Design and Evaluation of Passive RFID-based Music Player Textile Prototypes

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***Abstract*—Music has always been an important way of expressing ourselves. Creating music from bodily interaction has gained much attention: Various gestures, touches, hand and foot movements are used to make music. The traditional identification and sensing technology—passive ultra-high frequency (UHF) radio frequency identification (RFID) technology—can be turned into a battery-free music player for creating music with a simple touch or gesture. Firstly, the technical feasibility of the created RFID system was evaluated by a simple on/off test. Next, this paper introduces two music player textile prototypes: The Touch Prototype can be activated by touching, while the Block Prototype can be activated by blocking, unblocking, or hovering over a specific spot on the created music player textile. Finally, the study gears towards the evaluation of the system in-use. Both developed prototypes showed a high input detection rate (95–100%) based on preliminary testing. The Block Prototype was found to be more flexible for the user, as the user does not need to be as precise in the movement as in the Touch Prototype. However, as the Touch Prototype allows separating the RFID IC and the antenna, it provides flexibility for the placement of the music player textile, for example when used as part of clothing.**

***Index Terms*—Music player, passive UHF RFID, textile-based interaction**

I. Introduction

MUSIC has always been a medium to communicate our emotions and feelings and express ourselves [1]. Reviewing the literature, we witness several advances in music production techniques, instruments and novel forms of music interface, such as the human body. Skin contact, body touch and gestures are getting attention as ways to make music. "Freqtric Drums" is one example of a music communication tool using skin contact as an interface [2]. Theremin is an electronic musical instrument with two metal antennas that allows music to be played and controlled by the performer's hand without any physical contact [3]. Sony's Motion Sonic is a wearable band that uses hand gestures to play instruments like guitar and piano, as well as create sound effects [4]. Previous studies also utilized a camera-based system to create music; the user's hand or foot movements were converted into auditory and visual output. This system was used as a music-making tool for physical rehabilitation [5]. This kind of system allows also children with severe physical disabilities to play and create music [6]. Some commercial music video games, such as Nintendo's Wii Music, provide a smart controller for playing music; Rocksmith and Guitar Hero are video games where you can play the guitar [7],[8]. Lei Yu, co-founder of DrumPants, made a wearable device for pants or other locations of the body, where users can tap to play music [9]. Mogees Play can be attached to any surface to make music based on vibration detection [10]. These music-making devices must be held or attached to a surface or body. Facilitating musical expression can be done by grasping, pulling, scrunching, and twisting the fabric [11]. The Embroidered Musical Ball allows the user to create music by squeezing and stretching the fabric ball [12]. Further, with gloves, users can create expressive musical sounds by bending their fingers [13]. FabricKeyboard is a deformable keyboard that plays music through touch gestures like pressing, pulling, stretching, and twisting fabric, as well as noncontact gestures like hovering and waving [14]. KnittedKeyboard [15] and Multi-Touch eTextile [16] are more examples of textile-based or bodily music players.

However, these devices require batteries and complex electronics, making them costly and not maintenance-free. Therefore, a solution that would be battery-free, wireless, cost-effective, and simple-to-manufacture, might help with the production and usability of those kinds of systems, which at the end may lead to higher adoption and wider utilization of bodily and textile-based music instruments. In that direction, passive ultra-high frequency (UHF) radio frequency identification (RFID) technology can be utilized.

Passive UHF RFID has travelled far from its original field of logistics to, for example, act as versatile battery-free sensors [17]–[19], RFID tags as a tracker of body positions, different exercises, and arm movements [20]–[22] and recently, in our RFID-TA 2021 publication, as a textile-based music player [23]. Based on the initial results, passive UHF RFID-based music player textiles enable the implementation of touch-based music instruments. Also, the technology's cableless and

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battery-free nature can help us, for example, dynamically change such music input's location on clothing.

This paper is an extended version of our paper in RFID-TA 2021 [23]. There, we introduced a music player textile, where the player "activates" a specific IC by touch to create music via our music software. In this paper, we introduce new ways of interaction for playing the sounds—blocking, unblocking, and hovering parts of the music player textile—contributing to producing embodied sounds. The main novel aspect of this study is the new way of interacting with passive UHF RFID technology and establishing a software to act based on that.

The paper is organized as follows: After this introduction, Section 2 will present the original Touch Prototype; Section 3 will present the new Block Prototype. Section 4 covers the working principle of a music player textile system and software development. Section 5 discusses how the practical test is conducted and the measurement setup employed. Section 6 reveals the results and discusses them. Finally, Section 7 contains a conclusion.

II. Touch Prototype: Design and Fabrication of Music Player Textile

In the Touch Prototype, the user touches a specific part of the textile with their finger to play music. For the Touch Prototype, a textile-based RFID touchpad is made using commercial electro-textile material, nickel-plated Less-EMF Shieldit Super Fabric (Cat. #A1220). Fig. 1 shows the antenna and touchpad dimensions. As shown, two electro-textile dipole antennas are used with three IC straps. These straps are NXP UCODE G2iL series RFID ICs (a wake-up power of −18 dBm, 15.8 µW). Each IC strap has two copper pads ($3{\times}3$ mm^2 each) for easy attachment to the antenna. The electro-textile is ironed directly onto one copper pad of the IC strap, while the other copper pad is left open for touch interaction to connect with the electro-textile antenna. The electrical connection between the IC and the antenna is made when user touches the copper pad of IC and electro-textile material. Thus, the IC gets detected only when the user touches IC's copper pad.

Previously, an RFID-based remote controller with keys has been composed of an antenna, a plurality of N passive RFID ICs, and N switches [27]. This system used a multi-port microstrip network that interconnected the ICs, allowing them to share a common antenna. However, this system was more complex than our touch prototype and not based on textile materials. In our design, all three ICs are connected to the same transmission line and through more sophisticated antenna designs the number of ICs can be probably increased.

The antenna system used is based on earlier work [26]. In that work, the antenna system was fixed on the table to act as a push button that could be used for desired digital output. Now, the solution is moved to a textile substrate for a new type of music player. The touchpad's length is now fixed at 80 mm to allow enough space for hand movement.

In the Touch Prototype, we implemented a touching gesture in which the copper pad must be precisely touched to make it work. Eventually, however, the copper pad becomes dirty and no longer recognizes touches. Thus, the system's reliability decreases with use.

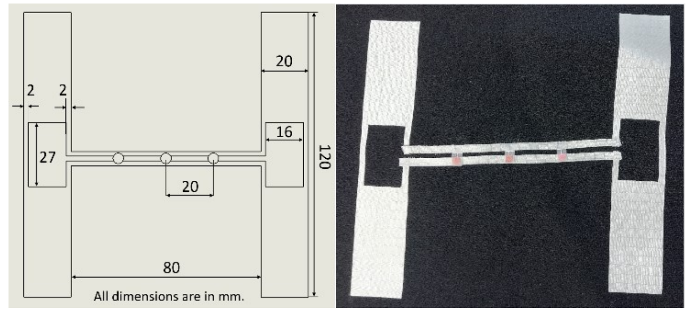

Fig. 1. Touch Prototype: Music player textile design (left) and a ready-made prototype (right).

III. Block Prototype: Design and Fabrication of Music Player Textile

In the Block Prototype, the user blocks, unblocks, or hovers over a specific part of the textile with their hand to play music. The reader constantly reads the RFID tags in all three gestures. When the reader reads the tag with blocking and hovering gestures, the software checks whether the tag is in the database. The software will not play anything if the tags are in the database; it will play a specific sound if the specific tag is no longer detectable by the reader. Thus, the hover gesture works the same way as blocking the tag, except the user does not need to touch the tag as in the blocking gesture. For unblocking, if the reader detects the tag in the database, the software will play the specific sound. Thus, the tag must be initially blocked from the reader with hand. The logic of how the gestures work and play sounds is visualized in Fig. 2.

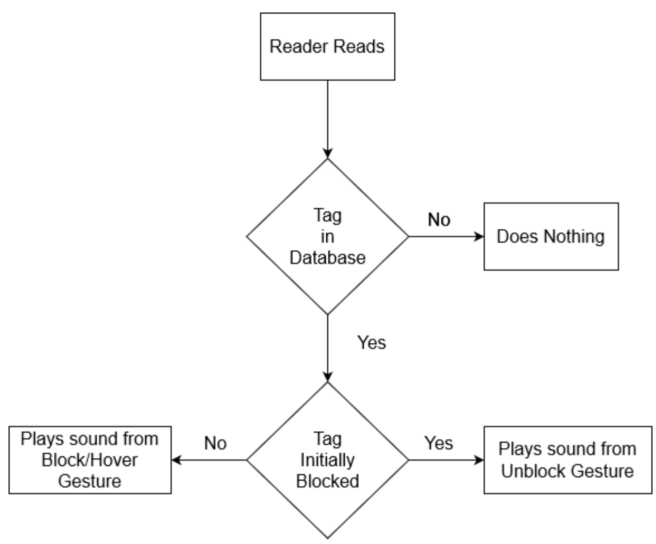

Fig. 2. Flowchart showing how the gestures work and play sounds in the Block Prototype.

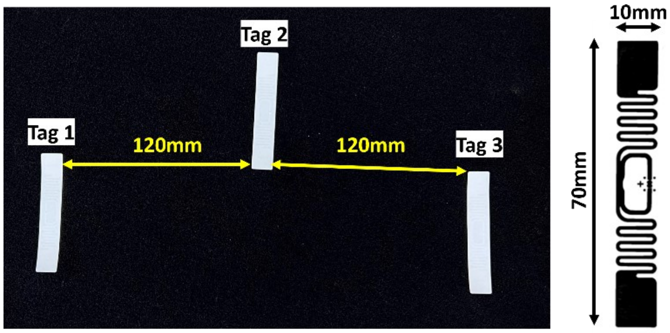

Fig. 3. Block Prototype: Placement of the tags on the textile (left) and tag's dimensions (right [28]).

Commercial tags from SMARTRAC [28] were used to develop the Block Prototype. These tags come with self-adhesive glue, making attaching them to any surface or cloth simple. Fig. 3 illustrates the placement of tags on a textile. The tags were initially set equal distance (70 mm) apart. However, this resulted in our hand blocking a neighboring tag when covering the desired tag. After some trial and error, the tag arrangement was modified—shown in Fig. 3 — to an equal distance of 120 mm.

IV. System Development

As explained, the music player textile system has two input prototypes: Touch Prototype and Block Prototype. The background system is the same in both. Fig. 4 shows the working principle of the music player textile system. As in Figs. 1 and 3, three ICs (Touch Prototype) and three tags (Block Prototype), respectively, were attached to the textile; each IC/tag has a different sound. When the user touches one IC copper pad (Touch Prototype) or blocks/unblocks/hovers over the RFID tag (Block Prototype), the IC gets "activated" or "deactivated", meaning it is read or unread by the RFID reader and detected by a developed basic music software, which plays a specific sound.

The music software is developed in C# as a Windows Forms application and built on the .NET Framework. This software uses ThingMagic Mercury API, which provides continuous reading from the used M6 Reader and can filter received RFID tag IDs to only those in the software's database. The relationship between the ID and music is defined in the software database. Selecting which sound to play by each specific input is done by placing the desired audio file in the software database in .wav format. In this study, we used three different drumbeats and piano notes as sounds.

The basics of the used RFID detection software were created in [29]. The software was unintended to play music; however, in our original conference paper [23] and preliminary implementation of the music player textile, we focused on making software capable of playing sounds. During this extended work, we discovered that as the reader constantly reads the tag/IC, the software continuously plays a sound, which is problematic because user cannot play music beat by beat. To address this issue, a "same tag delay" feature was implemented, which allows users to delay timing from 50 ms to any number. This also implies that the same tag will not be activated again for that duration of time after it has been activated.

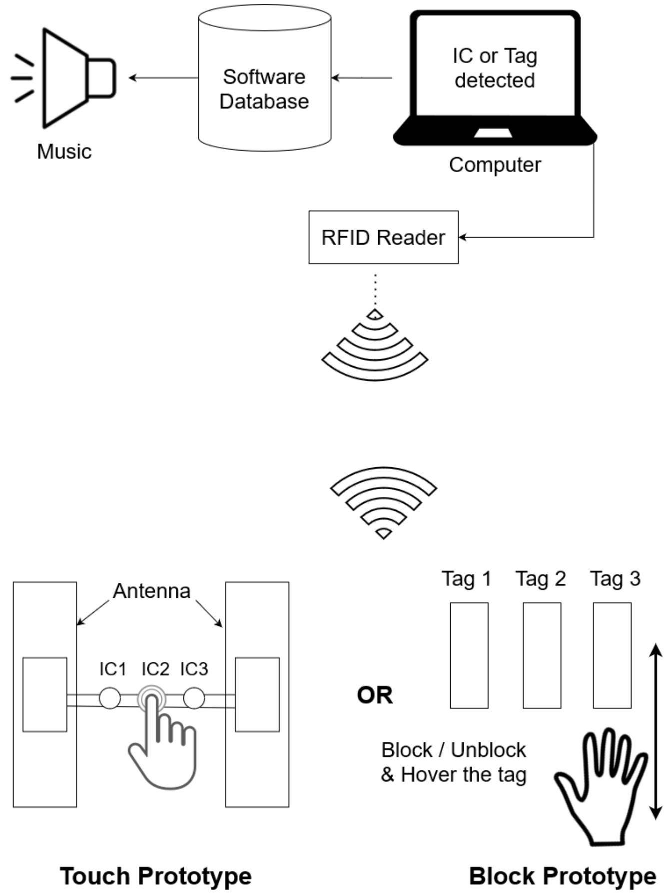

Fig. 4. Working principle of the music player textile system.

V. Practical Testing of Music Player Textile Prototypes

In both prototypes, ThingMagic Mercury 6 UHF RFID reader was used at the European standard frequency range (865.6–867.6 MHz). A circularly polarized RFID reader antenna was connected via a connecting cable to the M6 reader. Testing was done in an office environment using two different setups, shown in Fig. 5. Setup 1 was a reader antenna positioned in front of the textile. Thus, the reader and the cloth are perpendicular to each other. In Setup 2, a reader antenna was placed on top of the textile. So, the cloth and reader are parallel to one another. Setup 2 allows music to be played via the hovering gesture, which is impossible in Setup 1.

Firstly, to test the system's feasibility, a basic test was performed to activate and deactivate the system without user input (gesture), i.e., by simply showing the tag to the reader and hiding it again as soon as the sound plays. To do this test, SMARTRAC [28] tag was attached to a piece of cloth. In both setups, the cloth with the RFID tag was shown to the reader 50 times and the distance between the reader and the cloth was 100 cm. The power level was set at 20 dBm. Each time our software detected the tag and played the sound. This demonstrates that the technical setup is reliable.

Next, the aim of a practical test was to assess the system in-use. The RFID reader power was set to 20 dBm. During the Touch Prototype testing, the distance between the music player textile and the reader was 85 cm in Setup 1 and 85 cm in Setup 2. For the Block Prototype testing, the distance between the music player textile and the reader was 150 cm in Setup 1 and 100 cm in Setup 2. These distances for Setup 1 and Setup 2 were determined based on the backscattered signal measurements presented in Table I and Table II, respectively. Here, the backscattered signals of the prototypes were measured directly (0 degrees) and at 45-degree angle from the RFID reader antenna.

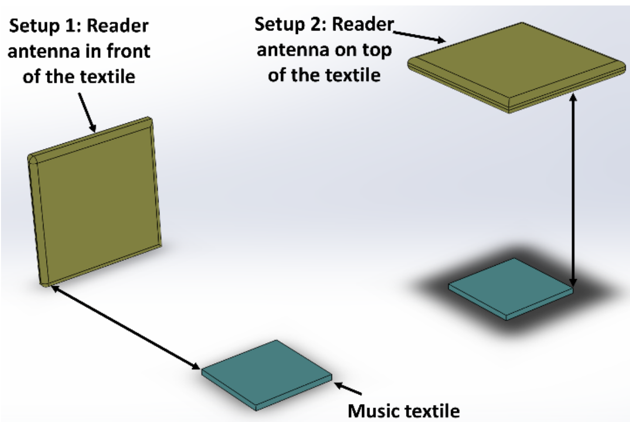

Fig. 5. Measurement Setups 1 and 2: position of reader antenna and music player textile.

TABLE I
BACKSCATTERED SIGNAL MEASUREMENTS FROM DIFFERENT ANGLES AND DISTANCES FOR SETUP 1.

Distance (cm)/ 0◦ angle	Touch Prototype RSSI (dBm)	Block Prototype RSSI (dBm)
50	-47	-53
100	-46	-52
125	-49	-55
150	Not detectable	-57
200	Not detectable	-78
Distance (cm)/ 45◦ angle	Touch Prototype RSSI (dBm)	Block Prototype RSSI (dBm)
50	Not detectable	-57
100	Not detectable	-62
150	Not detectable	-57
200	Not detectable	-71

TABLE II
BACKSCATTERED SIGNAL MEASUREMENTS FROM DIFFERENT ANGLES AND DISTANCES FOR SETUP 2.

Distance (cm)/ 0◦ angle	Touch Prototype RSSI (dBm)	Block Prototype RSSI (dBm)
50	-42	-49
100	-45	-48
125	-48	-55
150	Not detectable	-62
200	Not detectable	-66
Distance (cm)/ 45◦ angle	Touch Prototype RSSI (dBm)	Block Prototype RSSI (dBm)
50	Not detectable	-49
100	Not detectable	-59
150	Not detectable	-70
200	Not detectable	Not detectable

Five people participated in the testing. Each participant was instructed to touch the IC's copper pad (Touch Prototype) or block/unblock/hover over the tag by hand (Block Prototype) in random order, 100 times, to play music. When a gesture is performed on a textile and the music associated with that tag/IC is played, it is scored as a successful detection. If music associated with that tag/IC is not played, or different music is played due to hand blocking another undesired tag, it is rated as an unsuccessful detection.

Further, the time between gesture and sound was measured to determine latency for the software. The measurements were done via a video analysis, where frame by frame analysis was done from the gesture to the sound. The video was recorded by iPhone 13 Pro with 60 frames per second (fps). The total number of frames in between the gesture and sound were divided with 60 to get the software latency. The video analysis was done in DaVinci Resolve 17 video editor.

VI. RESULTS AND DISCUSSION

The results demonstrate the use of the developed system with all the practical external factors (a normal office setting with all the surrounding electrical and wireless equipment as well as the user and the human body) potentially influencing the outcomes. Touch Prototype's results (shown in Table III) demonstrate that 95% detection in Setup 1 and 97.6% detection in Setup 2 are achieved. Following are some external factors that affected the results. Certain people's fingers performed more poorly than others, probably due to sweat or dryness. Also, the input point, i.e., copper pad of the IC strap, was found to be too small for practical use. After testing, we chose one IC copper pad to evaluate their reliability and kept performing touch gesture until the detection rate fell below 50%. This happened after 800 touch gestures. Thus, although the testing results can be considered very good, the long-term reliability of the Touch Prototype cannot be considered suitable for practical use. Further work is needed to create a touch point that is reliable and has a bigger size for easier use.

In the Block Prototype testing, for each gesture, all participants performed the blocking, unblocking, and hovering gestures (shown in Fig. 10) 100 times. In Setup 1, the average detection rate for blocking and unblocking was 98.2% and 99.4%, respectively. As mentioned, hovering was impossible in Setup 1, as the reader was in front of the textile, which is then still visible to the reader. Hence, it was not possible to do the hover gesture, which in our prototype required a complete blocking of the tag from the reader. On the other hand, in Setup 2, the reader was on top of the tag, and the hand can block the tag by the hover gesture. Through tag antenna designs and placements of the tag and the reader antenna, these setups can be modified to desired functionalities. Further, it would be one possibility to use the change in the backscattered signal as an input in the hovering gesture [20]-[22]. In Setup 2, the average detection rate for blocking and unblocking was 100%. The hover gesture works in the same way as blocking, except the user does not need to touch the tag. The average detection rate for hovering was 96.8%. Compared to other results in the Block Prototype, hovering has the lowest detection percentage: If any space exists between the fingers while blocking the tag with the hover gesture, a probability of false tag detection of the nearby tags exists. Still, even the hovering results can be considered very promising, as we are only testing the first prototype.

Fig. 6. In the Touch Prototype, all IC copper pads are initially separated from the electro-textile antennas (left); a specific IC can be "activated" by touching the copper pad, which will connect the IC to the antennas (right) and make the IC readable for the RFID reader.

Based on the testing results, the Block Prototype is more reliable than the Touch Prototype when considering long-term use and slightly better regarding detection. Further, it is simpler for the user to use the gesture of blocking/unblocking/hovering than touching a small IC strap copper pad. However, in Touch Prototype, we can place the RFID tag IC anywhere on the body, away from the RFID tag antenna, which means it could even be on the opposite side of the body for better readability. This is a clear advantage over the Block Prototype.

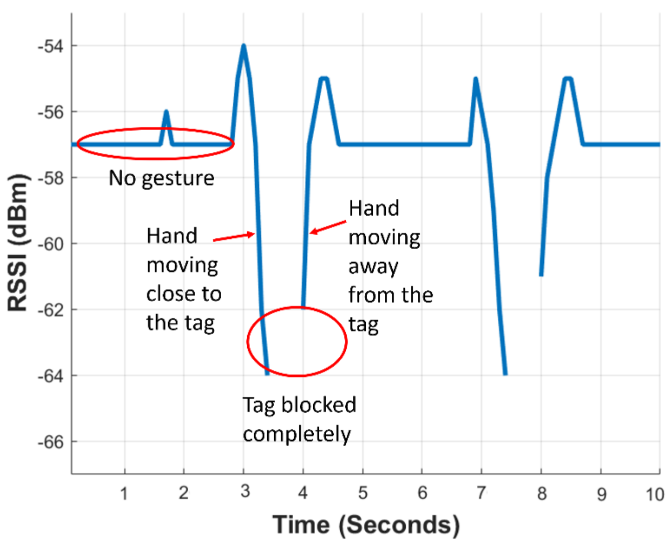

Fig. 7. Backscattered signal during a block gesture.

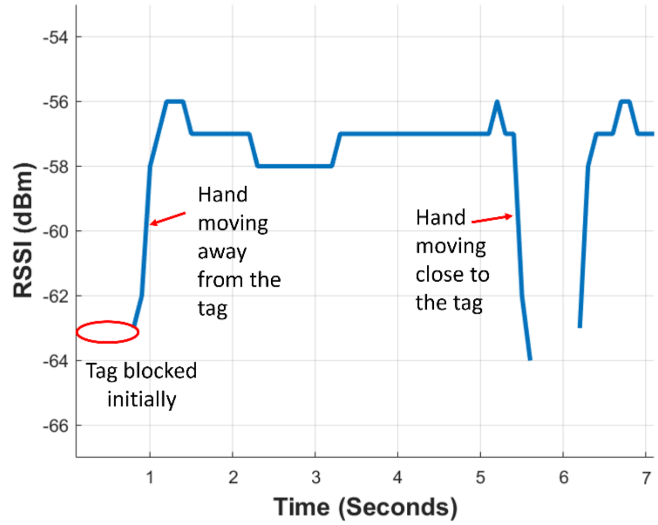

Fig. 8. Backscattered signal during an unblock gesture.

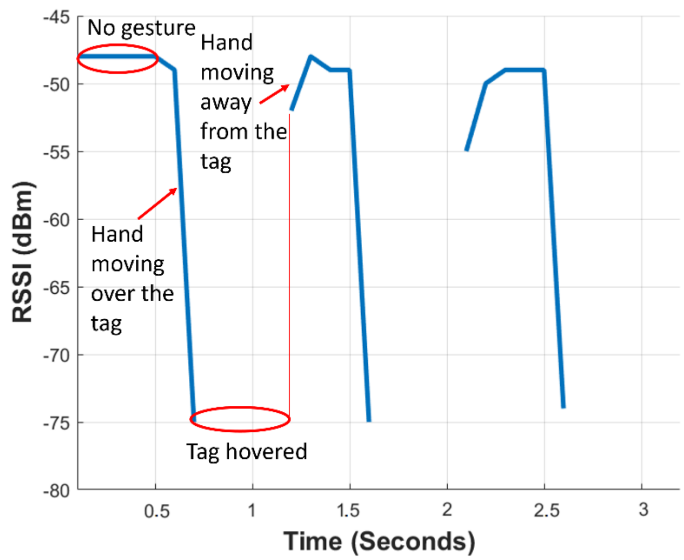

Fig. 9. Backscattered signal during a hover gesture.

Figs. 7, 8 and 9 show graphical representations of the backscattered signal when performing blocking, unblocking, and hovering, respectively. The distances in these measurements are 150 cm in Setup 1 (block/unblock) and 100 cm in Setup 2 (hovering).

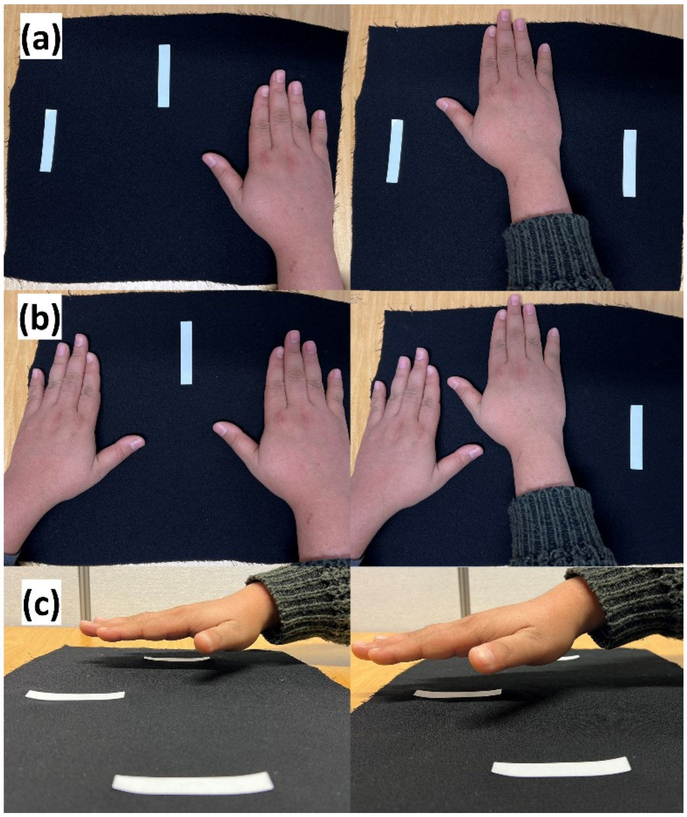

Fig. 10. Playing music using the Block Prototype with different gestures - (a) Blocking: Initially, the reader detected all tags. One or more tags should be covered to play music; (b) Unblocking: Whichever tag is visible to the reader will play music; (c) Hovering: Initially, the reader detected all tags. One or more tags should be hovered over to play music.

TABLE III
TEST RESULTS OF BLOCKING, UNBLOCKING & HOVERING

User	Setup 1			
	Touch	Block	Unblock	
1	97%	100%	100%	
2	99%	98%	100%	
3	96%	100%	100%	
4	88%	97%	98%	
5	95%	96%	99%	
Average	95%	98.2%	99.4%	
User	Setup 2			
	Touch	Block	Unblock	Hover
1	97%	100%	100%	100%
2	97%	100%	100%	96%
3	98%	100%	100%	93%
4	99%	100%	100%	95%
5	97%	100%	100%	100%
Average	97.6%	100%	100%	96.8%

In general, all the gestures in both setups achieved detection rates of 95% or more. Such can be considered a good result at this prototype stage. Further, no major differences among the results of different users existed.

Finally, a video analysis was used to complete the latency test. The total number of frames between the gesture and the sound was 10, which equals to 167 ms as the software latency.

VII. CONCLUSIONS

We introduced two music player textile prototypes using passive UHF RFID-based interaction. Two electro-textile dipole antennas were used in the Touch Prototype with three passive UHF RFID ICs. The user can touch a specific IC copper pad to activate the specific ID, and the developed music software will play the related sound. In the Block Prototype, three commercial passive UHF RFID tags were attached to the textile; simple gestures, including blocking, unblocking, and hovering over the tags, were used to play music. Five people did practical testing using two setups. Setup 1 had the reader antenna in front of the textile, and the average touching, blocking, and unblocking detection rates were 95.0, 98.2, and 99.4%, respectively. For Setup 2, where the reader antenna was placed at the top of the textile, the detection rates for touching, blocking, and unblocking were 97.6, 100, and 100%, respectively. Moreover, the hovering gesture, with a detection rate of 96.8%, was possible.

Regarding detection, the Block Prototype outperforms the Touch Prototype. Further, it is more reliable in long-term use. Our music player textile platform can be used on everyday clothing or any other textile around us because of its simple design and cost-effective manufacturing. Studying the technology's placement on different clothing is the next step of our work. Further, basic dipole antennas were used in both prototypes to test the functionalities of the system. The next step is to optimize the antenna design, for which there are several sophisticated existing designs, e.g. [24][25]. More, when used near the human body, i.e., when integrated into clothing, a new antenna design is again needed.

Our goal is to develop a full-fledged music cloth instrument to play sounds using various touch patterns such as tapping, double-tapping, and swiping. In the future, this technology can be applied to everyday clothing for educational musical purposes such as teaching music to kids and professional musical purposes such as helping performers and lecturers give playful performances.

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