In-Hand Radio Frequency Identification (RFID) for Robotic Manipulation

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***Abstract*— We present a unique multi-antenna RFID reader (a sensor) embedded in a robot's manipulator that is designed to operate with ordinary UHF RFID tags in a short-range, near-field electromagnetic regime. Using specially designed near-field antennas enables our sensor to obtain spatial information from tags at ranges of less than 1 meter. In this work, we characterize the near-field sensor's ability to detect tagged objects in the robots manipulator, present robot behaviors to determine the identity of a grasped object, and investigate how additional RF signal properties can be used for "pre-touch" capabilities such as servoing to grasp an object.**

The future combination of long-range (far-field) and short-range (near-field) UHF RFID sensing has the potential to enable roboticists to jump-start applications by obviating or supplementing false-positive-prone visual object recognition. These techniques may be especially useful in the healthcare and service sectors, where mis-identification of an object (for example, a medication bottle) could have catastrophic consequences.

I. Introduction

Radio Frequency Identification (RFID) is an emerging enabling technology for an object-centric view of robotics. Given a small amount of environmental augmentation, an RFID tag provides an unambiguous, digital feature on each tagged object. Ultra High Frequency (UHF) RFID has garnered increasing interest in the robotics community due to its battery-free, "long-range" operation. With today's tags and readers, tags can be detected out to 6 meters or more.

As shown in Figure 1, commercial UHF RFID tags are small, thin, low-cost (sub-$0.25), self-adhesive, and fully passive (no battery). One can distribute tags throughout the environment, affixed to locations, people, and objects of interest. Then, using commercially-available UHF RFID readers, robots can detect these tags from an appreciable distance (exceeding 6 meters) even when the line-of-sight between the reader antenna and the tag is occluded. Anti-collision protocols between the reader and tags permit hundreds of tags to coexist in the environment without interference [1]. Furthermore, tag detections occur with effectively zero false positives, and a robot can either query for all tags at once or selectively query for a single tag out of all nearby tags using a process called tag singulation [2].

Due to these properties, UHF RFID has been used extensively in the robotics community for navigation and localization. However, comparatively little work has been reported on RFID for manipulation. In this paper, we present a UHF RFID system embedded in a mobile robot's manipulator for

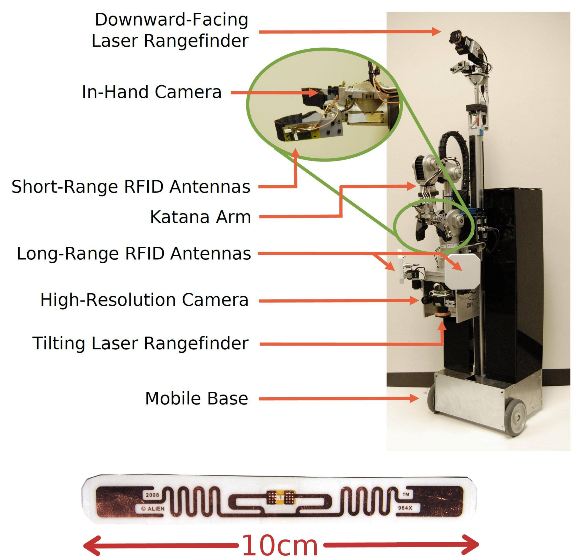


Fig. 1. *Top:* EL-E (pronounced "Ellie") robot. EL-E possesses two long-range body-mounted UHF RFID antennas for long-range (6+ meter) operation and four short-range (≈30cm) in-hand UHF RFID antennas in its manipulator. Image reproduced from [3]. *Bottom:* A UHF RFID tag used in these experiments.

use in locating and identifying tagged objects in and around a robot's gripper.

The contributions of this paper are three-fold. First, we present the design and construction of a unique multi-antenna RFID reader (a sensor) embedded in the robot's manipulator that is specially designed to operate with ordinary UHF RFID tags in a short-range, near-field electromagnetic regime. This is an atypical mode of operation that allows our system to interact with UHF RFID tags at distances less than 1 meter. This unique sensor allows a robot, such as the EL-E (pronounced "Ellie" and shown in Figure 1) to identify objects in and around its gripper with near certainty (extremely low false positives) using the same UHF tags that can be read in the long-range, far-field electromagnetic regime (at up to 6 meters, the typical operating regime).

Second, we characterized the system's ability to detect a variety of tag types (Figure 2). Using two different tag types, we evaluated the robot's ability to detect tagged household objects under various orientations being held in the robot's manipulator. Our experiments suggest that care must be taken to select a tag appropriately matched to an object's material

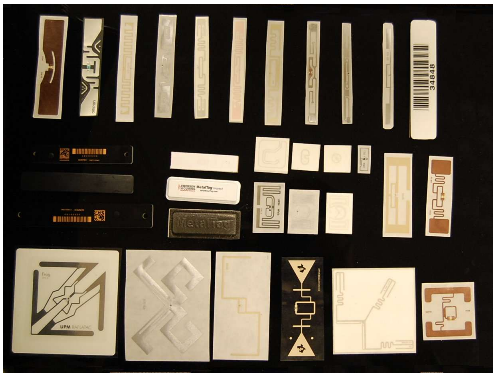


Fig. 2. EL-E's in-hand reader has been demonstrated to work with numerous types / variants of UHF RFID tags, including the thirty-two different types of tags shown here.

composition.

Finally, we go beyond mere tag identification. When a RFID reader detects a tag, it returns the tag's unique identifier (ID) and the strength of the RF signal received from the tag, which is referred to as a received signal strength indicator (RSSI). The RSSI measurements reported by our commercial RFID reader are scalar quantities (8-bit) proportional to the RF power (in dB) received during a tag's response. Through extensive experiments, we characterized our sensor's performance under various positions and orientations of tagged objects in and around the gripper. We also report results about a series of robot behaviors we developed, such as identifying an object in a robot's manipulator and RFID servoing, that demonstrate the usefulness of our system.

II. Related Work

RFID tags come in both battery (active) and battery-free (passive) varieties. For most of the literature examined, passive tags are most common. The different technologies are also distinguished by their operating frequency, which dictates how the tag is powered and its read range (how close the tag needs to be to the reader's antenna in order for the tag's ID to be perceived). For example, Low Frequency (LF) RFID operates at 125 kHz and High Frequency (HF) operates at 13.56 MHz. Both are powered magnetostatically, by inductive coupling. Unfortunately, inductive coupling affords a read range of just a few centimeters (sub-20 cm). In contrast, UHF RFID tags operating at 902-928 MHz (nominally, 915 MHz) are powered by far-field electromagnetic coupling and can be detected at distances exceeding 6 meters [4].

All three passive technologies have been used extensively for localization [5], [6] and waypoint navigation [7]. Numerous applications have been put forth: autonomous vehicles [8], "smart" vacuum cleaners [9], guidance systems for the visually impaired [10], "intelligent" kitchens [11], and hospital inventory tracking [12].

There are few examples of robotic systems using RFID for manipulation purposes. Existing examples for manipulation include HF RFID to locate books on shelves [13] and HF RFID to identify Lego blocks for building [14]. However, these examples are in the minority, and all use the short-range-only forms of RFID tags. However, while RFID in robotic manipulation is rare, there are myriad examples of RFID readers "in-hand" for human manipulation. One example from Smith (et. al.), used a wrist-mounted RFID reader to determine which object is being held in one's hand. This information provided a powerful contextual awareness that allowed for very robust activity recognition [15], [16], [17]. This contextual awareness, when applied to the robotics domain, has the potential to be a boon to human-robot interaction (HRI) applications. Along a similar vein, there are a number of human-computer interaction (HCI) systems that use RFID to determine which objects are nearby. This has been applied to situated story telling [18] and other childrens' games [19].

This paper focuses on short-range UHF RFID sensing, which uses the exact same tags as long-range UHF RFID sensing. Thus, our short-range system can leverage existing tag deployments. Furthermore, the two operating modes are complementary. Long-range UHF RFID sensing tends to focus on tag localization, with reported tag localization uncertainties on the order of 0.75 meters [20], [21], [22]. Meanwhile, our system is designed to operate from 0.0-1.0 meters, precisely the distances where long-range RFID sensing is no longer accurate. The future combination of these two operating regimes has the potential to be a powerful tool for robots operating in household environments, where robots can use long-range UHF RFID sensing to get in the vicinity of tagged objects and short-range RFID to improve their estimates and verify objects' identities post-grasp [3].

Finally, it is worth noting that near-field UHF antennas are an active area of research in the electromagnetics community [23]. However, most near-field UHF RFID antennas in the literature are too bulky to be contained on or near the robot's manipulator. In some of our prior work, we succeeded in fabricating a near-field antenna mounted to a robot's wrist [24]. We demonstrated that the wrist-mounted sensor was useful for disambiguating visually-identical objects in the near-field; however, due to a restrictive read-range and mounting considerations, the system was incapable of identifying an object once grasped. In this paper, we extend this concept of near-field operation by embedding the near-field antennas directly in the robotic manipulator (referred to as "in-hand") to provide further discriminative capabilities.

III. Design of In-Hand Reader

Our in-hand RFID system consists of two main electronic components: a Thing Magic Mercury5e RFID reader capable of outputting 1 Watt of RF power, and a custom reader carrier board with USB connectivity and a SP4T RF switch that multiplexes the reader's output to each of the four in-hand antennas – as shown in Figure 3. The electronics are mounted at the base of the robot's arm, with SMA and UMC cables extending up the arm to the actual antennas, as shown in Figure 1.

The antenna design is the crucial determinant of system operation. Initial efforts to adapt the loaded microstrip design

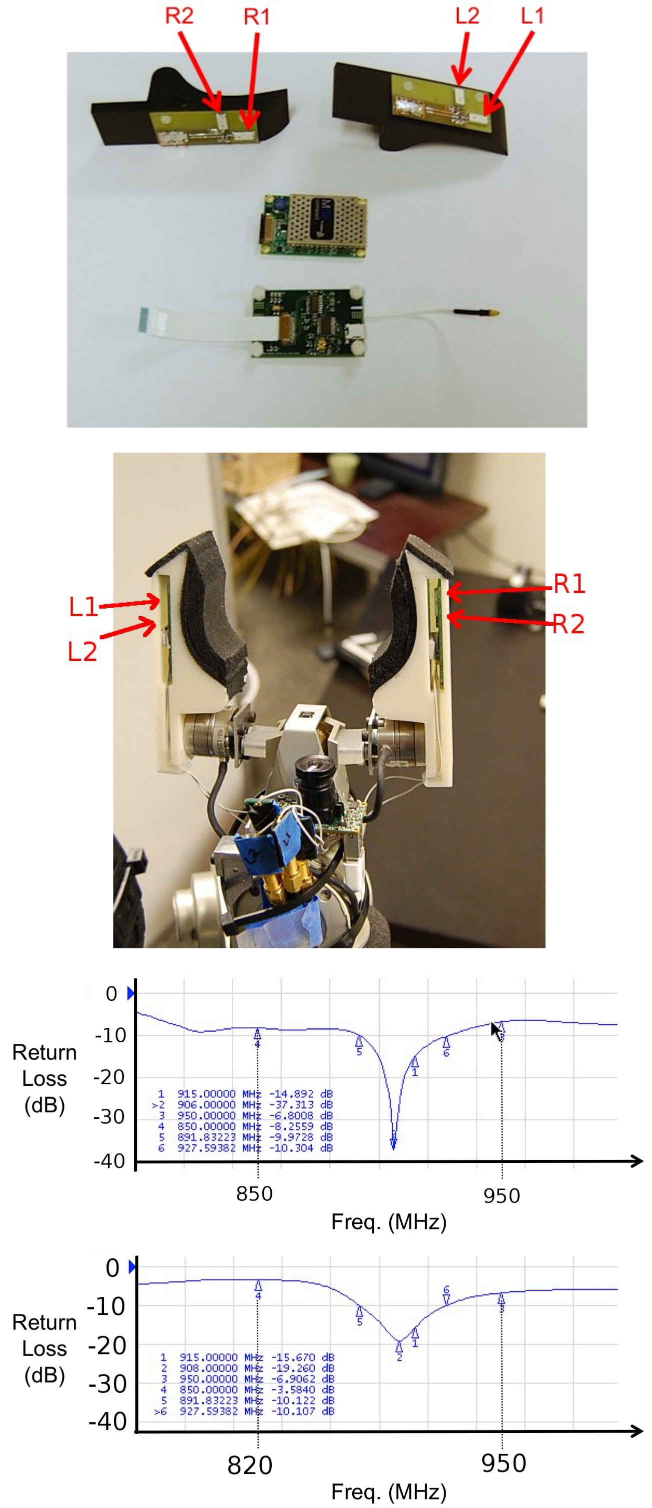


Fig. 3. *Top:* An early prototype of the in-hand reader shows two ceramic antennas in attached to each ABS plastic finger. *Middle:* Later designs embed the antennas inside the fingers to prevent damage and avoid tangled cables. *Bottom:* Network analyzer plots show antenna return loss of less than -10 dB over the 902-928 MHz UHF RFID range for an orthogonal pair of antennas (L1 and L2) embedded in the robot's fingers.

from previous work did not yield sufficient read range and/or form factor [24]. Instead, we settled on ceramic microstrip antennas from Johanson Technology (part number 0920AT50A080E) with π-type LC matching networks to achieve $\approx$-10 dB return loss, as shown in Figure 3. These antennas provided superior performance compared to traditional loaded-microstrips. They demonstrated read ranges in excess of 50 cm under ideal conditions, and consistent readings at 15 cm under practical conditions. However, we observed significant polarization bias (strong dependence on the orientation of the tag relative to the microstrip) for these antennas. To help address this issue, we employed a pair of antennas at 90^o offsets to provide comprehensive RF coverage from each finger. We also observed significant performance degradation when using the ceramic microstrip antennas in the presence of metal, including the original robot's fingers. Thus, we fabricated new fingers out of 3D-printed ABS plastic and included compliant foam on the interior of the grippers to assist in manipulation. We adjusted the π-type matching network to tune the antennas with these nearby materials, as shown in Figure 3.

IV. Characterizing In-Hand Reader Performance

A key contribution of this work is characterizing the ability of the system to detect the identity of a tag affixed to an object in the robot's manipulator. To test the system, we focused on ten objects: TV remote, cellular phone, fork, medication bottle, metal soda can, book, cordless phone, wallet, medication box, and water bottle. These particular items were chosen for a number of reasons. First, most of these items can be found on "A List of Household Objects for Robotic Retrieval Prioritized by People with ALS" [25]. Second, the medication-centric items cannot be handled by service animals, making them appealing to service robot applications. Finally, some of these objects have material properties that have a high likelihood of interfering with RF signals, requiring careful consideration of tag selection.

We performed a total of 140 trials, wherein we affixed each object with a UHF RFID tag, placed the tagged object in the robot's manipulator, and then instructed the robot to query each of the four short-range antennas once (a process taking less than 300 ms). We repeated these trials for two different UHF tag variants (Alien Technologies Gen2 Squiggle tag and the MetalTag Metal-Mount Flex tag) and seven canonical configurations within the manipulator (i.e. as though a successful grasp had already been performed). We considered a trial successful if any one of the four antennas correctly acknowledged the tagged object's presence.

We show the results of these experiments in Table I. Note that there are four marks under each trial, corresponding to the four antennas. In order, the marks correspond to antennas L_1, L_2, R_1, and R_2 (referring to Figure 3). A "✓" represents a successful read, whereas an "×" represents a failed read attempt on that particular antenna.

The results for the Squiggle tag were:

- TV Remote: Successful 7/7 attempts.
- Cell Phone: Successful 7/7 attempts.

- Fork: Successful 1/7 attempts.
- Medication Bottle: Successful 7/7 attempts.
- Metal Soda Can: Successful 0/7 attempts.
- Book: Successful 7/7 attempts.
- Cordless Phone: Successful 7/7 attempts.
- Wallet: Successful 7/7 attempts.
- Medication Box: Successful 7/7 attempts.
- Water Bottle: Successful 4/7 attempts.

For the \$0.20 Squiggle tag, objects composed of RF-transparent materials such as plastic and cardboard were successfully detected on all read attempts. However, the Squiggle tag was less effective on conductive and polar materials, such as the metal soda can, fork, and water bottle. This is a known issue for generic UHF RFID tags (such as the "Squiggle" tag). This limitation can be mitigated by purchasing specialty tags designed to work with these material types. For example, we also evaluated in-hand tag detection using a MetalTag Metal-Mount Flex tag. The results for the metal-mount tag were:

- TV Remote: Successful 7/7 attempts.
- Cell Phone: Successful 7/7 attempts.
- Fork: Successful 7/7 attempts.
- Medication Bottle: Successful 7/7 attempts.
- Metal Soda Can: Successful 7/7 attempts.
- Book: Successful 7/7 attempts.
- Cordless Phone: Successful 7/7 attempts.
- Wallet: Successful 7/7 attempts.
- Medication Box: Successful 7/7 attempts.
- Water Bottle: Successful 7/7 attempts.

However, the improved detection likelihood comes at a price; the metal-mount tag was more than an order of magnitude more expensive per tag (\$2.50 each). For both tag types, there were instances where one or more antennas failed to read a particular tag. This speaks to the sometimes unpredictable (stochastic) nature of RFID readings. Frequently, making additional read attempts will result in a positive reading.

We also observe that objects that are well-suited to in-hand RFID detection (comprised predominantly of cardboard and plastic) are precisely the ones that are difficult to sense using electric-field sensing [26], and vice-versa for predominantly metal objects. This dichotomy may prove to be an interesting avenue of future research.

V. Identifying Grasped Objects

Determining the identity of an unknown object in the manipulator is different than detecting the ID of a tagged object in or near the manipulator. A crucial observation is that any object within the read range (anywhere up to 50 cm) will also be detected. Unfortunately, associating the in-hand object with the tag detection producing the largest RSSI value is not a valid solution, as RSSI is a complex and difficult-to-characterize function of: tag pose (distance and orientation between the tag and reader antenna), tag type (Squiggle versus Metal-Mount, etc), object material composition, surrounding material composition, and even RF interference created by the robot itself.

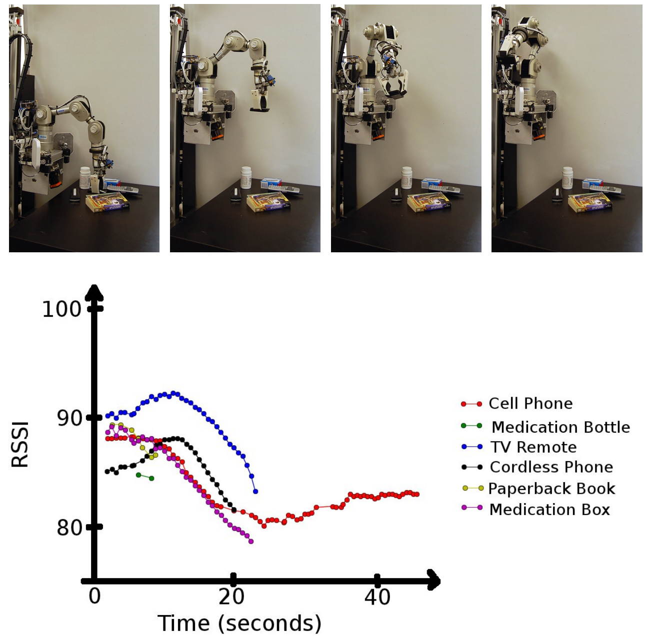


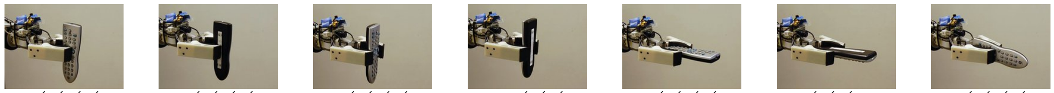
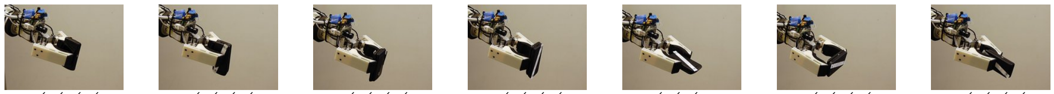
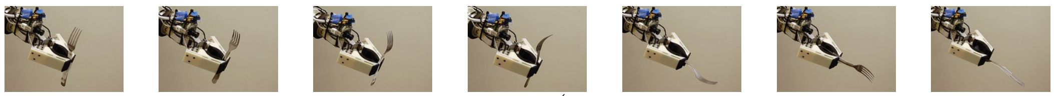
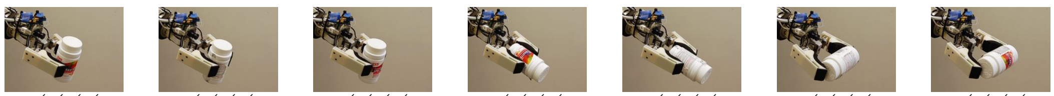
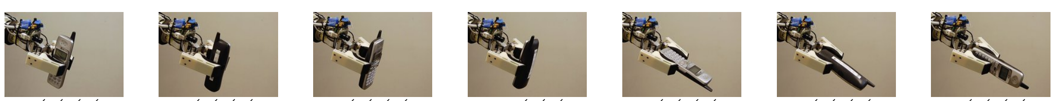
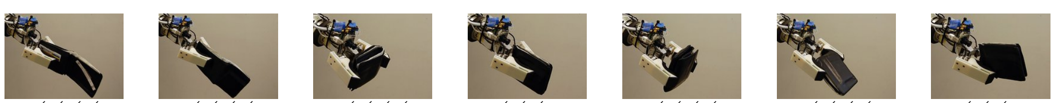
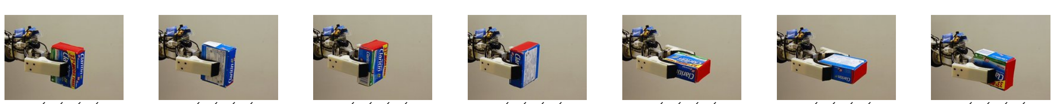
Fig. 4. Monitoring RSSI values (only the L2, left vertical, antenna shown) over time while moving the arm up and away from distracting objects allows the robot to identify a grasped object: a cell phone.

One method of identifying a tagged object in the manipulator is to leverage the robot's mobility to monitor RSSI values (or even presence / absence) of a tag over time as the read antennas are moved away from the initial location. In this case, the tagged object in the manipulator should be persistently detected, while distracting tags nearby disappear from the measurements. For example, Figure 4 shows a scenario where the robot has grasped a tagged cell phone from a table containing a number of other tagged objects (all objects using Squiggle tags). The cell phone has one of the lowest initial RSSI values of any of the objects, likely owing to significant metallic components. As the arm moves up and away from the other tagged objects, the cell phone remains present while the other tagged objects are no longer detected. This confirms that the cell phone is the most likely object in the robot's manipulator.

VI. Pre-Touch Capabilities

Between long-range behaviors and grasping behaviors is the intermediate "pre-touch" regime [26], where a robot makes small changes in the pose of its gripper in preparation for manipulation. We performed several experiments with our in-hand RFID reader that suggest its usefulness for short-range pre-touch applications. Specifically, we show how the signals acquired from the in-hand reader could be used by specialized robot behaviors to help hone in on the location of nearby tagged objects. These short-range behaviors are analogous to behaviors using long-range UHF RFID sensing [27].

TABLE I
VALIDATING GRASPED OBJECTS' IDENTITIES OVER VARIOUS ORIENTATIONS

TV Remote:							
Squiggle Tag:	✓✓✓✓	✓✓✓✓	✓✓✓✓	×✓✓✓	✓✓✓✓	✓✓✓×	✓✓✓✓
Metal-Mount:	✓✓✓✓	✓✓✓✓	✓✓×✓	✓✓✓×	✓✓✓✓	✓✓✓×	✓✓✓✓
Cell Phone:							
Squiggle Tag:	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓×	✓✓✓✓	✓✓✓✓
Metal-Mount:	✓×××	✓✓×✓	✓×××	✓×✓✓	✓×✓×	✓✓×✓	✓✓✓✓
Fork:							
Squiggle Tag:	××××	××××	××××	×××✓	××××	××××	××××
Metal-Mount:	✓×✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Med. Bottle:							
Squiggle Tag:	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Metal-Mount:	×✓✓✓	×✓✓✓	✓✓✓×	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Metal Can:							
Squiggle Tag:	××××	××××	××××	××××	××××	××××	××××
Metal-Mount:	×××✓	××✓×	×✓××	✓×✓×	✓×××	✓×××	✓✓✓×
Book:							
Squiggle Tag:	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Metal-Mount:	✓✓✓✓	✓✓✓✓	✓✓✓×	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Cordless Phone:							
Squiggle Tag:	✓✓✓✓	✓✓✓✓	✓✓✓✓	×✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Metal-Mount:	✓✓✓✓	✓✓✓✓	×✓✓✓	×××✓	✓✓✓✓	✓×✓✓	✓✓✓✓
Wallet:							
Squiggle Tag:	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓×	✓✓✓✓	✓✓✓✓	✓✓✓×
Metal-Mount:	✓✓✓✓	✓✓✓×	✓×✓×	✓✓✓✓	✓✓×✓	✓×××	✓✓✓×
Med. Box:							
Squiggle Tag:	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Metal-Mount:	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓	✓✓✓✓
Water Bottle:							
Squiggle Tag:	×××✓	××✓×	××✓×	××××	××××	××××	✓✓×✓
Metal-Mount:	✓✓✓✓	✓×✓✓	×××✓	✓✓×✓	✓✓×✓	✓✓✓✓	×✓×✓

A. Servoing Using RSSI

Much like long-range RFID servoing [27], EL-E's opposing pair of finger antennas can be used to perform RFID servoing at short range. The data in Figure 5 shows the mean RSSI values from two antennas in opposing fingers (L2 and R2), with the gripper opened 12 cm wide, while the arm is moved in front of a tagged medication bottle (located at x = 0 cm). We show the left finger's readings in blue, and the right finger's readings in red. When the gripper was to the right of the tagged bottle, the left finger obtained stronger readings. When the gripper was to the left of the tagged bottle, the right finger obtained stronger readings. When the gripper was roughly in front of the object, the measurements from both fingers were approximately equal. This demonstrates the feasibility of servoing: if stronger readings are obtained by the left fingers' antennas, the robot arm should move its gripper left; if stronger readings are obtained by the right fingers' antennas, the robot arm should move its gripper right. When the difference between left-and-right measurements is zero, the gripper should be (roughly) centered about the object. As can be seen in Figure 5, the zero crossings all occur when the tagged object is within the 12 cm gripper opening.

We implemented servoing on EL-E and were successfully able to servo (and then grasp) a moving, tagged object held by a person (Figure 6). These initial results look promising, but careful characterization across many positions and orientations would be an important component of future work.

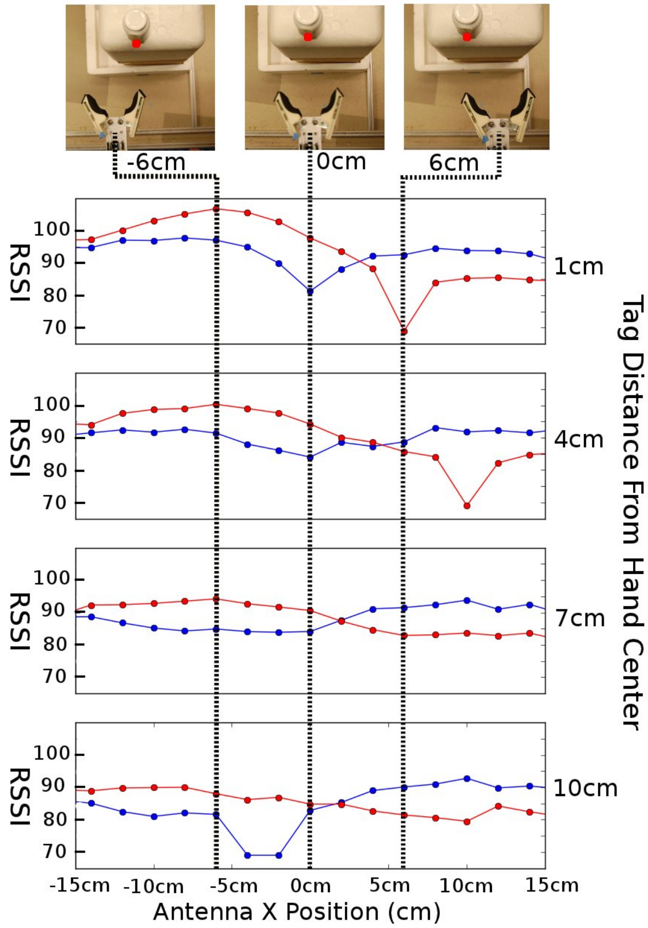


Fig. 5. Mean RSSI taken while moving the arm along a trajectory from left to right in front of a tagged object. The fingers are 12 cm apart, and the object's true position is at offset 0 cm. We moved the tagged object from a distance of 1 cm to a distance of 10 cm away from the center of the fingers, in 3 cm increments. Left finger readings are shown in blue, and right finger readings are shown in red.

B. Raster-Scanned RSSI Images

To visualize the (otherwise invisible) shape of the RF fields produced by the in-hand reader, we constructed 2D images of RSSI readings from all four antennas in front of a tagged object, as shown in Figure 7. We call these images "heatmaps" of RSSI; they are akin to long-range "RSSI images" produced in some of our previous work [28]. Using a 2-axis linear stage, we raster-scanned a mockup of a robot arm in a 60 cm x 60 cm discretized grid with 1 cm spacing. We placed a tagged medication bottle at the center of the grid (x = 0 cm, y = 0 cm). The color of each pixel in the heatmap represents the average RSSI value obtained by a particular finger with the arm at that pixel's corresponding location on the 2D grid. For example, Figure 7 shows the average RSSI values obtained by the left vertical antenna (L2) as a function of arm position.

Figure 8 shows heatmaps for all four in-hand antennas when the tagged medication bottle is 5 cm in front of the fingers (when positioned at the origin). We observe trends similar to the 1D case in Figure 5: the left fingers obtain stronger measurements when the gripper is to the right of the tagged object, and the right fingers obtain stronger measurements when the gripper is to the left of the tagged object. The robot could use the difference between the right-and-left fingers' RSSI values (Figure 8) to determine how to move its arm in order to center the tagged object within its gripper, thus implementing near-field RFID servoing. If stronger readings are obtained by the right fingers' antennas (strong positive difference), the robot arm should move its gripper right; if stronger readings are obtained by the left fingers' antennas (strong negative difference), the robot arm should move its gripper left. When the difference between right-and-left measurements is zero, the gripper should be (roughly) centered about the object. As shown in Figure 8, the zero crossings all occur near the tagged object's true position (x = 0 cm, y = 0 cm).

VII. Conclusions

In this paper, we examined a novel in-hand, short-range UHF RFID sensor embedded in a mobile manipulator's gripper. The sensor is used to read ordinary UHF RFID tags in the electromagnetic near-field, at distances of less than 1 m. We evaluated the robot's ability to detect tagged objects in the gripper, developed robot behaviors to identify a grasped object, and characterized the RSSI signals acquired by the robot in the "pre-touch" regime. We also provided evidence

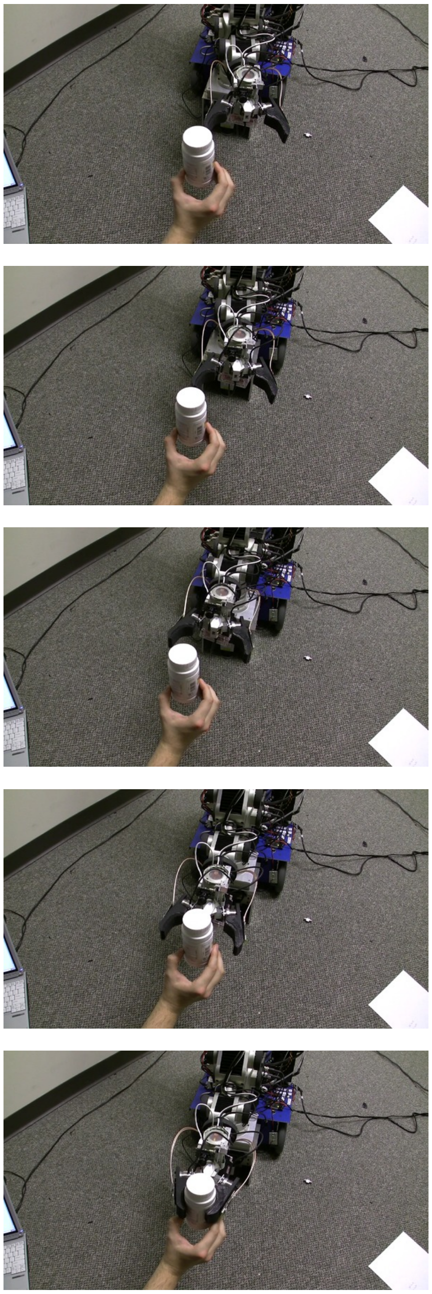


Fig. 6. Servoing to the medication bottle using the difference in RSSI between opposing fingers' antennas, and then performing a grasp.

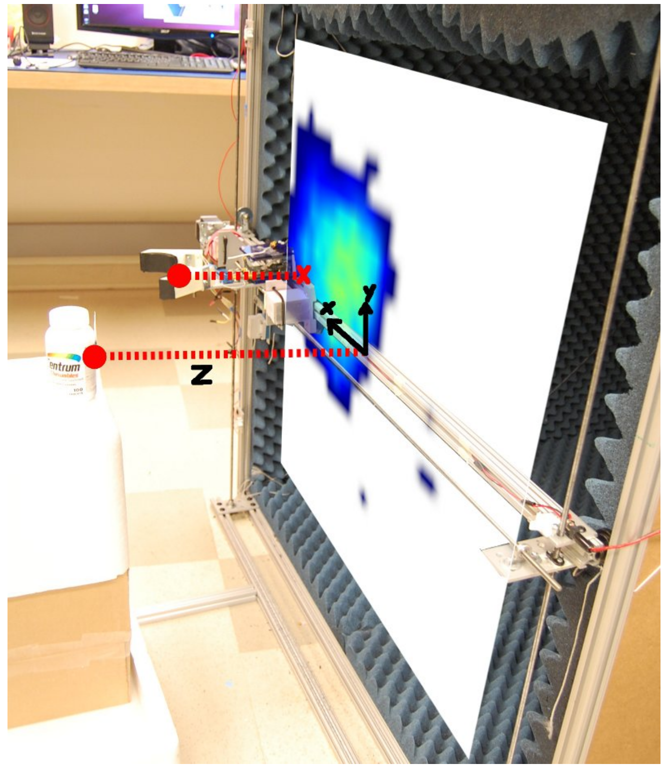


Fig. 7. We use a 2-axis linear stage to move a mockup of the robot arm with in-hand reader to different positions in front of a tagged object. We record the average RSSI values obtained by the left vertical antenna (L2) as a function of arm position to build a "heatmap" of RSSI. The left finger antenna obtains stronger measurements when the arm is to the right of the tagged object. We repeat this process for all four in-hand antennas.

that suggests our system might be useful for more advanced robot behaviors such as short-range tag localization, RFID servoing, and other forms of contactless inference.

Ultimately, this short-range (near-field) UHF RFID system has the potential to be complementary to existing long-range (far-field) systems that interact with the exact same tags. Furthermore, the unambiguous digital signals afforded by UHF RFID are a compelling feature to either supplant or complement existing robot sensing modalities.

VIII. Acknowledgements

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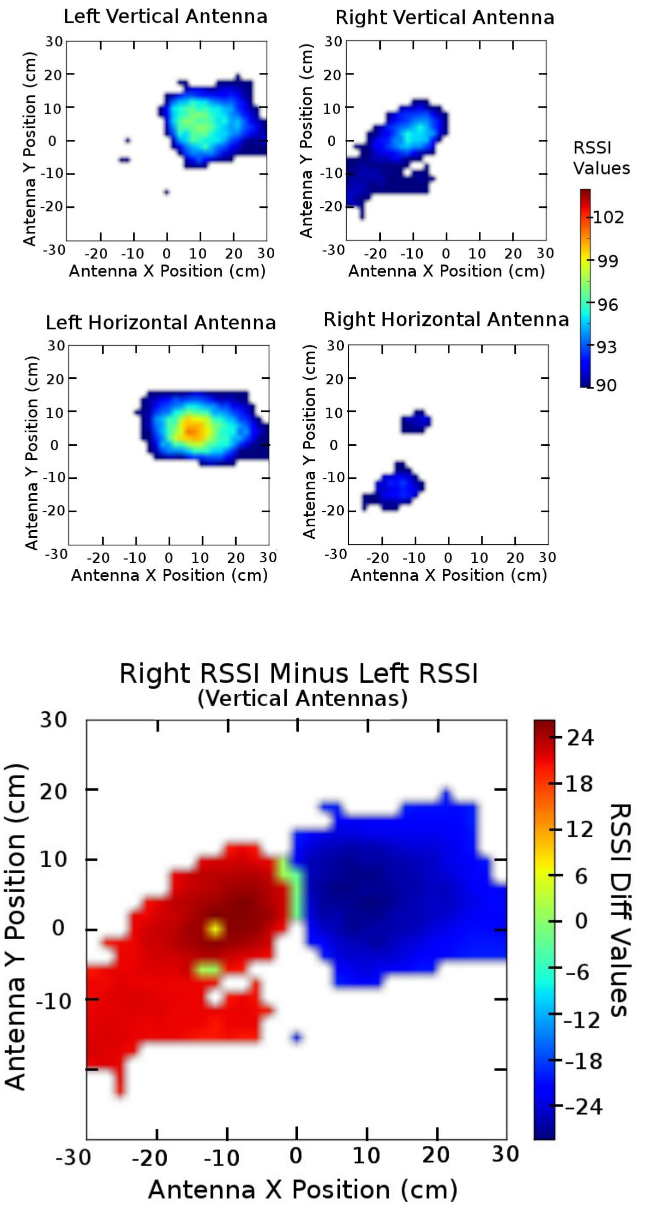

Fig. 8. *Top:* RSSI measurements vs robot arm position for each of the four RFID antennas embedded in the robot's gripper. *Bottom:* Taking the difference between right and left vertically-oriented antennas (L2 and R2), we can create a difference image. This image shows a stable equilibrium for RFID servoing when the difference in RSSI is 0, near the true tagged object's location at x = 0 cm, y = 0 cm.

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