Towards scalable soft e-skin: Flexible event-based tactile-sensors using wireless sensor elements embedded in soft elastomer

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Abstract— **Scalable, high-density electronic skins (e-skins) are a desirable goal of tactile sensing. However, a realization of this goal has been elusive due to the trade-off between spatial and temporal resolution that current tactile sensors suffer from. Additionally, as tactile sensing grids become large, wiring becomes unmanageable, and there is a need for a wireless approach. In this work, a scalable, event-based, passive tactile sensing system is proposed that is based on radio-frequency identification (RFID) technology. An RFID-based tactile sensing hand is developed with 19 pressure sensing taxels. The taxels are read wirelessly using a single 'hand-shaped' RFID antenna. Each RFID tag is transformed into a pressure sensor by disconnecting the RFID chip from its antenna and embedding the chip and antenna into soft elastomer with an air gap introduced between the RFID chip and its antenna. When a pressure event occurs, the RFID chip contacts its antenna and receives power and communicates with the RFID reader. Thus, the sensor is transformed into a biomimetic event-based sensor, whose response is activated only when used. Further, this work demonstrates the feasibility of constructing event-based, passive sensing grids that can be read wirelessly. Future tactile sensing e-skins can utilize this approach to become scalable and dense, while retaining high temporal resolution. Moreover, this approach can be applied beyond tactile sensing, for the development of scalable and high-density sensors of any modality.**

Keywords- tactile sensing, e-skin, event-based, wireless, passive, high-density

I. Introduction

Skin is the human body's largest organ, and arguably one of the most complex [1]. For humans to simultaneously obtain tactile information across the entire area of the skin with fast reaction time, mechanoreceptors in the skin employ event-based encoding through neural spiking [2]. This encoding allows for the neurons to generate activity only during relevant events, allowing for lower data requirements and faster communication than non-event-based synchronous communication which acquires and processes data at a particular sampling rate [3]. For example, the Meissner corpuscle (rapidly adapting type I mechanoreceptor) and the Pacinian corpuscle (rapidly adapting type II mechanoreceptor) generate spikes only during transition events, and not for static pressure [3]. Replicating this information processing scheme can be beneficial for fabricating e-skins that cover large areas like the human skin and that can obtain tactile information across the entire e-skin [4,5].

However, research in tactile sensors has lagged the development of a large-scale e-skin with tactile sensing capabilities across the entire area of the skin. The state-of-the-art e-skins use grid-based tactile sensing arrays made from piezoresistive [6] and piezoelectric materials [7], or organic photodiodes for optical based measurements [8]. Research focuses on increasing the tactile array size [9], developing new sensing materials [10,11], or improving the density of tactile pixels (taxels) [12] or temporal resolution [13]. Additionally, to obtain comprehensive tactile information, frequent sampling of the array elements is performed to read pressure inputs across the entire grid of sensors [9]. This is not scalable as it leads to slow read times when sensing arrays have many sensing units. For example, sensing arrays with more than 1000 elements rarely have sampling rates higher than 100 Hz [9]. This is problematic as sampling rates of up to 1.0 – 2.5 kHz are necessary for accomplishing many tasks such as texture recognition [14,15]. Another consequence of constant sampling is redundant data acquisition [16]. This can become a significant problem for portable applications with limited memory or with limited processing power.

At the human fingertips, there is a mechanoreceptor density of 241 units/cm^2 [17]. Even with an impressive sampling time of 50 microseconds per taxel [9], this corresponds to waiting 12 milliseconds to sample each cm^2 of the fingertips. Therefore, for large e-skins, with spatial resolution comparable to the human skin, it can become impractical to cover multiple square centimeters without significant loss of temporal resolution.

Limited progress has been made towards combining high-density taxels with a high temporal resolution over a large area, because of the inherent trade-off between temporal and spatial resolution [18]. Tee *et al* attempt to mitigate this problem through the use of asynchronous coding with a constant latency of 1 millisecond [19]. However, this solution has a high degree of computational complexity in the receiver, and it is also impossible for the receiver to know if a loss of a sensing event occurs [19].

Some progress has been made towards large area coverage, compact design, flexibility, and low cost; however, where progress has been made, this has led to a compromise on high-density taxels with high temporal resolution [20,21,22]. Sundaram *et al* achieve these criteria through their scalable tactile glove (STAG), but with limited temporal resolution [20].

The STAG represents the first time that researchers developed a large-scale tactile sensing hand with 548 taxels [10]. Taxels have a 2.5mm spacing and the hand has a sampling rate of 7 Hz. This low sampling rate is a result of the high number of taxels and the need for sequential reading of pressure from all of these taxels, pointing to the inherent tradeoff between spatial and temporal resolutions.

To mitigate this problem, an event-based approach can be used [4,5]. This eliminates the need for a constant sequential sampling of all of the taxels and instead allows for only the taxels with pressure events to be read. This dramatically

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increases the temporal resolution and mimics how tactile signals are processed in the human body [4,5].

For many e-skin applications, such as humanoid robotics, it is desirable for the e-skin to be highly robust to damage [23]. This is especially important for applications involving robot-human interaction, exploration, or other portable applications where robustness to damage is advantageous. Wireless sensing networks are inherently robust to damage because damage to one wireless sensor has no impact on the remaining network. Wireless sensors also have the benefit of being highly modular; allowing for different sensors to be easily integrated into existing networks [24]. Moreover, wireless sensors have the added benefit of not requiring wires; allowing for a much cleaner interface when sensing arrays become very large.

Many wireless tactile sensors have been developed [25,26,27], however to the best of our knowledge, none are scalable and event based. For example, Kou *et al* reported a wireless wide-range pressure sensor based on a graphene/PDMS sponge; but the sensor has no event-based encoding and lacks temporal scalability [28]. Additionally, Khalil *et al* reported a CMOS event-driven tactile sensor, but it requires large off-chip electronic setup to operate the sensor and is not compact [29]. A summary of these developments, noting which desirable e-skin criteria they satisfy, can be seen in Table. 1. As shown, limited progress has been made towards the development of large, flexible e-skins with both a high-density of taxels and high temporal resolution.

Ref	High-density taxels (<4 mm)	High temporal resolution (<15 msec)	Flexible	Large area coverage	Low cost
[8]				✓	
[9]	✓	✓		✓	
[10]			✓		✓
[11]		✓	✓		✓
[12]	✓				✓
[13]	✓	✓			
[19]	✓	✓		✓	
[20]	✓		✓	✓	✓
[21]				✓	
[22]	✓		✓	✓	
[27]			✓		
[29]		✓			

Table 1. Summary table showing the different criteria that different tactile sensing e-skins possess.

A new approach to realize a high-density grid of event-based, wireless tactile sensors can be to use wireless communication modalities such as radio frequency identification (RFID) or near-field communication (NFC). RFID devices can communicate their unique ID numbers to a RFID readers through radio wave modulation, and because the size of RFID tags have gotten very small (0.05x0.05 mm^2) in recent years [30], it is now possible to directly link each unit of a tactile sensing array to an RFID tag. This is beneficial because a grid of RFID tags can be read wirelessly using a single RFID reader antenna, and many tags can be read simultaneously through the use of anti-collision protocols [31].

Modern RFID readers can read 100-1000+ tags per second [32]. This allows for high speed communication between the RFID reader and pressure taxels tagged with RFID tags. If the communication between the RFID tag and the reader can be designed to be event-based, this could allow for the construction of high-density e-skins with good temporal resolution (up to 1000 Hz). Such devices could be good candidates for solving complex tactile discrimination tasks such as texture recognition.

This work aims to explore the use of RFID to create a new type of tactile sensor that inherently mimics the human skin in its high-density of mechanoreceptors, high temporal resolution, high flexibility, and large area coverage while remaining compact and low cost for easy integration into portable applications such as prosthetic devices.

II. Methods

The goal of this work was to design a flexible, tactile sensing e-skin in the shape of a hand, that we call the RFID Hand. Inspiration to build a hand shaped tactile sensor was also taken from the STAG. Here we attempt to develop a proof-of-concept device to show how large area tactile sensing arrays with many taxels, such as the STAG, can be made wireless, event-based, and more scalable.

To accomplish this task, a flexible grid of event-based pressure sensors is built using RFID. To transform the RFID tag into an event-based sensor a contact-based approach is utilized. The premise behind this approach is that the RFID chip is disconnected from its antenna and a small air gap is introduced between the chip and antenna (Fig. 1). Once pressure is applied, the RFID chip contacts its antenna, allowing it to receive power and communicate with the RFID reader.

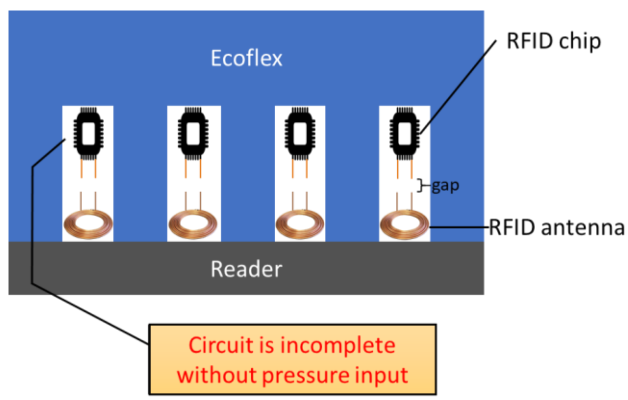

Figure 1. Contact-based approach to transform the RFID tag into an event-based pressure sensor. RFID chips are seperated from their antennas and only reconnected when a pressure event occurs.

To fabricate the RFID Hand, 13.56 MHz RFID tags were first dissolved in acetone to recover the RFID chips and their antennas (Fig. 2).

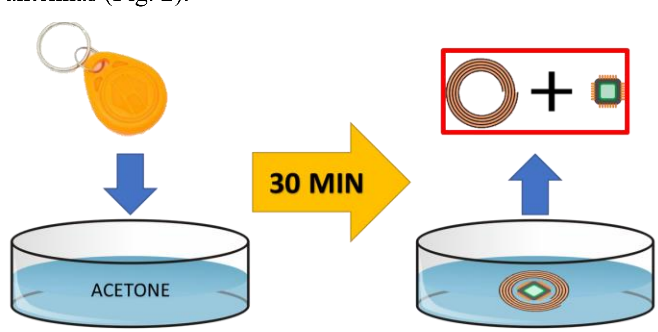

Figure 2. Drawing showing the process of removing the RFID chip and RFID antenna from a commercial RFID tag.

A series of silicone molds were then 3D printed using a LulzBot TAZ 5 3D printer. These molds allowed for three

Ecoflex™ layers to be cast: one to support the RFID antennas, one to support the RFID chips, and one layer to support a custom RFID reading antenna (Fig. 3).

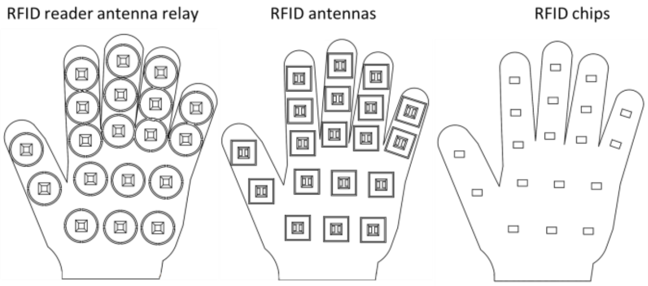

Figure 3. 3D Printed silicone molds. Three molds were printed to cast the three different layers of the RFID Hand.

The antennas and chips were then placed inside of their respective Ecoflex™ layers and glued in place. The layers were then stacked on top of each together and sealed with Sil-Poxy™. These assembled layers can be seen below (Fig. 4).

Because the human hand is not in a circular or rectangular shape, like most RFID antennas, a custom reading antenna was wound in the shape of a hand to communicate with the RFID tags. A relay system was also built to relay the RF communication from the integrated antenna on the MFRC522 RFID reader to the hand-shaped antenna (Fig. 5).

To characterize the RFID Hand, the minimum force required to activate the sensor was measured. This was measured by probing each taxel on the RFID Hand 30 times with a small 3D printed indenter (diameter 1 cm) of various weights, and recording the responses from the RFID Hand. The probability of response for each weight was then calculated as the number of responses divided by the number of trials. An Arduino UNO was used to connect a computer with the MFRC522 RFID reader. The overall system setup is shown below (Fig. 6).

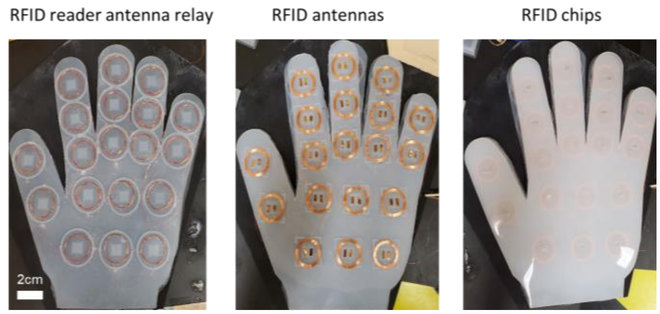

Figure 4. Three assembled layers of the RFID Hand made from Ecoflex™. The RFID relay anntena can be seen on the left layer, the RFID antennas and attached copper contact pads can be seen in the middle layer, and the RFID chips can be seen embedded in the right layer.

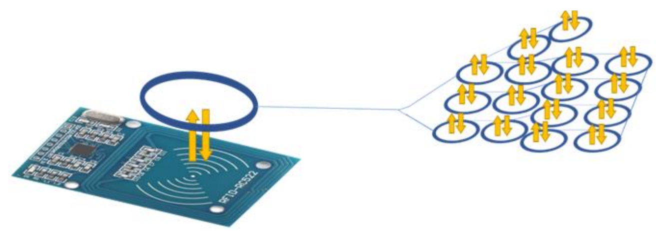

Figure 5. Schematic showing the working principle of the RFID relay antenna as well as the custom wound reading antenna. The MFRC522 RFID reader is shown on the left and the integrated, on-board antenna can be seen. The relay consists of one large loop of copper wire with 10 turns near the original RFID reader that mimics the current pattern in the RFID reader antenna and relays it to the hand-shaped antenna. The hand-shaped antenna consists of 19 (only 16 shown) small loops of copper wire with 10 turns as well. These 19 small loops were built to be approximately the same size as the RFID tag antennas.

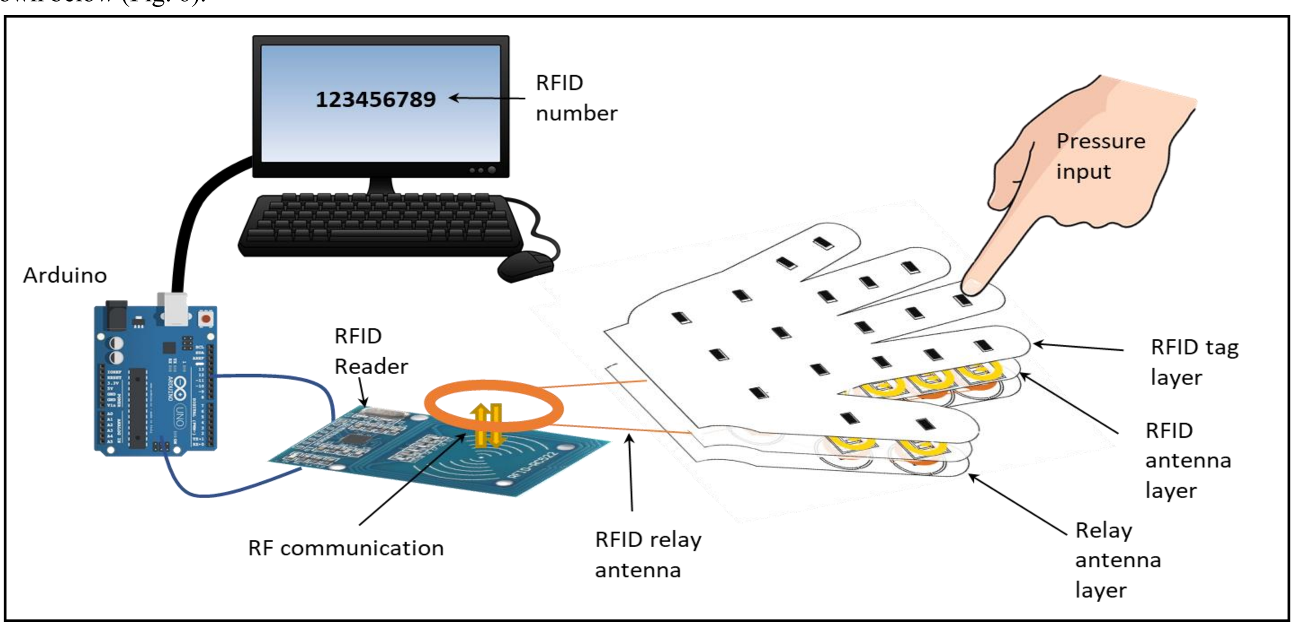

Figure 6. Overall system setup to power and read pressure data from the RFID Hand. An Arduino UNO is used to interface a computer with the RFID reader. A computer program records and displays which RFID taxels respond to different pressure inputs. The pressure location can be realized due to a one-to-one mapping between each tag's ID and its location in the RFID Hand.

III. RESULTS

All 19 taxels of the developed RFID Hand were functional validating the proof-of-concept. Moreover, a basic characterization of the taxels was obtained to understand the minimum force necessary to activate a taxel (Fig. 7). The RFID Hand consistently detected all weights greater than 100 grams (force of 0.98 newtons), and the 50% detection threshold was 70 grams (force of 0.68 newtons).

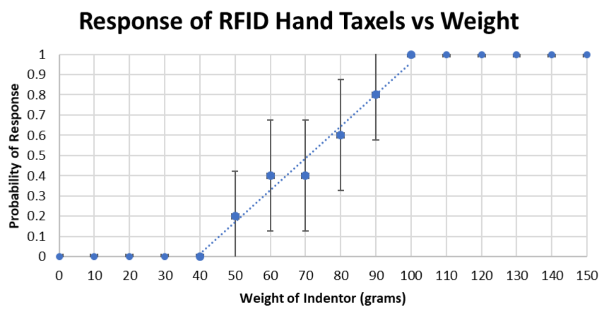

Figure 7. Characterization of the RFID Hand tactile sensor. The response of the RFID-based taxels were measured in response to different indenter weights. Extrapolating the line of best fit shows that a probability of 0.5 is achieved at a weight of 70 grams. Therefore, 70 grams represents the 50% detection threshold of the RFID Hand tactile sensor. Error bars represent the standard deviation of the response.

The RFID Hand had an average response time of 50.1 milliseconds and was capable of detecting simultaneous pressure events from up to 5 taxels at a time. The device consisted of three main layers, with each layer containing an Ecoflex™ support layer as well as an electronics layer. A schematic illustration of these different layers is shown below (Fig. 8). The RFID Hand was flexible, and could be bent at a 90 degree angle without damaging any of the sensing elements. The hand was also soft, mimicking the firmness and feel of human skin. During testing it was noticed that the taxels responded best to perpendicular forces, but had difficulty responding to shear forces. The RFID Hand was also highly robust to damage. This is because damage to one of the many sensing elements has no effect on the function of other taxels due to independent wireless sensing and lack of any multiplexing and wiring.

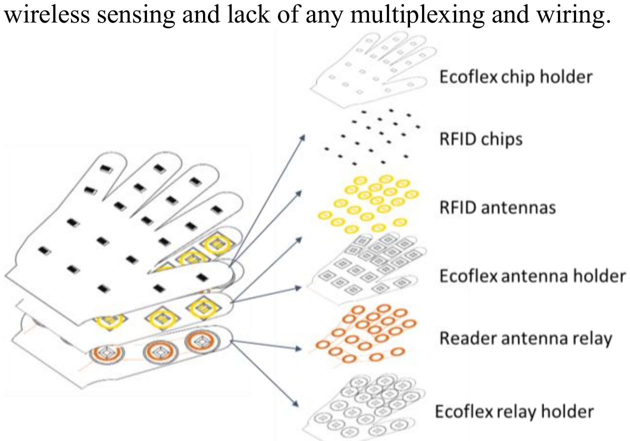

Figure 8. Schematic representation of the different layers of the RFID sensing hand, and a seperation of the layers and the components to show the inner working of the hand.

A GUI was also developed in Python to visualize which RFID taxels were activated on the hand (Fig. 9). The taxels would switch from white to black in response to a pressure event.

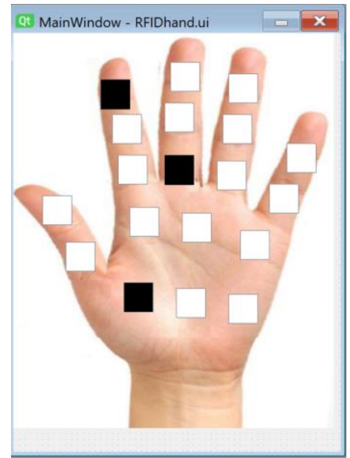

Figure 9. GUI to translate the pressure signals into a visual representation. GUI shows multiple simultaneous pressure inputs on various locations on the RFID Hand. The 19 sqaures in the GUI map directly to the 19 corresponding taxels of the RFID Hand. Black squares represent detected pressure events, and white squares respresent no detected pressure.

IV. DISCUSSION

The RFID Hand developed in this work serves as a proof-of-concept to show how large e-skins with high spatial and temporal resolution can be developed through the use of RFID. Although the developed device has an average response time of 50.1 milliseconds, has a taxel size of 2x2cm^2, and only 5 pressure events can be simultaneously detected, all these limitations may be overcome by using a more expensive RFID reader and by using smaller RFID tags.

During testing, the RFID Hand responded consistently to normal forces, but responded inconsistently to pressure inputs that were less perpendicular. This is likely a consequence of the contact-based approach that was utilized to transform the RFID tag into an event-based sensor. Because the pins on the RFID chip must make complete contact with the RFID antenna pins, shear forces may displace the RFID chip horizontally causing partial misalignment of the RFID chip and antenna.

To solve this problem, other forms of actuation can be considered. For example, two approaches are a distance-based and a Faraday shielding-based approach. A distance-based approach takes advantage of the limited read range of the RFID reader [33]. By placing an RFID tag on a flexible membrane slightly outside the range of the RFID reader, the tag can be transformed into an event-based pressure sensor. A shielding-based approach could utilize an RFID blocking material that would shield the RFID tag from the RFID reader when no pressure events are occurring [34]. Then when pressure events occur, the shielding material would deform to allow communication between the reader and chip.

High frequency (HF) RFID systems operating at 13.56 MHz like the MFRC522 are typically able to resolve up to 20 tags simultaneously through the use of anti-collision algorithms in the ISO 14443 communication protocol [32]. However, during initial tests, the fabricated RFID Hand was only capable of realizing 5 simultaneous pressure events. Moreover, if more than 5 taxels were probed simultaneously, only 5 would respond. A potential explanation for this reduction can be attributed to the 'homemade' RFID relay antenna. The number of turns and diameter of the RFID relay antenna was determined through empirical testing, and therefore may not have been optimized for the integrated antenna on the MFRC522.

Future iterations can use ultra-high frequency (UHF) RFID systems that operate above 900 MHz [32]. These systems are designed to simultaneously communicate with 100-1000+ tags [32]. Cheaper, 125 kHz RFID, tags can be utilized as well, but most 125 kHz RFID systems do not have built-in anti-collision protocol, and therefore only 1 tag can be read at a time without user modification. Standard passive 13.56 MHz RFID tags can be read at rates ranging from 10-100 tags per second [32]. UHF tags are also currently the smallest RFID tags on the market, with tags approaching sizes in the micrometer range [30]. Thus, while the developed RFID Hand did not have a very high taxel density, UHF tags are an excellent candidate for transforming the RFID Hand to be much more dense. This would allow for the development of dense e-skins with good spatial and temporal resolution. Such e-skins could be developed to have sophisticated texture recognition capabilities.

Overall, the RFID Hand responded consistently to multiple perpendicular pressure inputs with forces greater than 0.98 newtons. This threshold force can be further decreased by decreasing the thickness of the airgap. This would make the RFID Hand more sensitive. Another method of making the RFID Hand more sensitive would be to reduce the stiffness of the soft elastomer that supports the RFID sensors.

The RFID Hand presented here had a high degree of flexibility and was soft due to its Ecoflex™ exterior. Such highly flexible, and soft, e-skins are desirable for many applications; including the development of humanoid robots and realistic, 'human like', prosthetics [35]. However, during testing, the RFID Hand performed best in its non-flexed state. This is again due to the contact-based method utilized in this design. Non-contact methods of actuation would allow for greater flexibility while maintaining consistent performance.

The RFID Hand was also resilient to damage. This is because if any individual RFID taxel was broke, the remaining taxels could still function properly. Such damage resilience is a desirable feature for many e-skin applications.

However, one major downside of the RFID Hand is its lack of analog pressure sensing. For many applications, such as complex texture discrimination, analog pressure sensing provides greater dimensionality to the pressure data, and can improve the performance of classification tasks. One way to solve this problem is to explore the use of NFC tags. Many commercially available NFC tags have analog-to-digital convertor (ADC) channels, and can supply small amounts of current [36]. Thus it could be possible to integrate an NFC tag with a piezoresistive material to build an NFC Hand analogous to the RFID Hand. Such an NFC Hand could be programmed to respond only after a certain pressure threshold is surpassed, allowing for event-based analog pressure sensing.

V. Conclusions

In this work, a proof-of-concept is demonstrated for how to build flexible, event-based, wireless tactile sensors using RFID. This approach is more scalable than non-event-based and non-wireless methods and may be useful in the development of large-scale e-skins. The primary e-skin application lies in prostheses; however, other applications such as smart robotics are also attractive. Moreover, although this work focuses on tactile sensing, the approach of using a high-density grid of event-based RFIDs can be applied for any type of sensing modality such as temperature, light, sound, or voltage. The essential concept of this work is that each unit of a sensing grid is tied to a unique ID, and that all of the units of the sensing grid are read by one reader, wirelessly, in an event-based manner.

Building a high-density, event-based, wireless, sensing system for any type of sensor can be achieved if an application-specific integrated circuit (ASIC) is designed to replace the RFID tags. In this case, the generic sensing platform can work as follows: (1) The ASIC chip reader provides power to the grid of ASIC chips through inductive coupling, (2) ASIC chip with integrated sensor makes a measurement, (3) Once a certain voltage threshold is met during the measurement, the ASIC chip communicates its measurement and ID back to its reader. This general scheme allows for scalable and wireless, event-based sensing in any paradigm – limited only by the type of sensors that can be incorporated into the ASIC chip.

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