PaperID: A Technique for Drawing Functional Battery-Free Wireless Interfaces on Paper

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Figure 1. Left to right: A wireless polling device, a pinwheel animation that adapts with spin speed, a conducting baton, a dollhouse controlled with custom RFID tags on paper interfaces, and a pop-up book with embedded tags which trigger audio content.

ABSTRACT
We describe techniques that allow inexpensive, ultra-thin, battery-free Radio Frequency Identification (*RFID*) tags to be turned into simple paper input devices. We use sensing and signal processing techniques that determine how a tag is being manipulated by the user via an RFID reader and show how tags may be enhanced with a simple set of conductive traces that can be printed on paper, stencil-traced, or even hand-drawn. These traces modify the behavior of contiguous tags to serve as input devices. Our techniques provide the capability to use off-the-shelf RFID tags to sense touch, cover, overlap of tags by conductive or dielectric (insulating) materials, and tag movement trajectories. Paper prototypes can be made functional in seconds. Due to the rapid deployability and low cost of the tags used, we can create a new class of interactive paper devices that are drawn on demand for simple tasks. These capabilities allow new interactive possibilities for pop-up books and other papercraft objects.

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INTRODUCTION
Modern tools and techniques now make it quite easy to construct a graphical interface with only minimal training and effort. Advances in low-cost, micro-controller-based electronics (e.g., [1]) and accompanying tools such as hardware toolkits (e.g., [13, 8, 10]) have sought to bring that same ease of creation to physical interactive devices as well. However, because of physical constraints, such as the size of electronic circuits, required wiring, and the need to supply and/or replenish power to those circuits, creation of physical interfaces has remained difficult. Thus, construction of such devices still cannot really be considered easy, lightweight, or simple. As a result, we might normally start any design effort aimed at creating such an artifact with an exercise in paper prototyping [21]. We do this in part because the paper is *lightweight* – both in a physical and economic sense, but also with respect to the ease with which we can work with it and modify it on demand. For prototyping, this lightweight nature is useful to keep our investment in early concepts to a minimum and, as a result, it allows more alternatives to be quickly explored.

However, these (and other) good properties of using paper as an interface medium could be taken further. We ask the question: What if we could (nearly) as easily make interfaces that *actually function* using paper as a central medium? This could be of substantial interest for our well-established prototyping practices. In addition, the lightweight nature of the medium may also offer the possibility of a new class of simple but highly customized interface devices that are created quickly on demand for small tasks [17] and possibly discarded (or recycled) when the task was completed or changed.

In this work, we develop technology that provides a new set of capabilities in this direction for the creation of functioning interfaces affixed to, or even partially drawn on, paper. In particular, we describe techniques for processing signals from inexpensive off-the-shelf UHF Radio Frequency Identification (*RFID*) tags, which can be easily affixed to sheets of paper in the form of small adhesive-backed *stickers*. These techniques use details about the low-level radio frequency signals normally used to retrieve identification information to also infer properties of how each tag is being manipulated by a user. For example, when the user touches the antenna of the tag, even without making direct electrical contact, the touch changes how the antenna functions. Similarly, when a tag moves in space, a shifting in the phase of the signal occurs. These subtle changes can be detected in properties of the low-level signals from the tag that are detected by a remote reader (that can be positioned up to several meters away). With sufficient processing, several types of basic user manipulations – touch, covering of the tag by a conductive or dielectric (insulating) materials, and tag movement – can be detected and differentiated. This allows the tags to provide the basic functions necessary to act as sensors for user inputs, despite the fact that they are ultra-thin (coming in a paper sticker form factor), inexpensive (as little as USD$0.10 [15] per tag and therefore usable in applications where they are considered disposable), and have no power source of their own (as they are powered entirely by the reader).

Our contributions in this paper are multifold. We first introduced a new approach for augmenting tags that increases their usefulness as input sensors. In particular, we describe how specifically designed conductive traces can be placed underneath the commercially available UHF loop tag containing an integrated circuit (IC) (henceforth called a "loop IC"). These traces capacitively couple to the existing tag antenna and change how it functions, essentially providing a new antenna for the loop tag without requiring removal of, or even electrical contact with, the existing antenna. As described in detail later, one form of these conductive traces creates an unbalanced monopole antenna that detunes the resulting tag sufficiently that it can no longer be read. However, the traces are constructed in such a way that if a particular spot is touched by the user (and capacitively couples to them), their body serves as the ground plane, boosting the reflected signal, and the tag begins to operate again, creating what amounts to a touch-sensitive antenna. These augmenting traces can be very easily constructed using conductive inks. We demonstrate that they can be inkjet-printed either directly onto the paper that will form part of the interface or onto adhesive stickers that can be placed onto the final interface as needed. Furthermore, we show that they can be constructed using simple stencils and even drawn by hand using a commercially available pen filled with conductive ink. Small RFID loop IC tag stickers can then be placed over the augmenting conductive traces to provide fully functional input sensors.

Furthermore, we introduce our Trace Recovery techniques to enable the continuous tracking of the tag's velocity, motion magnitude, and relative direction of motion towards and away from the reader. Finally, we introduce new RF features that (when combined with a SVM classifier) can support real-time multi-class gesture classification including hand-waving over the tag, light finger touch, whole-hand cover, swipe touch, and no touch. Even though these two techniques share similarity with the motion and touch sensing in previous work [14], this work introduces new signal processing techniques that allow the continuous trajectory of a tag's motion to be monitored as well as support a rich set of interactions that significantly expands upon previous work.

RELATED WORK

Paper is one of the most ubiquitous forms of media in everyday life. In this work, we demonstrate the lightweight, passive, and recyclable nature of our sensing approach by augmenting paper with sensing capabilities for gesture and object state. Previous research has leveraged paper-based input interfaces for interactive applications that include cross-media hyperlinking, documentation tagging, and other interactions [2, 16, 9, 11, 25]. The challenge is how to enable paper-based, unobtrusive input sensing while still preserving the lightweight, passive, and disposable nature of the paper.

Paper-based interfaces have been explored previously as a method for rapid prototyping. Qi and colleagues [20] introduced a paper circuitry approach where a user could build control interfaces on a sheet of paper, attaching electronic components with conductive ink and copper tape. Kawahara and colleagues [12] extended this work by creating inkjet-printed circuits on photo paper for rapid prototyping. They demonstrated easy and effective ways for printing connection circuits or even sensors to enable interactive scenarios. However, the utility of the paper-based control interfaces is limited to on-paper devices, which in turn are constrained by the difficulty of augmenting paper with wireless communication capacities. Attaching wireless communication components, such as Bluetooth and Wi-Fi modules, or a power source makes it very difficult to retain the flexibility and lightweight nature of paper. Additionally, using active components counteracts the benefit of using inexpensive paper as a medium due to the high price of components.

Enabling sensing capabilities on RFID tags could make the technology an ideal alternative for use in paper-based wireless control interfaces. Early work on the use of RFID tags for input constructed power-free buttons from modified RFID tags [4]. In more advanced work, the Wireless Identification and Sensing Platform (WISP) [24] provided custom-built RFID tags with an embedded micro-controller. Although expensive due to their special-purpose nature (about USD $100 per unit), these tags were capable of a number of sensing tasks. For example, prior work [5] describes its use for tracking the movement of tags within a large room and was able to distinguish between 12 common household activities. Other sensing approaches that use RFID technology have required a large number of tags or reader antennas. For example, Asadzadeh and colleagues [3] implemented an 80cm by 80cm matrix with 64 tags and 3 antennas to detect hand gestures. Their system was able to classify 12 predefined hand gestures with 93% accuracy. Later, Wang and colleagues [27] proposed a system for tracking tag movement that used 8 anten-

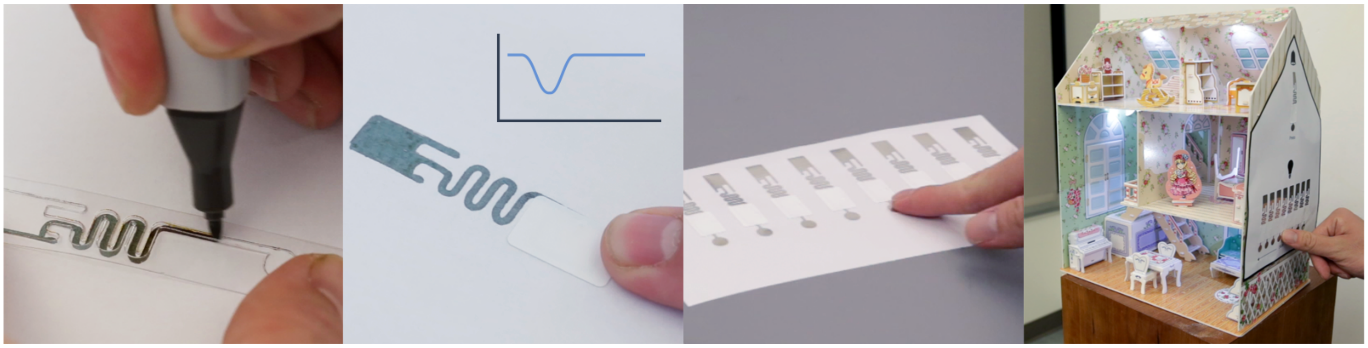


Figure 2. Left to right: A user creates an antenna with a stencil, affixes a loop IC, builds a slider, and uses the slider to control light brightness in a dollhouse.

nas in 4 pairs; they enabled trace tracking of a tag with a median error of 3.7cm. Marquardt and colleagues [18] explored the implementation of input buttons and sliders by modifying RFID circuits and adding electrical components around RFID chips. Together, these projects demonstrated the feasibility of basic RFID-based input sensing. However, constraints in size, installment cost, or user burden make them undesirable for augmenting paper in realistic scenarios.

In work that is more similar to the type of sensing used in the approach described here, Fishkin *et al.* [7] was able to demonstrate the use of inexpensive, passive UHF RFID tags as a sensor for detecting motion. However, only rotational motion was detected robustly and required both multiple tags per object and multiple readers. Parlak and colleagues [19] presented a passive UHF RFID motion detection system designed for a trauma resuscitation scenario. The authors focused on detecting constant tag movement and rotations which showed 90% accuracy in four lab-controlled experiments. However, the motion detection classifier described in their system is solely based on received signal strength (the *RSSI* measure described later) and therefore requires multiple antennas to distinguish between the binary states of still and moving. Li and colleagues [14] used a single antenna to enable motion detection in their object interaction detection system, detecting motion faster than 10cm/s with 93% accuracy.

These previous research projects demonstrate the feasibility of using UHF RFID systems to monitor the state of an object. However, their state detection is limited to binary classification using fixed function off-the-shelf RFID tags. In this paper, we extend prior work by creating new tag types that can be quickly prototyped using conductive inks. Specifically, we introduce the “half antenna tag” which is a passive RFID tag that can use the human body as part of the antenna structure for operation when touched. Additionally, we enable a number of new input modalities that include several types of on-tag and free-air interaction types, such as hand waving around the tag, as well as sensing the real-time motion velocity and trajectory of the tag relative to the reader.

TECHNICAL OVERVIEW

The process for creating an RFID-enhanced paper interface employs a familiar set of supplies and techniques consisting of paper, RFID tags in the form of stickers, and pens with conductive ink, along with extras such as glue, scissors, tape, and markers. Here, we provide a brief overview of the necessary steps and techniques as an outline for the in-depth discussion in the following sections where we focus on the fabrication, signal processing, and machine learning techniques related to prototyping interactive interfaces using off-the-shelf tags as well as customized tags.

As shown in Figure 2, fabrication using tags with customized antennas typically begins with placement of an RFID tag on the paper or by drawing the antenna itself and adding a loop IC sticker to form a fully functional RFID tag. The ability to hand draw, ink-jet print, or use commercial RFID tags provides a great deal of flexibility in visual design, RF performance, and the types of interactions. We discuss the fabrication of these antennas in the Custom Tag Fabrication section.

In order to harness the wireless sensing capabilities of commonplace RFID tags (Figure 3 panel d), we monitor changes in the low-level channel parameters of the reader / tag communication to infer human / tag interaction events. In the Signal Detection section, we discuss in detail the signal processing and machine learning techniques applied to low-channel parameters of this commonplace tag to enable a wide variety of on-tag and free-air interaction sensing capabilities.

Once the mechanics of building and sensing interactions are established, a number of primitives can be built in the form of paper knobs, sliders, pop-ups, etc. These building blocks are then combined with on-tag and free-air RFID tag gestures to create a variety of interaction types that can be used to build and prototype new interfaces and applications.

Background

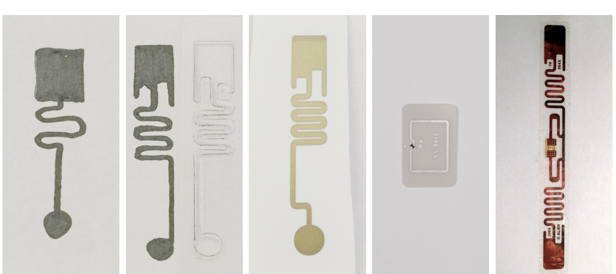
In this work, we utilized a commercially available EPC Gen 2 UHF RFID system [6] that operates with a carrier signal at a frequency from 902 MHz to 928 MHz and is capable of powering and reading hundreds of RFID tags simultaneously within a range of 6-10 meters. RFID readers vary in shape, size and performance with prices from $200 to $1,500. Generally, any full-featured reader that reports RSSI and RF phase can be used. We utilized commodity UHF Squiggle RFID tags and UHF loop tags that are inexpensive (10 cents), disposable, and completely passive in conjunction with user-customized tag antennas created with conductive ink.

CUSTOM TAG FABRICATION

UHF RFID tags are readily available in a wide variety of shapes and sizes that typically take the form of two-dimensional stickers or labels. While commercial tags offer the greatest possible performance in terms of read range, they are not suitable for dense deployment due to near-field interference. In this paper, we overcome this limitation by presenting a half-antenna design together with a sticker RFID IC as depicted in Figure 2(a,b,c). The design acts as an ungrounded monopole antenna, which performs poorly at harvesting RF energy thus making the tag invisible to the reader. When the antenna pad is touched, the human body (which is reasonably conductive at these frequencies) acts as a ground plane, which improves received signal power allowing the tag to harvest enough power for operation. The design of these "silent" touch buttons will dramatically reduce interference between near-field tags. For rapid touch interface prototyping, we outline a few antenna construction methods that can be used to fabricate this type of customized RFID tag.

One standard approach to designing custom antennas is to use an inkjet printer with conductive ink [22, 28], which was used to print the half-antenna in figure 3(e). This provides the greatest amount of control and repeatability. One challenge to this approach is bonding the RFID IC (which is approximately 0.5mm x 0.5mm) to the printed antenna, which cannot be hand-soldered. This can be overcome by re-purposing an ultra small form-factor, near-field UHF RFID tag [26] into what we refer to as a loop IC, as shown in Figure 3(d). Instead of having to mechanically and electrically bond an IC to the antenna, we use the loop IC to inductively couple to the spine of the printed antenna, thereby forming a fully functional custom RFID tag (i.e., antenna plus IC).

An alternative approach is to use conductive ink pens to draw the antenna freehand (Figure 3(a)). While it is quite simple to draw a straight line design, other more compact antenna shapes can also be drawn, as shown in Figure 3. While hand drawn antennas do not have the 10-meter read range of their commercially available counterparts, with a little trial and error, it is quite easy to make hand drawn RFID antennas with a functional range of 5-6 meters. In order to help users become comfortable with drawing UHF antennas, a plastic antenna stencil can be used as a guide (Figure 3(b)). This also insures consistent performance from one tag to the next while still allowing people to prototype their interface quickly. In practice, we noticed that the conductive ink should have a resistance less than 10 ohms per inch in order to ensure an antenna with reliable performance.



(a) Drawn (b) Stencil (c) Printed (d) Loop IC (e) Sticker

Figure 3. Tag antenna types.

SIGNAL DETECTION

In addition to fabricating conductive ink antennas for loop ICs to enable responsive hand touching detection, we also utilize other commodity tags to support interactions, including on-paper or in-air hand gesture detection as well as motion tracking of the paper interface.

In order to integrate rich hand interaction types that include touch, wave, swipe, cover and tag movement into a single tag (Figure 6(a)-(e)), we employ the channel parameters reported by the RFID reader, such as Received Signal Strength Indicator (RSSI), RF Phase, and Read Rate, which represent a unique signature of the RF environment of each individual tag. Each tag's RF environment is comprised of the far-field signal path from the reader to the tag (including all multipath elements), as well as the near-field region of the tag, which has an effective radius around the tag of half of a wavelength (~16cm). Thus, any changes in either the far-field or near-field regions of the tag, such as hand touch, wave, cover gestures, or tag movements, will result in altering the signal paths and be reported as changes in RF channel parameters. By putting tags onto the paper interface and observing and extracting the patterns of each tag's channel parameters, we can establish a quantitative understanding of people's interactions with the interface. In the following subsections, we explain how we make use of low-level channel parameters including RSSI, RF Phase and read rate to enable tag motion tracking, as well as on-tag and free air gesture detection.

Understanding Channel Parameters

RSSI

When an RFID tag receives power from a reader, part of the received power is reflected back to the RFID reader. This reflection is called backscatter and RSSI is a power measurement of the backscattered signal from each tag received by the reader. RSSI is predominantly determined by the distance to the tag as well as the power level of the reader, as shown in equation 1.

$$RSSI = 10log(P_r) = 10log(\frac{G_t \lambda^2 \sigma}{(4\pi)^3 d^4}) + 10log(P_t) \quad (1)$$

where P_r = backscatter signal power, P_t = reader transmit power, G_t = reader antenna gain, λ = carrier wavelength, σ = tag radar cross section, and d = distance between the reader and tag.

Phase

The difference in phase between the signal transmitted by the reader and the backscattered signal from the tag as seen by the reader provides additional insight into the state of the tag. RF phase is dominated by the antenna-tag distance d as well as signal carrier frequency $f = 1/\lambda$, and repeats every wavelength. The constant shown in Equation 2 is introduced by the transmit circuits, receiver circuits, and the tag's reflection

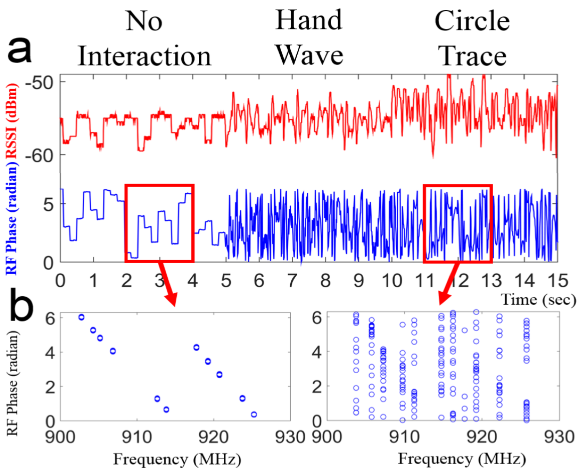


Figure 4. (a) Raw RSSI and Phase data for a single RFID tag remaining still or experiencing near-field hand waving and circular movement. (b) Due to pseudo-random frequency hopping, a 2-second window of RF phase is sorted by channel to reveal characteristics of these events.

characteristic.

$$\theta = 2\pi \frac{2d}{\lambda} mod(2\pi) + constant \quad (2)$$

Read Rate

The RFID read rate is defined as the number of packets received from each tag per second. Read rate can be influenced by dramatic changes in signal strength as a result of blocking or capacitive coupling of the human body. To get a better understanding of these RF parameters, we attached a tag to a sheet of paper and show 15 seconds of the raw RSSI and phase signal streams of the tag in Figure 4. There was no interaction during the first 5 seconds, and for the next 5 seconds, the tag is undergoing constant hand waving in the near-field region. For the last 5 seconds, the tag is moving in a circular trace. The still state with no interaction can be distinguished from other states by observing the RSSI and phase raw signal variations shown in Figure 4(a), noting larger variations in RSSI as well as Phase signal.

We noticed discontinuity in RSSI and phase samples in the first 5 seconds of Figure 4(a). When there is no interaction involving the tag, this is a result of the RFID reader constantly changing its transmit signal frequency. FCC regulations require RFID readers in the 915 MHz ISM band to pseudo-randomly change their transmit frequency in order to minimize interference with other devices. To satisfy this requirement, RFID readers frequency hop across 50 channels from 902 MHz to 928 MHz (in the USA) at a time interval of approximately 0.2 seconds.

To better reveal the underlying characteristics of phase hidden by frequency hopping, we take a 1-second slice of phase from the still state and one from interaction state and re-plot against channel frequency in Figure 4(b). For the first 5 seconds, phase is linearly correlated with the carrier signal and wrapped into segments within $[0, 2\pi]$. Hand waving around the tag as well as circular movement of the tag resulted in

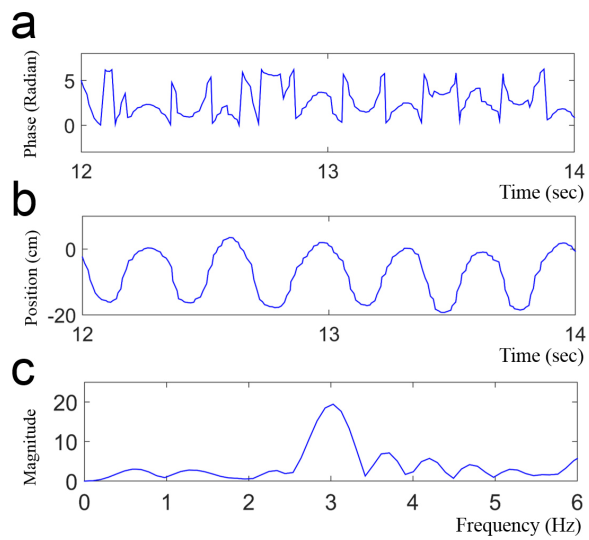


Figure 5. (a) Two segments of raw phase data; (b) application of the trace recovering technique to reveal the moving trace relative to the RFID reader; (c) applying a Fast Fourier transform to reveal the frequency of the movement.

dramatic phase variations within each channel, as depicted in the right panel of Figure 4(b).

Trace Recovering

Here, we demonstrate a technique for tracking the movement traces of tags using the phase signal. This technique enables the "continuous tracking" of the tag's velocity, motion magnitude, and relative direction of motion towards and away from the reader. Figure 5(a) is a 2-second slice of seconds 12 to 14 shown in Figure 4. According to the phase definition in Equation 2, after unwrapping the phase signals, we can calculate the distance change d_1 and d_2 with the following equation:

$$d_1 - d_2 = \frac{1}{2} \frac{\lambda}{2\pi} (\theta_1 - \theta_2). \quad (3)$$

We apply this equation to the phase signal in panel (a) and then apply signal smoothing between timestamps where frequency hopping occurs. We recover the trace of the circular movement of the paper, as represented in Figure 5(b). Note that according to Equation 2, distance d is the relative distance between the tag and the reader. In this case, the movement represented in the recovered trace is a 1-dimensional component of the circular trace, which is close to a sine wave.

We apply a Fast Fourier transform to this trace signal to get the frequency component of the trace in panel (c). This trace-tracking technique is later applied to paper-based toy applications. Consider the "conductors wand" application where the frequency at which the wand is waved side-to-side is mapped to the tempo of the music while the magnitude of motion is mapped to volume. Our technique provides a rich user interface, in contrast to the binary motion detection in IDSense [14], which would only be able to turn the music on or off.

Multi-Gesture Classifier

Here, we discuss the technical details of a multi-gesture classifier that is later utilized to enable controlling applications. Here we support interactions including finger touch, cover, swipe and in-air directional hand waving on a single tag.

In order to enable a variety of gesture input methods on paper interfaces, we apply machine learning to these lower RF channel parameters to describe the unique RF environment of each tag on paper interfaces. For each segment, we calculate the following features.

Read Rate

- Read Rate: This feature is defined as the number of packets received from each RFID tag per second. This feature is effective for characterizing interactions that dramatically change the ambient RF environment, such as a cover gesture, or detuning events happening on the tag, such as a touch gesture.

Phase Features

- Tag position change: The relative position change within each segment characterized by our trace recovering technique. This feature is effective for describing motions related to a paper interface.
- Standard deviation of phase within each channel: This feature is effective for describing periodic hand gestures in the near-field region of the tag, such as swiping or touching the tag surface.
- Standard error of the linear regression of phase versus channel frequencies: As demonstrated in the left panel of Figure 4(b), when no interaction is happening on the paper interface, the phase is linearly correlated with the channel. Here, we unwrap the phase samples and calculate the error of the linear fit, which is useful for separating non-interaction states from other interactions on the paper interface.

RSSI Features

- Average Standard Deviation of RSSI per channel: As demonstrated in Figure 4, RSSI variation will increase when there are interaction events happening with the paper interface. The magnitude of the variation is dependent on the interaction type, so we include this feature here to describe the variation in signal strength related to different interaction types.
- Sum of RSSI difference per channel: This feature describes the directional changes of the RSSI magnitude, which is useful for monitoring immediate change in reflected signal as a result of near-field interference, such as hand touching.
- RSSI Average Value: The RSSI value can vary according to the relative distance, antenna orientation, and power level of the reader, so uncontrolled RSSI values cannot provide effective information about the interaction states of the paper interface to which it is attached; however, we actively calibrate the initial RSSI value to approximately -25dBm. In this case, we can utilize the RSSI Average Value (within each segment) to indicate the interaction types that will change the RSSI, including on-tag and free-air interactions.

Machine Learning

Here, we introduce the machine learning pipeline for the purpose of distinguishing multiple simultaneous gestures on RFID tags. More details on how we apply this pipeline to gesture classification applications will be discussed in later sections. First, we segment the RF channel parameters reported by the reader. Through experimentation, we decided to utilize a window size of 1 second that advances every half second with 50% overlap. This achieves a good balance between classification accuracy and delay in real-time. A longer window may help to further boost classification accuracy, but it would also increase the latency of the real-time system.

Phase, RSSI and read rate features are utilized to implement a Support Vector Machine (SVM) with the Radial Basis Function (RBF) kernel. Training data is collected offline. We record and label training data for each of the interaction classes at multiple locations to improve the robustness of our classifier. Then, we optimize parameters of the RBF kernel by maximizing 10-fold cross-validation results. Our classifier makes real-time predictions based on the most recent 1-second RF parameters and refreshes prediction results every 0.5 seconds.

INTERACTION METHODS AND PRIMITIVES

Thus far, we have presented several methods for quickly building custom RFID antennas using construction techniques consistent with prototyping on paper. By applying the signal processing techniques described above, we are able to turn our custom tags and commercial tags (that normally only report their ID number) into battery-free, ultra-thin, wireless user input devices.

In this section, we describe several user interaction primitives that can easily be made with RFID tags. The first set of primitives consists of a single RFID tag that can be implemented in several ways. Next, we combine multiple RFID tags together to make complex interactive structures, such as rotary dials and sliders. Finally, free air gestures and actions are presented wherein the user is either interacting with a static paper object or is manipulating the paper object dynamically.

Single Tag Primitives

This is the simplest interface we present as it only requires the use of a single RFID tag. We describe gestures including cover, two types of finger touch, swipe touch, and hand waving (represented in Figure 6(a)-(d)). By applying the SVM classifier onto the RF features discussed earlier, all of these primitives can be integrated onto a single tag for real-time interaction detection and classification.

Waving

This technique is for detection of the free air hand waving gesture proximate to a paper interface. It can be applied to a single tag or multiple tags on one paper interface.

With a single tag, we can detect the binary wave / no wave as represented in Figure 6(a). This is achieved by applying the SVM classifier to RF features. With the support of multiple tags on the paper interface, we can also detect the direction

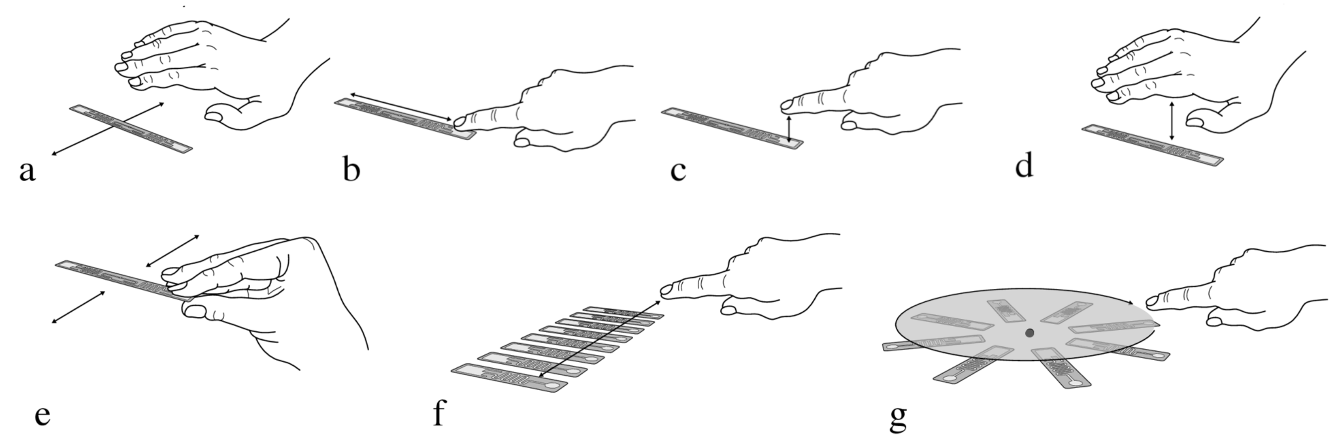


Figure 6. (a) Wave (b) Swipe (c) Finger Touch (d) Cover Touch (e) Free air tag motion (f) Slider (g) Knob

of waving by monitoring the sequence of variation in RF features of the two corresponding tags.

Button Touch

Button touch interactions can be accomplished in two different ways. First, a commonplace RFID tag will be affected when a finger touches either end of its antenna. This type of touch will cause a change in the RSSI and RF phase as reported by the reader, but will not block the signal such that the tag can no longer be read as is the case with cover touch. Using SVM, it is easy to reliably classify touch events when the tag is still. However, if this type of button is used to prototype a remote control for a TV, it would be challenging to detect button pushes while the remote control is in motion.

To overcome this limitation, a second type of touch button based on a "half antenna" has been developed, as described in the Antenna Fabrication section. In this configuration, the tag operates as a button or key press. Multiple tags can be set up on a single sheet of paper and multiple buttons can be touched simultaneously. Because the actual operation of the tag is binary, it is very robust to the motion of the prototyped device the tag is on. However, since the button is *normally off / momentarily on*, the RFID reader will not know that the device is present until the button is pushed. If desired, the designer can add a second normal tag to the prototype to indicate if the button is within view of the reader.

Cover Touch

One of the most basic RFID interaction methods is covering the RFID tag such that the signal from the reader is completely blocked or such that the tag's antenna becomes detuned to the point where it cannot receive enough power for operation (Figure 6 (d)). This can be done by covering the tag with a person's hand or body or with a conductor like copper tape. The most effective way to detect these cover events is to measure the read rate of the tag and set a threshold for activation. One drawback is that when the tag leaves the interrogation zone of the RFID reader, its read rate will also appear to drop (i.e., go to zero) and will be registered as user input. To overcome this edge condition, a time-dependent interaction can be employed, such as covering the tag for a window of 1-2 seconds and then uncovering it.

Swipe Touch

We also include a swipe touch interaction, which is the interaction of swiping a fingertip across the tag surface (Figure 6(b)). This gesture brings dramatic variation to both RSSI and phase signals, which can be characterized using our RF features.

Multi-Tag Primitives

The "silent" nature of the customized touch button tag type makes them ideal for dense deployment. Below, we introduce more complicated primitives using multiple customized touch button tags.

Slider

For the slider interface, the user slides his or her finger across a row of customized button tags as depicted in figure 6(f)). Multiple tags with half antennas are placed on one static layer of paper; the finger is placed near the edge of the tab. As the finger is moved across the static half antennas, it can couple with each one to provide enough power to backscatter signals to the reader. Thus, the reader can detect the position of the finger as a discrete touch state sensor. For example, each static tag can be paired with a different light bulb/LED, sound effect, or onscreen event that is activated when the moving hand and static half antennas align.

Rotary

This interface relies upon a group of static tags with half antennas and a single moving half antenna that triggers a unique response when moved to pair with each static tag. In our sample implementation, the static tags are placed on the front of a single sheet of paper in a spoke-like design. On top of this, a single circle is attached that has a single half antenna placed on one radius. The circle can spin freely, rotating the half antenna on the circle relative to the static tags (Figure 6 (g)). When the rotating antenna contacts a static tag, it provides enough power to backscatter signals to the reader for detection and triggers a set response.

Note that in addition to using the hand as a ground plane to enable touch interaction, we can also overlay a second antenna to complete the circuits as a dipole antenna, which can also trigger the same effect as hand touching. In this case, the state of the slider and rotary will stay in place even if the hand moves away.

Free Air Motion Primitives

We also create tag-based interfaces that track motion signals over single and multiple tags. Below, we describe a free air system with a single tag moving in space. This primitive can be applied to a paper interface of a stand-alone RFID tag where we provide functionality for fine-grain trace tracking of the interface relative to the RFID reader as well as frequency tracking for periodic movements. This primitive is supported by our trace tracking technique introduced in the Signal Processing section.

LED User Feedback

Most of the RFID tags described thus far are geared to user input. However, it is possible to construct an LED-enhanced RFID tag that harvests enough power for the RFID reader to flash an LED. Although not as complex and full-featured as prior work [23], this tag does not need a "loop IC" to communicate with the reader. Instead, the RFID reader can programmatically modulate its output power from high to low to turn the LED on or off. The LED tag can also be made into a half tag such that the user completes the antenna and lights the LED when touched.

APPLICATIONS

In this section, we present several applications that use combinations of the primitives described above to build new interactive paper interfaces that come to life when read by an RFID reader.

Polling Device

One of the most widely used test-taking and grading methods involves the Scantron test form. In this classic paper interface, users fill in bubbles with a number two pencil to denote answers to multiple choice test questions. By using the RFID half tag concept, we are able to re-imagine test taking as a real-time, interactive experience. In Figure 7, we demonstrate two methods to use RFID tags to create polling/multiple choice devices. First, users can indicate a choice among multiple tags by either covering a complete RFID tag (touch interaction) or by completing a half antenna with a finger (button interaction). Second, users can complete one of multiple half antennas by coloring in the end of the antenna with a conductive pen. In both cases, data can be collected and assessed in near real time. This method allows nearly instantaneous processing of users' opinions or knowledge without requiring that each user has access to an individual wired or otherwise powered system, resulting in lower cost.

Magic Wand/Conducting Baton

Besides augmenting a static 2D piece of paper with touch controls, the "free air" gestures described above can be used to transform a piece of paper into a tangible gesture interface.

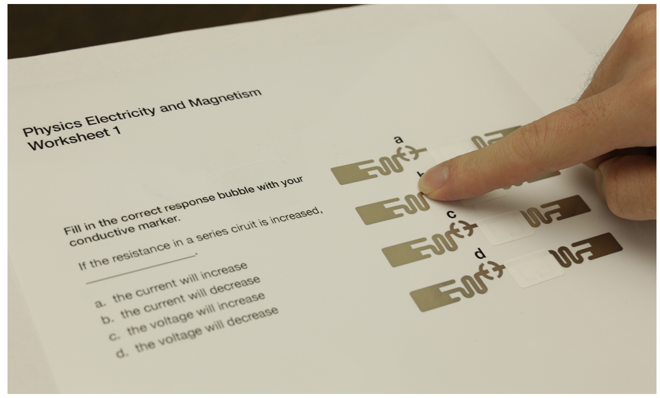


Figure 7. In this polling application, a student can pick a response on a worksheet and receive live feedback.

Figure 8. The wand frequency is mapped to music tempo and the velocity is mapped to gain.

In this example, a commercially available RFID tag sticker is placed on a single sheet of paper that is then rolled up into a cylinder to form a magic wand, as shown in Figure 8. As a user waves the wand back and forth through the air, the RFID reader streams the RF channel parameters to the signal processing pipeline (on a host PC) to extract wand motion in terms of frequency content and velocity. These two metrics are then used to control the tempo and the volume of music played through the host PC. The effect is that the user can control the tempo of the music by the rate at which they swing the wand back and forth. To increase the volume of the music, the user increases the size of the gesture (i.e., the velocity it takes to complete one repetitive swinging motion). Thus, large, repetitive gestures make the music play louder and small, repetitive gestures make the music play softer.

Pinwheel

A corollary to the wand application is the pinwheel made of construction paper shown in Figure 9. For this application, we attach a single RFID tag sticker to a pinwheel. A user can blow on the pinwheel and use the velocity of the tag to control the animation flow of blowing particles with varying number and force, as shown in the supplementary video.

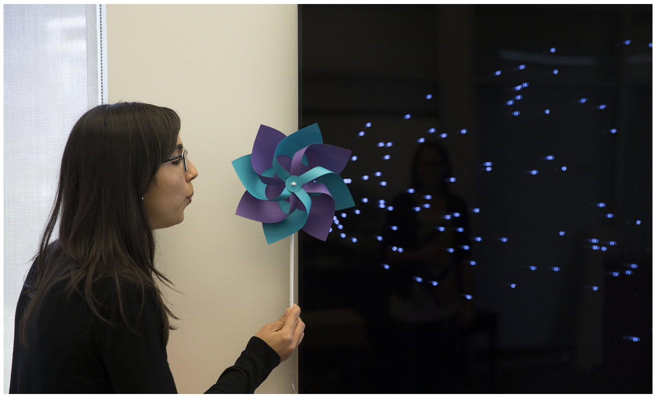


Figure 9. The speed of the spinning tag on the pinwheel is mapped to onscreen graphics.

Pop-Up Books

Pop-up books offer a wide array of mechanical motions where pieces of paper are sliding across each other, bending, folding, and lifting. Using the RFID interaction primitives described above, these motions can inexpensively be instrumented to stream interaction events back to a computing device via the RFID reader.

For this application (Figure 10), we create an interactive, pop-up book page with a barn. First, we create an LED light circuit that turns on when the page is opened and the barn pops out. Next, a single tag is placed on an exterior wall of the barn that is blocked by a piece of copper tape when the page is closed. Opening the page stops the copper from blocking the RF signals so that the tag can be read, which in turn triggers the host PC to play the song "Old McDonald Had a Farm". Second, we present a rotary dial that allows the user to trigger various sounds. By aligning the customized button tag on the dial with the half antenna on the paper underneath, the RFID reader can determine the state of the rotary and prompt the sound that corresponds with that particular state. In the pop-up book example, the rotatory dial is covered with images of barnyard animals. Thus, when the child rotates the wheel to an image of a sheep, a "baa" sound is played.

Dollhouse

In the dollhouse example shown in Figure 11, we use both the button and the slider. When a user presses the button, the house emits a doorbell sound. For the slider, there a set of stationary half tags connected to LEDs in each room in the house. As a finger is dragged across the stationary tags, it completes each tag antenna to adjust the brightness of the lights.

Interactive Light Control

We combine our cover, swipe, and wave interactors into a single RFID tag to create a control system for a desk lamp with a Phillips Hue light bulb that can be controlled remotely by Bluetooth® and offers a full-color spectrum at varying levels of brightness (Figure 12). We use the cover action to turn the light on and off. The touch interaction changes the color of the light bulb across the light spectrum, and the swipe and wave gestures control the brightness.

Figure 10. This pop-up book contains a knob interactor which selects audio tracks and a shielded tag in the pop-up barn.

Figure 11. Paper interfaces can be used to create new sensors to control the lighting and doorbell of this foam doll house.

RFID Powered LED

Although RFID is primarily designed for communication, it also transmits RF power that is harvested by the RFID tag for operation. This mechanism of wireless power transfer can be hijacked and used to wirelessly power LEDs. In the example application shown in Figure 13, an image of a cartoon skull is augmented with two LED enabled RFID tags in the eyes, and one hand-drawn stub antenna for a button tag in the mouth. When the user touches the button tag. the RFID reader is commanded to increase its output power level and cause enough power to be harvested by the two LEDs for them to turn on, creating the effect of shining eyes in the paper skull.

EVALUATION

In this section, we evaluate our interaction methods and primitives used in our applications. One factor influencing performance is the reflected signal strength. To control this factor, we automatically calibrate the antenna power so that RSSI is at approximately -25dBm.

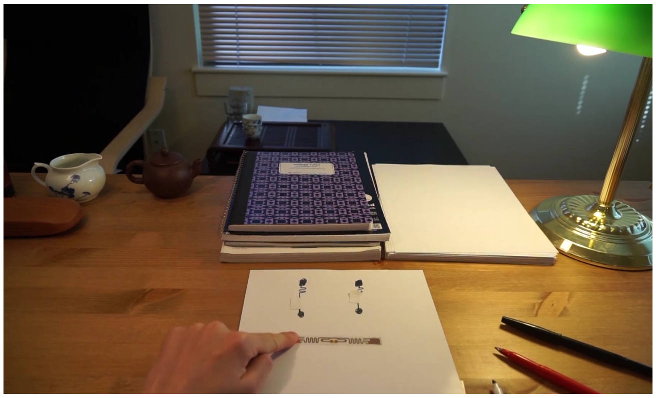


Figure 12. The intensity and color of light can be altered using wave and touch gestures.

Figure 13. Using the same antenna with which we sense our input tags, we can wirelessly power LEDs. We are using a single touch tag as our input to increase or decrease the reader's power output.

Gesture Sensing Evaluation

We integrate our wave (Figure 6(a)), swipe (Figure 6(b)), touch (Figure 6(c)) and cover (Figure 6(d)) interaction primitives into a tag gesture-sensing application using features and classification methods described in the Signal Detection Section. Our training data was recorded at 3 locations (2m, 4m, and 6m away from the reader). Our classifier has 5 classes, including the 4 gestures and the still state when no interaction is performed. We recorded 30 instances from each class, 10 at each of the 3 locations. Training is done offline by optimizing parameters in the RBF kernel maximizing the 10-fold cross validation results of gesture classification. We recruited 5 participants (4 male, 1 female) with a mean age of 24.4 years. Each participant was asked to follow visual instructions on a monitor to perform 20 instances of each of the 5 gesture classes. Each participant repeated the task 3 times at each of the 3 locations (2m, 4m, and 6m away from the antenna). Visual gesture instructions were given once every 4 seconds, and pauses between gestures were utilized to generate still instances. The instruction script was used as ground truth and user mistakes were manually annotated. We achieved an average of 94.1% accuracy classifying gestures into 5 categories with a 2.4% STD across participants and 1.4% STD across locations. This study result demonstrates the high performance of our system across all locations with low variations, showcasing the promising potential for deploying our technique for real-world user interfaces.

Customized Touch Button Evaluation

We evaluated the effectiveness of our customized touch button design in this study for when we detect touch vs no-touch states using a read rate threshold of 5 reads/per second. We arrayed 10 hand-drawn touch buttons in a row on a sheet of paper. Note that there are 3 ways to fabricate the button antenna: hand-drawn, stencil-traced, and inject printing. We evaluated the most challenging hand-drawn ones to establish a performance baseline. We recruited 5 participants (3 male, 2 female) with a mean age of 26.0 years. Each participant was asked to follow visual instructions on a monitor to perform 10 touches on each of the 10 tags, one tag at a time. The study was repeated 3 times at 3 different locations (2m, 4m, and 6m away from the reader). Instructions were given once every 2 seconds. The instruction script was used as ground truth and user mistakes were manually annotated. Pauses between touches were utilized to generate no-touch instances. Our design achieved an average of 96.2% accuracy on detecting touch events, with a 1.1% STD across participants and a 0.4% STD across locations. Because the Knob and Slider primitives were designed based on customized touch button elements, their performance will be similar to what we see in this evaluation.

Velocity Metric Evaluation

We utilized the magic wand described in the Applications section to evaluate our Trace Recovering technique. We moved a tagged wand between 2 points with a separation of 20 centimeters back and forth at 1, 2, 4, 6 Hz per second from 2, 4, and 6 meters away from the antenna, each for 20 seconds. Velocity is calculated by accumulated displacement divided by time difference and frequency is estimated by the most significant frequency component after the Fast Fourier Transform is performed. These two metrics are calculated in real time using window length of 2 seconds and updated every 1 second. Study results demonstrated that velocity sensing had an average standard error of 6.4% and frequency sensing had an average standard error of 8.2%.

CONCLUSION

We demonstrate techniques to create simple, lightweight, recyclable paper interfaces that rely on RFID technology. Using a single RFID reader antenna and inexpensive passive tags, we can create applications with numerous controllable features, including lights, sounds, software control, and animations. Subtle changes in the low-level radio frequency signals that typically retrieve tag identification information are leveraged to determine how each tag is manipulated by the user. Additionally, we introduce multiple techniques for creating RFID tag antennas in order to customize tags for different contexts. Our methodology expands the functionality of RFID tags to quickly and easily create user interfaces on paper, a ubiquitous, lightweight medium.

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