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Designing Haptic Feedback Stimuli to Convey Gestures of an Orchestra Conductor to Visually-Impaired Musicians

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***Abstract*—This paper explores the feasibility of conveying the expressive gestures of orchestral conductors to Blind and Visually Impaired (BVI) users using haptic feedback systems. We interviewed a group of musicians, including sighted and BVI subjects, to gather insights on their experiences with haptic feedback, preferred body placements for wearable devices, and the role of conductors in orchestral performance. From these interviews and literature analysis, we derive design specifications for a haptic system capable of conveying distinguishable conductor gestures via vibrational motors. Our goal is to identify promising directions for the prototyping of wearable systems capable of supporting accessible interpretation of conducting gestures.**

***Index Terms*—Orchestra Conduction, Haptic Feedback, BVI Users**

I. Introduction

Orchestral conducting serves as a sophisticated form of non-verbal communication, where gestures encode musical intent, dynamics, timing, and phrasing. These visual cues are fundamental for coordinating ensembles and shaping performance interpretation. However, for Blind and Visually Impaired (BVI) individuals, this gestural layer remains largely inaccessible, making their participation in traditional orchestral settings more challenging. While haptic and tactile feedback systems have shown promise in compensating for visual information in various domains, the translation of complex conducting gestures—which simultaneously convey beat patterns, dynamics, phrasing, and emotional expression—into intuitive and interpretable haptic feedback presents unique challenges. Such systems must carefully balance both technological and perceptual design constraints to effectively bridge the gap between visual conducting cues and tactile perception.

Through interviews with sighted and BVI musicians, we identify key constraints and preferences for haptic feedback in musical contexts. We combine these findings with technical literature to propose design specifications for a wearable haptic system. Specifically, we present: (i) an analysis of body placement suitability across different instruments, (ii) technical requirements for vibrotactile actuators and signal design based on perceptual studies, and (iii) functional specifications for a prototype system that captures conductor gestures and translates them into structured and interpretable vibrotactile patterns known as *tactons* [1], delivered through wearable devices. Our findings lay the groundwork for future research into inclusive, embodied musical systems for BVI users.

The remainder of the manuscript is organized as follows: Section II provides some background notions on musical conduction and haptic feedback technologies. Section III describes the questionnaire construction and reports the results of the conducted interviews, whereas the design guidelines derived from the analysis of the collected answers are presented and mapped onto functional and non-functional specifications for prototyping in Section IV. Conclusions are offered in the last Section.

II. Background

A. Notions on Musical Conduction

While conductors generally develop their own unique styles, conducting courses in conservatories and academies present a variety of techniques, both as historical knowledge and as practical tools that can be applied in different scenarios and with different ensembles [2].

In [3], a systematic framework for describing the gestural vocabulary of conductors is discussed, which proposes a lexicon organized into four main categories: Articulation, Dynamics, Attack, and Cut-off. Within each category, gestures are further classified into distinct classes according to their structural and expressive properties. The model highlights how movement shapes combine with hand configurations to produce gestures with recognizable meanings in rehearsal and performance contexts.

An important aspect of conducting practice is the asymmetry of conducting, which reflects the distinct roles of the two hands. The dominant hand, typically holding the baton, is primarily responsible for keeping time and marking the ictus (i.e., the precise point at which the beat occurs), whereas the non-dominant hand is more involved in expressive communication—indicating dynamics, phrasing, or cueing specific sections of the ensemble. This asymmetry plays a crucial role in the efficiency and clarity of communication between conductor and musicians [3], [4].

Beyond hand gestures, conducting also incorporates significant non-verbal and aural cues, such as breathing, facial expressions, and eye contact. These subtle signals can strongly influence ensemble coordination and musical expressivity

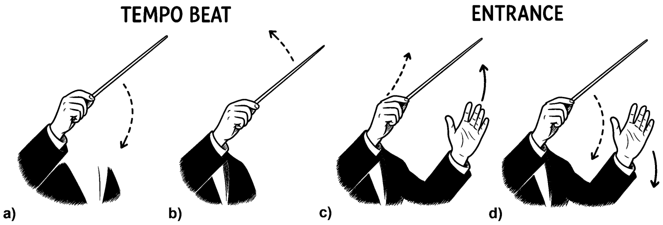

Fig. 1. Examples of typical conduction gestures: tempo cues for a binary pattern (a-b) and entrance cue (c-d).

[5], particularly in entrances and phrase shaping, where the conductor's breath often acts as a shared preparatory cue analogous to that of a singer or wind player.

Finally, conducting differs significantly between rehearsals, teaching and performance. During rehearsals, conductors often interrupt, isolate sections, or exaggerate gestures to provide feedback and clarify musical intentions. In [6], it was found that conductors' gestures in rehearsals were more expressive and varied, while in teaching settings, gestures were more focused and instructional. In performance, however, gestures tend to be more compact, refined, and focused on maintaining flow and ensemble cohesion.

Recent developments have also explored telematic conducting, where conductors lead ensembles across physical distances using network technologies [7]–[9]. While technically feasible, such practices face challenges related to latency, limited transmission of subtle gestures, and the reduced effectiveness of non-verbal communication. Nevertheless, research in this area highlights the adaptability of conducting practice to new technological contexts.

In order to identify the gestures that are most widely adopted in practice, we interviewed an experienced choir and orchestra conductor (male, aged 76, with more than 40 years of conduction experience, mainly in classical repertoires). The outcome of the interview is the list of gestures reported in Table I, which can be grouped into three different categories: tempo-related gestures (e.g., beat, *accelerando*, *rallentando*), dynamic gestures (e.g., *crescendo*, *diminuendo*, sustain pitch), and articulation or phrasing gestures (e.g., *legato*, *staccato*, sharp entrance, gentle entrance, gentle cut-off, sharp cut-off). These categories highlight the dual function of conducting gestures: on one hand, to provide precise technical information such as beat, tempo, or articulation, and on the other hand, to convey expressive intent and musical character.

An illustration of two fundamental types of gestural cues—respectively indicating tempo beat and entrance—is presented in Figure 1. More in detail, for what concerns beat indications, conductors typically trace standardized trajectories in the air with their baton or right hand. Each beat has an ictus, serving as the decisive timing cue for the ensemble. For instance, in a simple duple pattern (2/4 or 2/2), the first beat is shown with a downward motion (the strong beat, see Figure 1a), followed by an upward motion for the second beat (the weaker beat, preparing the next downbeat, see Figure 1b). Figures 1c-d show instead a typical entrance gesture: the conductor first prepares the players with a slight upward or lateral motion, comparable to giving a visual "breath," (Figure 1c) and then marks the exact moment of sound with a small, sharp ictus (Figure 1d). The quality of the gesture varies with the character of the attack—firm and energetic for a strong entrance, or smooth and delicate for a softer one. The left hand may reinforce the cue by opening for a broad sound or closing for a more focused entry.

TABLE I
LIST OF COMMON CONDUCTION GESTURES

Gesture	Description
Beat	Gestural indication of beat patterns
Accelerando	Quick, energic gesture indicating tempo increase
Rallentando	Soft, relaxed gesture indicating tempo decrease
Crescendo	Expanding gesture indicating volume increase
Diminuendo	Contracting gesture indicating volume decrease
Sustain pitch	Adjust to compensate falling pitch
Sharp entrance	Firm gesture indicating begin of musical phrase
Gentle entrance	Delicate gesture indicating begin of the piece/phrase
Sharp cut-off	Firm stop motion indicating end of a piece/phrase
Gentle cut-off	Delicate stop motion indicating end of a piece/phrase
Legato	Smooth, flowing motions to convey legato articulation
Staccato	Crisp, quick motions to convey staccato articulation

B. Notions on Haptic Feedback

Numerous studies have demonstrated the potential of tactile feedback to compensate for visual or auditory information, particularly for users with sensory impairments. For example, haptic navigation aids for blind users [10], [11], obstacle detection systems using vibrotactile feedback [12], and tactile art experiences [13] all underscore the value of touch as an alternative communication channel. Prior studies have demonstrated the potential of haptic systems in enhancing spatial awareness of BVI subjects [10], guiding movement through vibrotactile cues [14], and improving accessibility in virtual environments [15].

A particularly relevant concept in tactile communication is the "tacton" (tactile icon) [1]. Tactons are structured, abstract tactile messages designed to communicate information non-visually, serving as the tactile equivalent of visual icons and auditory earcons. These messages can be constructed using various parameters, including frequency, amplitude, duration, rhythm, and spatial location of tactile stimulation. Tactons enable the encoding of complex information into distinguishable tactile patterns, making them particularly valuable for situations where visual displays are unavailable, overloaded, or inaccessible to users with visual impairments.

In the musical domain, haptic technologies have been leveraged to support a variety of tasks, including vibrotactile metronomes for deaf or hard-of-hearing musicians [16], [17], tactile systems for the conveyance of pitch, timbre, melody [18] or musical emotions [19], for assistance in instrument learning [20], or for providing real-time feedback for interactive performances [21]. However, these systems focus on reinforcing time-based cues or on conveying some musical features of an audio track, but they rarely address the expressive, multidimensional qualities of conducting gestures.

C. Related Work

The DIAMI (Distributed Intelligent Environment for Blind Musicians) architecture presented by Bajo et al. [22] provides an early example of using motion capture and tactile feedback for BVI musicians in orchestral settings. Their system employed WiiMote technology to capture conductor gestures via an infrared sensor on the baton, with movements interpreted by a central computer using GlovePie software and transmitted wirelessly via Arduino Bluetooth to a bracelet worn by the blind musician. The system encoded conducting information by analyzing directional changes in baton movements and mapping these to four strategically placed vibrators on the musician's arm. In testing with five blind musicians and two conductors, the system achieved a 98% acceptance rate among blind musicians, with error rates decreasing from 20% to 2% as users gained experience with the system. However, the systems limits the motion capture to the dominant hand and imposes the usage of the baton to the conductor.

III. Questionnaire Structure and Results

A. Questionnaire Structure

To gather user-centered insights for the design of a system that conveys conducting gestures via haptic feedback, we conducted a qualitative questionnaire targeting both sighted and BVI musicians. The questionnaire aimed to understand musicians' experiences with haptic devices, identify suitable body placements for wearable systems, and gather perspectives on the role of conductors in orchestral performance.

The questionnaire was administered by means of oral interviews. Through open-ended questions, participants were asked to reflect on:

- Their familiarity with tactile sensory feedback (vibrations, touch) and contexts of use;
- Which body parts they consider most suitable for perceiving tactile signals, considering their own musical instrument and tactile acuity;
- Areas of the body where they would not want haptic devices placed;
- Preferences regarding haptic device characteristics (fixed vs. adjustable, intensity levels of vibrational feedback).
- Which conductor cues are most effective, and at what moments is it essential to visually engage with the conductor (for sighted musicians);
- Challenges encountered in orchestral settings and methods used to follow conductors' cues (for BVI musicians);

B. Questionnaire Outcomes

A total of 16 sighted musicians, aged 20 to 28, and 10 BVI musicians, aged 38 to 79, participated in the study. In Table II, we present the participants' profiles, the type of visual impairment (for BVI musicians), the instrument(s) played, the reported years of experience (when available) and level of expertise, and the main music genre played. Additionally, Table III summarizes, by instrument group, the body parts that participants indicated as preferred or to be avoided for the placement of vibrational motors used to deliver haptic feedback.

In the following, we summarize the main survey outcomes regarding the role of conductors in orchestral performance, preferred modalities for non-visual feedback, body placement preferences, and potential usage concerns.

1) Role of the Conductor: Based on interview responses, participants identified the conductor's essential functions in orchestral performance:

- **Temporal coordination**: Establishing and maintaining the beat throughout the piece, signaling tempo changes, and ensuring rhythmic unity across the orchestra.
- **Expressive guidance**: Conveying dynamics, phrasing, and emotional interpretation through gestures, shaping the overall sound and artistic dimension of the performance.
- **Structural navigation**: Providing clear cues for entrances of different sections, indicating the start of musical phrases, leading climaxes, and managing transitions between sections.

Participants noted that, even during silences, the conductor's presence remains essential for shaping duration and maintaining ensemble cohesion. For BVI musicians specifically, the visual nature of these cues presents the primary barrier to orchestral participation.

2) Preferred Modalities: Although the focus was on haptic communication, several respondents advocated for a multimodal approach, combining tactile and auditory cues to enrich the interpretability of the information.

3) Wearability and Use Contexts: Most respondents expressed enthusiasm about using haptic systems in educational or rehearsal settings, but raised concerns about their practicality in live performance contexts. The interviews revealed several essential requirements for such devices to be truly useful for musicians. Comfort and unobtrusiveness were paramount, the device must be lightweight and discreet enough not to interfere with body movements or instrument handling, even during extended use. Respondents emphasized that vibrations should be clearly perceptible yet carefully calibrated to avoid creating distraction or stress through excessive strength or frequency, therefore continuous vibrations must be avoided.

Practical considerations emerged as equally important: the system should be wireless (preferably using Bluetooth) to preserve freedom of movement, and must be designed for independent use—musicians should be able to put on and remove the device without assistance, a particularly crucial requirement for BVI users. Additionally, respondents stressed

TABLE II
PROFILES OF INTERVIEWEES

ID	Age	Sex	Visual Impairment	Instrument (years of experience)	Expertise	Music Genre
S1	23	F	-	Harp (13)	Amateur	Classical/Contemporary
S2	21	M	-	Flute (10)	Amateur	Classical
S3	28	M	-	Trombone (8)	Amateur	Classical
S4	21	F	-	Violin (14)	Amateur	Classical
S5	21	M	-	Trombone (12)	Amateur	Classical
S6	21	M	-	Trombone (13)	Amateur	Classical
S7	25	F	-	Flute (12)	Amateur	Classical
S8	24	M	-	Cello (18)	Amateur	Classical
S9	23	F	-	Harp (10)	Amateur	Classical
S10	23	M	-	Guitar (13)	Amateur	Classical
S11	24	F	-	Piano (7)	Amateur	Classical
S12	24	F	-	Piano (10)	Amateur	Classical/Contemporary
S13	22	F	-	Flute (10)	Amateur	Classical
S14	23	M	-	Trumpet (15)	Amateur	Classical/Marching Band
S15	23	M	-	Violin (15)	Amateur	Classical
S16	20	F	-	Cello (14)	Amateur	Classical
B1	65	M	Shadow after 45	Trumpet (- before shadow)	Beginner	Marching Band
B2	38	F	Shadow since birth	Vocals (5), Piano (1), Accordion (-)	Beginner	Classical/Opera
B3	54	M	Light and contrast perception only, after 5	Guitar (-)	Amateur	Contemporary
B4	63	M	Blind after 21	Accordion (-)	Beginner	Classical
B5	54	M	Blind since birth	Piano (50)	Professional	Various
B6	57	M	Blind after 8	Piano (50), Accordion (-)	Professional	Various
B7	59	F	Blind after 44	Vocals (-), Tom Tom (-)	Beginner	Traditional
B8	51	M	Light and contrast perception only, since birth	Guitar (-)	Beginner	Classical
B9	79	F	Light and contrast perception only, since birth	Piano (-)	Professional	Various
B10	76	F	Light and contrast perception only, after 62	Percussions (-)	Amateur	Marching Band

that the device should be intuitive enough to use without extensive training, making it accessible to musicians regardless of their technical expertise. While participants recognized the potential value of haptic feedback systems, they consistently emphasized that successful adoption would depend on balancing functionality with the practical demands of musical performance.

C. Per-Instrument Discussion

In this section we discuss the interview outcomes, summarizing, for each instrument, the body parts that were found suitable/unsuitable for the placement of a haptic feedback device, providing motivations derived from the answers by the interviewees. Individual answers are reported in Table III.

1) Harp (2 sighted musicians): The two harp players mentioned that freedom of hand and finger movement is essential, particularly for actions such as hand closure and the performance of harmonics. Thus, any haptic device must not interfere with fine motor skills. Participant S1 identified wrists and the back of the hand as acceptable locations, as long as they do not restrict hand movement. Conversely, the hand was considered unsuitable by participant S9, as it may be too distracting and impede finger movements. Both S1 and S9 agreed that the forearms and upper arms are viable, provided that the system remains in place. Certain zones are unsuitable due to the posture and movement involved in harp performance, including the thighs, as identified by S1, where placement would be too intrusive, and the head and back, as identified by S9, which could be uncomfortable during seated playing. For S9, the ankles and the feet were considered suitable as they do not interfere with the instrument.

2) Piano (2 sighted, 4 BVI musicians): Piano players did not find consensus on the identification of a suitable location for haptic feedback placement. Two of them (S11 and B6) considered the wrist as one of the suitable areas, as it does not interfere with hand/finger movement essential to performance. On the other hand, S12 and B5 identified the arms as acceptable, due to their proximity to the hands. However, all of them explicitly mentioned that any device placed near the hands must avoid restricting movement. The back and the belt were considered unsuitable by B5, as placing a wearable device in those areas may cause discomfort during seated playing. It is worth noting that some interviewed piano players (B2 and B6) also play additional instruments: the areas deemed suitable by those participants hold for all instruments they play.

3) Trumpet (1 sighted, 1 BVI musician): For trumpet players, the body movement while playing is quite static. None of the two participants mentioned any unsuitable area. However, depending on the playing position, some areas may be perceived as uncomfortable. For example, feet may not be

TABLE III
INSTRUMENT COMPATIBILTY WITH HAPTIC FEEDBACK

Instrument	Participant	Feet	Ankles	Legs	Knees	Thighs	Belt	Belly	Chest/Torso	Back	Hands	Wrists	Arms	Shoulders	Neck	Face	Head	Ear
Harp	S1					✗					✔	✔	✔					
	S9	✔	✔					✗		✗	✗		✔		✗		✗	
Piano	S11	✔										✔					✗	
	S12			✔									✔				✗	
	B2				✗		✔				❍							
	B5						✗			✗	❍		✔	✔				
	B6		✔									✔					✗	✗
	B9																	
Trumpet	S14		✔						✔			✔			✔			
	B1																	✔
Trombone	S3								✔		❍		❍					
	S5									✗	❍					✔		
	S6						✔				❍			✗	✗		✔	
Flute	S2			✗			✔		✗			✔						
	S7			✔		✗					✗		✔				✗	
	S13			✔					✔	✔	✗		✗					
Accordion	B2				✗		✔				❍							
	B4									✔	❍							
	B6		✔									❍					✗	✗
Violin	S4			✗					✔				✗					
	S15	✔	✔	✔	✔	✔	✔											
Cello	S8		✔						✗		✗	✗	✗				✔	
	S16			✔				✗		✗				❍				
Percussions	B7	✔										✔	✔				✔	
	B10										✗		❍		✔			
Guitar	S10			✔			✔		✔		✗		❍					
	B3		✗				✗				❍		✔					
	B8						✔		✔									
Vocals	B2				✗		✔				❍							
	B7	✔										✔	✔				✔	

✔ Suitable, ❍ Partially suitable, ✗ Unsuitable

recommended, as the player can either stand or sit depending on the orchestral settings, as well as knees and thighs. Here, no clear preference emerged, with S14 mentioning ankles, torso, wrists, and neck as most suitable areas, while B1 mentioned only ears.

4) Trombone (3 sighted musicians): For trombone players, participants highlighted that haptic placement must account for the asymmetrical use of the arms during performance: the trombone is posed on the left shoulder, whereas the right one remains free. The right arm and right hand, which are in constant motion to operate the slide, are deemed unsuitable by all the participants. On the other hand, the left arm and left hand, which are more stationary, can be considered as a suitable location, particularly the hand or forearm. The back was considered unsuitable by S5 due to incompatibility with sitting, whereas shoulders and neck were considered unsuitable by S6, as they may interfere with supporting or manipulating the instrument.

5) Flute (3 sighted musicians): For flute players, no clear preference emerged, as the participants showed contrasting opinions. S2 and S7 identified the wrist and the forearm as suitable locations for receiving haptic feedback, as long as it does not interfere with the delicate hand positioning required for playing. Conversely, S12 considered arms as too involved in the performance to receive additional complex stimuli. On the other hand, S7 and S12 considered legs as suitable, as they would not interfere with the performance. Differently, S2 considered legs (in particular thighs), as unsuitable due to the seated posture typical in orchestral settings. Other suitable positions were identified, such as the belt, chest, and back. However, S12 explicitly mentioned during the interview that those are valid only if vibrations remain very subtle, so as not to interfere with the playing.

6) Accordion (3 BVI musicians): All accordion players agree on the right arm and the back of the right hand as suitable positions for haptic placement, as playing mainly involves fingers only, whereas the hand position remains relatively still.

In contrast, the left hand is too involved in controlling the bellows and thus requires full freedom of movement, making it unsuitable for the placement of haptic devices. Placement near the belt or the back is also considered viable by some of the players, since it does not obstruct the instrument. Instead, B2 considered the knees as not recommended, particularly when playing standing up, as physical tension in that area may reduce sensitivity. Additionally, B6 excluded both head and ears, as placing the haptic device on those areas could be too distracting during the performance.

7) Violin (2 sighted musicians): Among violinists, S4 considered the central area of the chest as a possible location for haptic feedback, as long as the device does not interfere with movement. Conversely, she mentioned that arms and shoulders must remain entirely free to allow for the precise movements required in playing, making these areas unsuitable. S4 also considered the legs as unsuitable, since they could cause imbalance or discomfort during performance. On the other hand, S15 considered the whole bottom part of the body as suitable, since it is less involved in the performance as more static, as long as placement of the haptic feedback device does not interfere with sitting.

8) Cello (2 sighted musicians): Cello players agreed that haptic feedback is best suited on the lower part of the body, with ankles and legs identified as compatible areas that do not interfere with performance. Conversely, they considered vibrations in the upper body, particularly the arms, chest, wrists, and hands, as highly disruptive, since these areas are actively engaged in playing. The participants reported difficulty when playing while wearing a watch on their wrist, highlighting the need to keep the upper limbs completely free. The chest and back were also considered unsuitable areas, since haptic feedback placement would interfere with breathing and posture. S16 mentioned shoulders as potentially suitable areas, but clarified that they could also be problematic due to their involvement in instrument support.

9) Percussion (2 BVI musicians): For percussionists, both hands are involved in the performance, with different movement amplitudes and speeds, thus they were considered unsuitable by B10. The arms, in particular the left forearm, were considered as a suitable location by both participants. However, they mentioned that, if placed in this location, the device should be designed to avoid restrictions of the movements of the arms.

10) Guitar (1 sighted, 2 BVI musicians): For guitar players, haptic feedback is best placed on the fretting arm's forearm (typically the left arm for right-handed players), as indicated by S12, since it remains free during performance and the device would not interfere with playing. In contrast, the strumming arm rests against the guitar body, making it unsuitable due to the risk of transferring unwanted vibrations. The hands and fingers are also deemed unsuitable, as they are essential for precision and tactile sensitivity, with only potentially the back of the hands being a valid location, as suggested by B3. The chest/torso may be compatible, though its proximity to the instrument could affect its usability. Hips or waistline are mentioned as possible locations when seated, while the legs may be less suitable due to reduced sensitivity.

11) Vocals (2 BVI musicians): For singers, the belt area (especially on the side) is considered by B2 to be a favorable location for haptic feedback, as it does not interfere with vocal performance. However, vibrations should not occur during singing to avoid disruption. The arms and feet are also identified as acceptable by B7, though the usability of such parts would heavily depend on the device's design. The knees are considered unsuitable by B2, particularly when standing, due to physical tension that reduces sensitivity.

D. Final Observations

From the interviews it emerged that, while for some instruments players had clear consensus on preferred body areas for device placement, in numerous instances the choice of body parts depended strongly on individual user preference. For musicians who play multiple instruments, versatility also influenced their decisions, as they often favored locations that could work across different instruments. This suggests that the device should be designed to be easily customizable and adaptable to various body parts.

Another aspect to consider is that there are several body parts for which the participants did not specify their opinion on suitability. These unexplored areas may still hold potential for device placement. They could be evaluated based on both practical convenience, as suggested in prior studies [23], [24], and tactile acuity, with preference given to regions more sensitive to vibrational stimuli [25].

IV. From Requirements to Specifications for Prototype Design

Based on the insights gathered from interviews with musicians and an analysis of the literature regarding orchestra conduction and haptic systems, this section explores a range of potential design solutions to translate conductor gestures into tactons, enabling BVI musicians to perceive and respond to conducting cues in real-time.

A set of requirements is therefore defined to provide a foundation for the system's technical development and to support its future implementation and validation. For each requirement, multiple design options are presented and analyzed in terms of advantages and limitations. The exploration of possible design solutions is guided by three core functional requirements:

- Motion data acquisition and processing;
- Gesture-to-tacton feedback via wearable devices;
- User customization.

These functional requirements are considered alongside a set of non-functional requirements essential for real-time and wearable use. In particular, system latency must be minimized to ensure effective temporal alignment with musical gestures. Moreover, since the system involves both a conductor and a musician, the physical footprint of any body-worn components must be kept as small as possible for both roles. This ensures that the conductor's movement remains unobstructed and that

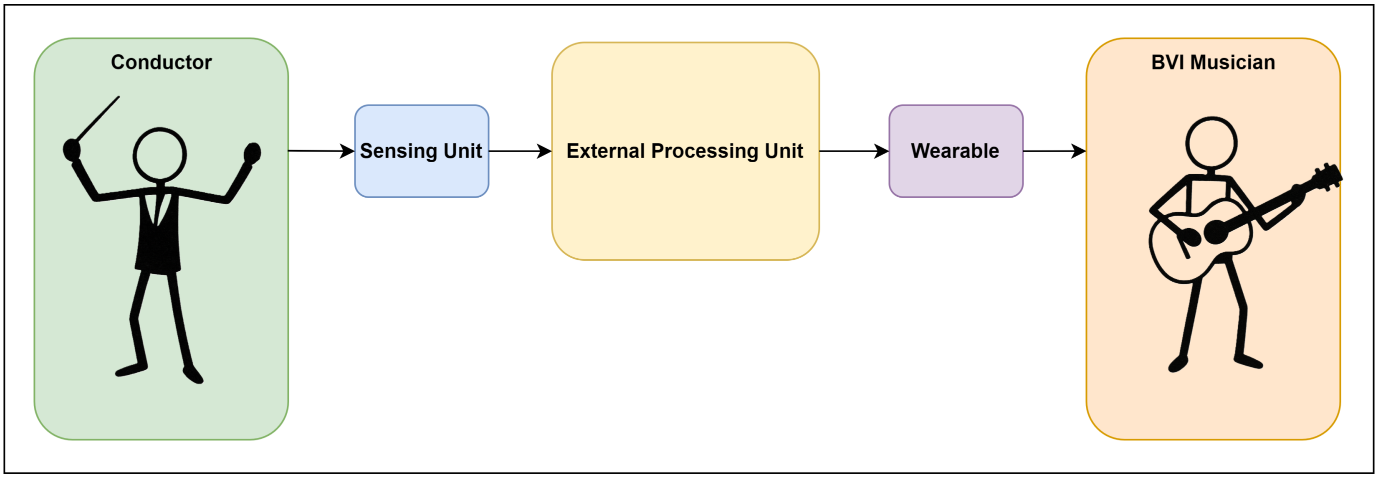

Fig. 2. The image illustrates a conceptual framework where the modular system architecture can take place. The conductor's gestures are first captured through a sensing unit and transmitted to an external processing unit. There, gesture recognition algorithms interpret the input and generate control messages. These messages are then encoded and sent wirelessly to a wearable device worn by the BVI musician, which delivers corresponding tactons to support synchronized musical interaction.

the musician's comfort is preserved during performance. Additionally, the power consumption of the wearable unit should be optimized to support portable, untethered operation over extended periods.

To accommodate these requirements, the design space points toward a modular architecture (see Figure 2). This comprises an external processing unit, which handles gesture acquisition and interpretation, and a wearable feedback device, which receives control messages and delivers tactile stimulation. This division allows for powerful and flexible processing without compromising the size, comfort, or energy efficiency of the wearable device.

A. Motion Data Acquisition and Processing

The first requirement addresses the acquisition and interpretation of conductor gestures in real time, with the goal of translating them into structured tactons that can be perceived and understood by BVI musicians. This process involves two main stages: the acquisition of gesture data through appropriate sensing technologies, and the subsequent processing and classification of those signals into meaningful control commands.

Two sensing approaches are particularly relevant in this context, each offering distinct trade-offs. The first option involves the use of wearable inertial sensors, such as Inertial Measurement Units (IMUs), which can be embedded in gloves, wristbands, armbands, or mounted on a lightweight headpiece worn by the conductor [26]. In the proposed setup, these sensors are connected to an external processing unit, where raw motion data is transmitted for analysis. This configuration keeps the sensors extremely lightweight and power-efficient, and minimizes local processing requirements, which aligns well with the design constraints of low energy consumption and reduced wearable footprint. On the other hand, requiring the conductor to wear multiple IMUs can introduce physical encumbrance and may interfere with natural expressivity, particularly in performance settings. The presence of cables also demands careful setup to avoid restricting movement.

Alternatively, gesture acquisition can be performed using stereo RGB-D cameras, placed on a stationary stand positioned in front of the conductor. This configuration eliminates the need for body-worn sensing hardware altogether, allowing for natural, unrestricted motion. The camera captures detailed spatial and temporal information about the conductor's movements and streams this data directly to the processing unit. While this setup supports vision-based recognition pipelines and avoids distributing electronics on the conductor's body, it introduces higher latency compared to inertial sensors. In particular, RGB-D cameras typically exhibit end-to-end latencies in the range of 25–35 ms due to frame acquisition [27], internal processing, and data transfer delays, whereas IMUs can achieve latencies well below 10 ms [28]. Moreover, the functional reliability of camera-based systems is influenced by environmental factors such as lighting and visual occlusion, which may affect the quality of gesture capture.

Once gestural data has been acquired, it must be processed to extract discrete symbolic information suitable for controlling haptic feedback. This extraction of symbolic information is crucial to avoid a direct, continuous mapping of conductor movements into vibrations—which, as discussed in sec. III-B3, would create the distracting continuous stimulation that musicians seek to avoid. Instead, the processing stage must intelligently interpret the conductor's gestural intent, translating meaningful musical cues into discrete tactile events. The nature of this processing stage depends on the chosen sensing modality.

When using wearable IMUs, traditional signal processing techniques are typically sufficient for detecting well-defined gestures with limited variability. These include time-series segmentation, thresholding, and classification based on handcrafted features such as peak acceleration, angular velocity, or trajectory patterns. Algorithms such as Dynamic Time Warping (DTW) [29], [30] have been successfully used to recognize rhythmic and temporal cues with low computational overhead, which is particularly beneficial for real-time applications. However, when greater generalization or robustness is required, machine learning approaches can be employed to process IMU data. Since computation is handled off-board, such models can be implemented without impacting the wearable's energy efficiency.

Unlike IMUs, data from RGB-D streams provide a richer and more detailed representation of both movements and facial expressions, making them well-suited for advanced deep learning techniques for multimodal recognition, such as combining gesture recognition and emotion recognition. To identify conducting gestures in real time, adaptations of state-of-the-art techniques, such as those described in [31]–[34], may be adopted. These models can capture complex spatio-temporal dynamics and are more robust to variation across users or environments. While such methods require more computational resources, they are compatible with the proposed architecture, where the processing is performed on an external general-purpose computing unit.

In both sensing scenarios, the output of the processing stage is a compact symbolic representation of the detected gesture, such as a cue identifier, tempo value, or intensity level, which is subsequently transmitted to the wearable system for real-time vibrotactile feedback.

B. Real-Time Gesture-to-Tacton Feedback via Wearable Devices

To enable real-time tactile feedback in response to conductor gestures, the system requires a suitable communication protocol and a wearable embedding a processing unit able to drive the actuators delivering distinct and timely vibrotactile patterns to the musician.

The first step involves the transmission of the compact, encoded message representing the detected gesture (e.g., tempo, beat intensity, or cue type) from the external processing unit to the wearable system. For this purpose, Bluetooth Low Energy (BLE) is a practical choice due to its wireless operation, low power consumption, sufficient data rate for control signals, and widespread hardware support in embedded platforms. BLE provides adequate responsiveness, typically 10 ms latency [35], and simplifies integration with consumer-grade microcontrollers.

Once received, the message is handled by the wearable. Among the possible technologies such as Field-Programmable Gate Array (FPGA), System on Chip (SoC), or Microcontroller Units (MCUs), the most feasible choice is an MCU. Compared to FPGA or SoC-based solutions, MCUs offer a superior trade-off between computational capability and system complexity. Alternative architectures such as FPGAs and SoCs can offer higher performance and flexibility. However, their increased power consumption, development complexity, and larger physical size make them poorly suited for wearable applications, where compactness and energy efficiency are critical. Microcontrollers, on the other hand, are well-suited to the task.

The final component is the actuator, which physically conveys the tacton to the user. Several technologies are available, each offering distinct trade-offs in terms of responsiveness and power consumption. These characteristics have been extensively compared in recent literature, which reports typical rise times and integration constraints for common actuator classes used in haptic systems [36].

Linear Resonant Actuators (LRA) produce clean vibrations at a fixed resonant frequency and typically offer fast response times (around 25 ms), combined with relatively low power usage. Due to their compact size and consistent performance, they are well suited for integration into wearable elements such as straps, bands, or garments, where space and power constraints are critical. However, their fixed operating frequency can limit the range of tactile effects that can be delivered.

Eccentric Rotating Mass (ERM) motors represent a cost-effective and widely adopted alternative. However, their mechanical structure leads to significantly slower response times, often exceeding 100 ms, and less precise control of vibration onsets. As a result, they are generally less suitable for applications requiring timely and well-defined cues, such as beat alignment in musical performance.

Piezoelectric actuators provide the fastest response among the three technologies, with rise times typically ranging from 1 to 4 milliseconds. They are capable of generating highly detailed and sharp tactile sensations with a wide bandwidth. Nevertheless, these actuators require high-voltage drivers and more sophisticated control electronics, which can limit their practical deployment in low-power and compact wearable systems, especially where safety and energy efficiency are concerns.

Taking all constraints into account, including responsiveness, power budget, and physical integration, the combination of BLE communication, a low-power MCU, and LRA actuators represents a balanced solution for real-time, body-worn tacton delivery.

C. User Customization

To guarantee effectiveness of use, the proposed system design also requires a degree of customization for both the conductor and the BVI musicians. For the conductor, customization is necessary at the gesture recognition stage, since conducting styles vary widely across individuals and the system must allow adaptation of mapped gestures, interpretation rules, and detection thresholds in order to preserve each conductor's personal expressivity. For the BVI musicians, customization is required at the haptic feedback stage, since preferences in tactons intensity, duration, or actuators mapping differ according to instrument, tactile sensitivity, and performance context.

For both user types, two complementary levels of customization can be foreseen. Predefined profiles would allow for a quick setup through ready-to-use modes optimized for

TABLE IV
COMPARISON OF DESIGN ALTERNATIVES FOR THE HAPTIC FEEDBACK SYSTEM

Requirement	**Aspect**	**Component**	**Advantages**	**Limitations**
Motion data acquisition and processing	Sensing modality	IMU	Low latency (<10 ms); precise motion tracking	Requires wearable sensors; may constrain gestures
		RGB-D Camera	No need for worn sensors; natural conductor movement	High latency (25–35 ms); sensitive to lighting
	External processing unit	General-purpose PC	Balanced performance and cost; supports ML pipelines	Lower latency requires more specialized and costly hardware
Gesture-to-tacton feedback via wearable devices	Communication protocol	BLE	Wireless; low latency ($\sim$10 ms); low power consumption; widely supported	Higher latency than wired options (e.g., USB)
	Wearable	MCU	Good performance, easy to integrate, compact	Limited computational capacity; low flexibility
		SoC / FPGA	High performance and flexibility	High power consumption; complex; large size
	Actuator type	LRA	Good trade-off in terms of response time ($\sim$25 ms) and power consumption	Fixed frequency; limited expressiveness
		ERM	Low cost	Slow response time(>100 ms); high power consumption
		Piezoelectric	Fast response time (1 to 4 ms); low power consumption	Needs high-voltage drivers; more complex integration
User customization (Conductor and BVI Musicians)	Configuration method	Predefined profiles	Easy to activate; performance-ready	Requires external UI; Limited flexibility
		Adjustable parameters	High personalization (intensity, timing, mapping)	Requires external UI; more setup effort

typical conducting styles or for specific instruments, minimizing configuration effort during rehearsals and performances. Adjustable parameters, on the other hand, would provide deeper personalization, enabling conductors to fine-tune gesture mapping and BVI musicians to refine vibrotactile feedback according to individual needs.

In all cases, customization requires the support of an external user interface, which should remain simple enough to be managed by conductors or orchestra staff without specialized technical skills.

The design options discussed across the three subsections are summarized in Table IV, which provides a comparative overview of key components, trade-offs, and suitability for wearable haptic feedback systems.

V. CONCLUSIONS

This work aims at distilling design guidelines for the realization of haptic feedback systems to convey conductor gestures to Blind and Visually Impaired (BVI) musicians. By conducting interviews with both BVI and sighted musicians, design guidelines for wearable haptic devices were identified, including preferred body placements and key factors affecting usability in musical performance contexts. The derived guidelines were exploited to define the requirements of a prototypal system capable of real-time gesture recognition and vibrotactile feedback delivery with minimal latency.

Future works will involve incorporating such specifications in a working prototype, conducting user evaluations to assess effectiveness in rehearsal and performance scenarios, refining and validating gesture-to-haptic mappings based on direct feedback from BVI performers.

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