Adding Input Controls and Sensors to RFID Tags to support Dynamic Tangible User Interfaces

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ABSTRACT
Providing high resolution tangible user interface components without batteries such as dials and sliders that support dynamic user interface arrangement is challenging. Previous work uses RFID to support limited resolution custom-built components. We demonstrate improved techniques using commercial off the shelf input controls incorporated into passive RFID tags using an on-off key subcarrier to encode state information into the RFID signal. Our method supports high resolution components that do not require power cables or batteries. We provide exemplars demonstrating how the technique supports a range of user interface components including buttons, dials, sliders, flex and light sensors. Compared to previous work, we obtain a higher resolution, only limited by sample time, for all components and demonstrate 115 discrete dial positions. Our technique allows the TUI components to be freely placed and rearranged without hardwiring or batteries.

Author Keywords
Tangible User Interfaces; RFID; User Interfaces; Haptics; Sensors;

ACM Classification Keywords
H.5.2. User Interfaces: Input devices and strategies, Prototyping, Theory and methods

INTRODUCTION
Tangible user interfaces (TUIs) provide unique functionality for user interface (UI) development. They naturally deliver passive haptics to the user to increase immersion, and can be visually enhanced with projected virtual information [12]. TUIs can incorporate input controls, such as buttons, dials and sliders, as well as other passive or active sensors, bridging the gap between the physical and virtual information [2], advancing the functionality and improving the feel of UIs [11]. One challenge of this approach is that TUI components require a power source, imposing scaling and maintenance challenges, especially as 10s or even 100s of components are employed.

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To address this challenge previous research has explored methods of employing RFID to support UI development. Avrahami et al. presented a system that captured button press events through switches attached to RFID antennas [2]. They also demonstrated low resolution sliders using multiple RFID tags arranged in a line. Their proof of concept demonstrated great potential but was limited in resolution and only supported custom built components rather than off the shelf input controls (such as potentiometers). Thomas et al. developed a system that employed a glove-mounted reader to capture button presses for UI development in a Spatial Augmented Reality (SAR) environment [27]. This system demonstrated the use of 3D printed tangible buttons, with enclosed RFID tags, that were both spatially rearrangeable and visually reconfigurable (using projected imagery) during runtime. A drawback of this system is the lack of support for any UI component more complex than a two- state momentary switch.

These systems have begun to explore how UI development can be enhanced with RFID technologies. They provide a strong motivation for the theory and have exposed challenges such as the difficulty in maintaining simplicity while integrating of off-the-shelf input controls and sensors with RFID. This paper provides two contributions to the advancement of UI prototyping. Firstly, we demonstrate how input controls can be incorporated into passive RFID tags using on-off keying to encode state information as a subcarrier on the RFID signal. This approach is simpler in implementation compared to other comparable technologies such as WISP. Secondly we provide exemplars to demonstrate how the technique supports controls such as buttons, dials, and passive sensors and provide context why this is a powerful tool for physical UI development.

BACKGROUND
This paper extends on previous research areas including prototype interface developments, re-configurable interfaces in virtual environments and RFID-based TUIs. This section provides a summary of each area and how they are linked together.

Prototypes are a tool commonly used during the design phases of a products developmental cycle [20] allowing designers to examine ergonomic, spatial and functional aspects of the product during development. Physical mock-ups are an important prototyping tool, often providing the only way for designers to examine an object with both the physical look and feel of the final product [1], and allowing design issues to be identified during design rather than on the final product. However, incorporating functional user interfaces into a mock-up is challenging. One solution is the use of computer simulators that can prototype the product interface, although this can constrain designers to develop a product that either looks like the mock-up or functions like the simulator [10]. Developing tools to support functional, dynamically reconfigurable prototypes allows designers to develop mock-ups that both look and function as the final product while supporting quick, iterative UI design.

One technology that is suited to this task is SAR, which uses projected light to augment physical objects with digital images. The digital nature of SAR allows for UIs to be visually reconfigured quickly and easily compared to physical interface components. For example, SAR can be used to 'virtually paint' tracked objects within a SAR environment [3, 14]. Two examples of SAR-based prototyping systems are DisplayObjects [1], which allows designers to explore user interface controls on a prototype, and the work presented by Porter et al. which demonstrated improvements to the design evaluation system through the use of SAR using a cheap wooden substrate to approximate the shape of the prototyped object [19].

Reconfigurable User Interface Input Controls

Previous research has demonstrated spatially reconfigurable UIs using physical electronic toolkits, such as Phidgets [9]. Pushpin Computing [4] used components powered by pushing power pins at the base of the tangible object into a foam substrate containing conductive planes. A similar approach was taken with the VoodooIO Gaming Kit [29] to provide a real-time adaptable gaming interface. While such systems make placement and reconfiguration of the interface component layout simple, the required complexity and rigidity of the substrate does not easily lend itself to organically shaped objects. The Calder Toolkit [13] extends Phidgets, adding wireless input modules. The resultant toolkit facilitates both faster and higher fidelity prototype UI development compared to the use of custom electronics. However, although these technologies address the restrictions caused by wiring UI components, a disadvantage of this approach is the need for batteries which increases the maintenance requirements and cost of use. More ideal solutions use wireless, battery-free technologies such as RFID.

RFID-based TUIs

An RFID system comprises of two parts, a reader and transponder (tag). In a passive RFID system, the reader and tag antennas are inductively coupled. The inductively coupled tags use subcarriers to modulate the carrier from the reader to generate sidebands containing the tags information [7]. The tag is powered by current generated through magnetic field coupling with the reader, allowing the tag to function without the use of a battery. RFID is a flexibly and inexpensive technology increasingly used in everyday life [15] in domains such as education [6], medicine [28], stock management and object identification [21].

To address the challenge of powering sensors in TUI, energy can be harvested from RF sources to power circuitry [17]. Wireless energy transfer, from both uncontrolled (ambient) sources such as TV towers and from controlled RF transmitters, such as an RFID reader, has been used to wirelessly power sensors [22]. RFID [7] is an ideal energy harvesting technology to use when constructing wireless TUI as it can provide both a power source and a communications medium for the TUI components [30].

Previous work has used RFID to construct TUI with varing degrees of state resolution and electrical complexity. While it is possible to infer interactions between a user and an object using RFID [8], for UI development it is necessary to be able to read the state of a UI component. Encoding a single bit of information in an RFID transmission can be achieved by placing an electrical switch between the RFID circuitry and antenna [25]. A different approach was employed by Thomas et al. using a glove-mounted reader to capture button presses for UI development in a SAR environment [27, 26], although this system does not support any TUI components more complex than a two-state momentary switch. Encoding more than a single-bit of data is necessary to support more complex UI components such as joysticks or dials. Simple approaches have used multiple tags (one tag per state) to support sliders [2], although this approach has drawbacks: it is unwieldy to implement beyond very low resolution, and only supports custom built components rather than off the shelf input controls (such as potentiometers).

To support more complex UI components, techniques to integrate sensor input with RFID tags are being investigated. One approach is to use the tag antenna as a capacitive touch interface [24]. A different approach is to use tag modulation. An example is the Microchip MCRF202 [16] which provides a 1-bit data stream containing the state of a sensor. A more complex implementation is demonstrated by the Wireless Identification and Sensing Platform (WISP) project, using tag modulation to transmit a single bit of data from a sensor [18]. Two RFID tags are used, with the transmitted tag representing the state of the sensor. Later wisps use programmable microcontrollers to store sensor information in on-board flash memory, which can be read by an RFID reader using a READ command [23, 5]. This approach is being extended to support pervasive sensor networks [21]. However, the WISP project is also considerably more complex than [2], requiring a developer to have a higher level of knowledge and understanding in both RFID and electrical engineering. When considering the use of TUI within augmented reality (AR) environments, this level of knowledge is a drawback to the WISP approach as AR designers are not necessarily experts in either RFID or electrical engineering.

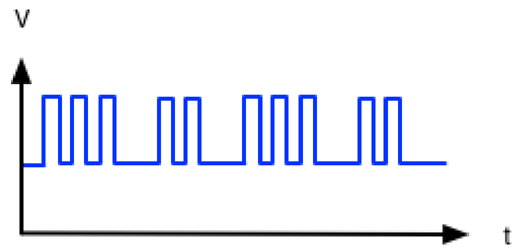


Figure 1: The tag modulates the magnetic field at a frequency of 13.56MHz, transmitting data to the reader. In this figure, a conceptual representation of this effect can be seen. The high portions represent transmission of a '1' while the low portions represent transmission of a '0'.

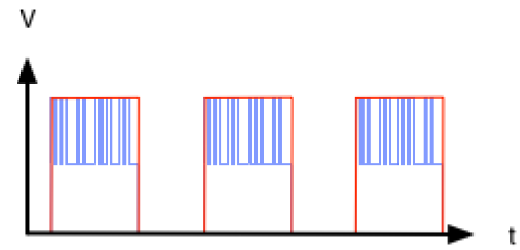


Figure 2: A conceptual representation of the OOK subcarrier (red) with a low frequency (less than 150Hz) on the 13.56MHz RFID signal (blue). The state of the component is encoded in the time the red signal is high.

In this paper we improve on these existing techniques to present new methods of supporting functional input controls and sensors in prototyping systems using RFID to maintain the dynamic reconfigurability of the prototype interface. One motivation of this paper is to allow designers to prototype UIs that have active controls. These new methods of constructing prototypes do not require the designers to learn new electronic skills, but enhance their existing skills of building physical prototypes. This solution allows us to move from momentary buttons and limited resolution sliders in previous work [2] to more complex input controls including switches, dials and sliders. In addition this technique supports passive environmental sensors, including light-resistant diodes, accelerometers and temperature sensors.

INTEGRATING INPUT CONTROLS WITH RFID TAGS

Integrating an RFID tag with an input control provides wireless and identification capabilities required to make the component functional. However, some way to encode the current state of the component and include it as part of the RFID information transaction is necessary. While RFID tags can be designed to incorporate sensors or other information sources, this is usually done at the time the tag is manufactured. Although standard compliant soft tags built up from microcontrollers are known and can easily accommodate added input devices, their size and external power requirements, such as the need for batteries, make them generally unsuitable for integration into small user controls. The challenge here is to add the ability to send data from an external information source such as an input control to existing, off the shelf, fully passive RFID tags.

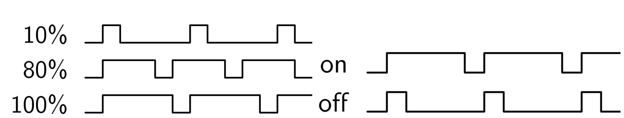
In this paper we demonstrate the idea of using on/off keying (OOK) with RFID for transmitting input control state information. This is consistent with the way inductively coupled tags normally use subcarriers to modulate the carrier from the reader to generate sidebands containing the tags information [7]. When an RFID tag is in range of the reader, inductive coupling forms between the reader and tag antennas, creating a current in the tag antenna.

In normal inductive RFID operation, such as defined by the ISO15693 standard, the tag produces sidebands on each side of the 13.56Mhz carrier that are read by the reader (see Figure 1). We create an OOK subcarrier on the RFID signal returned to the reader by the tag (see Figure 2). The OOK subcarrier in effect modulates the sidebands produced by the tag, slowly turning them on and off as a function of the value of the input control. The time that a tag is visible to the reader is used to signal the value of the potentiometer — the input control state information is thus encoded in the frequency of the presence of a reply from the tag. For example, three positions of a dial, rotated 10%, 80% and 100%, could be transmitted using three different frequency OOK signals, shown in Figure 3. This encoding scheme assumes that the tag is always in range of the reader and that a lack of tag signal indicates the 'off' phase of the encoding scheme.

The circuit to generate the OOK signal as a function of the input control can be simply a low power variable frequency oscillator such as an asynchronous multi-vibrator or 555-timer. Such a frequency oscillator can be powered using energy generated from the magnetic inductive coupling of the readers carrier in a manner similar to the way the passive tag itself is powered and without the need for batteries. By repeatedly performing tag ID transactions and determining the interval between successful tag replies an estimate of the input control setting can be obtained.

Multiple Tags and Collisions

Multiple tags operate with different performance depending on the configuration. The input controls are suitable for both wearable and surface-mounted RFID readers. For wearable reader systems, we previsouly found it optimal to place the transponder antenna as close to the reader antenna as possible to minimize the range between the users finger (if a finger-mounted reader antenna is used) and the transponder (depicted in Figure 4a). For surface-mounted readers, the tag



(a) Conceptual OOK signal for a dial, rotated 10%, 80% and 100%.

(b) Conceptual OOK signal for a binary input control.

Figure 3: Input control state information is encoded into the frequency of the OOK signal.

antenna is placed at the bottom of the input control housing (depicted in Figure 4b) allowing the input control value to be read when placed on the surface.

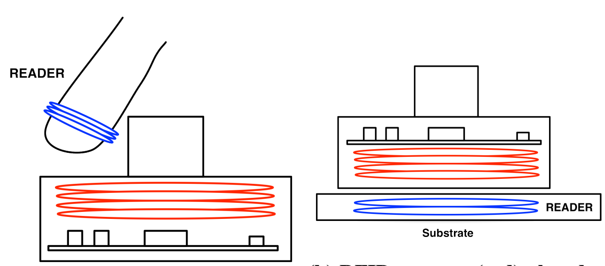
One challenge for this technology is collisions when multiple tags are in close proximity to a single reader. Previously we focused on developing a glove mounted reader system that was more prone to close proximity RFID tags. We performed an analysis to measure close proximity tag parameters [27]. The outcome of this work demonstrated a maximum read distance (21.5mm using optimal tag and reader orientations), with few collisions when tags were in close proximity. For AR-based UI prototyping where the users finger is situated in close proximity to a limited number of simultaneous UI components, we believe collisions are currently not a primary concern although this can be re-visited if required.

IMPLEMENTATION

In the current system, inductive ISO15693 compliant RFID with a carrier frequency of 13.56 Mhz is used by embedding tags into the dynamically re-configurable functional input controls. There are several aspects of the RFID-based input control that must be implemented, including: the OOK-signal generator, a tag switch mechanism, and a method of powering the OOK-signal generator. A circuit diagram for the implemented input control can be seen in Figure 5.

OOK Signal Generator: We utilize a LMC-555 timer as the OOK-signal generator using a standard astable 555-timer circuit. To generate a variable-frequency output oscillation, we integrate a linear potentiometer over one of the 555-timer resistors. The signal frequency generated by this component is controlled by two resistors. The ratio between the two resistors determines the duty cycle of the frequency. In our implementation, both resistor values are 430kohm, giving a duty cycle of 66.67%. The resistance range of the component (dial, flex sensor etc) has a large effect on the change in OOK signal frequency generated.

Switching off the RFID tag: The RFID tag is switched off using a 2n2222a transistor as a switch.



(a) RFID antenna (red) placed at the top of the housing, directly below the dial. The RFID reader antenna (blue) is mounted on the users finger.

(b) RFID antenna (red) placed at the bottom of the housing, below the circuitry. The RFID reader antenna (blue) is depicted mounted on a substrate, such as a table.

Figure 4: The position of the RFID antenna within the housing can be placed to ensure close proximity to the reader. For wearable RFID readers, placing the antenna at the top is appropriate. For object-mounted readers, the antenna should be placed beneath the circuitry.

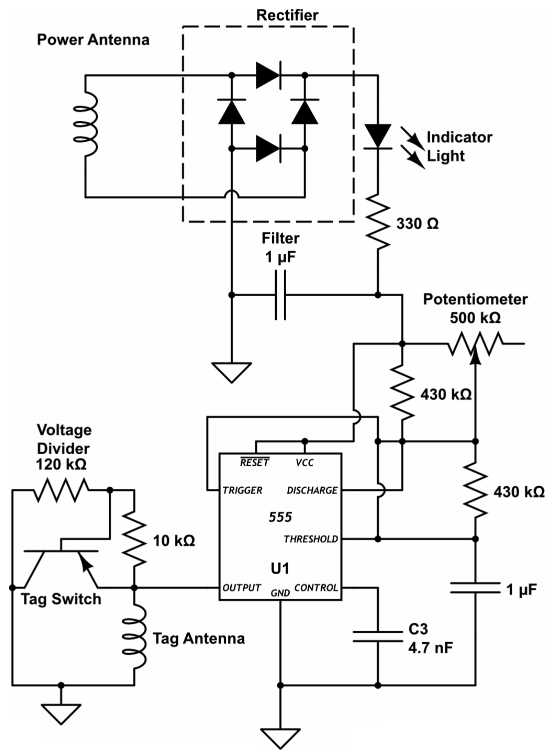


Figure 5: Full circuit diagram of the RFID-enhanced UI component.

Providing power for the timer: The RFID transponder uses magnetic induction with the reader to power the tag microcontroller circuitry. If the OOK is powered using this antenna, when the OOK generator switches the tag off by generating a HIGH signal on the OUTPUT pin the OOK power source (the tag antenna) no longer provides power. This prematurely ends the HIGH period. To address this challenge, a secondary antenna was constructed using 30 turns of copper wire and attached to the rectifier. This second antenna undergoes magnetic induction with the reader, and maintains this induction while the transponder signal is modulated.

Rectifier: The magnetic induction produces an alternating current in the antenna which was rectified using a standard four-diode configuration.

Reducing the OOK-generator output power: The voltage produced by the power antenna was measured at 14V when the power antenna was placed in the center of the readers magnetic field. This causes the output wave of the OOK-generator to swamp the 2n2222a transistor base pin. To reduce the voltage on the base of the transistor, a voltage divider was used, reducing the voltage to around 1V.

Indicator Light: An indicator LED was attached to the circuit, providing a visual indication of the OOK signal.

Signal Filter: A 1uF capacitor was used to smooth the power signal for the OOK-generator.

MINIMUM READ RESOLUTION

An important characteristic of the modulated RFID system is the read resolution — the minimum change in transponder modulated on/off frequency that can be determined by the RFID reader. The read resolution determines the degree of fidelity that can be used in the input controls and sensors.

There are many factors that contribute to the read resolution of the modulated RFID system. These include the RFID reader used (hardware), the firmware of the RFID reader (software), the type of RFID transponder and the software used to manage the system as a whole. Thus, the read resolution can vary between similar systems that use slightly different components.

To determine the minimum read time of the demonstrated system, we used an unmodified tag and reader. The controlling software used a loop with the following commands:

1. Begin a timer
2. SELECT for tag
3. Attempt to read the response from the tag
4. When the response is read, stop the timer
5. Calculate the time taken

This was repeated 100 times. The average time taken was 6161μs.

The RFID reader module used in this analysis is an SM130. The SonMicro SM130[1] performs a number of steps when executing a "seek for tag" command to begin communication with an RFID transponder. On receiving the command, the module executes an authenticate command, followed by a select tag command. When a transponder enters the RF field, the reader selects the tag and responds to the host with the serial number of the selected tag. If there is no tag present, the reader module replies to the host with an error code.

There are several sources of delay when executing this command. Firstly, the time taken for the host to send the command to the module. Secondly, upon receiving the seek for tag, the reader module replies to the host with an acknowledge response. Thirdly, the time taken to execute the authenticate and select commands. Finally, the time taken to respond to the host with either the transponder serial number or an error code.

EXEMPLARS OF RFID INPUT CONTROLS

There are a variety of UI components that are useful, including the following: switches, dials and sliders. We present both binary and valuated input controls, as well as valuated passive sensors, using off the shelf variable resistance components and a 555-timer used for the OOK signal generator. The technique demonstrated provides much higher resolution input controls than previous methods (a dial implemented using our technique provides 115 discrete positions).

Valuated Input Controls

Valuated input controls have a state represented by a position on an analogue scale. A volume control is an example

[1]https://www.sparkfun.com/products/10126

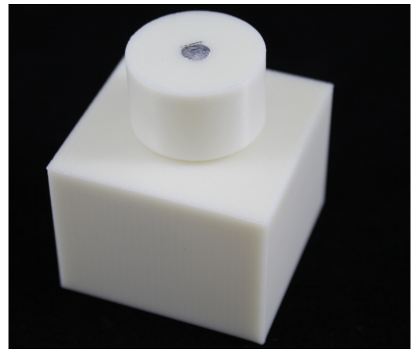


Figure 6: A dial. The RFID circuitry is housed in the 3D printed housing.

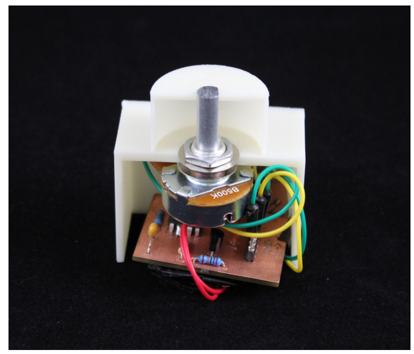


Figure 7: Cutaway of an implemented dial showing the RFID circuitry. The antennas are located below the circuit board.

of a valuated input control. The state of the valuated input control may be any value between a maximum and minimum. Practical considerations give a minimum resolution that restricts the valuated input control to a finite maximum number of states. Common physical forms of valuated input controls are rotary dials and bidirectional sliders.

Discrete valuated input controls have a state represented by a position on a discrete scale. A multi-state switch is an example of a discrete valuated input control. Discrete valuated input controls have similar physical forms to valuated input controls including rotary dials and sliders. A discrete valuated input control can be implemented by reducing the resolution of a valuated input control until there are a set number of states — in essence, rounding the analogue values to a discrete value.

Dials and sliders are a common UI component for variable input applications such as volume controls, fan speeds and temperature settings. Dials and sliders can be considered as two different form factors for analogue multi-state switches. Because these components are so prevalent in UIs, providing designers with realistically functioning components with resolution mimicking real-world components enhances the realism and immersion of prototype UIs. We envision RFID-based dials and sliders as key components in a designers toolkit for developing prototype UIs.

We constructed a dial using the OOK state transmission technique outlined in this paper. The dial was constructed using a 500k ohm linear potentiometer with a rotational arc of 300 degrees. When integrated into the transponder circuitry, the system can transmit 115 discrete states. To verify that the dial implementation works, a small experiment was conducted in which the dial was rotated to a specified position and the state of the potentiometer read by the RFID reader. The recorded position was then compared with the physical position of the dial. The test was repeated 10 times. The average error between the physical rotation and the recorded rotation was 1.2 states (3.6 degrees).

An operational use of these valuated input controls could be a MIDI interface. Dials and sliders could be added or deleted from the control panel while a system is operational. The number and configuration of the interface is not always known before it is placed in use, and current interfaces provide a large fixed number of controls. With the RFID enhanced these controls could be added as required. Current MIDI interfaces force the slides to be orthogonal to the orientation of the MIDI's structure. RFID sliders may be placed in any orientation. One layout could have the sliders, that are under the user's fingers, placed into a comfortable inverted "V" configuration that would allow users to more naturally move their arms, elbows, hands, and fingers during operation.

Passive Sensors

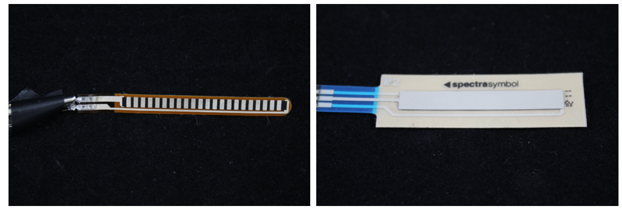
Passive sensors communicate data similar to valuated input controls, and these can be read and powered via RFID technology. Support for passive sensors such as light or temperature sensors provides users with a wider range of components that are easy to place and are activated when in range of an RFID reader. This imposes a limitation on the application of the sensor, but there are many domains the sensors only have to be activated and read while the user is close to the sensor.

We implemented a light sensor using a photocell with a resistance range of 10k ohms. When integrated into the RFID circuitry, this allowed transmission of three states ('light', 'dark' and 'in-between').

In SAR environments where physical objects are augmented with projected light, light sensors have interesting applications, allowing the UI component to react to differing light conditions. A UI control may have different modes depending on the light projected on it. For example, if a particular UI panel is augmented with red light, indicator lights may be lit on the panel. Temperature sensors may be placed at inspection points on objects, allowing a user to easily examine the temperature at those points or enhancing system monitoring by providing a value which can be read by a computer system.

Flex Sensor

Flex sensors provide unique UI controls with interesting applications. Flex sensors could be used to determine how open a door is, or the position of a joystick or wheel. A



(a) Flex sensor. **(b) Linear touch sensor.**

Figure 8: Two of the sensors we integrated into RFID-enhanced UI components.

Flex Sensor manufactured by Spectra Symbol was integrated into the RIFD tag[2] (see Figure 8a). The sensor has a flat resistance of 25k ohms, and a bend resistance range of between 45k and 125k ohms. Using a simple testing scheme, the RFID-enhanced flex sensor successfully transmitted four states ('flat', 'slightly bent', 'medium bend', 'sharply bent').

We have designed (but not implemented) a *book metaphor* for a UI component. Two thin boards are hinged together with a flex sensor attached to determine the angle between the boards, and the book is 6DOF tracked in 3D space. SAR information is then projected onto the boards. The sensed angle from the flex sensor influences the information presented. For example different angles present different menu options or pages in an operations manual. The action of opening and closing the book "flips" through the different options or pages.

Touch Sensor

Variable resistance touch sensors allow users to interact with a UI by touching surfaces rather than interacting with a specific component. These are manufactured in a linear and circular form factor. In this way, they allow touch UI components that are sensitive areas for single finger swap or circular gestures. We implemented a touch sensor using membrane potentiometer manufactured by Spectra Symbol[3] (see Figure 8b). The potentiometer has a resistance range between 100 and 10k ohms. During simple testing the RFID-enhanced tag successfully transmitted three states when touched ('near end', 'middle', 'far end').

Touch sensors are flexible, and are capable of being used in many different ways. For example, touch sensors are used for keypad interfaces and volume controls. Touch sensors are commonplace in UI designs for many applications. In the MIDI example, the physical sliders and dials could be replaced with touch sensors. The user would have the choice between haptically rich physical devices or low profile touch sensors. The user could mix and match as require from the different devices.

DISCUSSION

The RFID technology presented in this chapter has several benefits when compared to previous work [2, 26, 27]:

[2] https://www.sparkfun.com/products/10264

[3] https://www.sparkfun.com/datasheets/Sensors/Flex/SoftPot-Datasheet.pdf

1. It is relatively simple construct, particularly compared to the switched tag method demonstrated by [2].
2. It can use a large variety of sensors that exploit changes in resistance or capacitance to operate.
3. Derivations of the design could be created to also accommodate sensors that exploit inductance.
4. Enough energy can be generated from the reader's magnetic field to easily power the UI components.
5. It can be used with off the shelf readers and tags from a variety of vendors and in a large number of form factors.
6. The system is inexpensive to build. Although a 555 timer is used, so could a 2 transistor asynchronous multivibrator with an estimated cost of a few cents.

A key aspect of the RFID-based interface components presented in this paper is their dynamic reconfigurability, allowing designers to move and rearrange the UI components, because the components do not require static integration to the UI substrate (such as nails, screws or wires). Another aspect is modularity — the ability of the designer to view each component as a module that can be replaced within the UI at will. Interactions such as replacing a dial with a slider, or a toggle button with a momentary switch, are supported with the RFID technique presented here. This presents advantages over traditional UI design techniques, where replacing a dial with a slider requires time-consuming labor. The RFID technology may present some additional limitations, including data rate or latency, particularly when utilizing multiple TUI within a single SAR scene. The magnitude and effects of these potential limitations should be investigated in future work in this area. The limited range and bandwidth of the TUI could perhaps also be considered limitations.

Limitations of this method are related to the maximum frequency that can be used to generate the OOK modulation, and the time resolution with which the presence or absence of the tags reply can be measured. Both of these are very dependent on the architecture and firmware used in the reader, but it is possible to calibrate the system for a particular reader. In general, the minimum period of an input controls OOK subcarrier can be no less than two times the minimum time needed to successfully perform a complete tag transaction. This guarantees that in the absence of other errors that a full reader command followed by a tag reply has time to complete without being interrupted by the tags antenna being disabled by the input controls OOK subcarrier. Possible limitations involving collisions when using multiple tags in proximity to a single reader may also exist. Improving on these limitations is left for future work.

CONCLUSIONS AND FUTURE WORK

In this paper we present our new method for supporting sensors and input controls with enhanced RFID tags for dynamic tangible user interfaces. We demonstrated how commercial off the shelf input controls can be incorporated into passive RFID tags using an on-off key subcarrier to encode state information into the RFID signal, supporting high resolution components that do not require power cables or batteries. Our technique is simpler than other comparable technologies such as WISP. We provided exemplars illustrating how the technique supports a range of UI components and sensors including buttons, dials, sliders, flex sensors and light sensors. Our technique allows the components to be freely placed and rearranged, supporting operational user interface and prototyping.

There are several areas in which the modulated RFID transponder could be improved. A brief list of these limitations include the following issues: 1) Symbol rate is not as high as it could be. 2) The resolution obtainable is dependent on the performance of the reader and on the characteristics of the RFID standard used. 3) Likewise, latency from sensor change to system change is not expected to be consistent across different equipment manufacturers and may be excessive in some applications.

There are several areas of future research that should be addressed. Investigation of custom firmware or additions to the RFID protocol, could allow synchronization between devices. Other modulation schemes could improve control latency, for example using AM instead of OOK. Improved host controller software could use statistical methods to examine the observable on/off patterns reported by the reader module, to allow finer grained read resolution. Custom microchips in the transponder could reduce the power draw and integrate 555-timers in a single package. This could improve the usability of the technology, and provide a plug-and-play style of use. In addition, several further areas could be addressed in future research, including the use of alternative power sources, such as magnetic induction, to facilitate more complex functionality, such as low power light sensors or accelerometers, in the transponder.

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