Envisioning Smart Musical Haptic Wearables to Enhance Performers' Creative Communication

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Abstract. This article presents our concept of smart musical haptic wearables for performers (P-SMHWs), a novel class of wearable devices for music performers encompassing haptic stimulation, gesture tracking, and wireless connectivity features. P-SMHWs were conceived to enhance communication between performers as well as between performers and audience members by leveraging the sense of touch. We present our design approach and describe the architecture of the system enabling both co-located and remote interactions. We present a prototype of P-SMHW and discuss various types of creative interactions between performers and audience members that P-SMHWs will facilitate as illustrated by several use cases. This is followed by an overview of the implications and challenges posed by the vision.

Keywords: Haptic, wearables, Internet of Musical Things, participatory art

1 Introduction

The advancements in haptic technology of the last decade, along with the increased physiological and perceptual understanding of the sense of touch, have offered new possibilities for creating haptic devices designed for musicians. Whether embedded in wearables or not, systems providing haptic stimuli to performers have been proposed to address various musical applications.

A notable domain of use is music learning. Huang et al. proposed *Mobile Music Touch* a glove-based system designed for passive piano learning. The system, characterised by five embedded actuators (one for each finger), and wireless connectivity to mobile devices, was successfully validated with experiments [1]. Another example of haptic device for passive learning, preliminary validated with perceptual experiments, is *Haptic bracelets*, a bracelets-based system designed to help drummers learn multi-limbed rhythms [2]. Dalgleish and Spencer proposed *Postrum*, a posture aid for trumpet players composed by a belt embedding four vibrotactile actuators and camera-based tracking techniques [3]. Berdahl et al. programmed a PHANTOM haptic device to assist musicians in the task of selecting pitches from a continuous range. Preliminary experimental results showed that the use of such assistive tool improved the accuracy in pitch selection [4]. Grosshauser and Hermann proposed a prototype system composed by sensors and actuators embedded in a violin bow, for movement and posture tuition of violin learning [5]. Van der Linden et al. proposed *MusicJacket*, a wearable system for violin tuition comprising an inertial motion capture system and seven actuators placed on the player's arms and torso, capable of providing vibrotactile feedback about bowing style and posture. A validation of the system revealed that novice violin players' bowing technique was significantly improved by the received haptic stimuli [6].

Other systems were developed to augment with haptic feedback the experience of playing digital musical instruments (DMIs) devoid of tangible feedback. Chafe developed a DMI for the control of a physical model of a brass instrument, which comprised a voice-coil placed underneath a metal bar to provide vibrotactile feedback to the fingertips of a player, in order to a physical model of a brass instrument [7]. Bongers used a ring with an embedded miniature solenoid providing tactile feedback, the *Tactile Ring*, to augment different DMIs, such as the *LaserBass* and *SonoGloves* [8]. Rovan and Hayward proposed the *VR/TX system*, a set of voice-coil stimulators of various size and shapes (to be mounted on a ring, a glove-based controller, and a surface for feet-interactions) and dedicated software, designed to augment gestural electronic music controllers with vibrotactile feedback [9]. Perceptual assessment of the system proved that the tactile feedback was effective in improving players' interaction with the controller. Marshall and Wanderley developed the *Viblotar* and the *Vibloslide*, respectively a stringed and a wind DMI equipped with voice-coils to produce both sound and vibration as feedback for the performer [10].

In a different vein, various devices were designed to exploit tactile stimuli as carriers for manifold types of performance-related information to performers. Giordano and Wanderley developed a tactile metronome to be placed on the left upper arm of the performer [11]. Experimental results involving guitarists indicated that such device was effective in reliably cue participants to follow a target tempo. Hayes developed a glove with embedded actuators to provide vibrotactile stimuli as a signalling and suggestion system for the performer [12]. This system was conceived for communicating information about the music and score during a performance, while avoiding the need for visual feedback. McDonald et al. developed Vibrobyte a small and wireless apparatus capable of providing vibro-tactile stimuli, designed to coordinate performers in free-improvisation music performances with live electronics [13]. Michailidis and Berweck developed a tactile system for the feet to provide feedback about foot-based actions of the performer during live electronic performances [14]. Schumacher et al. developed a tactile notification system involving two vibrating actuators placed on the back of the performer, in order to provide performers with tactile feedback about their own actions on live electronic systems as well as about the internal state of the live electronics system [15].

Other applications have concerned networked music performance (NMP), which typically refers to music performances where performers and/or instruments are connected over a network (for a recent review see [16]). Hayes and Michalakos developed *NeVIS* a wired NMP system leveraging vibrotactile feedback as a signalling tool between performers as well as between laptop and performers, within an improvisational setting [17]. In the *NeVIS* system, the haptic stimuli are the object of the communication over the network. This represents a novel application in the NMP domain as the content typically involved in NMP systems is auditory or audio-visual [16].

Almost all the systems mentioned above rely on wired connections and leveraged exclusively vibrotactile feedback. A wireless design for (networked) wearable devices would be less obtrusive for performers as the presence of wires necessarily limits the freedom of movement, which may impact negatively the way music is produced. Moreover, a wireless setup does not impose on performers to stay at a specific location on stage. In addition, types of haptic feedback other than vibrotaction could be exploited to enhance creative communication between performers (e.g., thermal, pressure, texture stimuli), as well as between performers and their DMIs. Furthermore, haptic stimulation could be exploited not only for enabling a typically unused communication channel between performers, but also between the audience and performers. This could be achieved not only in co-located settings, but also in remote ones. To the best of authors' knowledge, these types of interactions have not been addressed in previous research and a comprehensive framework supporting them is currently missing.

Recently, we proposed the concept of *Internet of Musical Things* (IoMUT), which refers to the network of *Musical Things*, i.e., computing devices embedded in physical objects dedicated to the production and/or reception of musical content [18]. The IoMUT digital ecosystem gathers interoperable devices and services that connect, locally or remotely, performers and audiences to support performer-performer and audience-performers interactions. In this paper we propose a design approach for an embodiment of Musical Things, the *smart musical haptic wearables for performers (P-SMHWs).* Such interoperable devices are conceived as a creative communication tool between performers of live music performances, between performers and their Musical Things (such as DMIs or Smart Instruments [19]), as well as between performers and audience members. They provide a means of wirelessly exchanging information via the haptic channel (both locally and remotely) without affecting neither the performer's freedom of movement nor the focus of attention on the auditory and visual flow.

2 Design Approach

The design for P-SMHWs was motivated by various possible scenarios that would benefit from the use of the haptic channel as a further sensory information pathway during live music performance. These scenarios include three types of network-based interactions, which may take place both in co-located and remote settings: i) between performers; ii) between performers and their Musical Things; iii) between performers and audience members. Figure 1 illustrates a schematic view of such interactions. Notably, all these interactions might occur concurrently.

Performer-Musical Thing Interactions We envision four types of interactions between performers and their Musical Things, technologically-mediated by P-SMHWs: one performer-to-one Musical Thing and vice versa; one performer-to-many Musical Things and vice versa; many performers-to-one Musical Thing and vice versa; many performers-to-many Musical Things and vice versa.

Live electronics (involving e.g., real-time processing and generation of sound during a live performance of electronic/electro-acoustic music) is an example of practice in which such interactions could be envisioned. In such a context the typical action-perception loop occurring when playing traditional acoustic instruments is not present, as there is no constant physical connection between the performers and the live electronics systems they are using [20]. This might cause insecurity in the performers. Typically, live electronic music performers learn about the internal state of the live electronics system by means of visual displays (e.g., on-stage screens) or auditory displays (e.g., in-ear devices providing tempo-related clicks). These solutions, however, might be distracting, invasive, and cumbersome during the act of playing since they rely on sensory channels already cognitively loaded. Similarly, in many cases the lack of human-system physical connection prevents the performers to have immediate knowledge of the system response to their own actions. These practical problems in performances of live electronic music are especially relevant if the electronic music system is remote.

Such issues related to a lack of proper feedback information, can be addressed by delivering haptically rendered information via wireless networks connecting performers and their Musical Things. Examples of the information that could be delivered by leveraging the haptic channel are the immediate responses to the performers actions on the system, the knowledge of its internal state, score-related information (e.g., tempo changes, current position/cue points in a score, the guide tempo of a part of a composition), feedback on what is played (e.g., providing signals to correct mistakes, to keep the rhythm, etc.), or parameters related to the position of virtual sound sources in a surround sound system. Some of these uses cases have been investigated in previous research (e.g., [13, 14, 12, 15, 11]), the preliminary results of which suggested that haptic devices can successfully facilitate the interaction between performers and the live-electronics system they are interacting with.

Performer-Performer Interactions We envision four types of interactions between performers, technologically-mediated by P-SMHWs: one performer-to-one performer (see Figure 2); one performer-to-many performers (e.g., a conductor leading other performers); many performers-to-one performer; many performers-to-many performers.

P-SMHWs are conceived to be useful in all those situations where haptic connections between performers are feasible but visual connections are not. These connections are especially relevant for blind performers as well as in presence of remote interactions where streaming visual content in addition to auditory one is more subjected to the limits of the network. Such wireless haptic devices could also be effectively employed when performers are out of sight (e.g., when they are placed in relatively distant positions in the concert venue, or when they have to play in scarce light conditions), when a performer's sight is fully occupied (e.g., to read a score), or in all cases in which is unclear who produced a sound and how. As preliminary shown with the use of the *NeVIS* system, the exchange of haptic information between performers may be successfully utilized in the communication of performance-related aspects, especially in improvised contexts [17].

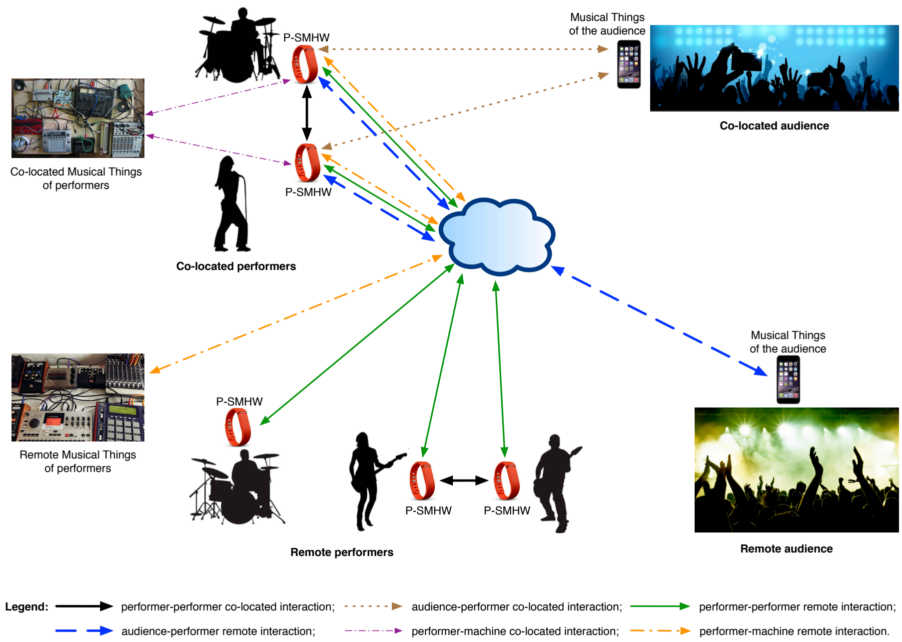

Fig. 1. A schematic view of the envisioned haptic interactions between performers, between performers and their Musical Things, as well as between performers and audience members, both in co-located and remote settings.

Performer-Audience Interactions We envision four types of co-located and remote interactions technologically-mediated by P-SMHWs held by performers and Musical Things held by audience members: one audience member-to-one performer and vice versa; one audience member-to-many performers and vice versa; many audience members-to-one performer and vice versa; many audience members-to-many performers.

The feature of communication of creative information from local or remote audiences, was conceived to enable scenarios in which performers can "feel" the audience which they play for (e.g., understanding the audience emotional

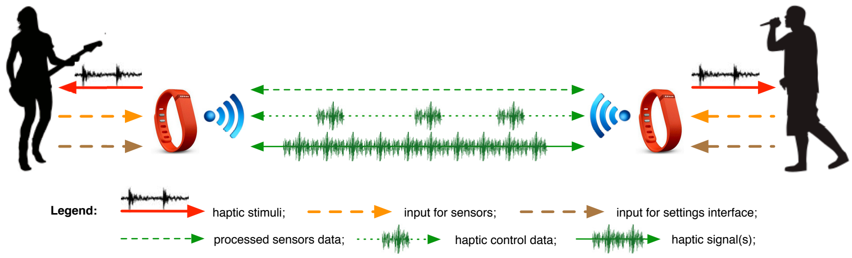

Fig. 2. A schematic view of the envisioned haptic interactions between two performers wearing each a P-SMHW during the act of playing in a co-located setting.

status), or receive information from it in order to direct the performance towards a particular goal (e.g., change of a song, change of tempo, change of mood in the musical content) or to other forms of collaborative music creations. Reciprocally, the feature of communication of creative information from the performers to the audience members via Musical Things they hold, was conceived to deliver sensorial information additional to the musical content (e.g., haptic stimuli). All these specific scenarios, to the best of our knowledge, have not been investigated yet either in academic or industrial research.

2.1 Design Requirements

The proposed architecture for P-SMHWs was designed in response to the aforementioned scenarios. The following mandatory and optional design requirements (respectively MDR and ODR) were set:

MDR1: To allow for effective performer-performer communication (co-located) via haptic stimuli;
MDR2: To allow for effective performer-Musical Thing(s) communication via haptic stimuli;
MDR3: To be unobtrusive, light, and comfortable;
MDR4: Neither to limit performer's freedom of movement nor to distract from the actual playing;
MDR5: To be easy to use and customizable;
ODR1: To enable creative audience-performers interactions;
ODR2: To enable communication with remote performers and/or audience members.

We distinguish P-SMHWs that act as receiver/transmitter of data between performers and P-SMHWs that enable communication possibilities between performers and audience members in possession of other Musical Things [18]. To allow for flexibility in the design of P-SMHWs we leave as optional data reception and forwarding functionalities from/to co-located the audience members, as well as from/to remote performers and the audience members.

2.2 Architecture of P-SMHWs

A SMHW for performers can be described by various building blocks representing the key aspects that must be seamlessly integrated to accomplish the vision (see Figure 3). The first aspect relates to the material layer, that is the underlying platform that will physically support the technology. The design of such a platform involves the exploration of materials (e.g., plastics, textiles), structures, as well as manufacturing technologies and methods. Specifically, the involved materials need to be chosen to optimize the efficient transmission of the haptic stimuli. The interaction with skin can be direct or through clothing.

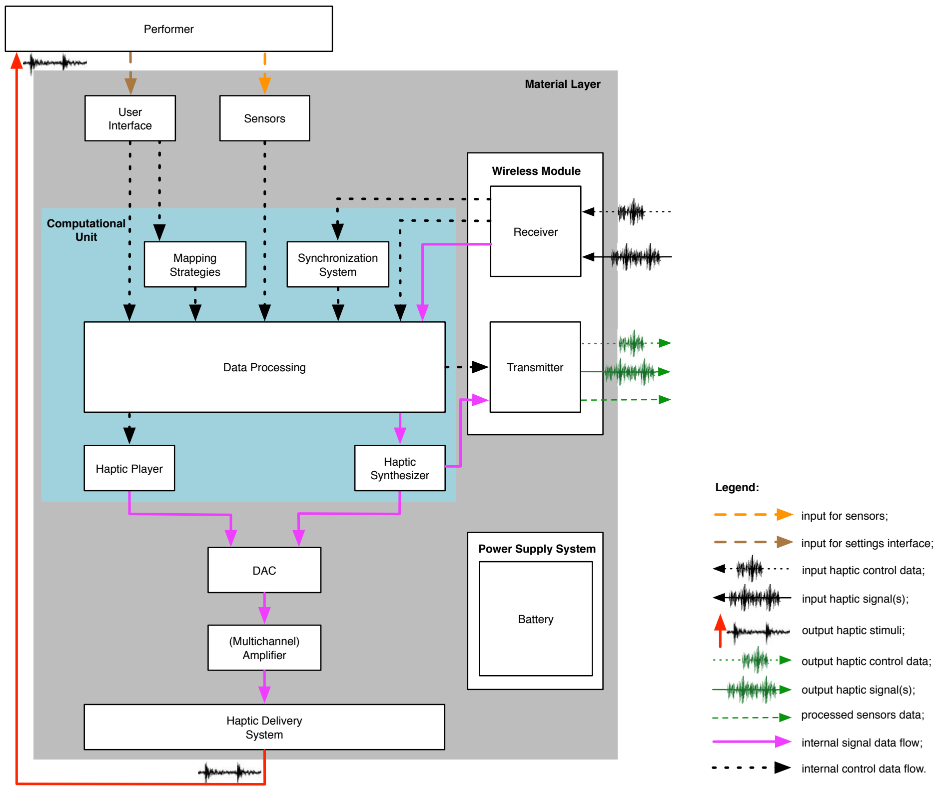

Fig. 3. A schematic view of the architecture of a SMHW for performers.

The second key aspect is the hardware technology that needs to be embedded in the physical layer. This aspect involves the design and integration of various technologies that are fundamental to the realization of the "intelligent" component of a P-SMHW, namely: a computational unit for data processing and synthesis of haptic signals; a wireless module for receiving and transmitting data over a local network, and optionally over remote networks and the Internet; a digital-to-analog converter (DAC) for the haptic signal (multichannel, if in presence of an independent control of multiple actuators), which is typically in need to be amplified by a dedicated amplifier; a haptic delivery system (e.g., actuators for vibrotactile stimuli, mechanical systems to deliver pressure, frictions or texture information to the skin); sensors capable to track the performer's gestures (simple and/or complex); an interface for custom settings of the delivered haptic stimuli (e.g., composed by buttons simple to access), that in our vision is not mandatory and could be replaced by a visual interface running on a smartphone app; a power supply system.

The third component of a P-SMHW consists of the software system. This accounts for several tasks including: the real-time analysis of input data from sensors (e.g., feature extraction), from the wireless module, and from the interface for custom settings; the application of mapping strategies between parameters related to the haptic stimuli and values of the custom settings (e.g., amplitude regulations); the real-time synthesis and delivery of haptic stimuli; the delivery via a haptic player of the haptic signals received from the wireless module; the synchronization of the produced haptic stimuli with other haptic stimuli for other performers (e.g., via a common clock); the real-time delivery of haptic control data or haptic signals to other connected SMHWs; the real-time delivery of sensors data to connected devices.

2.3 Evaluation Criteria for P-SMHWs

In Table 1 we propose a set of criteria to assess P-SMHWs. These rely on technical features (e.g., efficiency of functionalities), perceptual features (e.g., effectiveness of the haptic stimuli in communicating information), and artistic features (e.g., support creativity [21] of composers and audience members alike in the case of participatory art scenari), commercial aspects (e.g., costs, manufacturability).

3 Prototype

A prototype encompassing the features described in Section 2.2 was developed (see Figure 4). Its hardware components consisted of a small fanny pack; the Bela board for low-latency audio processing [22], based on a beaglebone black board; a Wi-Fi USB dongle (A6100-100PES by NETGEAR) for use as client, alternatively a small wireless router for use as server, (TL-WR902AC by TP-Link), which features a usb port for 4G dongles enabling Internet connectivity (both solutions feature the IEEE 802.11.ac standard); four vibration motors (307-103 by Precision Microdrives) placed at the front, back, left and right of the belt of the fanny pack; two push buttons with integrated led, placed at the front-left and front-right; a lightweight power supply (5V/2A).

At software level, data processing and synthesis of the tactile stimuli were accomplished by means of Pure Data patches. Data reception and forwarding were achieved by leveraging OSC messages over UDP.

User experience	Effectiveness in communicating information from co-located performers or from musical systems [Effectiveness in communicating information from co-located or remote audience] [Effectiveness in communicating information from remote performers]
Usability	Safety (e.g., hazard protection, electromagnetic compatibility certifications) Ease and intuitiveness of use, also for the visually and auditory impaired Comfortability, lightness, wearability, freedom of movement, portability Ability to support collaborative creative interactions between performers [Ability to support collaborative creative interactions between performers and audience]
Functionality	Haptic delivery capabilities Sensing capabilities Wireless reception and transmission capabilities Effective synchronization capabilities with musical content and with other Musical Things
Connectivity	Compatibility with wireless communication standards Ease of connection to power source (battery charging and replacement)
Efficiency	Low power consumption Efficient haptic stimulation Efficient computation capabilities
Durability	Long-lasting endurance of the device Long-lasting endurance of the battery High mechanical strength
Shape conformability	Ability to conform to various sizes of the intended body part Dimensional/shape stability during repeated use
Affordability	Cost of materials, manufacturing, and maintenance

Table 1. Evaluation criteria for P-SMHWs. Items in square brackets indicate optional criteria.

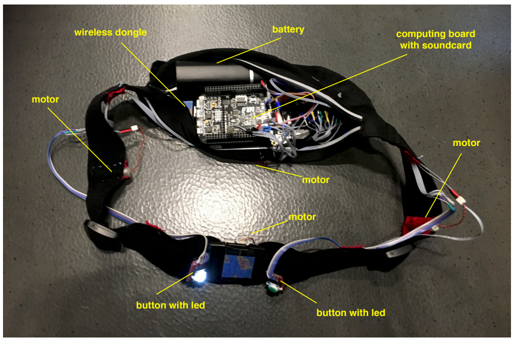

Fig. 4. The developed prototype with the indication of its components.

4 Discussion

The rationale for P-SMHWs is supported by results from previous studies, which showed that haptic communication in musical applications proved successful to improve the communication between performers and between performers and their Musical Things [13, 14, 12, 15, 11, 17]. Contrary to non-wearable haptic devices conceived for musical applications, such as haptic chairs for instance [23, 24], P-SMHWs' wearability and comfort features do not force performers to a specific position or limit the freedom of movement. These features are of fundamental importantce for performers since any obstacle to their playing comfort might negatively affect the expressive production to the musical content.

Although P-SMHWs are conceived as a communication facilitator, they could be involved also to enrich the playing experience during both live (e.g., concerts) and non-live contexts (e.g., rehearsals). For instance, one could hypothesize envision thermal stimuli responding to some characteristics of the music (e.g. mood). Similarly, the P-SMHWs' system for body movements sensing, together with the haptic delivery system, can be exploited as tuition tool for performers (e.g., to correct posture [3, 5]). Likewise, musicians could avail themselves of P-SMHWs as tactile metronomes (as show in [11]).

P-SMHWs could also have important implications for visually-impaired performers, as they allow them to exploit the haptic channel for exchanging information with other performers, which would otherwise be difficulty feasible. To date, this line of research has been scarcely addressed despite its potential to greatly benefit blind performers. Moreover, the haptic and sensing capabilities of SMHWs can be exploited for performances other than live music, such as theatre, dance, or opera. In addition, P-SMHWs have implications for composers since they are provided with a way to instruct performers on actions to pursue using methods and a channel different from the ones usually dedicated for such purposes (i.e., score). Furthermore, our proposed design for P-SMHW suits participatory live music performance applications (see e.g., [25]).

Notably, the design and development of P-SMHWs require collaborations among artists, scientists and engineers from a variety of disciplines, including music composition, Internet of Things, perception, computer science, sensor and haptic technologies. A main technological challenge, is represented by the application of methods for tight synchronization between the musical content and the haptic stimuli received by performers. This is in particular relevant when strict temporal constraints need to be ensured, as for instance delivering to all performers an identical and synchronized beat. Such a challenge encompasses mainly two aspects, which parallel the issues of technologies for networked music performance [16], in particular over wireless local area networks [26]: methods to reduce transmission latency over wireless networks and methods for synchronization mechanisms (e.g., sharing of a clock) [18].

Importantly, the proposed design of P-SMHWs opens various questions. Which are the most successful methods to convey performance-related information via haptic stimuli? To what extent a performer can rely on such haptic cues? How a performer perception of the music he/she plays can be affected by the presence of P-SMHWs and their use? Further research is needed in order to address these and other questions that challenge our P-SMHWs concept.

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