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Krigslund, Rasmus; Popovski, Petar; Pedersen, Gert Frølund

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Orientation Sensing Using Multiple Passive RFID Tags

Rasmus Krigslund, Petar Popovski and Gert F. Pedersen
Aalborg University, Department of Electronic Systems, E-mail: {rkr, petarp, gfp}@es.aau.dk

***Abstract*—Knowing the inclination of an object can be valuable information in a supply chain application, e.g. when handling orientation sensitive objects. In this work we present a method for sensing the inclination using Radio Frequency IDentification (RFID) technology. The method requires standard RFID equipment and assumes that each object is tagged with a passive UHF tag. We use a simple statistical estimator based on the Received Signal Strength (RSS) of the tag reply. The performance is evaluated via experimental measurements, and the results are positive with a good precision within distances of 2 m.**

***Index Terms*—Wireless sensing, Passive RFID sensors, Orientation sensing.**

I. Introduction

Radio Frequency IDentification (RFID) technology has been widely deployed in supply chain applications, as it, among others, enables a higher level of automation. Some items handled in such an automatic system might have a *This side up* marker, meaning that the orientation of the box is important and should be sustained.

In this work we devise an approach to estimate the orientation of an RFID tag based on the polarization of the signal received from the tag. This is a constructive utilization of polarization embracing the polarization mismatch between tag and reader antennas. An example of previous work utilizing polarization is polarization diversity, [1], where co-located antennas with orthogonal polarizations provide a diversity gain as an alternative to spatial diversity. Polarization diversity is also utilized in polarimetric radar systems providing a more complete set of information about the target and environment [2]. Polarization mismatch is however often considered a nuisance, e.g. in the area of localization, where a polarization mismatch decrease the precision, especially for methods based on ranging. In [3] methods for estimating the loss due to polarization mismatch are presented, in order to improve the precision of the final estimated location.

In [4] we investigated the potential of detecting the orientation of a passive RFID tag solely based on its response. The orientation estimate was constructed as a Bayesian estimator, where the likelihood required the mean Received Signal Strength (RSS) to be known a priori. Proper calibration for each different object and environment was therefore necessary. In this paper we use a simple generalized statistical estimator that effectively removes the requirement for calibration. Since the calibration represents knowledge of the environment, removing it is potentially at the price of precision. However, by using multiple tags per object, and estimate their joint orientation we decrease uncertainty of the estimate.

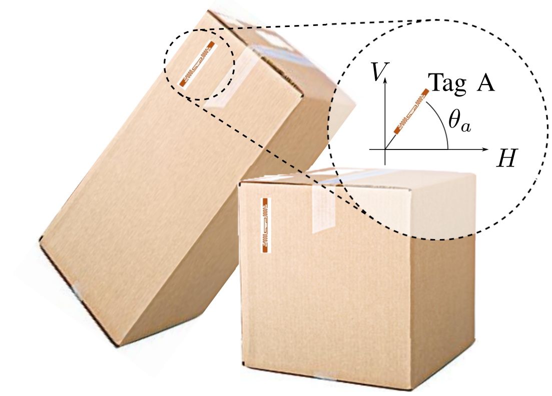

Fig. 1. A scenario were it would be valuable to know the inclination of the objects, based on the tag response.

The remainder of this paper is structured as follows: In Section II we describe the targeted scenario and present the proposed method to estimate the inclination of an object tagged with passive RFID tags. In Section III we present the statistical estimator of the joint inclination. The estimator is evaluated through experimental measurements in Section IV, and in Section V we draw the final conclusions.

II. Problem Definition and Proposed Method

Sensing the inclination based on the RSS of the tag response has been investigated in [4], where we assumed a single tag were attached to the object in advance for identification purposes, as illustrated in Fig. 1. This is a valid assumption especially for supply chain applications.

The proposed method were essentially based on decomposing the RSS from the tag into horizontal and vertical dimensions using dual polarized reader antennas, in order to extract the inclination angle from the polarization of the tag response. To achieve good precision the method required environmental and object specific calibrations, which in general is undesired. Hence in this work we seek to identify a statistical estimator in order to remove the calibration requirement. However, this comes at the price of precision, so to decrease uncertainty of the estimate we propose to use multiple tags per object.

In this work we delimit the number of tags per object to two, tag A and B. To identify the orientation of the object, it is assumed that the relative inclination of these tags with respect to the object is known in advance, and here tag A and B are orthogonal. Their inclinations are respectively denoted, θ_a and θ_b, as illustrated in Fig. 2. It should be noted that tag A and B

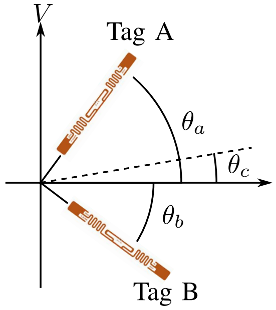

Fig. 2. The angular relationship between the two orthogonal tags A and B.

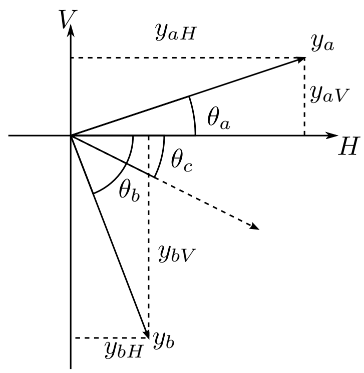

Fig. 3. Vectors illustrating the tag orientations.

are not required to be orthogonal, but their angular relationship must be known. In order to estimate their joint inclination we consider an artificial line, C, defined in the plane spanned by the tags. The inclination of C is referred to as θ_c, and θ_a and θ_b are in this work related to θ_c by shifts of $+\frac{\pi}{4}$ and $-\frac{\pi}{4}$ respectively, i.e. θ_c is centered in between the inclinations of tag A and B. Basically the artificial line C could have any inclination, given that the angular relationships towards tag A and B are known.

III. A Simple Estimator

The RSS of a tag response, y, is obtained in two dimensions using dual polarized reader antennas, and can be written as:

$$y_a = y_{aH} + j \cdot y_{aV}, \quad y_b = y_{bH} + j \cdot y_{bV} \tag{1}$$

The two dimensional structure of y_a and y_b allows us to consider them as vectors, as illustrated in Fig. 3, and each power component is modeled based on the following model for the received signal amplitude:

$$r_{ij} = h_{ij}x + z_{ij} \tag{2}$$

Where the index i and j takes values from the sets $\{a; b\}$ and $\{V; H\}$ respectively. The transmitted signal is denoted x, h_{ij} refers to the channel coefficient and z_{ij} is the noise component. We assume that no information about the signal parameters is available a priori, hence both the channel coefficient and the noise component are assumed to be modeled as two-dimensional Gaussian random variables, i.e. $h_{ij} = h_{1,ij} + jh_{2,ij}$ and $z_{ij} = z_{1,ij} + jz_{2,ij}$, where $h_{1,ij}, h_{2,ij} \sim\mathcal{N}(0, \sigma_h^2)$ and $z_{1,ij}, z_{2,ij} \sim\mathcal{N}(0, \sigma_z^2)$.

For convenience we assume x is constant and equal to 1. Hence all power variations are caused by the channel model, which is a reasonable assumption for an RFID backscattered signal. We can then rewrite the received signal as:

$$\begin{aligned} r_{ij} = h'_{ij} &= (h_{1,ij} + z_{1,ij}) + j(h_{2,ij} + z_{2,ij}) \\ &= h'_{1,ij} + jh'_{2,ij} \end{aligned} \tag{3}$$

Where $h'_{1,ij}, h'_{2,ij} \sim\mathcal{N}(0, \sigma_h^2 + \sigma_z^2)$, since h_{ij} and z_{ij} are independent radom variables. Hence $|r_{ij}|$ is thus Rayleigh distributed, and $|r_{ij}|^2$ is distributed exponentially, i.e.:

$$|r_{ij}|^2 = y_{ij} \sim \frac{1}{\mu_{ij}} \exp\left(\frac{-y_{ij}}{\mu_{ij}}\right) \tag{4}$$

Where μ_{ij} is the mean received power from the tag:

$$\mu_{ij} = 2\sigma^2 = 2(\sigma_h^2 + \sigma_z^2) \tag{5}$$

The mean received power is thus a combination of the mean signal power noise power.

A. Estimating The Inclination

In order to derive a statistical estimator for θ_c, $\hat{\theta}_c$, we obtain data sets of N samples of the received signal powers: $\boldsymbol{y_a} = \{y_a[0], y_a[1], \ldots, y_a[N-1]\}$ and $\boldsymbol{y_b} = \{y_b[0], y_b[1], \ldots, y_b[N-1]\}$. The ratio between each samples of the V and H components depends on the polarization angle, and hereby the inclination of the tag antenna. We use a simple estimator for estimating the mean received power, μ_{ij}, from the tag, and then calculate the tag inclination based on that estimate. The estimated mean power is given by the sample mean over N RSS samples:

$$\hat{\mu}_{ij} = \frac{1}{N} \sum_{n=0}^{N-1} y_{ij}(n) \tag{6}$$

The sample mean is the Maximum Likelihood Estimator (MLE) of the parameter μ_{ij} in (4). This estimator is a random variable with mean equal to μ_{ij}. The variance is given by the Cramer Rao Lower Bound (CRLB), and has been derived to be $\frac{\mu_{ij}^{-2}}{N}$. The estimator of the mean received power is thus an unbiased estimator of μ_{ij}, and its variance is inversely proportional to N. From (5) we know that $\mu_{ij} = 2(\sigma_h^2 + \sigma_z^2)$, hence for small distances between reader and tag the noise power will be negligible compared to the signal power. For large distances however, the noise power becomes dominant. The estimated mean power is therefore expected to have the best precision for relatively small distances between reader and tag. The estimated inclination of a tag is then given by:

$$\hat{\theta}_i = \arctan\left(\frac{\hat{\mu}_{iV}}{\hat{\mu}_{iH}}\right) \tag{7}$$

The joint angle, θ_c, is then estimated by combining $\hat{\theta}_a$ and $\hat{\theta}_b$ according to their angular relationship know in advance. In this work we have defined θ_c as the inclination centered between tag A and B. Hence $\hat{\theta}_c$ is given by:

$$\theta_c = \frac{\theta_a + \theta_b}{2} \quad \Rightarrow \quad \hat{\theta}_c = \frac{\hat{\theta}_a + \hat{\theta}_b}{2} \tag{8}$$

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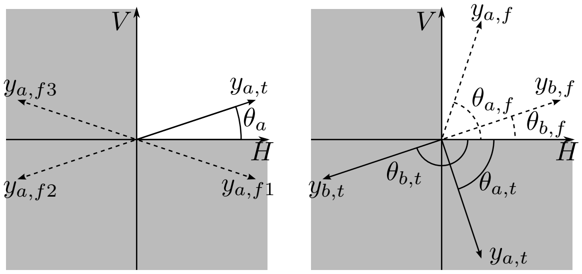


(a) Four examples of vectors whose components have equal absolute value.

(b) Mapping of angles to the first quadrant.

Fig. 4. The true signal vectors (solid lines) and the false vectors (dashed lines) all have the same absolute value. All angles are mapped to the first quadrant, which effectively reduces the range of θ_c.

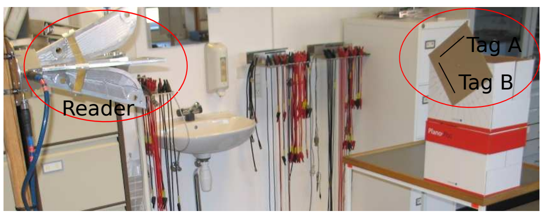


Fig. 5. The utilized experimental setup.

In principle this estimator is scalable to more than two tags, but it is an open question how to map the collected RSS samples and preserve their angular relationship.

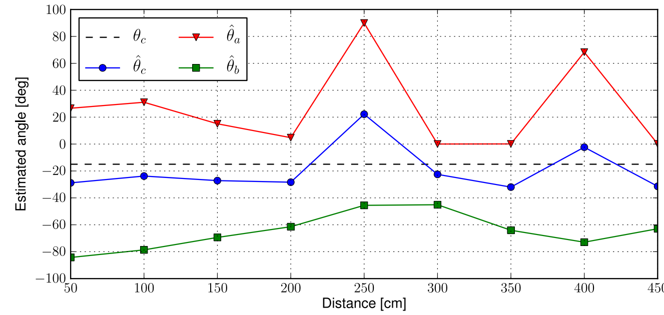
B. Combining Information From Two Tags

Signal power is positive per definition which introduces an ambiguity when estimating the inclination. As an example consider Fig. 4(a) where the true inclination of y_a is $20°$, and the vector is marked with a solid line and an additional index t. The dashed vectors with index f all have the same absolute value as the true vector. However, since the received power is positive, the estimated inclination will be in the interval from $0-90°$, i.e. in the first quadrant, when using (7). In Fig. 4(b) the inclinations of $y_{a,t}$ and $y_{b,t}$ are therefore interpreted as that of $y_{a,f}$ and $y_{b,f}$ respectively.

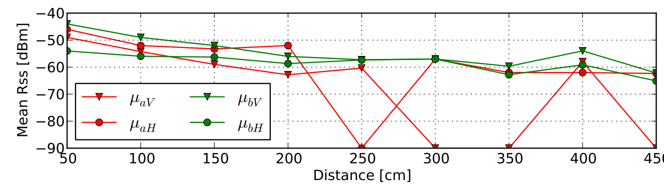
To maintain the orthogonal relationship between y_a and y_b it is therefore required to map y_b to the fourth (or second) quadrant. This reduces the range of the estimated θ_c, $\hat{\theta}_c$, to $\{-45°; 45°\}$, and will thus give a wrong estimate when the true inclinations of tag A and B are outside the first and fourth quadrant, respectively.

IV. Results

In order to evaluate the estimator, we have measured the practical performance in a real life setup using commercial devices. The experimental measurements were conducted in a lab environment with reflecting surfaces like desks, cabinets etc. using an Impinj Speedway Revolution reader [5] and two Alien Technology "Squiggle" ALN9640 Passive UHF tags [6]. Compared to [4] we use only one dual polarized antenna in this work, and the tags are mounted orthogonally on a piece of cardboard raised 1.25 m above the ground, see Fig. 5.



(a) The estimated inclination of tag A and B and their joint angle θ_c.



(b) Measured mean power as a function of distance.

Fig. 6. The joint angle, θ_c, estimated as the average of the measured inclination of tag A and B, $\boldsymbol{x_a}$ and $\boldsymbol{x_b}$ respectively, and the corresponding mean received power as a function of distance.

It is desired to investigate the ability to determine the joint inclination within the range of θ_c and as a function of distance between reader and tags. In each measurement the RSSs from tag A and B are sampled continuously for 12 s using an interrogation power of 27.5 dBm. This gives approximately $N = 500$ samples of the tag reply in the horizontal and vertical dimension respectively. By inspecting the measurement data we found that the variance in the RSS values was in the order of 0.01 to 0.2 dBm. It is therefore reasonable to assume that similar precision can be achieved using less samples and thereby less time, as the RSS is approximately constant. It should be noted that the CRLB on the mean received power, described in Section III-A, is not usefull when interpreting the results, as our reference is in degrees not power. Due to the non-linear nature of the tangens function it is not possible to map an error in degrees to a power ratio, or magnitude, of the vertical and horizontal power components.

A. $\hat{\theta}_c$ as A Function of Distance

The tag inclinations are fixed to $\theta_a = 30°$ and $\theta_b = -60°$ giving a $\theta_c = -15°$. The distance from reader to tag is then changed from 50 cm to 450 cm in steps of 50 cm, and for each distance the tag replies are sampled for 12 s. In Fig. 6 the estimated joint angle, $\hat{\theta}_c$, is plotted as a function of distance. The estimated joint angle $\hat{\theta}_c$ appears to be fairly constant, albeit $10-15°$ below the true angle, up to a distance of 200 cm. At greater distances we see some significant fluctuations corresponding to the dips in mean power in one or both dimensions. An RSS of -90 dBm is an artificial value specified in the situations where a tag is not read, as some value is required in both dimensions in order to estimate the angle. This occur when polarization mismatch and multi path fading make the RSS drop below the sensitivity of the reader.

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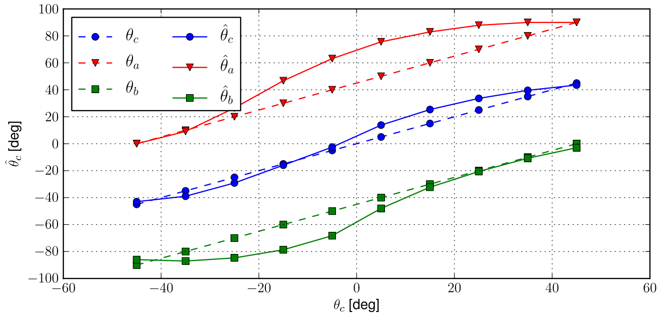

Fig. 7. The estimated joint angle, $\hat{\theta}_c$ and the inclinations of tag A and B, as a function of the true θ_c.

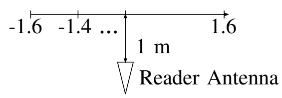

Fig. 8. Setup representing a supply chain application where tagged objects are passing in front of the reader antenna.

B. $\hat{\theta}_c$ as A Function of θ_c

With the most consistent estimations in distances within a few meters, we fix the distance to 100 cm and measure the RSSs for $\theta_c \in \{-45, -35, -25, \ldots, 45\}$. The interrogation power and time is the same as in the previous measurement, and in Fig. 7 the estimated angles are plotted as a function of θ_c. At this relatively low distance the estimators are quite robust, albeit the estimated inclinations of the individual tags have errors of up to $25°$. However, if we consider the estimated joint angle we see the expected diversity effect from averaging the inclinations. We thus obtain a precision of the joint inclination within $\pm 7°$ of the true joint inclination.

C. $\hat{\theta}_c$ When Passing The Reader Antenna

In the previous experiments the ability to determine the inclination have been tested in generic scenarios. However, it is desired also to test the method in a setup similar to a supply chain application, and we therefore move the tags on a straight line in front of the dual polarized reader antenna. This is similar to a tagged object on a conveyor belt passing a reader antenna. The scenario is illustrated in Fig. 8, were the reader antenna is positioned 1 m from, and perpendicular to, the line of movement. The additional complexity introduced by moving objects is outside the scope of this work, hence the movement is discretized into steps of 20 cm from -160 cm to 160 cm, where the 0 cm position is right in front of the reader antenna. It should be noted that due to the change in position along the straight line, the observation direction of the reader antenna will not remain perpendicular to the plane spanned by tag A and B. When seen from the reader, the inclination of the tags will therefore appear different from their true inclination. The precision of the estimated joint inclination is therefore expected to be superior in the center of the interval, where the reader antenna is perpendicular to the plane spanned by the tags. In Fig. 9 the estimated inclinations are plotted as a function of the position with respect to the reader antenna. As expected we see large estimation errors in both ends of

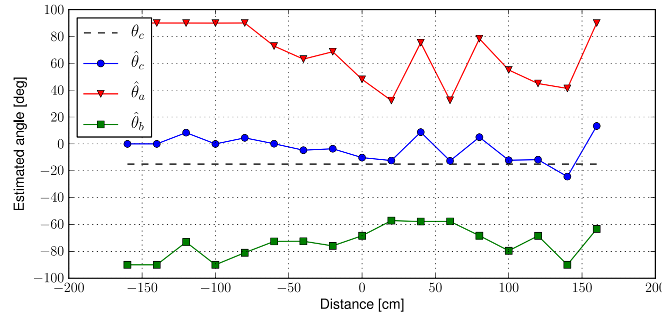

Fig. 9. The estimated joint angle, $\hat{\theta}_c$ and the inclinations of tag A and B as a function of position, when passing the reader antenna. The position 0 is defined as being right in front of the antenna.

the interval. This is best seen by considering the estimated inclination of the individual tags, where we can see how it approaches the true inclination as the tags approach the 0 cm position. Averaging the two angles we get a joint inclination with a precision between $2°$ and $10°$ in the interval from -10 to 10 cm. In 40 and 80 cm we see some quite significant fluctuations, and by inspecting the measurement data it is seen that the fluctuations are caused by sudden dips of ~ 6 dB in the horizontal power component of tag A, and can be ascribed to reflections from the environment.

V. Conclusion

In this work we use a simple statistical estimator of the tag inclination based on the RSS from the tag. This extends our work in [4] and effectively removes the requirement for calibration. We enable the use of multiple tags per object in order to increase certainty of the estimated inclination.

The estimator has been evaluated experimentally, and results show a robust inclination estimate up to a distance of 200 cm and the expected diversity effect when estimating the joint inclination using multiple tags. For tags passing by in front of the reader antenna we showed how the method had superior performance when the tags were located in the area right in front of the reader antenna, as expected.

For future work it would be interesting to see how the estimator performs with tags attached to real life objects, as the material affects the characteristics of the tag.

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