addition of mechanical systems that directly act on the vibrating elements responsible for the instrument sound production.

For instance, among the numerous examples, sensor-based augmentations have concerned the cello [13], the piano [29], or the drums [27]. A key component of these instruments is the implementation of mapping strategies that allow the performer to control parameters of the utilized sound engine via the interaction with the sensors, which result in the integration of novel types of gestures into the normal playing technique [16, 18].

Augmentations by actuators may be achieved by involving electromagnets capable of inducing vibrations. For instance, the Feedback Resonance Guitar [41] and the Magnetic Resonator Piano [28] use electromagnets to vibrate the strings of a guitar and of a piano respectively, while the EmVibe generates vibrations in a vibraphone's aluminum tone bars [6]. Other types of augmentations involve vibration-speakers directly attached to the resonating body of the instrument. For instance, in the Haptic Drum vibrations are induced into the drum's skin [4], while in the Overtone Fiddle [40] and in the actuated guitar reported in [22] the induced vibrations control the behavior of the instrument's soundboard.

In general, both categories of AMIs may be based on acoustic (e.g., a mandolin [49]) or purely electronic instruments (e.g., an electric guitar [21]). Within the former category, instruments at the basis of AMIs might be those that have been mostly involved in classical music (e.g., flute [42], trumpet [46], violin [5], cello [13]) or to traditional music (e.g., hurdy-gurdy [47], bagpipe [32, 48]).

Common to all these instruments is the setup, which consists of the conventional instrument, the sensors and/or actuator augmentations, a laptop, a soundcard, cables, an external power supply source, and possibly a loudspeaker.

2.2 Smart Instruments

A handful of examples of instruments sharing the features of SMIs proposed in [58] exist in both industry and academy. To our best knowledge, the first crafted SMI is the Sensus Smart Guitar developed by MIND Music Labs[2]. This hybrid electro-acoustic guitar, described in [58], consists of a hollow body guitar augmented with several sensors embedded in various parts of the instrument, on-board processing, a system of multiple actuators attached to the soundboard, and interoperable wireless communication (using state-of-the art protocols for wireless transmission and reception such as Wi-Fi and Bluetooth, as well as for exchange of musical data such as MIDI and OSC). The internal sound engine affords a large variety of sound effects and sound generators, as well as it is programmable via dedicated apps on desktop PCs, smartphones, and tablets.

Another example of SMI from the industry, is the Smart Acoustic Guitar by HyVibe[3], which share with the Sensus Smart Guitar low-latency on-board processing, Bluethooth connectivity, and a sound delivery system based on multiple actuators. Nevertheless, it does not possess an advanced sensor interface for gesture tracking, full interoperability features, a large range of sound effects and generators, or capabilities of programming.

In a different vein, the company DV Mark has announced the release of the first smart multiamp[4], an amplifier for guitars that supports several plugins simulating analog cabinets and sound effects, which can be configured via smartphones or tablets and that allow a direct connection of the instrument with social media. This product is based on ELK[5], an IoT music operating system recently developed by MIND Music Labs.

An instance of SMIs conceived in the academy is the Smart Cajón reported in [56]. This instrument consists of a conventional acoustic cajón smartified with sensors, Wi-Fi connectivity, motors for vibro-tactile feedback, the Bela board for low-latency audio and sensors processing [31], which runs a sound engine composed by a sampler and various audio effects. A peculiarity of the embedded intelligence is the use of sensor fusion and semantic audio techniques to estimate the location of the players' hits on the instrument's front and side panels as well as the type of gesture that produced the hit [57]. Such information is then mapped to different sound samples simulating various percussive instruments or used for automatic score transcription purposes.

Gregorio et al. developed a drum-based DMI that shares several features with SMIs: sensors and actuators enhancements, embedded sound processing, wireless connectivity for reception of OSC messages [15]. Turchet developed a Smart Mandolin [50] starting from a design of an AMI previously developed, the Hyper-Mandolin [49]. The instrument is based on a classic Neapolitan mandolin. The smartifying technology consists of a sensors interface capable of tracking several actions of the performers, a computational unit, and an integrated loudspeaker.

Specific use cases for these instruments are starting to emerge. For instance, the Smart Mandolin has been used to perform concerts leveraging real-time audio features extraction techniques. The Sensus Smart Guitar has been used to wirelessly control visuals, digital audio workstations running on laptops, virtual reality headsets, to control or be controlled by smartphones, to record audio files and share them on social networks [54]. The HyVibe guitar has been used to deliver audio contents streamed by YouTube using a smartphone as a bridge. The Smart Mandolin and the Smart Cajón have been utilized to control haptic wearable devices [52] in possession of audience members, by exploiting real-time audio features extraction techniques [51, 53]. The Smart Cajón has also been utilized to deliver tactile stimulation to the player in response of messages

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[2] www.youtube.com/watch?v=ePcLhRZ-PAg&t=141s

[3] www.youtube.com/watch?v=BTTVOk-OpaA

[4] www.mindmusiclabs.com/wp-content/uploads/2018/01/DVMark-Smart-Multiamp.pdf

[5] www.mindmusiclabs.com/ELK

received from smartphones. Sixteen of the Gregorio et al.'s drums were used in the context of networked music performance [15].

3 AUGMENTED VS SMART

In this section we counterpose the main features of AMIs and SMIs, as well as the deriving advantages and disadvantages. In the author's view, SMIs are not a subcategory of AMIs. Conversely, AMIs and SMIs are deemed as two distinct categories of instruments, which share some common features. Figure 1a clarifies this aspect by illustrating an overlap between the two categories in terms of features. Such overlap refers to the sensor and actuators enhancements. Core differences are described as follows.

Based on conventional vs conventional and non-conventional instruments. Whereas AMIs consists of enhancements to existing acoustic or electric instruments, SMIs are true IoT devices that may or may not be based on a conventional instrument. For instance, a device producing music, that embeds intelligence, sensing, and wireless connectivity (such as an amplifier, or even as laptop or a smartphone with ad-hoc applications) can be considered a SMI.

Sonic vs interaction possibilities. Differently from AMIs, SMIs were conceived not only to extend the sonic possibilities of a conventional instrument, but also to support various forms of technologically-mediated interactions between performers, as well as between performers and audience members, in both co-located and remote scenarios.

Partial vs comprehensive enhancements. The augmentation hardware that is embedded into an AMI belongs to two categories of technology: sensors (namely microphones and gesture tracking sensors) and actuators (e.g., electro-magnetic mechanisms, vibrotactile motors). Such enhancements represent only one component of the overall system of a SMI, which additionally includes a wireless system, on-board processing, a battery, and possibly a loudspeaker as well as a haptic and visual display systems. Such overarching nature enables ubiquitous music activities [20] otherwise difficult to realize with AMIs.

Wired vs wireless connectivity. One of the central features of SMIs is their being totally wireless, and in particular to be able to wirelessly connect to local networks and the Internet. AMIs are instead intrinsically bound to wires tethering the microphone(s)/ actuators to a soundcard, the sensors interface to the laptop, or all these components to external power supply sources. This is an aspect that designers and performers of AMIs usually deem as an issue to be improved [8, 49, 59]. Nevertheless, SMIs might embed connectors for input sources or output destination (e.g., the Sensus Smart Guitar has a stereo jack cable for connectivity to mixers or loudspeakers [58]).

Unidirectional vs multidirectional communication. In some cases the player of an AMIs might use the sensors to control other equipment external to the AMI setup, such as visuals. However, the type of control in this scenario is from the instrument (or better, from the supporting laptop) towards external devices, but not vice-versa. Conversely, SMIs offer the possibility to receive messages and therefore to be controlled. This opens novel forms of shared control of the instrument from other performers as well as from the audience (e.g., [51]). In addition, SMIs offer direct connectivity to the Internet, being true IoT devices can interface with cloud services for musicians.

Bespoke vs interoperable systems. Whereas AMIs are mostly bespoke standalone systems, SMIs have interoperability as a core design feature. SMIs are capable of exchanging information between each other and other Musical Things. This is achieved by supporting all most common standards in musical data and wireless communication (e.g., using MIDI messages over Bluetooth [2], or OSC messages over UDP over IEEE 802.11 Wi-Fi [37]).

External vs on-board processing. The typical setup of AMIs involves a laptop for sensor, sound, and actuation processing, which is external to the instrument. Differently, SMIs rely on embedded systems, which are responsible for all required computations.

External vs embedded power supply. While AMIs require an external source for power supply, SMIs are equipped with a rechargeable battery.

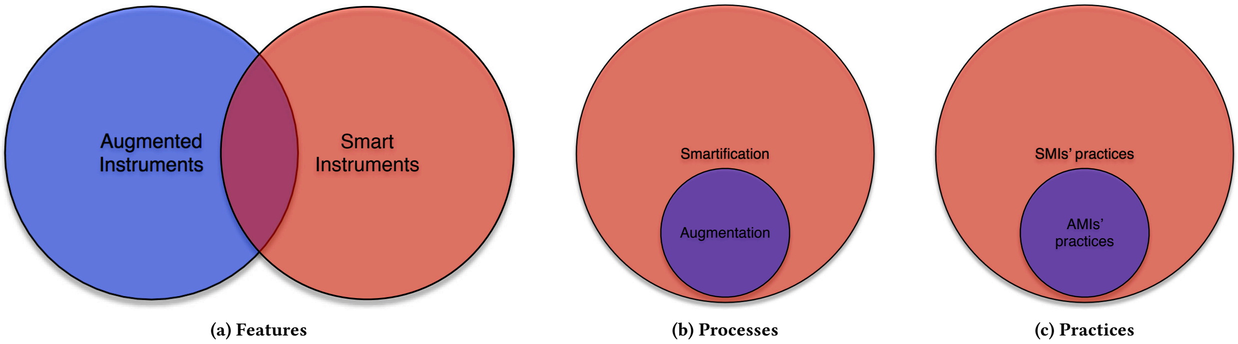
Sparse vs compact setup. The setup of an AMI involves different pieces of equipment while SMIs encompass all this equipment in a unique device. This fundamentally distinguishing aspect has clear implications for easiness of setup, portability, reduction of required space, and freedom of movement, which benefit musicians. Indeed, a SMI does not require to connect various cables, turn on and off different components, as well as using them. Musicians can simply turn on an instrument ready to use and easier to carry when traveling. A SMI also enables musicians to freely move on stage, while AMI force them to being bounded to a specific location where the setup is present.

External vs embedded intelligence. SMIs are intelligent systems. They allow for the on-board processing of various streams of data that can be simultaneously exploited for instance by sensor fusion techniques (e.g., data from sensors tracking gestures can be fused with data extracted from audio signals captured by microphones). This exploitation might be more convenient in a SMI than in an AMI. For instance, if different sources of information are sensed by different devices, each of which has its own clock and its own sample/frame rate, there are issues with temporal and spatial alignment (e.g., [24]). In a SMI all sources of information are processed with the same clock.

Unimodal vs multimodal feedback. An optional feature of SMI is that of having an integrated system for display of information leveraging the visual or the haptic channel (e.g., via a touchscreen, set of vibro-tactile motors). These multimodal systems, not present in an AMI, are conceived to display information related to the status of the instrument (e.g., navigation of banks and presets), or communicated from external devices (e.g., smartphones in possession of the audience).

4 AUGMENT VS SMARTIFY

The process of building an AMI is termed "augmentation", that of creating a SMI "smartification". This section aims to show how augmenting and smartifying an instrument pose distinct challenges and require one to follow different design, implementation and evaluation strategies. The two processes are related by an inclusion relationship as illustrated in Fig 1b: augmentation is a subcategory of smartification because smartifying an instrument encompasses all the set of actions required by the augmenting process.



(a) Features (b) Processes (c) Practices

Figure 1: Relationship between smart and augmented instruments in terms of features (1a), building processes (1b), and supported practices (1c).

Required competences and resources. The expertise required to create an AMI are mostly sensor technology development, sonic interaction design, programming languages for real-time audio such as PD or Max/MSP, and possibly instrument making. SMIs additionally require competences on embedded systems, IoT technology, and multimodal interaction design. The equipment needed to support the crafting of a SMI encompasses that of AMIs, and extends it (e.g., involving wireless sensors networks, routers, embedded systems). Therefore, the development of a SMI typically necessitates a joint effort of resources different from those of AMIs, in terms of equipment and individuals.

Hardware enhancements. In AMIs, hardware enhancements are only of two kinds: by sensors and by actuators. Conversely, the hardware smartification of an instrument may be much more complex as it encompasses additional systems (i.e., a wireless system, a power system, a soundcard, a computational unit, as well as possibly a loudspeaker, a haptic display or a visual display). Smartifying an instrument poses challenges not present in AMIs: all components need to be seamlessly integrated in a unique system, and this system needs to be placed into the instrument. Miniaturization of all the required components is therefore a critical aspect. The design, implementation, and technical validation of small, but computationally and power efficient electronics, is a process that is more difficult and requires much longer time than that involved for building a AMI.

Software enhancements. Whereas software in an AMI is used mainly to process sensors and input audio signals (to create gestures-to-sound parameters mappings and to control actuators), the software of a SMI is also dedicated to other tasks, which manifest the intelligence of the instrument. Such tasks range from the collection and analysis of sensed data, to the real-time application of sensor fusion, machine learning, pattern recognition, and semantic audio algorithms. Moreover, the SMIs' software is also responsible for handling communication with connected devices.

Easiness of programming. Generally, the software of AMIs may be much easier to program than that of SMIs. Indeed, working with an embedded system presents several constraints that a laptop does not have. Firstly, applications running on laptops have development tools that are easier to use, more widespread, more complete, and more supported than those of embedded systems. Secondly, developing software for and on embedded systems is much slower due to longer compilation times caused by the limited computational power. Thirdly, to date, most of embedded systems are based on Linux or proprietary ad-hoc operating systems, which in the vast majority of the cases do not support commercially available applications, such as DAWs, audio-plugins, Max/MSP. These have generally a greater sound quality, better interfaces to use and to program, more updated documentation. These aspects negatively affect the time and efforts of development.

Computational power. AMIs makers and composers have available a much greater computational power for sound processing, that offered by the laptop. Composers and makers of SMIs must cope with the stringent constraints of embedded systems, which require the development of code highly optimized, and often limited in terms of use of computational resources in order to avoid dropouts, glitches, and overheating of the processing board.

Mapping strategies. In AMIs, the performers' gestures are mostly mapped to parameters of sound effects or sound generators. In SMIs, mappings might also concern the simultaneous delivery of messages to connected devices, for instance generating multimodal content. Therefore, designers, composers, and performers of SMIs must carefully consider also this level of control when acting on the instrument (e.g., defining and using multimodal mapping strategies).

Evaluation. Given the additional features present in SMIs, the technical and artistic evaluation may also be more complex than that of AMIs. Evaluators need to consider all the affordances of the instrument, not only those offered by AMIs. Therefore, evaluating a SMI might take longer than evaluating an AMI.

5 AMI- VS SMI-BASED PRACTICES

The two families of musical instruments also differ in terms of artistic and pedagogical practices that they support. From a comparison between the use cases developed for AMIs and SMIs it is possible to infer that the supported practices are related by an inclusion relationship, as illustrated in Fig 1c: all practices accomplishable by AMIs can also be accomplished by SMIs, but not vice versa. In the following we detail examples motivating this statement.

Composing. Composing for an AMI entails the knowledge not only of sonic space offered by the audio engine, but also of the playing technique of the conventional instrument and how the new gestures can be integrated with it. Composing for a SMI additionally requests the knowledge of how the embedded intelligence works. Examples are the exploitation possibilities deriving from pattern recognition or sensor fusion, the integration of messages coming from external devices, or the exploitation of the capabilities of delivering messages to external equipment (both remotely and locally). By having a palette of options larger than that of AMIs, the SMIs entail a compositional process that may increase the expressive scope but may also be more challenging.

Rehearsing. Thanks to the compactness of their design, SMIs may facilitate the act of rehearsing by reducing the time and effort of setting up all the equipment otherwise required by an AMI. Musicians can carry and play anywhere their SMI by simply turning it on, while an AMI force the player to settings capable of hosting all the equipment needed. Musicians can practice with their SMI even few minutes before playing on stage, while during a concert for AMI all the equipment external to the instrument must be set in advance on stage.

Performing. AMIs can be used in a performance setting shared by the musicians playing them and the audience. SMIs also support point-to-point remote communications with other musicians or audience members. This enables a variety of artistic practices not contemplated by AMIs given their incapacity of being interoperable. SMIs afford the exchange of musical messages between each other and the display of them on the receiving instrument. This allows a performer not only to deliver information to other performers (e.g., visually or haptically), but also to control the behavior of their SMI (e.g., parameters of the sound engine). SMIs provide musicians with the possibility of communicating information displayed by smart devices used by audience members. Examples of information that can be streamed are messages controlling sounds, visuals, or text rendered by apps for smartphones, or control messages for wearables delivering tactile sensations [52]. Vice versa, audience members are enabled to stream information from their smart devices to the musicians. For instance, information that can be streamed may be messages suggesting the musicians to play a particular song, or informing about a particular emotional status of the audience. Audience members may even control some aspects of the sounds generated by musicians.

Learning. SMIs have the possibility to collect, analyze, repurpose, and wirelessly transmit data related to the musicians' playing, anywhere and at anytime. This may have pedagogical implications since the embedded intelligence could extract information useful to setup specific training programs tailored for a musician (e.g., by means of sensor fusion and machine learning techniques). Moreover, cloud-based systems capable of collecting large quantities of data automatically streamed from many SMIs could be harnessed to understand practices, behaviors, and needs of musicians. The collected information may be repurposed directly by the SMI (possibly in conjunction with external equipment such as a smart speaker, smart glasses) to support learning practices in presence or absence of a human tutor, for instance with automatic detection of the errors with respect to a score or by means of recommendation services about exercises to follow. Various AMIs have been developed for pedagogical purposes (see e.g., [11, 33]), but these do not offer Internet connectivity that could be exploited to communicate with cloud-based services, nor have been specifically designed with context-awareness and proactivity in mind.

6 DISCUSSION

In both AMIs and SMIs the addition of technology extends the performance possibilities of a conventional instrument, thus allowing for more potential for creative exploration than that offered by the instrument in its original version. While in AMIs this exploration primarily and almost exclusively concerns sonic possibilities, in SMIs it focuses on multimodal experiences and on technologically-mediated interactions between performers and audience members. SMIs have the potential to provide the player with more benefits than AMIs, but they are also much more difficult to create. To date, working with embedded systems is not as easy as working with laptops/desktop PCs. Current solutions for building SMIs are lacking efficient development tools, great computational power, a variety of applications, and support.

When they were first proposed, AMIs radically changed the manner in which the external energy was injected into the instrument. This enabled musicians to interact in new ways with the instrument. Similarly, today SMIs have the potential of changing the way of producing musical content by enabling novel interactions with the instrument (see e.g. [56]). SMIs may also support novel interactions with other performers as well as audience members (see e.g., [51]). All this poses a set of technological and artistic challenges from which AMIs are exempt, and which require further research.

The field of SMIs is in its infancy and several open questions concern them and their future. Will SMIs be affected by the same issues of AMIs? For instance, a recent review conducted by Morreale and McPherson [38] showed that the vast majority of NIME, including AMIs, is affected by longevity issues. Along the same lines, building a community of performers and composers around AMIs is also challenging and it might take years before a novel instrument establishes itself [30]. AMIs, like other DMIs, may benefit from "designing constraints" practices [25] capable of limiting the range of possibilities offered by a virtually infinite palette of digital tools available for music creation. This is even more relevant to SMIs, given the variety of features that have the potential to open a bigger expressive scope.

AMIs, like other DMIs, offer several possibilities for musical performance, but also create issues with regard to the musicians' ability to learn and control extra sound effects and sound generators [7]. Will the intelligence embedded in SMIs facilitate the process of learning and using them? Issues of AMIs related to increased cognitive load and/or transfer of skills are necessarily also present in SMIs, regardless of the fact that some musicians have "spare bandwidth" [7]. Several academic projects focused on extending the capabilities of conventional instruments, building on the expertise of trained performers [36]. We believe that co-design practices (e.g., [9]), learning all the lessons from AMIs creation and evaluations (e.g., [30, 39]), and taking into account the self-evaluations deriving from AMIs autobiographical designs (e.g., [49]) will be the key for developing future SMIs that can fully exploit the potentialities offered by their technology, while at the same time reducing the impact of the issues inherent to the learning and usage of novel musical systems.

7 CONCLUSIONS AND PERSPECTIVES

This paper attempted to delineate the differences and commonalities between two classes of musical instruments, the augmented instruments and the smart instruments. It also compared the processes to build them, namely augmentation and smartification, as well as described their relationship.

SMIs offer a framework for embedded music computing eschewing the use of the laptop on stage. They also allow for direct point-to-point communication between each other, the Internet, and other portable sensor-enabled devices, without necessitating a central mediator.

Today we live in a connected world and it is therefore natural that IoT technologies impact also the musical instruments domain, in the same way sensor and actuator technologies impacted it in the past decades leading to the family of the AMIs. SMIs might be game changing for musicians and their audience because their intelligence and connectivity properties have the potential to impact music education, create novel types of performance, as well as enable novel forms of technologically-mediated interactions, which are not afforded by AMIs.

Will augmented instruments become obsolete in the long term, while SMIs will occupy a more and more prominent position in the evolution scale of musical instruments? The future will tell us that. Nevertheless, in the present work there is no claim of superiority of SMIs versus AMIs. Rather, the work calls for a thorough verification through experimentation of the analysis, comparison and classification here presented.

To date, SMIs have not been classified yet in organological research (e.g., [26]). It is the author's hope that the attempted disambiguations exposed in the present work could be useful not only to SMIs designers, but also to organologists, and to the NIME community at large, as well as that could spur further discussions about these still evolving types of musical instruments.

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