TagSense: Robust Wheat Moisture and Temperature Sensing Using a Passive RFID Tag

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ICC 2022 - IEEE International Conference on Communications | 978-1-5386-8347-7/22/$31.00 ©2022 IEEE | DOI: 10.1109/ICC45855.2022.9838925

***Abstract*—Driven by the fast increase of food demand world wide, the safety of grain storage becomes increasingly important. Two key factors, i.e., temperature and moisture, greatly influence the safety of stored grain. The traditional methods of detecting grain temperature and moisture are time-consuming, expensive, and inconvenient to use. In this paper, we develop a TagSense system for robust wheat moisture and temperature sensing using cheap commercial-off-the-shelf (COTS) RFID devices. We first validate the feasibility of using tag impedance for robust moisture and temperature sensing. We then propose a distance-free algorithm and an angle-agnostic method to mitigate the impact of different measurement distances and angles. Our experimental results demonstrate that the TagSense system can achieve satisfactory sensing accuracy of wheat moisture and temperature in different rotation angles and at different distances.**

***Index Terms*—Radio frequency identification (RFID), food storage, moisture and temperature sensing, support vector machine (SVM).**

I. Introduction

Due to the rapid increase of global population, the demand for food will be doubled by year 2050 [1]. Grain storage is an effective way to meet the future food demand and to prepare for war, famine, or other unexpected events, and therefore, is crucial for national security. Specifically, the safety of grain storage becomes increasingly important. Temperature and moisture are the two key factors that greatly affect the safety of stored grain. However, how to accurately and effectively measure and monitor both factors becomes a challenging research problem in different phases of the grain distribution chain from producer to consumer.

Existing wheat moisture measurement techniques can be classified into drying methods, capacitance methods, resistance methods [2], microwave methods [3], and neutron gauge methods [4]. For measuring the temperature and moisture of stored wheat, a large amount of wire sensors are generally used. Once deployed, it is usually not easily to replace once a measuring node is damaged. The traditional measurement method based on sensors cannot meet the demands of high accuracy, easy deployment, and low cost. In recent decades, radio frequency (RF) sensing has attracted great attention in the Internet of Things (IoT). Specifically, various wireless technologies have been used for contact-less RF sensing applications, such as health monitoring [5], 3D pose estimation [6], and driver fatigue detection [7]. Our prior works have used WiFi signal for contact-less wheat moisture and mildew detection [8]–[10]. However, WiFi signals are sensitive to environment changes (e.g., a person walks by), which limits the robustness of the wheat moisture and mildew detection system.

Recently, RFID tags have been used for temperature measurement related to this work. For example, the authors in [11] proposed a standard-compliant measurement scheme for the discharging period by using a tag's volatile memory and built a mapping model between the discharging period and temperature. However, the accuracy of this system depends on the duration of the discharge persistence time of the tag circuit, and the recognition accuracy is affected by the distance, while the discharge persistence time is not linear with temperature. The authors in [12] proposed a passive RFID temperature sensor using a bimetallic coil as the temperature sensing unit, and the authors in [13] presented a system that uses a pair of tags to cancel out undesirable environmental effects. This system uses many assumed parameters to calculate the tag impedance, while ignoring the influence of frequency on impedance. The phase difference is used to obtain temperature, which can also be affected by the surrounding environment.

The RFID based sensing technologies mentioned above mostly leverage antenna gain or phase difference as features to sense locations, detect different materials, monitor health conditions, and detect temperature [14]. However, most of the RFID-based prior works still suffer from the impact of different measurement distances and angles. Motivated by the existing RFID-based sensing techniques, we propose to leverage RFID for wheat temperature and moisture sensing and present TagSense, an RF sensing system using a single passive RFID tag in this paper. TagSense is easy to deploy, where the passive RFID tag is attached to the sample target to measure its temperature and moisture.

The proposed TagSense system incorporates a novel distance-free algorithm based on the Fresnel reflection coefficient. In addition, the impact of different measurement angles is greatly reduced by using a circular polarization antenna as well as a multi-class support vector machine (SVM) method. Specifically, TagSense does not require the RFID tag to be tightly attached to the sensing target. The tag can be attached to a bag, a box, or a cup, and then the TagSense system can sense the internal conditions inside the bag or box. TagSense also does not require a specific sensing distance or direction; it works from any angle or at any distance (within the maximum sensing range). Unlike the existing systems that employ dedicated hardware or special-purpose of high-frequency signals to extract feature parameters for material sensing [15], TagSense leverages tag input impedance and resonance frequency of the RFID signal. It is implemented using a cheap commercial-off-the-shelf (COTS) RFID tag, where the S-parameters and resonance frequency can be easily obtained from a Vector Network Analyzer (VNA) in the frequency range from 860 MHz to 960 MHz.

To achieve robustness, we design a distance-free algorithm and an angle-agnostic method to allow TagSense to sense temperature and moisture of the wheat sample at different distances or any angles. We believe this work opens a new direction for performing material temperature and moisture sensing with low-cost COTS devices. The main contributions are summarized as follows.

- We validate the feasibility of utilizing RFID for sensing the temperature and moisture of stored wheat. To the best of our knowledge, this is the first work that only leverages one cheap RFID tag for simultaneously sensing wheat temperature and moisture.
- We propose a distance-free algorithm and an angle-agnostic multi-class SVM method to mitigate the impact of different detection distances and directions, respectively.
- Using the COTS RFID device and real stored wheat samples, we conduct extensive experiments in various scenarios to validate the performance of the TagSense system. Our experimental results demonstrate TagSense's robust performance on temperature and moisture estimation in different distances and angles, as well as its high detection accuracy.

The remainder of this paper is organized as follows. In Section II, we discuss the preliminaries and demonstrate feasibility of the proposed approach. In Section III, we introduce the TagSense system design. Results and accuracy analysis are presented in Section IV. We conclude this paper in Section V.

II. Preliminaries and Feasibility Study

In this section, we discuss the measurement of tag impedance and verify whether the change of surrounding environment will cause the tag antenna impedance to change.

First, we remove the microchip from the RFID tag, and connect the two ports of the tag antenna to a VNA device. We observe the S-parameter from the VNA device to measure the impedance of the tag antenna [16]. Generally, the input impedance refers to the equivalent impedance at the input of a circuit. We observe the current I after adding a voltage source U to the input port. The tag antenna input impedance Z_d is dependent on the S-parameter [16], which is defined as

$$Z_d = \frac{2Z_0(1 - S_{11}^2 + S_{21}^2 - 2S_{21})}{(1 - S_{11})^2 - S_{21}^2}, \qquad (1)$$

where S_{11} and S_{21} denote the reflection coefficient of Port 1 and the transmission coefficient from Port 1 to Port 2, respectively, which can be read from the VNA, Z_0 is the characteristic impedance of the transmission line, which is 50 (Ohm) in this test.

To observe the relation between tag antenna impedance and temperature, we freeze the wheat to $-10°$C, put the RFID tag close to the wheat, and measure the changes in the tag antenna impedance when the wheat temperature rises from $-10°$C to the room temperature, which is about $+20°$C. Fig. 1(a) shows the relationship between tag antenna impedance (the real part) and wheat temperature. It is obvious that there is a strong correlation between the wheat temperature and the impedance. We also measure the impedance of tag antenna when it is far or close from the wheat sample, respectively, for frequencies from 910 MHz to 928 MHz. As shown in Fig. 1(b), the two curves are obviously different. The real part of the impedance decreases with the increase of frequency, but the imaginary part shows the opposite trend (which is omitted for brevity).

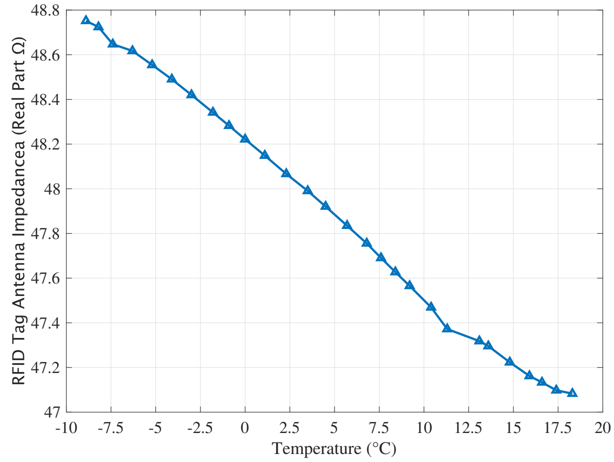
Through the above observations, it can be concluded that the input impedance of the tag is almost linearly related to wheat temperature, while its real and imaginary part change with the external environment. The system design as follows is based on these observations.

III. The TagSense System Design

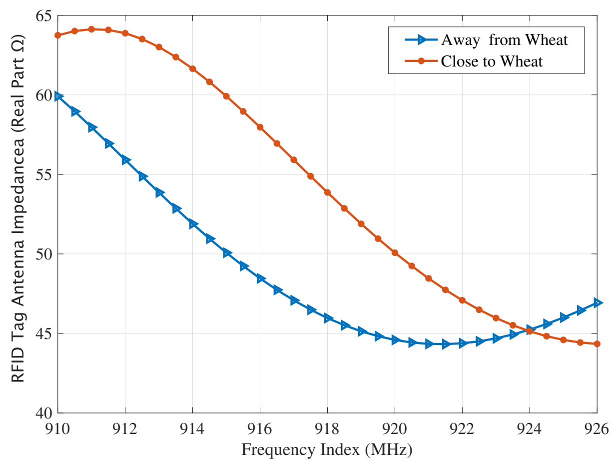
This section presents the TagSense system design, which is an RF-based wheat moisture and temperature sensing system using COTS RFID devices. The system comprises only one VNA with a reader antenna and a passive RFID tag that is attached to the box holding wheat samples. Then, the system can sense temperature and moisture of the tag sample simultaneously. The system architecture is show in Fig. 2, which includes four modules: (i) the Sensing Module, (ii) the Data Preprocessing Module, (iii) the Multi-class SVM Module, and (iv) the Temperature and Moisture Estimation Module. Specifically, the Sensing Module uses the VNA device and RFID reader antenna to obtain the backscattered signal from the tag. In the Preprocessing Module, we develop a Fresnel reflection coefficient based distance-free algorithm and a multi-angle method to obtain distance and angle agnostic tag impedance. In the Temperature and Moisture Estimation Module, a linear regression model and a machine learning model are used to predict the temperature and moisture of wheat, respectively.

A. Data Sensing

In the data sensing phase, we attach the tag to the wheat sample box in the sensing area. The antenna transmits electromagnetic waves to the surrounding. If the tag obtains enough energy, it will be excited and reflect the signal back



(a) Impedance of the real part vs. wheat temperature



(b) Whether the tag antenna is close to the wheat or not

Fig. 1. Changes in the tag antenna impedance in different surrounding environment temperature.

to the antenna. The system then measures the S-Parameters and other information through the VNA device. We set the frequency scanning range of the VNA from 860 MHz to 960 MHz. In addition, the sensed data is sent to a computer for preprocessing.

B. Impedance of Distance-Free

In order to make TagSense more robust and to sense wheat moisture and temperature at any distance, in this section, we propose a distance-free impedance algorithm based on the Fresnel reflection coefficient and electromagnetic wave transmission line theory. We first discuss the Fresnel reflection coefficient and the distance-free algorithm. Then, we show how to eliminate the impact of the thickness of the target medium and obtain the Fresnel reflection coefficient.

1) Fresnel Reflection Coefficient: According to the definition of Fresnel reflection coefficient [17], the S-parameter of the system can be described as in (2) and (3).

$$\Gamma_{12} = \frac{Z_c - Z_d^*}{Z_c + Z_d}, \tag{2}$$

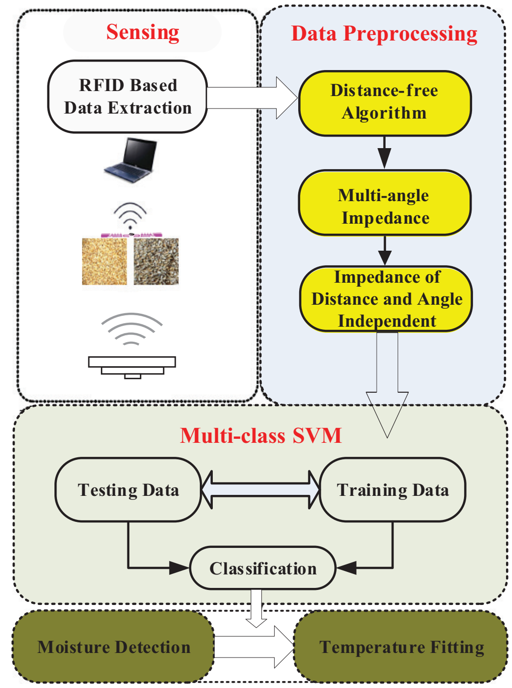


Fig. 2. System architecture of TagSense.

where Γ_{12} denotes the Fresnel reflection coefficient at the surface of Medium 1 and Medium 2, i.e., the Fresnel reflection coefficient of the tag; Z_c denotes the impedance of the chip, which is a constant; Z_d denotes the input impedance of the tag. The reflection coefficient S_{11} of Port 1 is given by

$$S_{11} = \frac{E_{1r}}{E_{1i}} = \Gamma_1 + \frac{\tau_1 \tau_2 \Gamma_3 e^{-2\gamma d}}{1 - \Gamma_2 \Gamma_3 e^{-2\gamma d}}, \tag{3}$$

where d denotes the thickness of the wheat sample (i.e., Medium 2) in meters, γ is the propagation constant that usually takes a complex value, and E_{1r} and E_{1i} are the incident wave and reflected wave of Medium 1, respectively. According to the definition of S_{11}, τ_1 and τ_2 denote the transmission coefficient of Medium 1 and Medium 2, respectively.

Define $C(d') = e^{-2\gamma d}$ and $\tau_1 \tau_2 = \tau$. According to the definition of S_{11}, (3) can be simplified as follows.

$$S_{11} = \frac{E_{1r}}{E_{1i}} = \Gamma_1 + \frac{\tau \Gamma_3 C}{1 - \Gamma_2 \Gamma_3 C}, \tag{4}$$

where Γ denotes the Fresnel reflection coefficient on the interface, which can be used to obtain the input impedance of the tag. Eq. (4) shows that the reflection coefficient Γ of the tag, which is independent to the distance from the reader antenna to the tag, and it is only related to the thickness of the wheat sample d. In fact, the thickness of the wheat sample box is known in our experiment (i.e., 18 cm).

2) Distance-free Algorithm: The purpose of this section is to develop a method to calculate the Fresnel reflection coefficient Γ for estimating the distance-independent tag impedance. Then the impedance of the tag can be obtained by (2). We propose the distance-free tag impedance method based on the Fresnel reflection coefficient, named the DisFre-Imp algorithm, which is presented in the following.

Step 1: Assuming that the Fresnel reflection coefficient and transmission coefficient of the electromagnetic waves incident on the interface of air→wheat and wheat→air are $\{\Gamma_1, \tau_1\}$ and $\{\Gamma_2, \tau_2\}$, respectively. Let ε_{air} and ε_{wheat} denote the dielectric constant of air and wheat, respectively. According to the electromagnetic wave transmission line theory, we have

$$\Gamma_1 = \frac{\sqrt{\varepsilon_{air}} - \sqrt{\varepsilon_{wheat}}}{\sqrt{\varepsilon_{air}} + \sqrt{\varepsilon_{wheat}}} = \frac{1 - \sqrt{\varepsilon_{wheat}}}{1 + \sqrt{\varepsilon_{wheat}}} \tag{5}$$

$$\tau_1 = \frac{2\sqrt{\varepsilon_{air}}}{\sqrt{\varepsilon_{air}} + \sqrt{\varepsilon_{wheat}}} = \frac{2}{1 + \sqrt{\varepsilon_{wheat}}}. \tag{6}$$

Note that $\varepsilon_{air} = 1.00058986 \pm 0.00000050$ for air at normal pressure and temperature. Similarly, the transmission coefficient τ_2 is given by

$$\tau_2 = \frac{2\sqrt{\varepsilon_{wheat}}}{\sqrt{\varepsilon_{air}} + \sqrt{\varepsilon_{wheat}}} = \frac{2\sqrt{\varepsilon_{wheat}}}{1 + \sqrt{\varepsilon_{wheat}}}. \tag{7}$$

It follows (5), (6), and (7) that

$$\Gamma_1^2 = 1 - \tau_1\tau_2. \tag{8}$$

Recall that Γ_1 represents the reflection coefficient from air to wheat, while Γ_2, on the contrary, represents the reflection coefficient from wheat to air. We thus have $\Gamma_1 = -\Gamma_2$.

Step 2: We put a metal plate at the back of the target box. When the electromagnetic wave is incident on the metal plate, the total reflection is considered to be $\Gamma_3 = -1$. From (3) and (4), the S-parameter of the metal plate S'_{11} can be expressed as

$$S'_{11} = \frac{E_{1r}}{E_{1i}} = \Gamma_1 - \frac{\tau C}{1 - \Gamma_1 C}. \tag{9}$$

Step 3: We now consider the case without the metal plate at the back of the sample box. Since $\Gamma_1 = -\Gamma_3$, and according to (3), the S-parameter S''_{11} can be written as

$$S''_{11} = \frac{E_{1r}}{E_{1i}} = \Gamma_1 + \frac{\tau\Gamma_3 C}{1 - \Gamma_2\Gamma_3 C} = \Gamma_1 - \frac{\tau\Gamma_1 C}{1 - \Gamma_1^2 C}. \tag{10}$$

Step 4: According to (8), (9) and (10), we obtain

$$\begin{cases} S'_{11} = \Gamma_1 - \frac{\tau C}{1-\Gamma_1 C} \\ S''_{11} = \Gamma_1 - \frac{\tau\Gamma_1 C}{1-\Gamma_1^2 C} \\ \Gamma_1^2 = 1 - \tau_1\tau_2 = 1 - \tau. \end{cases} \tag{11}$$

The S-parameters S'_{11} and S''_{11} can be measured by the VNA device. With the three equations, we can calculate the reflection coefficient Γ_1 of the tag (i.e, the reflection coefficient Γ_{12}) and then the tag impedance can be obtained by (2).

C. Angle-agnostic Method

The main idea of TagSense is to map tag impedance to wheat moisture and temperature. Thus, it is important to obtain stable impedance values. However, when the wheat sample box is put at different locations, the accuracy of impedance measurement will be affected by the different incident angles between the tag and the reader antenna in the experimental environment. To make the TagSense system more robust, we propose a angle-agnostic method to reduce the sensitivity to the measurement angle, which includes two steps as follows.

1) Circular Polarization Antenna: Antenna polarization can help to control the spatial direction of antenna radiated electromagnetic wave vector. It considers the spatial direction of the electric field vector as the polarization direction of antenna radiated electromagnetic wave. Another characteristic of the antenna is the beamwidth which determines the coverage of electromagnetic wave scattering. Antenna polarization with a suitable beamwidth can well reduce the directional sensitivity of the tag. TagSense utilizes a circular polarization antenna with a 65° beamwidth to achieve resilience to different measurement angles.

2) Multi-Class SVM: The second step is a multi-class SVM method to measure stable impedance values, which operates in the following steps.

Step 1: We establish the training and testing datasets, which are constructed at the same time and selected randomly. The tag impedance value with 0° is set as the training target.

Step 2: The data input is normalized to the range of [0, 1].

Step 3: We select the kernel function and parameters to construct a multi-class SVM model. In this paper, we choose the Gaussian radial basis function (RBF) as the kernel function.

Step 4: The multi-class SVM is trained using the samples in the training dataset, where the LIBSVM toolbox is used to implement the angle-free impedance classification scheme [18].

Step 5: The trained model is then used for classification of a new impedance measurement with a random angle.

IV. Experiments and Results

A. TagSense Implementation

In our experiment, we use a box of size 31.5cm×18cm×18cm to hold wheat samples. The TagSense system is implemented with a passive RFID tag (i.e., Alien 9640 with Higgs 3 chip), a reader antenna (i.e., Laird2 S9028 PCR RFID antenna), a VNA device (i.e., Tektronix TTR506A, power 10dB), a tablet computer, and a metal plate (copper of 1mm thickness), as shown in Fig. 3. The tag is attached to the box holding wheat samples, which is placed in the sensing area. The reader antenna is connected to the VNA device to send and receive electromagnetic waves. The measured signal can be displayed on the tablet computer. The metal plate is used for experiment with total reflection.

B. Robustness Verification

We conduct different experiments in a laboratory at about 20° room temperature. We rotate the wheat box to which the RFID tag is attached from $-\pi/2$ to $\pi/2$ in steps of 5°, and record the measured tag impedance for each resulted measurement angle. The frequency range is from 860 MHz to 960 MHz. We also verify the distance-free algorithm at different distances within 100 cm at steps of 2 cm, and record the tag impedance for each distance.

The results are presented in Fig. 4. Fig. 4(a) shows that the tag impedance remains stable over different distances, while the real part is about 83 Ohm. It only starts to fluctuate

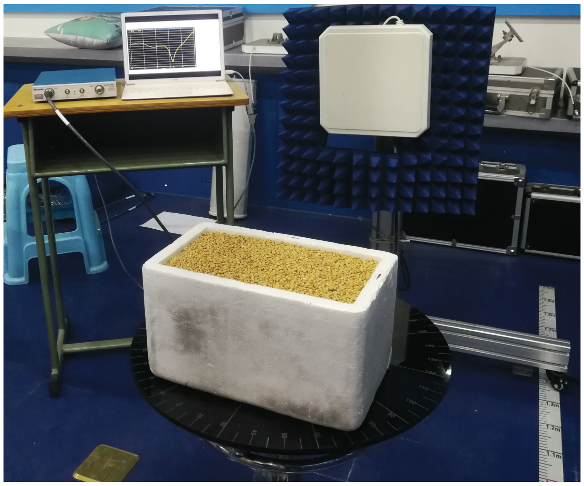


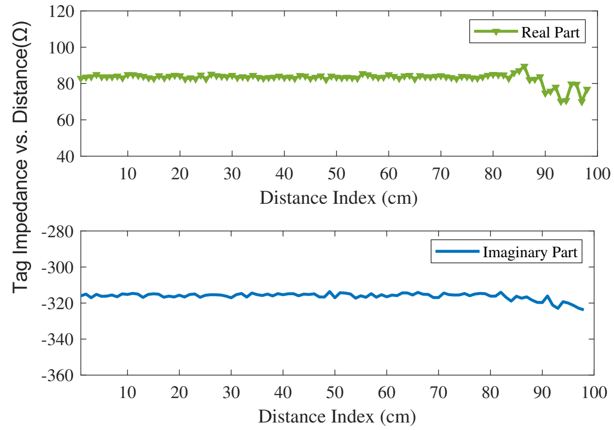
Fig. 3. Experimental configuration.

when the distance goes beyond 80 cm. This implies that the measurement becomes unstable when the distance is greater than 80 cm. Fig. 4(b) shows the variations of tag impedance over different rotation angles. We can see that with the increase of rotation angle, there are more cross-over points of the impedance curves for different moisture contents. However, we can still obtain impedance value at a 98.6% accuracy within 80 cm range and at angles from -30° to $+30^\circ$.

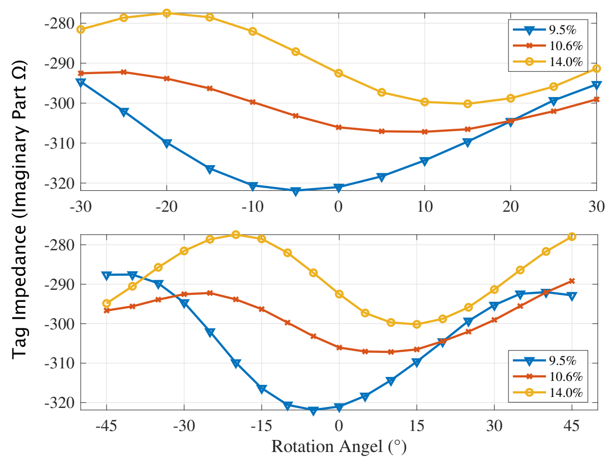
C. Sensing Wheat Moisture and Temperature

We next show how the measured tag impedance can be used as a feature to estimate wheat moisture and temperature. In this experiment, we use several wheat samples at moisture levels, i.e., {7.7%, 9.5%, 10.6%, 14.0%, 16.0%, 17.2%}, while the room temperature is about 20° and the resonance frequency is 942.5 MHz. The tag impedance versus moisture level curve is presented in Fig. 5(a). We can see that the real part of the tag impedance increases with the increase of moisture content in wheat samples. Thus, tag impedance can be a useful feature to detect the moisture change. In addition, we examine the relationship between tag impedance and wheat sample's temperature. Specifically, we freeze the wheat sample with 14.0% moisture content to the temperature of -10°C in a refrigerator and set the laboratory room temperature at 20°C. We then observe the changes of tag impedance at the resonant frequency when the wheat sample temperature rises from -10°C to 20°C. Fig. 5(b) shows the relationship between temperature and the real part of tag impedance (i.e., the linear fitting result between temperature and the real part of tag impedance). It can be seen that there is a nice linear relationship between temperature and the real part, with $R^2 = 0.9968$ and the average relative error of $RE = 4.4\%$. Note that R^2 is a measure of how well the model fits data ($R^2 = 1$ indicates a prefect fit).

Table I presents the detection accuracy of TagSense for six moisture levels from different angles and ranges achieved by the multi-class SVM method. It can be seen that for different moisture levels, TagSense can always achieve a high classification accuracy (e.g., 100% accuracy for the moisture level of 16.0%). Table II shows the R^2 and the relative error rate with the optimal fitting curve, where M denotes the moisture level, and R^2 represents the closeness between the fitting curve and the test data. It can be concluded from Fig. 5(c) and Table II that the tag impedance can well represent the changes of temperature (i.e., the temperature and impedance (real part) can be well fitted using a linear function).



(a) Over different distances

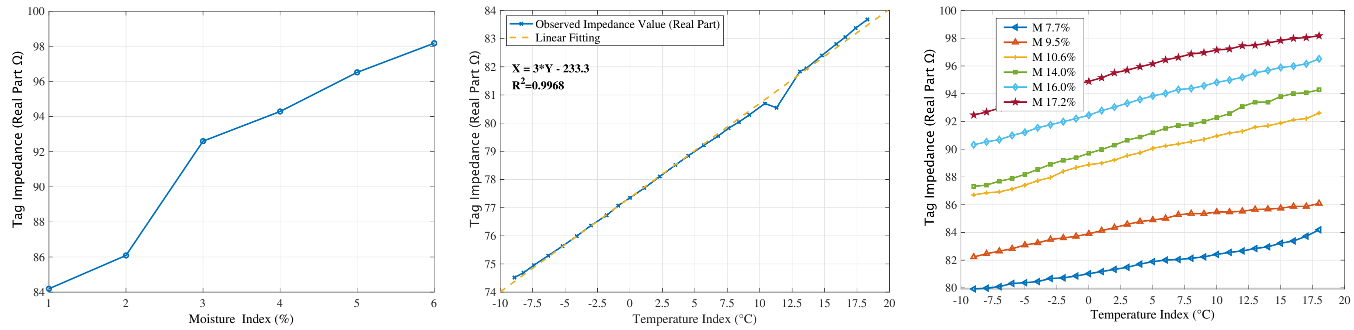


(b) Over different angles

Fig. 4. RFID tag impedance over different measurement distances and angles.

V. Conclusions

In this paper, we proposed the TagSense system for robust wheat moisture and temperature sensing using a passive RFID tag. We first examined the measurement method and the feasibility of using tag impedance for moisture and temperature sensing. Then, we presented the TagSense system including data sensing, a distance-free tag impedance measurement algorithm, and an angle-agnostic method using a multi-class SVM algorithm. Finally, our experimental results showed that the TagSense system can achieve high sensing accuracy of moisture and temperature in different rotation angles and at different distances.



(a) Moisture vs. real part of tag impedance (b) Temperature vs. real part of tag impedance (c) Temperature vs. real part of tag impedance

Fig. 5. Moisture and Temperature versus real/imaginary parts at the resonance frequency.

TABLE I
IDENTIFICATION ACCURACY OF SIX WHEAT MOISTURE LEVELS IN DIFFERENT ROTATION ANGLES

Rotation Range \ Moisture Levels	7.7%	9.5%	10.6%	14.0%	16.0%	17.2%	Average
$0°$	100%	100%	100%	100%	100%	100%	100%
$-\pi/6$ to $+\pi/6$	95.9%	97.5%	100%	100%	100%	94.8%	98.6%
$-\pi/4$ to $+\pi/4$	94.6%	100%	99.5%	92.9%	100%	94.5%	96.9%
$-\pi/3$ to $+\pi/3$	91.2%	97.4%	99.5%	87.4%	100%	87.0%	93.8%
$-\pi/2$ to $+\pi/2$	86.1%	91.2%	91.2%	88.1%	100%	83.6%	90.3%

TABLE II
ACCURACY OF CURVE FITTING WITH DIFFERENT MOISTURE LEVELS

	$M = 7.7\%$	$M = 9.5\%$	$M = 10.6\%$
Fitting Curve	Conic	Linear	Linear
R^2	0.994	0.9632	0.9951
Error rate	3.90%	10.0%	1.70%
	$M = 14.0\%$	$M = 16.0\%$	$M = 17.2\%$
Fitting Curve	Conic	Conic	Conic
R^2	0.999	0.9989	0.997
Error rate	4.20%	4.50%	2.10%

Acknowledgments This work is supported in part by the Program for Science & Technology Innovation Talents in Universities of Henan Province (19HASTIT027), National Natural Science Foundation of China (62172141), Zhengzhou Major Scientific and Technological Innovation Project (2019CXZX0086), Youth Innovative Talents Cultivation Fund Project of Kaifeng University in 2020 (KDQN-2020-GK002), the National Key Research and Development Program of China (2017YFD0401001), NSFC (61741107), and NSF (ECCS-1923163, CNS-2105416, and CNS-2107164).

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