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Smart Musical Instruments: Vision, Design Principles, and Future Directions

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ABSTRACT Smart musical instruments (SMIs) are a family of Internet of Musical Things devices for music creation. They are characterized by sensors, actuators, embedded intelligence, and wireless connectivity to local networks and to the Internet. In this paper, we depict a vision for this recent research area, which merges the research fields on digital musical instruments and smart objects, and fosters new types of interactions between the player and the instrument, between the player and other players, and between the player and audience members. We propose a set of capabilities and technical features characterizing SMIs, as well as a design for a technological architecture supporting them. To illustrate possible applications enabled by this vision, we present a set of scenarios exploiting the intelligence embedded in SMIs. We also propose a set of guidelines that can help digital luthiers in the process of designing SMIs. Finally, we present a set of directions for future research.

INDEX TERMS Digital musical instruments, Internet of Musical Things, smart objects, sound and music computing.

I. INTRODUCTION

Throughout history, every generation of luthiers has used the technology of its own era to create musical instruments, and digital technology is no exception. As Antonio Stradivari around 1700 used the latest findings in varnishes, glues, and woods to craft his superb violins, so today's luthiers can avail themselves of cutting edge technologies. Digital lutherie [47] requires skilled craftsmanship, intimate knowledge of the utilized materials, and artistry in the same measure of the luthierie for acoustic instruments. Since electronics made inroads into luthierie several digital musical instruments (DMIs) have been invented, along with applications based on them [14], [72]. With respect to this, different trends can be identified in the so-called field of new interfaces for musical expression (NIME) [44].

Some authors have focused on the creation of DMIs that extend conventional instruments with sensors, actuators, and digital signal processing techniques in an effort to balance technical and artistic novelty with established playing techniques. Sensor-based augmentations consist of enhancing the instrument with an interface composed of sensors dedicated to the tracking of performer's gestures, which are repurposed into electronically generated sounds via mapping techniques [41], [47], [57]. Among the numerous examples of this category, one can cite the Hyper Flute [87], the Augmented Violin [11], the Electrumpet [55], or the Hyper Mandolin [103]. Actuator-based augmentations consist of the enhancement of the instrument with mechanical systems that directly act on the vibrating elements responsible for the instrument sound production. Examples of this category are the Magnetic Resonator Piano [64], the Feedback Resonance Guitar [85], or the Overtone Fiddle [84]. All these DMIs, generally referred to as ‘‘augmented instruments’’, build on the rich cultural traditions of conventional instruments while expanding their range of creative expression. Typically the setup of an augmented instrument involves an external computing unit (e.g., a laptop), a soundcard, cables, an external power supply source, and possibly a loudspeaker.

Other authors have explored forms of collaborative music making resulting from the interconnection of DMIs through local or remote networks [3], [122], by leveraging the so-called networked music performance (NMP) systems (see [92] and [32] for recent reviews). One of the most noticeable examples of such DMIs is the ReacTable [48], [126]. This is a tangible interface consisting of a table able to track objects that performers move on its surface to control the sonic output. The ReacTable enables networked collaborative music performances involving multiple performers who produce music by interacting with physical objects placed on networked tables in geographically remote locations. Other NMP systems have involved wearable devices such as smart watches [71], and more frequently smartphones (see [26] for a recent review). Some of these systems have been developed for technology-mediated audience participation (TMAP) purposes [39], where the audience of live music performances takes part to the creative process and interacts with the performers [20], [27], [89], [125].

A different strand of research has prioritized self-containedness of DMIs [7], [12], [42], [56]. These instruments, whether extensions of conventional instruments or entirely novel designs, are based on embedded boards like Satellite CCRMA [8], [9] or Bela [65], [66]. Such DMIs have advantages in compactness, portability (as they avoid the use of multiple external equipment) and often stability against operating system version changes (by way of avoiding laptops or desktop computers). On the other hand, the utilized embedded systems (which are typically designed for the maker community and not for professional audio [79]) have a much more limited processing power compared to desktop solutions, which prevents the development of complex software for intensive real-time digital signal processing. Typically, the embedded intelligence has been relegated to the production of computerized sounds via gesture-to-sound parameters mappings, and to the creation of bespoke instruments not designed for interoperability or use in networked contexts.

Another set of authors have investigated computational methods for the extraction of information from the sound of musical instruments, within the fields of music information retrieval (MIR) [17] and semantic audio [99]. More often such methods are applied offline, especially by analyzing large datasets of audio files [5], while some authors have used real-time feature extraction for performance purposes [15], [43], [45], [74], especially employing machine learning techniques [29], [91]. More rarely, sensors and audio signals from augmented instruments are used together in hybrid feature extraction algorithms [88]. Sensor fusion techniques involving multiple sensor modalities have also been utilized in DMIs for improving gesture tracking accuracy [67].

While each of these approaches has been explored individually, there is a transformational value in the seamless integration of embedded computation, real-time feature extraction and sensor fusion, networked communication, and combination of gesture-to-sound parameters mapping with familiar playing techniques of conventional instruments. This has led the author and colleagues to propose the family of so-called "smart musical instruments (SMI)" or simply "smart instruments" [116]. Such instruments encompass different strands of technologies, including Internet of Things (IoT) [13] (e.g., wireless sensor networks [23]), networked music performance systems [92], sensors and actuator augmentations typical of augmented instruments [72], and embedded intelligence tailored to support real-time audio and sensor processing. Smart instruments were conceived to enable new performer-instrument, performer-performer, and audience-performer interactions. They were devised to be interoperable systems by design, offering direct point-to-point communication between each other and other smart devices, in both co-located and remote settings. One of their strengths is their capacity of reducing time and effort of setup, eliminating the use of a multitude of equipment otherwise needed to achieve similar purposes (e.g., soundcards, cables, laptop, controllers, stompboxes, multieffects processors), saving space, and facilitating the transport.

Smart instruments are instances of "Musical Things", within the "Internet of Musical Things" (IoMusT) paradigm [49], [112], [113], which refers to the network of interoperable devices dedicated to the production and/or reception of musical content. The IoMusT ecosystem gathers devices and services that connect performers and audiences to support performer-performer and audience-performers interactions. Such interactions might be both co-located and remote, by leveraging, respectively, wireless local area networks and the Internet. IoT technologies applied to musical instruments have the potential to enable new musical experiences that extend beyond those offered by current DMIs. To date, however, few musical instruments encompassing the features of SMIs exist in both industry and academy. Furthermore, research about how to exploit the embedded intelligence is still in its infancy.

While the concept of SMIs was initially proposed by the author and colleagues in [116], to date, a clear definition of what a smart instrument is has not been proposed yet, along with the identification of what are its components and what intelligence means for the case of smartified musical instruments. Moreover, different DMIs designers in both academy and industry have used the term "smart" or "intelligent" with different meanings.[1] For instance, the term "Smart Instruments" has been utilized by researchers of the active acoustics project of IRCAM[2] (see e.g., [69], [70]) to indicate musical instruments with onboard acoustic actuation, which is only one component of a SMI in the usage proposed by the author and colleagues in [116]. The company HyVibe calls "smart" an acoustic guitar enhanced with onboard processing and wireless connectivity, but lacks a system of collection, retrieval, and inference of information from the data in input to the computing unit.

This paper aims to contribute to the current strand of research on the "smartification" of musical instruments by discussing existing developments as well as proposing a vision, a formalization of the underlying technological infrastructure, and a set of design principles. We base our vision on the existing prototypes and on the most promising

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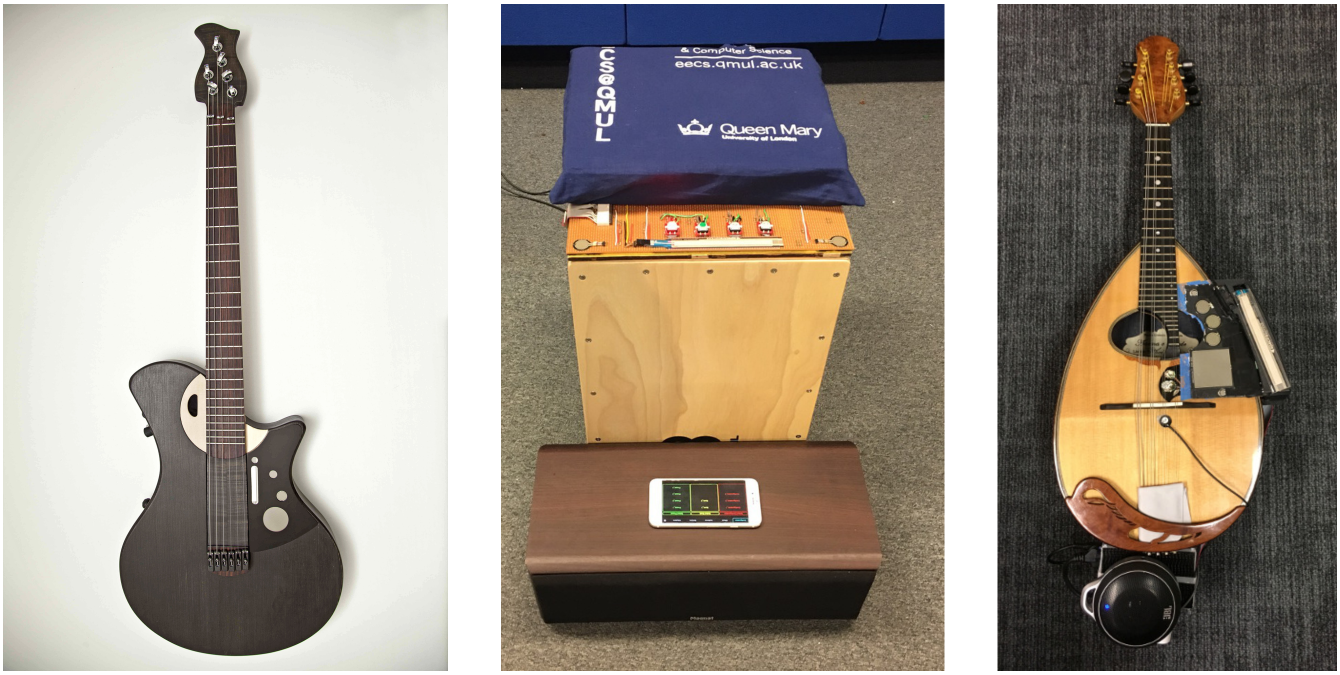
[1] In this paper "intelligent" and "smart" are used interchangeably, analogously for "smartness" and "intelligence".

[2] Full details on the IRCAM SmartInstruments can be found at http://instrum.ircam.fr/smartinstruments/



(a) (b) (c)

FIGURE 1. Pictures of existing smart instruments: (a) the Sensus Smart Guitar [116], (b) the Smart Cajón [114], (c) the Smart Mandolin [105].

technologies that could be employed in the near future to craft DMIs. SMIs are an emerging technology, which calls for guidelines that could support the design process of a SMI. Specific principles on how to design this new class of musical instruments have not yet been proposed. This paper also aims at closing this gap in research. Based on a qualitative literature review and on author's observations emerged while designing smart instruments in both industrial and academic contexts, nine design principles are identified, which practitioners in the field should take into account when crafting smart instruments.

It is worth noticing that the distinctions between the instrument designer, performer, and composer is becoming more and more blurred within the communities of makers, academics, and practitioners within the NIME field. As shown by two recent investigations conducted by Morreale and McPherson [77] and Morreale *et al.* [78], in most cases the creator and user of new DMIs is one and the same. This situation, which is rooted in the tenets of the autobiographical design [80], is the reason for which Jordá uses the term ''digital luthier'' for those who not only build but also perform with their instruments [47]. Nevertheless, within the context of this paper, the term digital luthier has a wider connotation, encompassing not only the meaning defined by Jordá for individuals, but also all members that may compose a team dedicated to crafting a SMI. As a matter of fact, the complexity of the smartification process appears to require a set of different and complementary skills that are typically not possessed by a unique individual (e.g., knowledge of instrument making, embedded systems, digital audio effects, human-computer interaction, IoT technologies) [106].

II. STATE OF THE ART

A. EXISTING SMART INSTRUMENTS

While research and development in augmented instruments has a relatively long history and many examples can be found in both the academic literature and industrial products, the same cannot be said for smart instruments. To date, only a handful of SMIs exist, almost all in a prototype stage. Moreover, despite the potential of their technological infrastructure only few use cases for them have been implemented. Bearing in mind that the term ''smart'' has not been used with an univocal meaning by DMIs designers, hereinafter we report existing musical instruments that broadly fall within the SMI concept.

To our best knowledge, the first crafted SMI is the Sensus Smart Guitar developed by MIND Music Labs[3] (see Figure 1 (a)). This hybrid electro-acoustic guitar, described in [116], consists of a hollow body guitar augmented with multiple 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

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

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,[4] which share with the Sensus Smart Guitar low-latency on-board processing, Bluetooth 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 in June 2018 of the first smart multiamp,[5] an amplifier for guitars that supports several plugins simulating analog cabinets and sound effects. This instrument is equipped with wireless connectivity that allow for the configuration via an app running on smartphones or tablets. These act as a bridge between the instrument and cloud-based services.

An instance of SMIs conceived in the academy is the Smart Cajón reported in [114] (see Figure 1 (b)). This instrument consists of a conventional acoustic cajón smartified with sensors, Wi-Fi connectivity, motors for vibro-tactile feedback, embedded low-latency audio and sensors processing, which supports a sound engine composed by a sampler and various audio effects. A peculiarity of the embedded intelligence is the use of sensor fusion and MIR 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 [115]. 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 [35]. Turchet developed a Smart Mandolin [105] a classic Neapolitan mandolin smartified with a sensors interface capable of tracking several gestures of the performer, a computational unit, Wi-Fi connectivity, and an integrated loudspeaker (see Figure 1 (c)).

In a different vein, Benford et al. developed the Carolan Guitar, an acoustic guitar augmented with decorations in form of QR codes that allow one to collect and access online digital records about the history of the instrument [6]. The Carolan Guitar represent an interesting case as it is a purely an acoustic system with no electronics at all, which is equipped with visual patterns that can connect to a broader ecosystem of information. Therefore, this instrument embodies an important principle of "smartness", the interconnectivity, but in a very different form.

Specific use cases for these instruments are starting to emerge within the IoMusT paradigm. 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 [111]. 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 [108] in possession of audience members, by exploiting real-time audio features extraction techniques [107], [109]. The Smart Cajón has also been utilized to deliver tactile stimulation to the player in response of messages received from smartphones. Sixteen instances of the drum reported in [35] were used in the context of networked music performance.

The development of a SMI is rooted in the embedded hardware and software platform utilized for low-latency audio and sensor processing as well as wireless connectivity. Nowadays, the vast majority of professional audio devices targeting the hard requirements of real-time performance are produced using ad-hoc real-time operating systems or dedicated digital signal processors. These are complex to program, offer very limited support to interface to other hardware peripherals, and lack modern software libraries for networking and access to cloud services. Such technical limitations are one of the main reasons for which so few SMIs have been created so far. Within the context of rapid prototyping boards for the maker culture [79], the state-of-the-art hardware and software for prototyping a smart instrument is Bela [65], [66]. Bela is a board for low-latency audio and sensor processing based on the Beaglebone Black and open source software (e.g., Linux, Pure Data, Supercollider). It has been utilized to prototype the Smart Cajón and Smart Mandolin described in [114] and [105] respectively. Another board recently developed for the same purposes is the one reported in [52]. As far as industrial contexts are concerned, the state-of-the-art technology for creating a smart instrument is MIND Music Labs' ELK music operating system.[6] ELK is based on Linux, guarantees round-trip latencies of 1 ms, supports music software plugins, provides wireless connectivity via BLE, Wi-Fi, and 4G, as well as offers efficient development tools. ELK is embedded in the Sensus Smart Guitar and in the DV Mark's smart multiamp.

B. DESIGN PRINCIPLES AND FRAMEWORKS IN NIME AND IoT RESEARCH

Intersections between the NIME and HCI fields have a long and rich history [40], [121] as they both rely on interactive technologies. However, in some cases their end goals are different. For instance, while HCI often targets the improvement of human performance with interactive technologies, measured in terms of efficiency and accuracy, NIME focuses on concepts such as creativity [60], expressivity [24], engagement [16], constraints [58], appropriation [127], and

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

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

[6] www.mindmusiclabs.com/ELK

personalization [68], which are difficult to quantify, measure, and account for in design processes. This is one of the reasons that motivated various authors in the NIME community to propose frameworks and principles specific to the case of designing and evaluating DMIs [76].

In 2001 Cook presented a set of principles for digital music controllers [21] and revisited them in 2009 [22]. Those principles originated form the author's experience in making musical interfaces, and related to both human and technical factors. In 2008, Johnston and colleagues proposed design and evaluation criteria specific for DMIs based on acoustic instruments controlling virtual instruments simulated with physical modeling techniques [46]. In 2009 Overholt proposed the Musical Interface Technology Design Space, a theoretical framework for the design of DMIs, which focused on expressivity factors relating human gestures with complex synthesis methods [83]. Yet in 2009 Paine proposed design guidelines for DMIs, which suggested the importance of leveraging in the digital realm the physicality of the interaction that is typical of acoustic instruments (which can be e.g., strummed, plucked, blowed, hit, or bowed) in order to control the electronically generated sounds [86]. In 2013, Xambó and colleagues proposed a set of design considerations for supporting collaborative learning on tabletop tangible user interfaces for musical performance [126]. In 2014 Morreale and colleagues presented a framework for musical interface design grounded in the experience of the player [76], where evaluation is considered as a central activity in designing musical interfaces including DMIs. In a different vein, in 2014 Ge Wang proposed thirteen principles for visual design for computer music, focusing in particular on real-time integration of graphics and audio. Those principles were categorized as aesthetic or user-oriented, with some additional observations. In 2016 Serafin and colleagues proposed nine design principles for virtual reality musical instruments (VRMI), focusing on the experience of the performer while interacting with the virtual world [95]. In 2017 Morreale and McPherson proposed a set of design considerations accounting for longevity of DMIs [77]. Such considerations were based on a survey conducted on designers of DMIs asked to reflect about design issues that limited the uptake of the crafted instruments or the aspects that facilitated their establishment and adoption.

The principles developed by the NIME community have mostly focused on the design of interfaces for the performer with no or little consideration for the range of possibilities of interconnection of the instrument with other devices that enable co-located and remote musical interactions of the player with other players, audience members, and machines. Networked interactions are instead the focus of IoT research. Design principles and considerations developed by the IoT research community include proposals for the characteristics and capabilities of the smart objects composing the IoT [18], [19], [50], on the services they can support [4], or on processes for industries [37]. The importance of designing interactions more human-friendly of such smart objects has been advocated by Miranda and colleagues [73], who highlighted how the current tools and technologies supporting the interaction between the IoT and humans force the user to adapt to technology rather than making technology adapt and assist the user. To cope with such issue, those authors proposed a set of design principles for smart objects that included context-awareness, proactivity, predictability, social aspects, and personalization. Nevertheless, none of the principles generated within the IoT academic community was specifically conceived for IoT-human musical interactions.

III. VISION

As shown in Section I, SMIs lie in an emerging field positioned at the intersection of new interfaces for musical expression [44], Internet of Things [13], music information retrieval [17], networked music performance [92], and technology-mediated audience participation [39]. Based on the examples of existing musical instruments termed as "smart" (as reviewed in Section II-A) as well as the author's observations, this section aims to propose a vision for the future smart instruments, by presenting a definition for them, describing their underlying technological architecture, and proposing scenarios illustrating the new capabilities they offer.

A. DEFINING SMART INSTRUMENTS

What mainly distinguishes SMIs from previous DMIs is their intelligence as well as the integration of different technological components which such intelligence operates on. We attempt to define SMIs as *"devices dedicated to playing music, which are equipped with embedded intelligence and are able to communicate with external devices"*. What is intelligence in a smart musical instrument? What is responsible for? And, more importantly, what SMIs can do that other DMIs can't? To address these questions on the added value of SMIs we corroborate the definition by proposing a set of capabilities that SMIs may have. Our proposal builds upon different lines of research on the concept of intelligence in smart objects (e.g., [38], [50]) and in particular the recent work of Cena *et al.* [18], who proposed a framework for the design and the classification of smart objects based on a multi-dimensional characterization of intelligence. Indeed, in line with those authors' view, the smart behavior of a SMI is the result of proper combinations of several dimensions of intelligence: a SMI should have the ability to support musicians in their activities, interacting and managing social relations with them, the context and possibly other SMIs and Musical Things. We single out the following five abilities that a SMI may have:

1) KNOWLEDGE MANAGEMENT

A SMI is capable of maintaining knowledge about itself and the environment. Regarding the former, a SMI may have a model about its physical (e.g., shape, materials, number of strings, types and position of sensors and actuators) and digital properties (e.g., how the sound engine is composed, how many audio plugins it can support, which plugins are installed). It may also have a model about what it can offer to the player in terms of services, interaction, information (e.g., the musical goals for which it was designed, the functions it can offer to achieve these goals, and how it behaves when such functions are activated). Regarding the knowledge about the environment, a SMI is context-aware, that is it may have knowledge about the physical and digital world around it. For instance, it may have a model about the musician playing the instrument, such as his/her preferences, needs, goals, and state (e.g., what actions is he/she performing on the instrument, what did he/she played, what genres he/she plays most, which mistakes he/she does with respect to a certain score), as well as a model about other connected Musical Things (e.g., their structural properties, functions, and control parameters). The instrument may also gather information about the context in which it operates (e.g., the distance between the instrument and the one of a connected musician, the temperature of a concert hall that might affect the tuning of the instrument).

2) REASONING

SMIs possess the ability to make inferences on the acquired knowledge. Reasoning may involve various types of processing, which may or may not happen in real-time. These include real-time sensor and audio signals processing (e.g., sensor fusion, real-time music information retrieval, control of the sound engine from the sensors according to defined mapping strategies, adaptive digital audio effects [119]), as well as other types of computations performed on the internal memory (e.g., offline music information retrieval on stored audio databases) or on information related to the state of the instrument (e.g., configuring the sensor interface and the sound engine according to a certain music piece) and of the environment around it (e.g., processing audio signals or data received from other connected SMIs or from the cloud). The SMI may also be able to take decisions by itself and act autonomously. Moreover, whereas the instrument has its own intelligence, it may also be capable of using the intelligence located in the network (e.g., leveraging the intelligence of other connected Musical Things, cloud computing).

3) LEARNING

SMIs have the ability to learn from previous experience. They can learn from the way musicians (and possibly other Musical Things) interact (physically and/or digitally) with them. They can also learn from how the musician and the environment react to their actions. For instance the instrument may learn new functions it can perform (e.g., recognizing a melodic pattern) or new behaviors to accomplish a function (e.g., triggering a sound sample when a certain melodic pattern occurs), or even learn new goals it can achieve. Moreover, the learned information may be used to update the acquired knowledge (e.g., the model of the player).

4) HUMAN-SMI INTERACTION

Besides the actual response to musical actions in terms of sound production, a SMI may encompass adaptation and proactivity abilities. It may be able to adapt its function or behavior and therefore the services it offers. For instance, a SMI may exploit its knowledge about the player's goal (e.g., learning to play Bebop jazz style) and the current context (e.g., playing in a jazz band of four elements) to decide the service to be offered (e.g., recommendations of which backing tracks to rehearse on when practicing alone, configuration of the instrument's sound engine to achieve timbres appropriate for the Bebop jazz style). In addition, SMIs may display information to the player about the status of the instrument or of the environment via auditory, haptic, or visual feedback.

5) SMI-MUSICAL THINGS INTERACTION

SMIs are capable of wirelessly exchanging information with a diverse network of interoperable Musical Things. These interactions may be co-located or remote. For instance, the instrument may respond with tactile feedback to notifications sent by an audience member using his/her smartphone, or it may stream audio content to another SMI during a remote rehearsal via point-to-point connectivity feature. The SMI may also exploit the distributed intelligence resulting from connected Musical Things, for instance for collaborative music making purposes (e.g., co-located audience members produce an accompanying music with their smartphones in response to directions transmitted from the SMI).

B. TECHNICAL FEATURES

To support the abilities described above, we propose that SMIs should have a set of core features, and possibly a set of optional features (which are a revised and extended version of those presented in [116]).

1) LIST OF CORE FEATURES

a: A SYSTEM FOR CAPTURING THE USER'S INTERACTION WITH THE INSTRUMENT

The user's interaction might be a set of actions not only performed to actually produce sounds (e.g., strumming the strings of a guitar detected by pickups, touching a widget on a touchscreen to trigger a sample) and to modulate sounds (e.g., changing the proximity of the hand from a distance sensor to continuously modulate a parameter of a sound effect), but also to deliver control messages to connected external devices

b: A LOW-LATENCY, HIGHLY RELIABLE, AND INTEROPERABLE WIRELESS COMMUNICATION SYSTEM INTERFACING WITH WLANS AND WANS

SMI must rely on hardware and software communication solutions that guarantee the stringent requirement of low-latency while preserving transmission reliability. At present, ad-hoc wireless transmitters/receivers systems are available on the market for transmitting, reliably and with low-latency, audio signal over a limited distance (maximum 30 m). Data streams at much lower sample rate can also be communicated with low-latency by using the latest commercially available routers for WLANs, which leverage the most updated standards. Nevertheless, typically the critical component of this transmission is ensuring a low and constant variability of such latency (which is referred to as ''jitter''). SMIs may also be equipped with direct connectivity to the Internet by exploiting a wireless router interfacing with the latest generation of mobile networks (in future, they could interface with the so-called Tactile Internet [61], which is expected to ensure low-latency and reliable remote communications). Alternatively, in absence of this direct connectivity a SMI may be connected to a device such as a smartphone acting as a bridge to stream content from the Internet. On the other hand, to ensure interoperability, a SMI must conform to state-of-the-art standards and widely used protocols rather than ad-hoc wireless transmitters/receivers. This will ensure the capability of a SMI to work in concert with other Musical Things, by enabling the exchange and the interpretation of the shared data. For instance, at the time of this writing, a SMI can be equipped with hardware supporting Bluetooth Low Energy and Wi-Fi 802.11.ac, as well as software utilizing protocols such as MIDI or Open Sound Control (OSC) [124], running over the User Datagram Protocol (UDP). Furthermore, such wireless communication must encompass methods for ensuring security and privacy.

c: AN EMBEDDED COMPUTATIONAL UNIT IMPLEMENTING THE INTELLIGENT COMPONENT

In a SMI intelligence is achieved by a software running over a real-time operating system, which operates on an embedded system designed for low-latency processing (e.g., [51], [53], [65]). The embedded system includes microcontrollers for acquisition of sensor data and for the analog to digital conversion of audio signals. The real-time operating system must ensure a round-trip latency of less than 10 ms to achieve credible musical interactions [66], [123] (i.e., the time difference from when the input signal is acquired by a device and the output signal is produced by the same device). This amount is an accepted target for latency in real-time interactive audio systems [30], [31], [123].

The software is responsible for sensor data processing, sound processing and generation including all capabilities of digital audio workstations (DAWs), as well as for the processing and control of received/transmitted data from/to connected devices. The software also accounts for all activities related to knowledge management, reasoning, and learning. Such activities rely on models of the instrument and of the environment, which may be based on ontologies [101] codifying the knowledge domain that is going to be captured, processed and used to interact.

In more detail, the processing of audio and sensors may leverage techniques to extract in real-time the musical information related to the player's interaction (e.g., by means of hard real-time onset detectors [104]) and exploit sensor fusion and machine learning methods [29]. The extracted information may then be organized according to ontologies (e.g., [2], [90], [100]), which are structured, machine processable representations of audio analyses that facilitate automated data processing and knowledge-based reasoning [28]. This is an endeavor of Semantic Audio, an emerging field at the intersection of MIR and Semantic Web [10], which aims at extracting meaning from audio signals that can be interpreted by humans and machines alike. It involves the application of signal analysis and machine learning to extract descriptors from digital audio, ranging from signal level features (e.g., amplitude), through perceptual characteristics (e.g., loudness), to high-level semantic descriptors (e.g., mood).

As far as the learning process is concerned, the models for complex machine learning predictions may be trained on large annotated databases of real-world data or a combination of real-world and synthesized data. For this purpose, the models can be trained offline on powerful computational units and then deployed on the embedded systems for the real-time use. To date, the most promising machine learning technology for complex tasks such as those envisioned by the intelligent capabilities of SMIs is deep learning [54]. Supervised techniques leading to better prediction performance should be involved as musician-instrument interaction requires high reliability. For this purpose, one could employ deep reinforcement-learning techniques [75], where a musician can interactively update a model based on his/her personal behavior.

Finally, it is worth noticing that the embedded intelligence is particularly well-suited for edge computing tasks [63], [93], [96], which allow for the reduction of the network latency and bandwidth pressure in IoMusT architectures, by offloading the computation from the cloud.

d: MEMORY

SMIs are equipped with a system to store and access digital data. Such digital data may be related not only to music content (e.g., database of audio files of backing tracks, recordings of played songs), but also to the models that the instrument has of itself and of the environment around it.

e: POWER SUPPLY

SMIs ensure an efficient and long-lasting functioning without constantly relying on an external source for power supply (although they may encompass a system for providing power supply from an external source).

2) LIST OF OPTIONAL FEATURES

a: AN EMBEDDED SOUND DELIVERY SYSTEM

SMIs may be capable of producing the electronically generated sounds, for instance via embedded loudspeakers or a system of multiple actuators attached to a soundboard (e.g., [84]). In this way the source of the computerized sounds is located onto the instrument. However, in absence of this feature, one can utilize the wireless transmission of audio signals for delivery by an external loudspeaker (an example of instrument of this type could be a microphone enhanced with sensors, wireless connectivity, and embedded processing, but without a loudspeaker).

b: ACOUSTIC SOUND SOURCE

SMI may be based on conventional acoustic instruments and therefore able to produce sounds in an acoustic way. On the other hand, they may be totally electronic (therefore, even a smartphone or a laptop with appropriate intelligent musical software can be considered as a SMI).

c: INPUTS/OUTPUTS FOR WIRED CONNECTIVITY

A SMI may encompass one or more connectors e.g., for audio or MIDI cables, in order to be fully retro-compatible with existing audio equipment not relying on wireless communication.

d: A SYSTEM FOR HAPTIC DISPLAY

SMIs may embed actuators capable of providing haptic feedback (e.g., vibrotactile, pressure, thermal). This feedback may be used to leverage the sense of touch as a communication channel between the performer and the audience, as well as between the performer and other performers, or to display information from the instrument (e.g., communication of the internal status of the instrument, rhythmic patterns for educational purposes).

e: A SYSTEM FOR VISUAL DISPLAY

SMIs may embed a screen to display various types of information about the internal status of the instrument (e.g., to navigate banks and presets) or received from other performers and audience members. For instance, such visual display system may take the form of a series of LEDs, an OLED display, or a touchscreen.

C. RELATIONSHIP WITH OTHER DMIs

Considering an organological perspective [59], one can draw the following relationships between SMIs and existing DMIs. Such relationships, graphically illustrated in Figure 2, account for both capabilities and technical features.

1) RELATIONSHIP BETWEEN DMIs, SMART OBJECTS, AND SMIs

SMIs lie at the intersection between DMIs and smart objects [33], [50], as they encompass capabilities and features of both of them. On the one hand typically smart objects are not designed for musical purposes, on the other hand DMIs do not encompass context-awareness or proactivity aspects. Therefore, SMIs create a bridge between these two domains.

2) RELATIONSHIP BETWEEN AUGMENTED INSTRUMENTS, EMBEDDED INSTRUMENTS, VIRTUAL REALITY MUSICAL INSTRUMENTS, AND SMIs

SMIs include features and capabilities of previous DMIs. They share in common with augmented instruments sensors and actuators enhancements [106], with embedded instruments the self-contained nature, with virtual reality musical instruments the fact that they can operate in the virtual world to generate music. Nevertheless, SMIs are envisioned to extend the capabilities of those DMIs as they leverage networked interactions (both co-located and remote), and feature the intelligent component described above that is not present in previous efforts.

3) RELATIONSHIP BETWEEN NMP SYSTEMS, TMAP SYSTEMS, AND SMIs

SMIs share in common with NMP systems the networking aspect. Some of TMAP systems are based on networks, which motivates an intersection relation with NMP systems. SMIs position themselves at the intersection between these two categories as they may encompass their features and capabilities. However, SMIs may offer more opportunities than NMP and TMAP systems (e.g., those resulting from the exploitation of the intelligence), as well as their features may be different (e.g., their embedded nature).

D. ENVISIONING INTELLIGENCE

To illustrate the new possibilities offered by SMIs, we propose a set of scenarios that are only possible with systems encompassing the capabilities and features of SMIs. These scenarios do not aim at representing real musicians', producers', and audience members' needs or desires, which need to be investigated. Their role is to enable a discussion about the potential of SMIs.

1) SCENARIO 1: REMOTE REHEARSALS, INTELLIGENT MIXING, AND INTERACTION WITH THE CLOUD

Caroline and Eduardo are an improvisation duo and play respectively a smart cello and a smart violin. They need to rehearse for a concert but they live at 140 Km from each other, and considering the cost of traveling and the time taken it is not convenient for them to meet in person. They opt for a remote rehearsal from their respective homes, leveraging the capability of their smart instruments to exchange the produced sounds between each other. The sound of the smart violin of Eduardo is received on the smart cello of Caroline and vice versa, and both instruments stream the received audio signals to a surround sound system. At some point the musicians decide to record, on the smart cello, what they are playing and send the result to Nicolas, a studio producer, asking for his feedback. The smart cello is capable of recording a mix of the sound produced by the instrument itself and that of the smart violin. Its internal mixer understands the properties of the smart violin (i.e., it is a smart violin, it has five sensors controlling the parameters of three

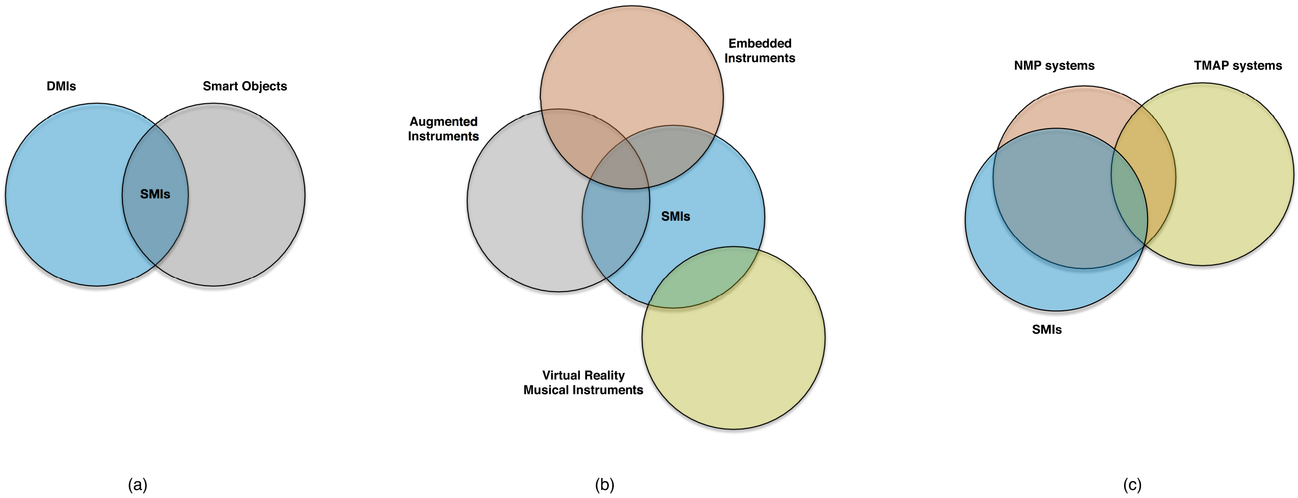

FIGURE 2. Relationships between SMIs and (a) DMIs and Smart Objects, (b) augmented instruments, embedded instruments and virtual reality musical instruments, (c) NMP systems and TMAP systems.

sound effects and two synthesizers) and acts accordingly to produce the best mixing. Both the smart violin and the smart cello produced not only the generated audio signals, but also the metadata associated with the instrument's configurations (such as the utilized sound effects chain, synthesizers, drum machines, as well as their presets), the sensors signals, and the score (automatically transcribed) of what they played. This information is also stored in the recording produced by the smart cello mixer. Nicolas receives the recording and suggests to Caroline to download into her smart cello a preset for the synthesizers that would lead to a better sonic output in relation to the sound effects of Eduardo's smart violin. He also modifies the recorded track of Eduardo and removes from it the sounds related to the first pressure sensor in the sensor interface, suggesting that the sound texture was too complicated otherwise. Carolina accept Nicolas' suggestion and connect her instrument to a cloud repository where she can access and download the recommended presets. Eduardo listens to the recording of his track modified by Nicolas and decides to follow his recommendation of not using the indicated sensor. Both musicians record again their improvisations and upload the recording on a social network for musicians, sharing also the score of their improvisation.

2) SCENARIO 2: ENHANCED MUSIC LEARNING

Liang has just started to self-teach himself how to play a smart guitar. He is following a method that comes with an app for his tablet, which is wirelessly connected to the smart guitar. The smart guitar is capable of inferring in real-time the errors Liang is making with respect to the score he has to play at a certain tempo. The score is stored in the instrument and displayed on the tablet, and the instrument also controls an haptic metronome, provided through an armband with motors, according to the selected tempo. When Liang makes a mistake the smart guitar sends this information to the app which displays the error in the score along with a short video about how to play correctly. Liang keeps doing the same errors in the same point so the smart guitar, via the tablet's app, suggests him that the tempo he is following is too fast. Liang accepts this recommendation and the smart guitar reconfigure the metronome's tempo. As Liang progresses in his practices, the system learns that he is doing less errors so it suggests a faster tempo, and Liang accepts this recommendation. The smart guitar is also connected to a cloud repository related to the learning program Liang is following. The cloud repository receives from the smart guitar the statistics about the progresses that Liang is doing (e.g., error rate, time needed to achieve perfect playing of the score, number of hours played per day) and on the basis of this information sends to the guitar a recommendation to play another score. Liang gets notified via the tablet's app that a new music piece to learn is ready for him, he accepts the recommendation, and the smart guitar reconfigures itself according to the new piece (e.g., setting an effects chain and sensors-to-sound parameters mappings).

3) SCENARIO 3: ENHANCED LIVE MUSIC EXPERIENCE AND AUDIENCE PARTICIPATION

The Floydstones band is composed by a smart ukulele, a smart drum, a smart bass, and a smart keyboard. The musicians are performing a gig in a theater and their show includes moments in which the audience can participate by creating accompanying sounds via their smartphones. Thanks to an app in their smartphones the audience members can connect to one of the smart instruments on stage. At certain points of the concert each smart instrument delivers to the connected smartphones some instructions on what the user can do to create an accompanying soundscape (e.g., shaking the smartphone, clicking on some widgets) and the audience follows the instructions. Some of the audience members wear smart glasses for augmented reality, others use a jacket capable of providing haptic feedback. All these devices are connected to the same local network in which the smart instruments are connected. Each instrument understands that there are connected smart glasses and smart haptic jackets and for each of those devices it delivers a different content to enhance the audience's music listening experience (e.g., the smart drum delivers to the haptic jacket control messages activating vibrotactile pulses synchronized to the played rhythm, the smart keyboard transmits to the smart glasses control messages that change the color of the lenses).

4) SCENARIO 4: ADAPTATION TO STRUCTURAL CHANGES AND KNOWLEDGE OF THE ENVIRONMENT

Kyra is a professional smart double bass performer. Her smart double bass has the possibility to easily attach and remove different layouts of the sensor interface. To play the next piece in the set during one of his performances Kyra changes the current layout she is using (which encompasses 5 pressure sensors and one proximity sensor) into another one (which consists of a ribbon sensor and an inertial measurement unit). As soon as the new layout is attached, the smart double bass recognizes it and automatically reconfigure itself to use it. After the performance Kyra leaves the smart double bass in the basement of the concert hall, as the day after she will perform there another gig. The smart cello is also equipped with a humidity sensor, which detects that the basement is very dry and sends a notification to Kyra's smartphone that this condition can potentially harm the instrument. Therefore, Kyra decides to turn on, for the night, the small humidifier she brings inside the case of the smart double bass.

5) SCENARIO 5: EDGE COMPUTING FOR MUSIC MOOD INFERENCE AND REPURPOSING

Fabio and Gisella, respectively a composer and a choreographer, have created a spectacle involving a symphonic orchestra of 70 smart instrument players and a corps de ballet. They have set up an IoMusT architecture at the concert hall where the music played by the symphonic orchestra interactively directs improvisation dancers wearing musical haptic wearables as well as controls pieces of equipment of the choreography (namely visuals displayed on four large screens attached at the hall walls, the hall lighting system, and the stage smoke machines). Specifically, groups of the involved Musical Things are controlled by the mood of the music played by each of the four sections of the symphonic orchestra (woodwinds, brass, percussion, and strings). The mood is inferred by a co-located central server which receives data from all the SMIs and repurposes the inferred mood in control signals for the other connected Musical Things. Each SMI does not deliver to the server the produced audio signal, but a set of features that have been extracted in real-time from it.

6) REFLECTIONS ON THE SCENARIOS

The described scenarios embody many key ideas of the SMI paradigm. Scenario 1 highlights the interoperability between SMIs, by showing point-to-point connectivity (leveraging the future Tactile Internet [61]) allowing to stream in real-time between each other not only audio content, but also other data associated to the configuration of the instrument and its functioning. The scenario also illustrates how SMIs can provide automatic services such as intelligent mixing, that do not require human intervention. Moreover, the scenario presents non-real-time interactions between the instrument and the cloud, such as the download of presets from online repositories or the sharing of recordings on social networks.

Scenario 2 shows interoperability between the SMI and other Musical Things (e.g., a tablet and a haptic metronome), as well as the proactivity offered through different services that support the musician's process of learning to play. Those services are based on the instrument capability of understanding and learning what the musician is playing and comparing this information with that stored in the memory. Scenario 2 also shows the instrument's abilitys to automatically reconfigure itself according to a certain task to be accomplished.

Scenario 3 shows how the instrument can enable new forms of interaction between the performers and their audience. In particular, it highlights the ability of the SMIs to create a model of the digital environment around themselves (by automatically understanding which devices are connected to them) and act on this environment accordingly (by delivering different information to the different devices).

Scenario 4 illustrates how a SMI has knowledge about itself and can react to structural modifications (such as the change of one of its components) by automatically understanding the occurred changes and reconfiguring itself accordingly. Furthermore, the scenario shows how the instrument is able to retrieve which are the conditions of the physical environment around it and inform the player about them.

Scenario 5 shows an application of the edge computing paradigm, where several SMIs preprocess and summarize information collected by their inputs before transmitting it over the network. This allows one to filter out everything but what is needed so as to remove unnecessary traffic and, therefore, largely reduce the global bandwidth consumption. The central server is offloaded from several computations and storage costs, which would have been otherwise necessary in order to infer the mood from an enormous amount of data. This also benefits the latency of the overall IoMusT architecture as longer times for calculations of all audio streams from the SMIs would have been necessary.

E. ARCHITECTURE OF A SMART INSTRUMENT

Based on the list of features described in Section III-B we propose a design for a technological architecture at the core of a SMI, in terms of building blocks representing the smartifying hardware and software as well as of pathways for audio and data routing. This architecture encompasses both the mandatory and optional features. The architecture, illustrated in Figure 3, is composed by five main components: inputs, a processing system, outputs, memory, and a power supply system.

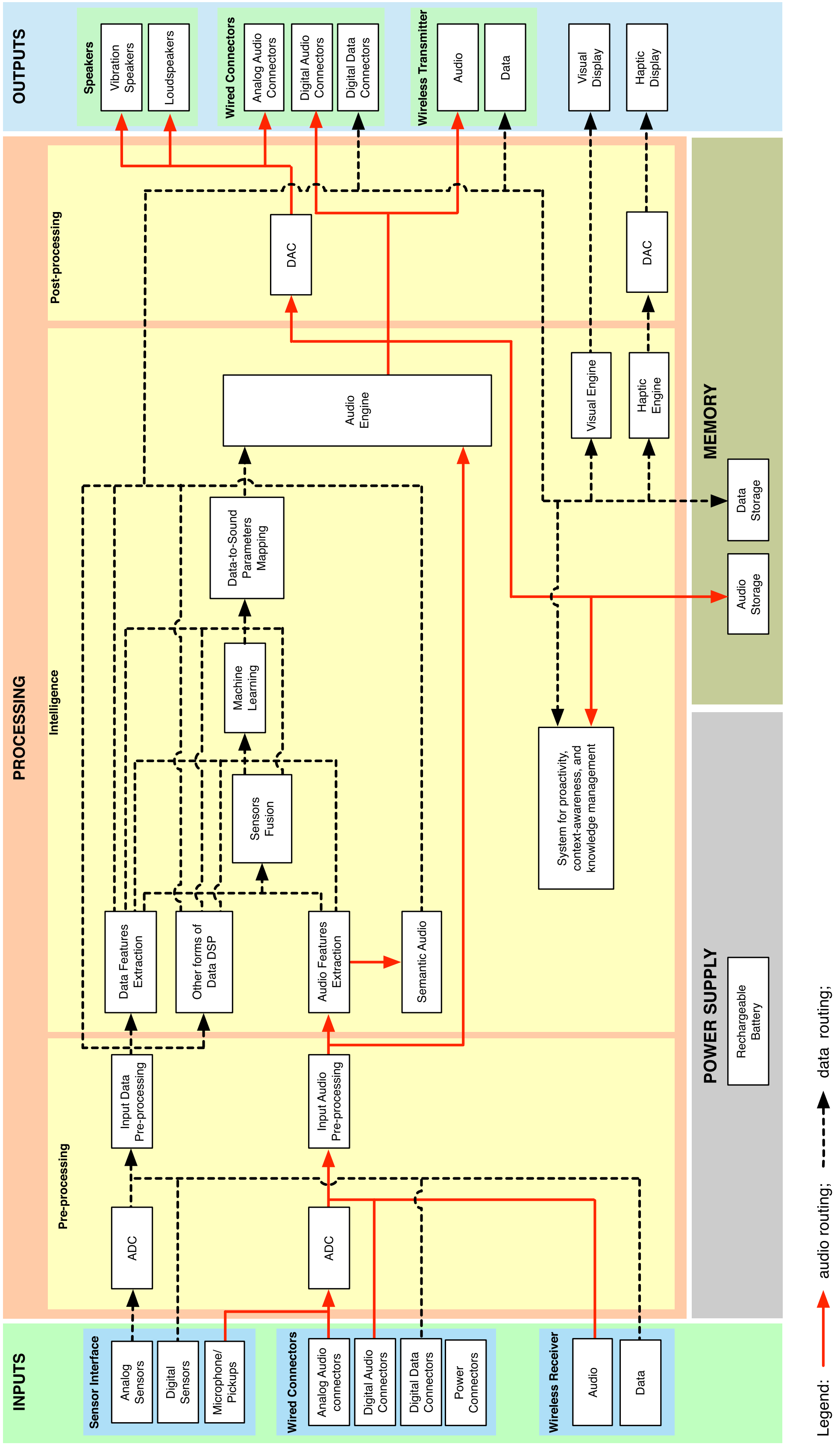

FIGURE 3. Architecture of a Smart Musical Instrument.

1) INPUTS

The Inputs component is composed by the following blocks:

a: SENSOR INTERFACE

It comprises various types of sensors, including those capturing audio signals (e.g., a microphone) as well as non-audio signals, which may operate both in the analog domain (e.g., pressure sensors) and in the digital one (e.g., touchscreen).

b: WIRED CONNECTORS

This block includes connectors for analog audio (e.g., inputs for jack cables), digital audio (e.g., ADAT), or digital data (e.g., inputs for MIDI cables), as well as for recharging the embedded battery or to provide power supply bypassing it.

c: WIRELESS RECEIVER

This apparatus ensures the reception of both audio signals and other types of data (e.g., OSC messages), and produces digital signals as output.

2) PROCESSING

The Processing component relies on an embedded system running a real-time operating system capable of achieving a round-trip latency lower than 10 ms, is composed by the following blocks:

a: PRE-PROCESSING

This block is responsible for transforming the inputs signals in formats usable by the embedded intelligence. Specifically, it consists of the analog to digital conversion of analogue signals, a system for thresholding, filtering, scaling/amplifying the input signals, as well as a system for parsing incoming messages.

b: INTELLIGENCE

It comprises all the components that allow the instrument to analyze and repurpose the pre-processed inputs, according to the capabilities listed in Section III-A. These include: systems for extracting features from audio and sensors (e.g., onset detection, spectral centroids, gestural or musical patterns recognition), systems for other forms of digital signal processing (e.g., algorithms acting on the sensors data), systems for labeling the information extracted from the audio signals (i.e., semantic audio algorithms), systems for sensor fusion and machine learning. These information can then become the input for algorithms controlling the parameters of Audio, Haptic, and Visual Engines, as well as for a system responsible for proactivity, context-awareness, and knowledge management. The Audio Engine is responsible for all electronically generated sounds, and comprises blocks for sound modulation (e.g., effects such as delays, reverberation, etc.), sound generation (e.g., samplers, synthesizers, drum machines, loop stations), as well as mix and transport functions typical of DAWs. Figure 4 illustrates an example of a design for the Audio Engine in terms of building blocks and audio/data routing. The Haptic Engine and the Visual Engine are units dedicated to the generation of haptic and visual stimuli.

c: POST-PROCESSING

It consists of the digital to analog conversion of the processed data, as well as any other post-processing algorithm needed before delivering to the outputs the sounds generated by the Audio Engine, or the haptic and visual signals.

3) OUTPUTS

The Outputs component is composed by the following blocks:

a: SPEAKERS

This block is responsible for the instrument electronic sounds diffusion. For this purpose, one or multiple vibration speakers can be attached to the instrument's soundboard to control its vibrations; alternatively, or even concurrently, one or multiple loudspeakers can be embedded into the instrument.

b: WIRED CONNECTORS

They include connectors for analog audio (e.g., outputs for jack cables), digital audio (e.g., ADAT), or digital data (e.g., MIDI out).

c: WIRELESS TRANSMITTER

This system ensures the transmission of both audio signals and other types of data (e.g., OSC messages).

d: VISUAL DISPLAY

This apparatus is used to provide visual information to the musician.

e: HAPTIC DISPLAY

This apparatus is used to provide information to the musician via the sense of touch.

4) POWER SUPPLY

The Power Supply component is composed by the following blocks:

a: RECHARGEABLE BATTERY

This block guarantees the standalone functioning of the instrument.

b: POWER SUPPLY RELATED ELECTRONICS

This block handles the charging system of the battery, the supply from an external power source, as well as the delivery of the current to all the components.

5) MEMORY

The Memory component is composed by the following blocks:

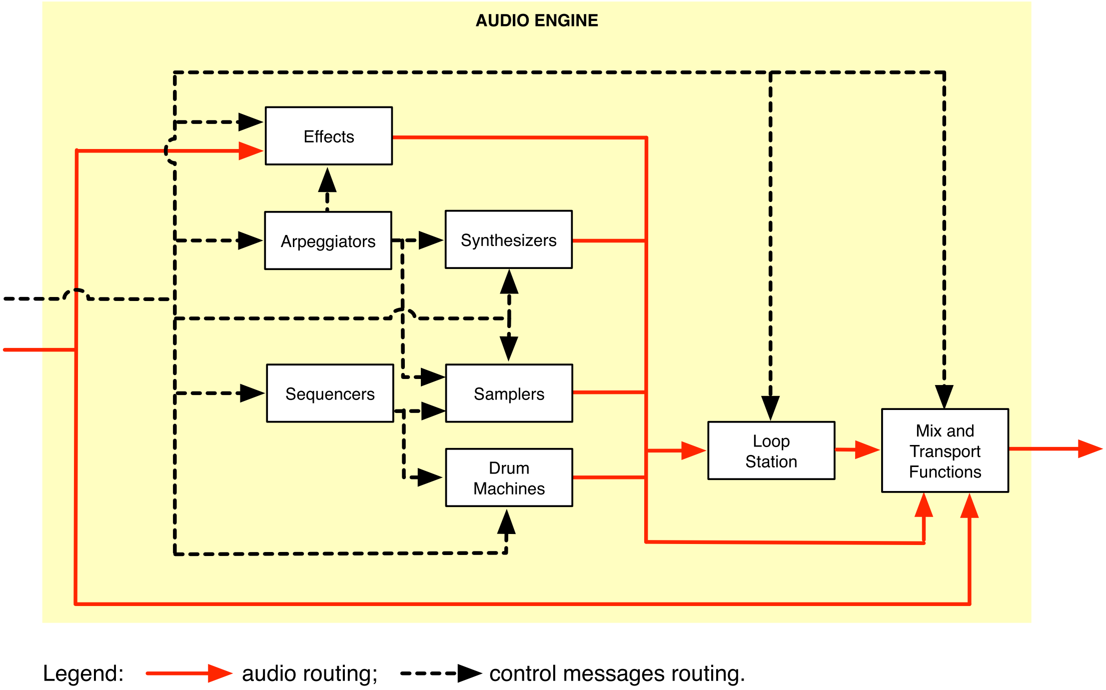

FIGURE 4. **Block diagram of an example of audio engine of a SMI.**

a: AUDIO STORAGE

This block allows to store audio files, for instance for the recording and playing purposes

b: DATA STORAGE

This block allows to save the data collected from the sensors, or those resulting from the internal processing.

IV. DESIGN PRINCIPLES

As shown in Section II-B various design principles have been proposed in the research communities around the NIME and IoT fields. Whereas some of the principles devised for digital music controllers, augmented instruments, and virtual reality musical instruments are still valid for SMIs, the new capabilities of SMIs entail the definition of new guidelines capable of supporting digital luthiers in the design process. As a matter of fact, it is worth noticing that SMIs are not mere controllers that support pathways of expressivity by mapping the performer's gestures to sounds digitally produced, which has been the target of previous endeavors in design principles proposals. SMIs are instead true IoT devices, that are in essence intelligent, pervasive, and interoperable systems, which may enable a new relation of the performers with their instruments. SMIs may also support new social experiences, which may occur both in co-located and remote settings and involve different actors such as performers, audience members, composers, conductors, live sound engineers, or studio producers. For instance, SMIs can be not only controllers for sound synthesis engines, but also for a multitude of external equipment leading to multisensory musical experiences, and even be controlled from external devices. Their internal status may also be changed by autonomous processes, and they can provide recommendations to the player. On the other hand, design principles proposed by the IoT community have not considered the specific case of musical instruments equipped with intelligence and communication capabilities, which come with their own set of challenges that may differ from those of typical smart objects in the IoT.

The capabilities afforded by smart musical instruments raise significant new challenges for digital luthiers, who typically design bespoke, non interoperable DMIs [77], [78]. It is observed that the design of a smart instrument entails considering not only the musician's experience of playing the instrument, but also the whole range of interactions provided by applications and services around the instrument. This requires a holistic approach to design that combines seamlessly new application possibilities and the mechanics of interaction of the player with the instrument, with other human actors, and with other connected machines. Following these considerations, hereinafter we propose design principles that are specific to SMIs and that aim to complement other design guidelines presented by various authors in the NIME community [21], [22], [76], [77], [95], [126]. Some of the principles are technical, some are aesthetic, other encompass human factors. They are not assumed to be universal, but are rather a set of considerations emerged from the smart instruments vision and from author's observations while crafting SMIs in both industrial and academic research.

A. PRINCIPLE 1: EMBED AS MUCH AS POSSIBLE

The instrument, at least in its basic use, should not rely on external equipment to work. On the one hand, the core hardware components of a SMI (such as sensor interface, computing unit, wireless system, battery, and possibly loudspeaker as well as haptic and visual display systems) should all be seamlessly integrated in a unique, compact system. On the other hand, effective digital simulations of analog equipment should be adopted to reduce or eliminate dependences from additional hardware. This also implies the use of the instrument's sensors as a replacement of the interface of the original analog equipment. For instance, this is the case of analog synthesizers or stompboxes for sound effects, which can be simulated by means of virtual analog techniques [117] and controlled via the embedded sensor interface. Such self-contained nature is one of the major strengths of SMIs compared to other interactive performance systems, which leads to benefits such as easiness of setup and portability, as well as the ubiquitous use of SMIs [110]. In particular, the design should consider the total weight of the instrument as a crucial aspect for the user experience and for easiness of transportation. Miniaturization of the technology is therefore a key aspect to achieve lighter instruments.

B. PRINCIPLE 2: DESIGN FOR INTERCONNECTION

Wireless communication is a fundamental component of the musical identity of a SMI and this is one of the aspects that mainly differentiate SMIs from other DMIs. While individual SMIs working in isolation may enable the creation of interesting opportunities for expressivity, their true power arises when they are connected to multiple objects cooperating to link their respective capabilities, both locally and remotely. Therefore, the design process of a SMI should not only account for the functioning of the instrument as a standalone entity, but also for the player experience when interacting with other external machines or human actors. This means to design in tandem the instrument and its services and applications. For connecting SMIs with each other and with other devices, common communication standards are of great importance. Interoperability should be ensured across a range of standards. These standards may include protocols for wireless transmission and for musical data exchange or synchronization over it, along with mechanisms for auto-configuration and auto-identification [25], [62]. While wireless connectivity is a fundamental capability of a SMI, interoperability may be also achieved by providing support for wired connectivity. Importantly, security and privacy issues should be also tackled (e.g., secure authentication, use of personal data).

C. PRINCIPLE 3: MAKE IT UPGRADEABLE AND UPDATABLE

The embedded operating system and software applications running over it should be designed to ensure upgrades and updates. These software replacements or extensions could be directly downloaded from the Internet or uploaded from an external device in case Internet connectivity is not supported by the instrument. However, upgrades should support backward compatibility of existing code or provide tools to easily deal with versioning conflicts that come with upgradability. This principle is in line with the findings of Morreale and McPherson on DMIs digital luthiers' needs, who consider this feature to facilitate the longevity of a DMI as long as upgrades to underlying software and operating system render existing code reusable [77].

D. PRINCIPLE 4: MAKE IT READY TO USE

The instrument should be always ready to use, exactly like an acoustic instrument. This may be achieved by designing systems having fast booting times, adopting mechanisms for standby mode with minimal awakening time, and long-lasting batteries with efficient recharging systems.

E. PRINCIPLE 5: MAKE IT PERSONALIZABLE

Personalization has been advocated as a fundamental design component for IoT devices [50], [73], and this is no less true for SMIs. As software-controllable aspects are concerned, players should be empowered to personalize how the instrument behaves under specific circumstances. Players should also be empowered to adjust their preferences to control how proactive the instrument and its services are. For instance, software applications could allow a player to configure the instrument as needed (e.g., enabling or disabling sensors, haptic feedback, or sound generators and modulators). This principle is in line with existing design frameworks that suggested that the execution and the identification of unique playing styles should be supported by means of personalization capabilities offered by a DMI [76], [120].

F. PRINCIPLE 6: MAKE IT SMART, BUT MAINTAIN THE MUSICIAN'S SENSE OF CONTROL

The intelligence embedded in the instrument should be designed to truly help musicians accomplish their tasks or support activities related to creativity and expressivity. Careful considerations should be made during the design process to prevent situations that may hinder or disrupt the meaningful, creative, and expressive interactions of the musician with the instrument. Despite some behaviors of the SMI can be automatized without requiring the human intervention, it is crucial that the musician feels to be in control of the instrument when playing, unless differently chosen for particular musical activities. This means that the interactions that the musicians has with the instrument, or with the connected Musical Things through it, have to be predictable according to the expected behavior which was previously predefined. Expanding the capabilities of an instrument while maintaining the musicians' sense of control should be one of the central concerns of the digital luthier, especially in the situations related to context-awareness and proactivity.

G. PRINCIPLE 7: ADD SIGNATURE FEATURES AND MAKE IT BEAUTIFUL

New DMIs may succeed where they contribute to expanding the creative possibilities of the player [77], [82]. To attract the musicians and favor the adoption of SMIs we suggest that the instrument should have ''signature features'' [79] (also called ''unique identity'' in [83]). These are clear capabilities that go beyond what is achievable with current DMIs. According to the findings of Morreale and McPherson [77] signature features have implications for the longevity of the instrument. In addition, including aesthetic considerations in the design process contributes to the creation of signature features. Besides the functional aspects of an instrument (which musicians assume to be perfectly reliable), aesthetic aspects are also very important to musicians, and may contribute significantly to the selection of an instrument at the moment of buying it. For a SMI, the design should account not only for the exterior aspect of the physical instrument (e.g., its look, its feel, its craftsmanship and woodworking, and its quality construction), but also for the digital counterpart, which may include visual and haptic content. For instance, aesthetic considerations should be made when designing haptic sensations for the musicians (both physically and digitally produced), as they may affect how pleasant the interaction of the musician with the instrument is perceived [36]. Similarly, graphical aspects of content visually displayed by the instrument (e.g., embedded displays) or by external equipment (e.g., apps for smartphone or tablets) should thoroughly be considered under the lens of aesthetics.

H. PRINCIPLE 8: BEAR IN MIND THE COGNITIVE LOAD AND THE LEARNING CURVE

SMIs have the potential to add many new dimensions of control and communication onto existing performances, compositional procedures, or pedagogical activities. However, the number of affordances and sensory stimulations offered by the technological infrastructure underlying a SMI implies a higher level of attention of the designer in finding the right balance between the human capabilities and those of the machine. Indeed an imbalance between these two variables may be detrimental for the requested amount of cognitive load and for the steepness of the learning curve, which hinders a player to successfully and creatively exploit the capabilities of a SMI. Designing constraints to the musician's experience may be a powerful tool for creating such a desired balance [58]. Another solution could be to let the users select the most appropriate configuration of the instrument according to their skills or intended use. Notably, this principle is in line with the considerations advocated by different authors (e.g., [47], [83], [102]), who stressed the importance of focusing on how to convey the expression of the performer while designing a DMI, or on how to exploit its capabilities to reduce some of the human control overload.

I. PRINCIPLE 9: ADDRESS THE SECURITY AND PRIVACY ISSUES

Security and privacy are of paramount importance for several smart objects in the IoT, and SMIs are no exception. The ability of SMIs to autonomously collect data from the users or to support mechanisms of direct authentication with could-based services, along with the vulnerability risks of wireless communications, requires the adoption of the highest security standards and the compliance with policies on data protection of regulatory bodies. It is therefore crucial that designers of SMIs adopt a privacy by design approach and incorporate privacy impact assessments into the design phase.

V. OPEN CHALLENGES AND FUTURE DIRECTIONS

IoT technologies have provided new possibilities for exploration of musical interactions between the players and their instrument, between players, and between players and audiences, in both co-located and remote settings. Nevertheless, the proposed vision poses several technological, artistic, and pedagogical challenges. Some of these open challenges are common to those of the general field of IoMusT (the reader is referred to [112] and [113] for a discussion on this topic). In this section we present those challenges that are more specific to the digital luthierie for SMIs, drawing paths for future directions.

A. HARDWARE AND SOFTWARE

To date, the main obstacle to the creation of SMIs is the lack of appropriate and affordable tools supporting their hardware and software development. The manipulation of musical signals with a processor is a task that requires very low processing latency. This hard requirement on real-time performance is the reason why today most audio devices are still built using dedicated digital signal processors and real-time operating systems, which are difficult to program and lack of modern software libraries for networking and access to cloud services. Nevertheless, cutting edge technologies such as MIND Music Labs' ELK music operating system are expected to be a game changer in the smart musical instruments landscape. Future embedded platforms for SMIs will necessarily need to integrate the new communication technologies that are envisioned in the Tactile Internet, which will enable the ultra-low latency and highly reliable exchange of musical content.

The envisioned ability of SMIs to understand what and how the musicians play (e.g., which notes, with which performative gestures, how they hold the instrument, how they interact with the sensors, or how they exploit the wireless communication channel) requires the definition of novel techniques for embedded sensor fusion, pattern recognition, real-time music information retrieval, and real-time machine learning. To date, considering the specific case of musical instruments scarce research has been conducted on each of these topics, which represent fertile areas for future research and have strong implications for the edge computing paradigm [63], [93], [96] considering IoMusT ecosystems. The vast majority of existing research on such topics relies on offline methods and on desktop solutions, likely because of the lack of embedded systems and related software libraries capable of efficiently supporting the use of such techniques (e.g., in terms of real-time performance, computational load).

B. DESIGNS

Current industrial and academic efforts on development of SMIs have focused only on subclasses of percussive and plucked strings instruments. Neither smartification methods for the vast majority of conventional musical instruments or radically new musical devices encompassing the features of the theorized SMIs have been devised yet.

The challenges include the miniaturization of computing units dedicated to low-latency sound processing, sensing, communication, as well as of batteries and heat dissipators, which is necessary to make light and transparent the embedded technology. Another fundamental challenge is understanding the unique potential that SMIs can bring to the experience of the player as well as of the audience. Also, it is necessary to investigate what are the novel needs of musicians, which can then inform the design. The adoption of a User Centered Design approach [81] based on co-design activities [94] may be a valuable strategy to pursue this endeavor [77]. As the design of a SMI entails not only the instrument, but also its services and the types of supported interactions, co-design activities need to involve not only the player, but also other human actors related to it (e.g., audience members, other players, music teachers). This may require the definition of novel co-design procedures and evaluation paradigms specific to SMIs. An initial step towards this direction is reported in [114] for the development of the Smart Cajón. The authors utilized participatory design procedures such as the creation of tangible mock-up designs to identify cajón players' needs and requirements.

To date, scarce attention has been devoted to the use of connectivity features that would allow a SMI to interact with other SMIs or other devices over local and remote networks, for instance during live music performance or rehearsals. Moreover, no research has been conducted yet on the enhancement of musical instruments with context-awareness and proactivity features. Fundamental methods for the use of SMIs in conjunction with cloud computing or online repositories are also yet to be devised, along with methods to effectively present to the musician information produced by the SMI or received by external devices (e.g., used by a local or remote audience).

One of the emerging technologies for ultra-low latency and highly reliable wireless communication is Millimeter Waves [97], [98]. Such a technology uses wireless frequencies within the range of 10 to 300 GHz and offers data rates of giga bits per seconds over short distances. These frequencies make possible the design of small antennas that can be easily embedded in musical instruments. Therefore, Millimeter Waves represent a promising technology for enhancing musical instruments with ultra-low latency and highly-reliable wireless communication capabilities.

C. STANDARDS

The success, creation and adoption of the various technologically-mediated interactions between a SMI player and other human actors or machines heavily depends on the definition and use of standards. Standardization offers benefits such as interoperability, compatibility, reliability, and effective operations on both local and global scales. Standardization efforts for the specific case of communication between SMIs are currently mostly unrealized, and this is an issue that has several aspects in common with the more general field of IoMusT [112], [113]. For instance, new protocols for the exchange of musical messages are needed to cope with the limitations of existing widely adopted protocols and standards (such as MIDI and OSC). Nevertheless, it is worth noticing that there are ongoing efforts within the MIDI Manufacturers Association to define the MIDI HD standard, which is is expected to extend the current MIDI standard with novel features that have the potential to improve interoperability. Moreover, new protocols for the ultra-low latency exchange of musical content need to be devised to support interactions such as remote rehearsals. This challenge falls in the agenda of the Tactile Internet community [1], [61]. Furthermore, no formats are available today to efficiently store or exchange all information that can be collected from the use of SMIs (e.g., audio and sensor signals, metadata), which could be exploited by studio producers in a more creative and efficient way compared to current production pipelines. Current efforts towards this end are represented by the MPEG-A: Interactive Music Application Format [34], which combines multiple audio tracks and appropriate additional information and is expected to enable interoperability among the interactive music services recently emerged. In a different vein, since SMIs have the capability to collect data from users and transfer this data on the cloud, standardization efforts will also need to address issues related to security and privacy.

D. ECOSYSTEMS

As stated earlier, SMIs are not conceived as standalone, bespoke musical instruments, but as interoperable entities that live in a network of connected devices. They are one of the main building blocks of the envisioned IoMusT ecosystems [112], [113]. Besides the crafting of the instruments themselves it is important to conceive measures to build technological and socio-economical ecosystems forming around SMIs. However, at present, such ecosystems are yet to come. At technical level ecosystems may for instance be enabled by defining common application programming interfaces and pursuing standardization activities. At socio-economical level, firstly the whole chain of manufacturers, retailers and vendors needs to be created, along with personnel of music shops trained to provide technical support and repairs for the SMIs components. Secondly, measures should be taken to build a community of SMIs players, for instance via dedicated social networks, online market places for buying services or freely share open source plugins, presets.

E. PEDAGOGY

One of the most important qualities of SMIs is their potential for supporting learning. To date, despite the advent of smartphone apps for gamified music learning, musicians and teachers do not have access to lots of digital data related to how a person plays while learning (e.g., how he/she holds the instrument or which mistakes are more recurrent). Having data collected from several SMIs around the world may lead to novel forms of pedagogy, merging the information extracted from such data with established practices of music teachers. This implies the creation of systems capable of modeling the learner (e.g., learning his/her beheaviours) understanding what and how he/she is playing (for instance involving techniques fusing sensors data and audio), along with the definition of data analysis methods tailored for learning purposes (for instance involving machine learning techniques such as deep learning [54]), as well as the identification of the best strategies about how to convey to the learner information related to how to improve its playing (for instance leveraging devices connected to the instrument).

F. REPERTOIRE

SMIs are instruments that have not been established yet and lack a practice tradition and a repertoire. Performing and composing for them is crucial for their longevity [118]. Indeed, throughout the history, musical instruments have evolved from a stage to another not only thanks to technological progresses, but also thanks to the requests of new features by musicians and composers. For the case of SMIs, a repertoire is not bounded to the sound produced by the instrument itself, but may encompass different levels of technologically-mediated interaction with other human actors or machines. For instance a repertoire for smart instrument could build upon the use of connected musical haptic wearables [108] for the audience, and therefore composing for a SMI may entail composing for the sense of touch and for a participatory experience.

VI. CONCLUSIONS

This paper put forth a vision for SMIs, aiming at contributing to the ongoing discussion centering around this class of new interfaces for musical expression within both the scientific and the practitioners' community. The novelty of SMIs lies in the emergent properties of combining different technologies into a single package, which enable a set of applications that make intelligent use of audio and sensor data while also making the network a fundamental part of the communication, expressivity, creativity, and pedagogy. We believe that the application of IoT technologies to musical instruments shows the greatest potential when creating or facilitating experiences that cannot be encountered with conventional or augmented instruments.

In this paper, we have also presented nine principles that we believe digital luthiers should address in the SMIs they build, in order for musicians to take advance of the capabilities and features of this new class of musical instruments. The reported principles were derived from the analysis of current SMIs, their possible integrations with other cutting edge technologies, as well as the author's observations. By providing a vision and a set of design principles for SMIs, the paper creates a common understanding of the term, which is needed for a reasonable scientific discussion on the topic. Furthermore, this vision and these principles highlight factors that digital luthiers can use to make their designs more enduring, and pitfalls they can avoid, as well as support them in identifying, describing, and selecting SMIs application scenarios. In future work the author plans to assess the accuracy of the proposed principles, in particular under the lens of the instruments longevity. Researchers and practitioners are welcome to test the accuracy and usefulness of the proposed design principles and are invited to further enhance the paper's contribution in order to make the SMIs vision an integral part of future manufacturing and production processes. Furthermore, much research needs to be done on the evaluation on the impact these technologies will have on musicians' practices of learning, composing, performing, and recording. The results of this research in turn will be useful to inform the design of novel SMIs and their applications.

The field of SMIs is a complex, evolving and exciting research area, still in its infancy, with much work yet to be done. The author looks forward to seeing what comes in the future and hope that the content of this paper can be used to help SMIs to establish themselves.

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