Distance-sensitive High Frequency RFID Systems

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Abstract

Location information about a high frequency RFID tag is currently limited to the location information associated with the position of the RFID reader. The distance of a tag from the reader remains unknown. However, more precise location information of objects provided at low cost is critical to create smart spaces. In this paper, we present a distance-sensitive RFID system that accurately resolves a tag's distance from the reader. In contrast to other distance sensing systems that operate on the emission of electro-magnetic waves, high frequency RFID systems make use of magnetic coupling for data transmission. The paper details the system design and implementation with discrete components, presents the distance measurement procedure, and evaluates the accuracy of the measurements.

Keywords: Smart Spaces, RFID, Sensors, Localization.

1. Introduction

Radio frequency identification (RFID) has received significant attention to serve as a means to digitally enhance the working or living environment. The popularity of using RFID derives from the fact that it provides explicit identification of objects at low cost. For over a decade, researchers have made use of the distinct information provided by RFID to create smart spaces [1], [2]. However, research on harnessing detailed location information from RFID tags is limited even though information about an object's location is of great importance for many applications.

Currently, the level of local resolution is limited to the places covered by RFID reader infrastructure. The grid of reader deployment determines the granularity of location information retrieved from an RFID tag where the reader's physical location is assigned to any tag within the range of that interrogator. Consequently, the detection of a RFID tag provides only limited local resolution – in close vicinity to a specific reader. The exact physical location of the tag remains unknown. Currently, high frequency (HF) RFID readers neither resolve the distance nor the angle at which a tag is detected. In addition, the RFID infrastructure is often minimal (grid of interrogators) in order to keep the system costs low. A large grid size of reader deployment minimizes the degree at which the location of an object is resolved. This limitation is caused by the reader field that is usually non-directional to cover the largest area possible.

Passive HF tags operate on magnetic induction at 13.56MHz as opposed to ultra high frequency (UHF) tags that operate on the emission of electro-magnetic waves at 860-960MHz. Passive HF tags are widely used to equip items because of their small form factor, low cost, and resistance against interference (as opposed to UHF tags that show significant vulnerability to interferences). In this paper, we present a distance-sensitive high frequency RFID system that resolves a tag's distance from a reader antenna.

The paper is organized as follows: In the next section, we review and summarize previous academic research on location sensing. Section 3 describes the sensing principles for a distance-sensitive high frequency RFID system followed by the presentation of the design and the implementation of our system in Section 4. In Section 5, we present the actual distance measurement procedure, which is evaluated and discussed in Section 6. The paper concludes with Section 7, which briefly summarizes the findings.

2. Related Work

Electro-magnetic sensing at radio frequency (RF) offers capabilities to determine the distance and direction of an object in relation to a reference point. The major techniques to derive these properties are time-of-arrival, time difference of arrival, angle-of-arrival, and received signal strength [3]. Based on the distance measurement, the location is estimated through triangulation, which is done either through lateration that uses multiple distance measurements between reference points and the object or angulation, which measures angle or bearing relative to reference points [4]. Research on location systems that are based on radio frequency is highly advanced [5], [6], [4], [7]. Other research has focused on mapping and localization through RFID tags that are distributed in the environment [8], [9]. In their research, mobile RFID readers are mounted on robots, which navigate according to the local information retrieved through the detection of embedded tags.

The techniques for RF distance-sensing described above apply for systems that operate on the emission of electro-magnetic waves such as RFID at UHF. In contrast, HF RFID systems operate on magnetic induction [9]. This requires a different approach to resolve a tag's distance from a reader, because current techniques for distance-sensing are not applicable.

3. Sensing Principles

In inductively coupled systems the reader antenna generates a strong, high frequency electro-magnetic field to power the RFID tag and to serve as medium for data transmission. The electro-magnetic field penetrates the cross-section of the reader antenna coil and to some extent the antenna coil of the tag in close vicinity [9]. By inductance, a voltage u_{tag} is generated at the tag's antenna. This inductively coupled system can be treated as a transformer-type coupling with a primary and a secondary coil as long as the tag remains in the near field – approximately up to 3.5m ($0.16 \cdot \lambda_{13.56MHz}$) from the antenna (idem). A tag in the interrogation field draws energy from the magnetic field generated by the reader. This energy consumption results in a voltage change at the reader's antenna due to mutual inductance. A tag transmits data by switching a load resistor on and off thereby influencing the transformed transponder impedance. This change in impedance causes an amplitude modulation of the voltage u_{reader} at the reader's antenna coil. The intensity of the mutual inductance depends on the antennae properties and the distance between two antennae [9]. The intensity of the coupling decreases with increasing distance and results in reduced signal strength of the transmitted data. Consequently, the analysis of the signal strength allows concluding the distance between a tag and a reader. However, if the tag antenna is tilted away from the central axis by the angle φ, the induced voltage is smaller and follows the relationship given in Eq. (1) (u_0 is the voltage that is induced when the coil is perpendicular to the magnetic field and $u_{0\varphi}$ is the actual induced voltage).

$$u_{0\varphi} = u_0 \cdot \cos(\varphi) \qquad \text{Eq. (1)}$$

In order to apply proximity sensing to high frequency RFID systems information about the tag's orientation in relation to the reader antenna is required as well as information about the dimensions of the tag and reader antennae and the number of windings thereof. While the reader antenna and the tags used in our application remain unaltered, tilt angle and signal strength are subject to change. The orientation of a tag is derived from a tilt sensor or gyroscope that is directly attached to the RFID tag. The sensor data is transmitted along with the tag's ID. Based on the sensor data, the reader computes the deflection with respect to its own orientation. In combination with the signal strength of the received data, the reader estimates the distance of the tag from the reader antenna.

4. System Design and Implementation

Our RFID system comprises a tag, a reader, and a data processing unit (e.g. a notebook or a cell phone) that is attached to the reader. The reader and the reader antenna are commercially available. However, we built our own passive RFID tag with discrete components to provide an interface that allows attaching a tilt sensor [11]. This is required because current passive tags do not provide any interfaces to attach additional devices. Our tag consists of a coil to pick up the reader signal, an analog front-end to demodulate and modulate the RFID signals, and a logic unit to interpret the demodulated data and to encode and send tag data. Additionally, our tag contains a tilt sensor to provide information about the deflection of the tag away from the parallel plane of the reader antenna as well as an external power supply, e.g. a battery. The external power supply is required because a tag built with discrete components draws considerably more energy than a regular tag. Our tag's power requirements exceed the energy that can be provided by the reader.

4.1 Analog front-end to de-/modulate RFID signals

Our tag implements the widely used ICODE1 communication protocol developed by Philips [12]. The ICODE1 protocol operates at 13.56 MHz. It is a reader-talks-first protocol that uses amplitude modulation and pulse position coding on the reader-to-tag communication channel. The protocol uses a modulation index of 10% and, in standard mode, data is transmitted according the '1 out of 256' pulse position scheme. The value of a transmitted byte is encoded in the position of the pulse that is set to one of 256 possible consecutive positions (Figure 1). The data transmission is preceded by a start pulse of 9.44µs that signals the demodulator of the RFID tag that a new sequence of data is sent. The demodulator on the tag determines the bit position by measuring the elapsed time between the start pulse and the detection of the next pulse. Each bit has a length of 18.88µs. Dividing the measured time by the sequence of one bit results in the exact bit position and allows decoding the value of the byte. 4.833ms are required to complete the transmission of a single byte (excluding the start bit). Hence, the transmission of an entire RFID reader command, which consists of 8 consecutive bytes, takes 38.7ms.

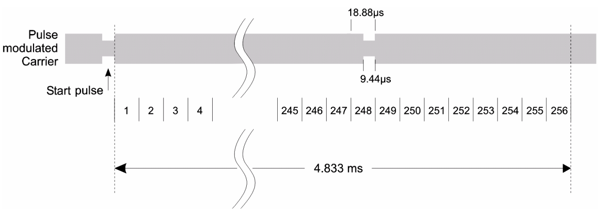

Figure 1: The value of a transmitted byte is encoded in the 256 possible consecutive positions for a pulse [12].

The analog front-end on the tag comprises an envelope detector to identify relative changes in amplitude. These changes indicate modulated bits. However, amplitude variations can also be caused by changes in coupling between a reader and a tag coil (e.g. tilting of the tag or a change in the distance to the reader). In order to separate amplitude variations that are caused by modulated bits during data transmission from those that are caused by changes in coupling, the output of the envelope detector is compared to a relative reference voltage. The reference voltage reflects variations in distance and orientation but its time constant is chosen so that the voltage remains unaffected by short pulses used for data transmission. Both, the envelope signal and the reference voltage are extracted by two RC filter elements (Figure 3). The RC elements are designed to meet the specifications of the ICODE1 air interface protocol with a 10% amplitude modulation and a signal drop of 9.44µs for a modulated signal. In addition, these RC elements account for negative peak clipping that is caused by the half-wave rectification.

The envelope signal and the reference voltage are compared by an operational amplifier element that generates a binary output based on the detection of a modulated signal. The output goes low as long as the signal is modulated and remains high otherwise (Figure 3). The system makes use of load modulation as described above to transmit data from the tag to the reader. A CMOS switch, controlled by a microcontroller, short-circuits the antenna coil according to a signal pattern that represents the encoded data.

4.2 Logic unit and signal processing

A PIC16F88 microcontroller with an internal clock speed of 5MHz forms the core of the tag. The clock is not obtained from the carrier signal of the RFID reader but from an external oscillator. We made use of an external oscillator to avoid building a clock extractor thereby simplifying the design.

The PIC16F88 microcontroller offers two different methods to listen for changes on the comparator's output – polling and interrupts. While polling proved inadequate because it does not meet the timing constraints for the detection of two consecutive pulses, the interrupt-based approach performs well. The asynchronous interrupt is triggered by a falling edge at the comparator's output. When an interrupt occurs, the interrupt dispatcher reads the value of the timer that was started after the detection of the start bit. This allows determining the value of the byte transmitted by the reader. After the detection of 8 consecutive bytes, the main routine in the microcontroller code starts decoding the complete command.

The most restrictive time constraints occur when a pulse is sent in the first slot. This pulse follows 18.88µs after the falling edge of the start pulse. The detection of each pulse triggers an interrupt that is used to measure the elapsed time between consecutive pulses. However, the processing of an interrupt must be completed before the next pulse can be detected. This sets an upper time limit for interrupt processing of 18.88µs. Our optimized interrupt dispatcher requires 77 clock cycles, which corresponds to 15.4µs. Hence, our design fulfills even the most restrictive time constraints.

In response to a "selected read" or "unselected read" reader command, the tag responds with the data stored at the location specified in the reader command. When data is sent from the tag to the reader, the short-circuiting of the tag's antenna generates only small variations of the voltage at the reader antenna. Therefore, a sub-carrier of 423.75kHz is used in accordance with the ICODE1 specifications to create modulation sidebands at the reader's antenna to simplify detection. Based on this sub-carrier, the tag data is Manchester encoded (Figure 6) (idem). The transmission of a single bit requires 37.76µs and an entire byte requires 302.08µs. The data is sent in a random time slot while the length of the time slot depends on the number of data packets to be sent. The transmission of one data packet requires 1208.32µs.

4.3 Tilt sensor

We use a dual-axis ADXL202E accelerometer to measure gravity. The accelerometer allows determining the tilt angle in one plane (Figure 2). For reasons of simplicity, our design is limited to the detection of deflections in the y-z-plane, but by attaching an additional tilt sensor or by using a gyroscope, the deflection in all three dimensions could be captured.

The analog outputs of the tilt sensor are connected to the A/D converter of the PIC microcontroller, which processes and transmits the data. The sensor values show a non-linear behavior of tilt angle and output value. On average, a sensor value unit corresponds to 1.0° to 1.8°. The standard deviation for a fixed tilt sensor is 2.8 units, or 3° to 5°. Due to the properties of the cosine function, small deflections away from the parallel plane do not result in a significant change of the actual inducted voltage.

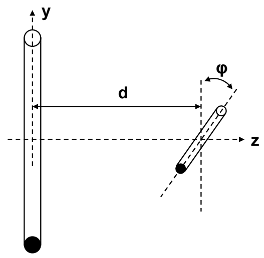

Figure 2: Cross-section through the reader and tag antenna, which are aligned on the coil axis. The tag antenna is tilted by the angle φ. [10]

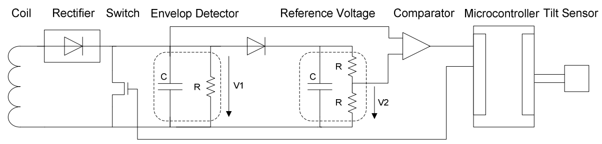

Figure 3: Schematic of the tag with the analog front-end, logic unit, tilt sensor, and CMOS switch for data transmission.

5. Distance Measurement

The measurement of a tag's distance from the reader antenna requires a three-step procedure. First, we analyze the signal strength of the data received from the tag. The signal strength directly relates to the distance between the tag and the reader antenna. Our RFID reader, a RIDEL5000 from Softronica, provides an interface to capture the signal strength of the received data. The signal strength of each data bit is sampled 8 times with a resolution of 12 bits. The amplitude of the signal strength is extracted with a simple peak extraction algorithm. In order to cope with signal strength fluctuations, we collect a set of 80 data values at once during a measurement period of about 60s to compute the average amplitude of the signal strength. In addition, we make use of a threshold-based noise filter to improve the data quality.

Second, the tilt angle φ that was transmitted to the RFID reader over the RFID communication channel is extracted from the received data. We compute the reduction in induced voltage caused by the tilt according to Eq. (1).

Third, we retrieve the absolute distance by comparing the transformed signal strength to a previously established look-up table. The look-up table was created with a tag in parallel to the reader and a steadily increasing distance with increments of 1cm. The signal strengths were recorded and stored in a look-up table along with their associated distances.

6. Evaluation and Discussion

In order to test our design, we collected a total of 900 samples of the signal strength's amplitude. The measurements were conducted with an ordinary tag in parallel to the antenna while varying the distances in between. The results are plotted in Figure 4 and show a nearly linear relation between the amplitude of the signal strength and the distance between the tag and reader antennae. Figure 4 also shows the standard deviation for each measurement. The nearly linear behavior is approximated with the linear function described in Eq. (2).

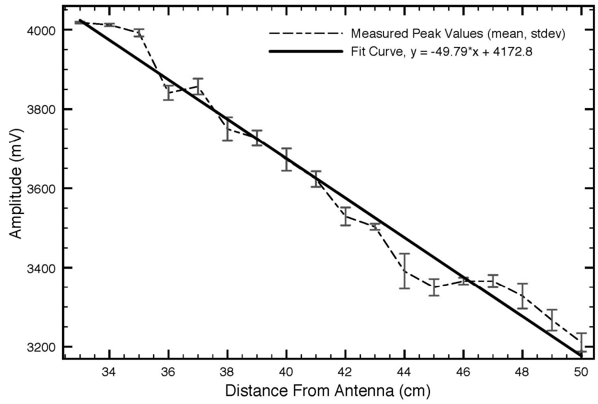

Figure 4: The measurements show a nearly linear relation between the extracted peaks u_0 and the distance from the antenna.

$$y = 4172.8 - 49.79 \cdot x \qquad \text{Eq. (2)}$$

We also verified our design with 10 different setups where the tag's orientation shows a deflection away from the parallel plane (a tilt angle greater zero). For all measurements, the voltage adjustments according to Eq. (1), necessary due to the tilt, resulted in a distance resolution within the standard deviation of measurements without deflections. For example, we tested our design with a tag positioned at a distance of 40cm from the reader antenna and a tilt angle of 30 degrees. The signal strength was measured at 3198mV, which corresponds to 3693mV at a tilt angle of 30 degrees (Eq. (1)). This result is within the standard deviation for measurements at 40cm of 3672.04mV + 28.10mV (equals 3700.14mV).

Our distance measurement procedure allows accurately resolving distances between 33cm and 50cm. Distances outside of this range are not reliably detected. The limitation of operation to a certain range is due to timing imprecision during bit encoding. The Manchester encoding of data generates an oscillating signal at 423.75kHz for one half of the bit length while the other half remains zero (Figure 5). Either the first or the second half shows oscillation depending on whether the bit value represents a logic "one" or logic "zero". According to the ICODE1 protocol, the length of each bit is 37.76µs, and therefore, the signal oscillates for 18.88µs (half of the bit length) at 423.75kHz. Within these 18.88µs, the signal changes 16 times between "low" and "high" and remains at each value for 1.18µs (Figure 5).

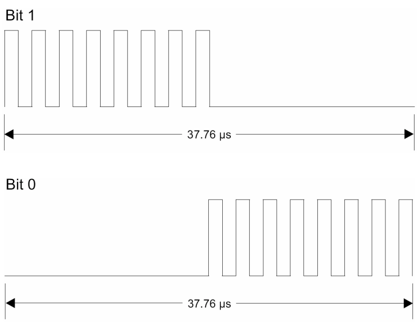

Figure 5: Manchester coding with sub-carrier that represent a 1-bit and a 0-bit.

Our microcontroller has an instruction cycle time of 0.2µs. Therefore, it cannot generate the required oscillation frequency exactly. The best approximation is 1.2µs (6 instruction cycles), which results in an oscillation frequency of 416.7kHz. Consequently, the elapsed time after 8 oscillations is 19.2µs instead of 18.88µs. To sufficiently approximate the total bit length, the non-oscillating part is shortened to 18.6µs. This results in a total bit length of 37.8µs, which is 0.04µs longer than the exact value of 37.76µs.

The difference in frequency proved not critical because the reader's band-pass filter shows sufficient bandwidth to successfully filter the approximated sub-carrier. We compensated for the longer bit lengths by shortening the transmission of an entire byte by one instruction. This shortening reduces the time divergence from 0.32µs to 0.12µs. With these adjustments, our tag successfully transmits data to the reader.

Nevertheless, the distance of operation for data transmission from the tag to the reader remains limited to a certain range due to timing imprecision at the transition point from an oscillating output to a zero output. The timing inaccuracies lead to signal distortions at the RFID reader. Figure 6 illustrates the spikes that occur because of these inaccuracies. As long as the signal strength is strong, and therefore, the spikes are small in relation to the maximum amplitude, the data is demodulated correctly. With decreasing signal strength the spikes become more significant because the amplitude of the spikes remains constant. This signal distortion results in incorrect detections with our peak extraction algorithm.

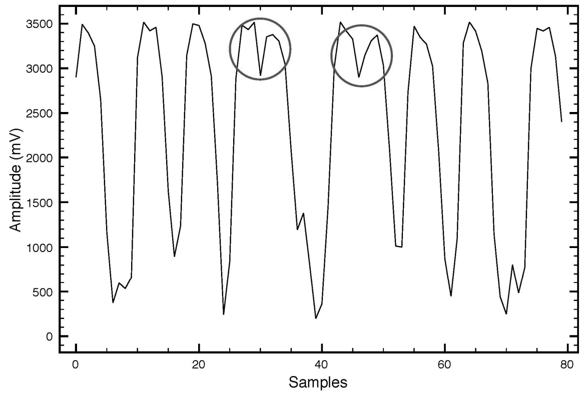

Figure 6: A plot of the signal strength u_0 at the distance 43cm reveals the timing problems in the Manchester encoding (circles).

Another restriction to our design is caused by the diverging lines of the magnetic flux. The magnetic field is considered homogenous only around the coil axis. Therefore, our design cannot accurately resolve distances for tags that show larger displacements away from the coil axis. However, we can assume a large coil diameter and an arrangement of the items close to the coil axis.

7. Conclusion and Future Work

We presented a distance-sensitive high frequency RFID system that allows resolving a tag's distance from a reader antenna. Our system is based on measurements of the voltages induced by magnetic coupling. The signal strength of transmitted data varies with the distance of a tag from the reader antenna. In addition, the signal strength is affected by a tag's deflection away from the parallel plane of the reader antenna. To account for deflections away from the parallel plane, we incorporated a tilt sensor into the tag. An accelerometer provides information about the tag's orientation. We built our own passive RFID tag with discrete components because commercially available tags do not provide an interface to attach such a tilt sensor. The information about the tag's orientation is transmitted along with the tag's ID over the RFID communication channel according to Philip's ICODE1 air interface protocol. Our system accurately resolves distances with a resolution of 1cm within the range of 33cm to 50cm. Distances outside of this range are not reliably resolved due to timing imprecision that occur during data encoding on the tag. This timing imprecision is caused by the use of an external clock that cannot exactly generate the frequency of the sub-carriers used for data transmission from the tag to the reader. We intend to increase the tag's range of operation by incorporating a clock extractor into the tag to accurately generate the carrier frequency for synchronized data transmission to the reader.

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