Foreign Material Detection and Localization in Stored Grain with Passive RFID Tag Arrays

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***Abstract*—In the early stage of harvesting, transportation, and storage, the grain could be mingled with clods from the field, metal pieces from aging machines, and other objects of foreign material, which will greatly influence the grain quality and food security. In this paper, we propose a novel radio frequency (RF) sensing system termed TagSee, which leverages passive RFID tag arrays. The goal is to simultaneously sense the presence of foreign materials and locate their locations in the 3D space, to automatically monitor the stored grain. Specifically, we use RFID received signal strength (RSS) and phase as features for foreign material detection. To design the TagSee system, we first introduce a sensing space division method. Then, an Euclidean Distance Ratio (EDR) algorithm and a heuristic method are proposed to achieve high localization accuracy. Experimental results show that TagSee can effectively detect foreign materials in stored grain and achieve a centimeter-level localization accuracy.**

***Index Terms*—Radio Frequency Identification (RFID), Radio Frequency Sensing, Foreign material detection, Localization.**

I. Introduction

As the rapid increase of global population, the demand for food will be doubled by year 2050 [1]. Grain quality is one of the key indicators related to food security. Through the stages of grain harvesting, transportation, and storage, the grain could be contaminated by foreign materials such as clod and rock from the field, metal and rubber pieces from various equipment due to aging, which will greatly affect the grain quality. Generally, the foreign materials are manually sorted by farmers in the early stage of grain harvest, which is time-consuming and laborious. Recently, radio frequency identification (RFID) based radio frequency (RF) sensing has attracted great attention due to the low cost, easy deployment, and high sensing accuracy. Successful applications of RFID-based sensing include indoor scene sensing and localization [2]–[4] , material identification [5], [6], human pose monitoring [7]–[9], moisture sensing [10], [11], and human vital sign monitoring [12].

Inspired by the above applications, we propose TagSee for simultaneous detection and localizing foreign material in stored gain using commercial off-the-shelf (COTS) RFID devices. The goal is to quickly identify foreign materials and remove them from stored grain. TagSee utilizes the phase and received signal strength (RSS) data from RFID signals that propagate through the grain for material identification and localization. Both phase and RSS are provided by many commodity RFID devices. TagSee works well with a small 8 MHz bandwidth (920 MHz-928 MHz). Specifically, *TagSee design is motivated by the key observation that the multi-path propagation and absorption effects on the RSS and phase of received RFID signal will be affected by the presence of foreign materials in grain.* The main contributions of this work are summarize in the following.

- To the best of our knowledge, the proposed TagSee system is the first contactless system to simultaneously sense and locate foreign materials with cheap COTS RFID devices. More important, TagSee can sense static targets without tags be attached on, even when the targets are unknown in non-line-of-sight (NLOS) scenarios.
- In NLOS scenarios, TagSee uses two tag arrays to achieve effective detection of foreign materials. Specifically, we propose a novel Euclidean Distance Ratio (EDR) algorithm and a heuristic method to achieve high localization accuracy.
- We develop a prototype of TagSee to verify the effectiveness of the proposed approach. The experimental results demonstrate that TagSee can effectively detect foreign objects and achieve a centimeter-level location accuracy.

The remainder of this paper is organized as follows. Section II introduces the design of the TagSee system. Section III presents the experimental evaluation of TagSee. Conclusions are drawn in Section IV.

II. TagSee System Design

In order to sense foreign materials in NLOS scenarios, we first mark the 3D sensing space by a 3D grid according to the two tag arrays deployed on the sides of the 3D space. Then, a foreign material detection and localization algorithm based on the concept of EDR will be proposed. Finally, a heuristic method will be used to re-locate the foreign material if the EDR method fails.

A. Partition the Sensing Space

TagSee deploys multiple RFID tags in the two adjacent planes (i.e., the XOY plane and XOZ plane) to form two

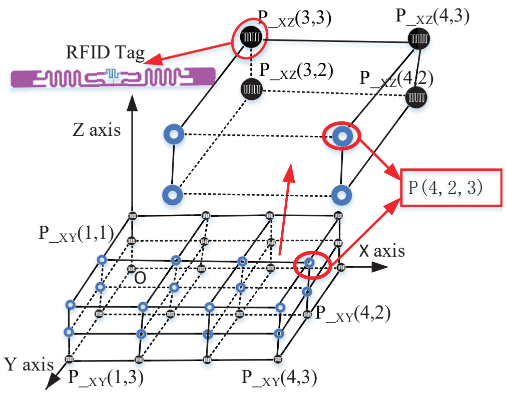

Fig. 1. The sensing space is marked by a 3D grid according to the two tag arrays deployed on the XOY and XOZ planes.

tag arrays. As shown in Fig. 1 and Fig. 2, the two tag arrays are deployed in plane XOY and XOZ (the two sides of the 3D sensing space), respectively. Then the internal region of the sensing space can be marked by a virtual 3D grid, while each grid point's 3D coordinates are given by the 2D coordinates of the corresponding tag on the XOY plan and that on the XOZ plane. A foreign material's location can be represented by the nearest grid point in the 3D space.

As the example in Fig. 1 shows, a 4×3 tag array is deployed on the XOY plane and another 4×3 tag array on the XOZ plane. Then the 3D sensing space can be marked by a 4×3×3 grid. Let $P(X, Y, Z)$ represent the $3D$ coordinate of a grid point (marked by the blue circles in Fig. 1), and $P_{XY}(X, Y)$ and $P_{XZ}(X, Z)$ represent the $2D$ coordinates of the deployed tags on the XOY and XOZ planes, respectively. For instance, the grid point $P(4, 2, 3)$ is determined by the tags at $P_{XY}(4, 2)$ and $P_{XZ}(4, 3)$. TagSee can locate an existing foreign material by determining the coordinates of the nearest grid point $P(X, Y, Z)$.

Although the above method can detect the spatial coordinates of the foreign material, the localization accuracy is limited by the density of tags in the two arrays, while the density may affect the electromagnetic coupling of the tags. Later we will show that TagSee can sense foreign materials at centimeter-level accuracy, making it useful for practical systems. Guided by the practical application, the aim of this work is to sense the existence of foreign materials and to obtain their approximate locations. Then such foreign materials can be easily removed.

B. Sensing with the Euclidean Distance Ratio Algorithm

The RSS and phase θ of RFID tags are collected as features in the form of vectors (RSS, θ) by TagSee. Both RSS and θ are affected by the distance d, the presence of foreign materials, and their properties. We show that the feature vector (RSS, θ) can be used for sensing the location and type of the foreign material. Our method can extract features that are sufficiently sensitive to the location and properties of the foreign material. In the remainder of this section, we develop an EDR algorithm to achieve these goals.

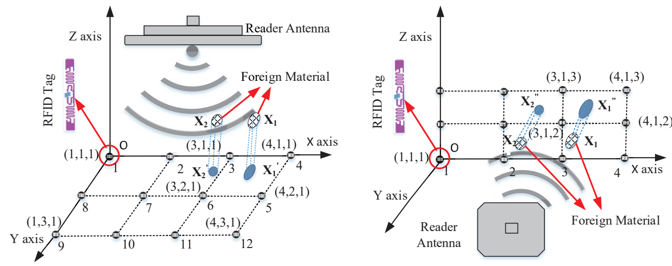

Fig. 2. Project foreign material onto the XOY and XOZ planes using the EDR algorithm.

1) Design of the Euclidean Distance Ratio Algorithm: When there is presence of foreign material between the RFID tag and reader antenna, its collected feature vector (RSS, θ) will be affected. We find that the feature vector from a tag will have a larger change if the foreign material is closer to the tag. More important, we leverage Euclidean distance to measure the change of the feature vector. The distance between two points of $V_1(x_1, y_1, z_1)$ and $V_2(x_2, y_2, z_2)$ in the 3D space is given by $d_{Eu}(V_1, V_2) = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2}$.

We collect the feature vectors (RSS, θ), with and without foreign material in the medium (i.e., grain), from a tag i, which are denoted by $V_0(i)(RSS\_0, \theta\_0)$ and $V_1(i)(RSS\_x, \theta\_x)$, respectively. We calculate the distance between two vectors $V_0(i)$ and $V_1(i)$ as $d_{Eu}(V_0(i), V_1(i))$, where $d_{Eu}(\cdot, \cdot)$ denotes the Euclidean distance between two feature vectors. Therefore, we define the Euclidean distance ratio (EDR) as follows.

$$EDR(i) = \frac{d_{Eu}(V_0(i), V_1(i))}{|V_0(i)|}, \quad (1)$$

then we can identify the tag j with the largest EDR value.

$$\text{tag}(j) = \arg\max_i \{EDR(i)\}, \forall i, i = 1, \cdots, n. \quad (2)$$

Theoretically, the value of $EDR(i)$ should be zero when there is no foreign material in the grain. Eq. (2) indicates that it is highly likely that tag j is the nearest to the foreign material. By (1) and (2), the foreign material in the grain is projected on the tag location (j) whose EDR is the largest.

Taking plane XOY as an example, An array with 4×3 tags are numbered from 1 to 12 as tag i, as shown in Fig. 2. X_1 represents a piece of foreign material in the space. We can project X_1 onto the XOY plane using the EDR algorithm, by locating X_1 at the grid point $X_1'(4, 2, 1)$ by (2), where the EDR value is the maximum. Similarly, we can also project X_1 onto the XOZ plane at the grid point $X_1''(4, 1, 3)$, which has the maximum EDR. This way, the foreign material can be projected onto the XOY and XOZ planes at the closest tag using the EDR algorithm.

2) Spatial Localization of Foreign Materials: The $M \times N$ tag array in the XOY plane and the $M \times L$ tag array in the XOZ plane can form an $M \times N \times L$ grid space. The grid points are labelled with coordinates $P(X, Y, Z)$. Denote the origin as $P(1, 1, 1)$.

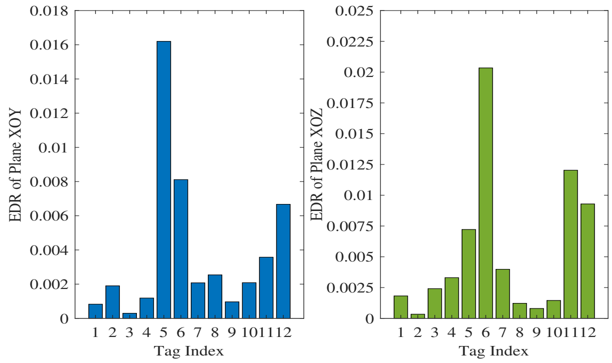

Fig. 3. An example of failed localization of the foreign material. Tag 5 at $P_{XY}(4,2)$ has the highest EDR on the XOY plan and tag 6 at $P_{XZ}(3,2)$ has the hightest EDR on the XOZ plane. Since $(x=4) \neq (x'=3)$, we cannot identify a grid point as the location of the foreign material.

Assume that a foreign material X presents in the middle of the grain with a feature vector $V(RSS\_x, \theta\_x)$. TagSee first uses the EDR algorithm to obtain the $EDR(X)$ values of all the tags in two arrays. Then, the projected locations are obrtained in the form of $P_{XY}(x,y)$ and $P_{XZ}(x',z)$. The spatial location coordinates $P(x,y,z)$ can be obtained if $x'=x$, and consequently the location of the foreign material can be determined. For example, the foreign material X is projected on the two planes with $P_{XY}(4,2)$ and $P_{XZ}(4,3)$, as shown in Fig. 1. Then X is located to be near the grid point $P(4,2,3)$, which can be removed next.

However, we cannot find a grid point if $x' \neq x$, which is considered as localization failure. It can be seen in Fig. 3 that there are two abnormal EDR values of tag 5 and tag 6 in the XOY and XOZ planes, respectively. The coordinates of the two corresponding tags are $P_{XY}(4,2)$ and $P_{XZ}(3,2)$, respectively. Note that $x' \neq x$ in this case, and we cannot find a grid point in this case and the foreign material is not located.

To improve the accuracy of localization, we propose a heuristic method. When the localization fails, TagSee seeks for other possible locations. The EDR values of all tags will be rearranged as follows: (i) For plane XOY, $EDR_{XY}(1) > EDR_{XY}(2) > \cdots > EDR_{XY}(j) > \cdots$; (ii) For plane XOZ, $EDR_{XY}(1) > EDR_{XY}(2) > \cdots EDR_{XY}(k) > \cdots$. The above arrangements indicate the possibility of projected locations on the two planes, from large to small. If localization fails for the first time, i.e., there is not a grid point satisfying both $EDR_{XY}(1)$ and $EDR_{XZ}(1)$, TagSee continues to search down the two lists to find a pair of EDR values that satisfy the $x'=x$ condition, which then provides the estimated location of the foreign material.

III. Experimental Verification

A. TagSee Setup

As shown in Fig. 4, the sensing space with size $116 \times 56 \times 26$ cm^3, is filled with wheat. The plastic container is chosen as the sensing space, which is made of poly-methyl methacrylat with little interference to electromagnetic waves.

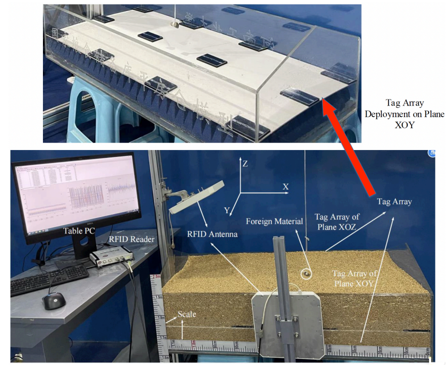

Fig. 4. Deployment of the TagSee system.

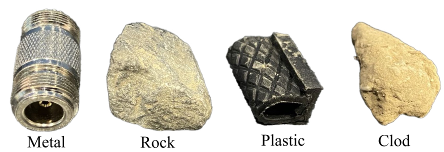

Fig. 5. Four types of material common in grain storage.

Metal containers have a shielding effect on signals, making TagSee unstable. TagSee is implemented with two passive RFID tag arrays (with the Alien 9640 tag with Higgs 3 chips) on the XOY plane and the XOZ plane, respectively. Each array consists of 4×3 tags. A reader with two Laird2 S9028 PCR RFID antennas is used to query the tags, and a tablet computer with Windows 10 system is used to process the collected data samples. Four types of foreign materials are used, including clod, plastic, rock, and metal screws, which are common in stored grain and are shown in Fig. 5. The size of the foreign materials is about 2.5×2.5 cm^2. RFID tag arrays are placed at the bottom and one side of sensing space, and the tag arrays on both sides form a virtual grid to mark the sensed 3D space holding the grain. We set the minimum tag space following [13] when deploying the tags. The tag signal propagation distance in wheat is about 120 cm. Therefore, the volume of the wheat sample is about $120 \times 120 \times 120$ cm^3.

B. Results and Discussions

1) Foreign Material Detection: In this section, we verify the sensitivity of EDR values to foreign material. We first measure $V_0(i)(RSS\_0, \theta\_0)$ with the clean wheat samples. Next, we place clod, metal, rock, and plastic blocks in the grain, respectively, and measure the corresponding $V_1(i)(RSS\_0, \theta\_0)$ values. To facility a fair comparison, we place a block of foreign material in the same position each time. Note that there is only one foreign material in the sensing space in each experiment. In each experiment, TagSee interrogates each tag 500 times to collect feature data (i.e., RSS and θ). There are 20 tags in the two tag arrays, and thus $500 \times 20 \times 2$ samples are collected. Finally the EDR value for each tag is computed as in (1). Take plane XOY as example, data is collected when the foreign material is placed above tag 4. Fig. 6 shows the EDR values for the four types of materials.

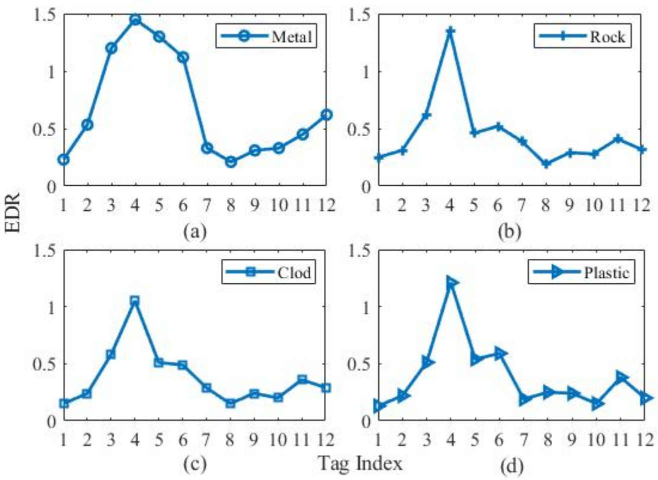

Fig. 6. EDR values for the four types of materials.

We can see that the EDR of tag 4 is abnormal since the foreign material is near the tag. Thus, it can be inferred there should be a foreign material in the grain. To validate the effectiveness of the proposed method, TagSee collects EDRs of each tag in plane XOZ. The results show when an object is present at any position in the wheat sample, TagSee can detect the corresponding abnormal EDRs.

Note that the size of the material can impact system performance. Research found that the smaller the size, the more difficult to detect it. When the object size is about 1 cm $\times$ 1 cm, TagSee could fail to sense the presence of the three types of objects, except for metal foreign objects.

2) Foreign Material Localization: Section III-B1 validates that TagSee can detect foreign materials in grain by abnormal values of EDR of tag(i) in plane XOY and tag(j) in plane XOZ. Thus, the foreign material can be projected on plane XOY and plane XOZ, respectively, using the EDR algorithm. The accuracy is presented in Table I, i.e., the accuracy for projecting material on the XOY plane and XOZ plane. We can see that metal has the highest accuracy of 100%, and plastic has the worst accuracy of 76%. These results are due to the dielectric properties of the material; Metal is more sensitive to electromagnetic waves than the other types of material.

After projecting the foreign material on the two planes, its location can be obtained by the 2D coordinates of the two tags that has the highest EDR value on the XOY and XOZ planes, respectively. Table I also presents the localization accuracy of TagSee before and after using the heuristic method. Obviously, the heuristic method improves the localization accuracy.

TABLE I
ACCURACY OF SPATIAL LOCALIZATION

Target Material	XOY	XOZ	Spatial Localization	Heuristic
Metal	100%	100%	98%	98%
Rock	92%	92%	88%	92%
Clod	88%	86%	72%	84%
plastic	78%	76%	70%	76%

IV. CONCLUSIONS

This paper presented TagSee, the first RFID-based system to leverage RFID phase and RSS as feature vectors for foreign materials detection and localization. We first introduced a 3D virtual grid to mark the sensing space according to the two RFID tag arrays deployed on the sides of the sensing area, respectively. Then we proposed an EDR algorithm and a heuristic method to achieve high localization accuracy. Our experimental study demonstrated that TagSee could achieve a centimeter-level accuracy. It would be useful to detect foreign materials in other penetrable materials as well (e.g., corn, soybean, oil, and soil) without much modification.

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