RFID Tag-equipped Drone for Antenna Array-based Localization: A Step-by-Step MATLAB Simulation Tutorial

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***Abstract*—In the last decades, Radio Frequency Identifiers (RFID) have gained massive popularity. RFID technology allows data to be encoded in a small form (tag). The data contained inside the RFID tag can be captured wirelessly by the RFID reader through electromagnetic (EM) waves. On the other hand, localization techniques have achieved significant developments in the last decade. There is a wide range of localization tool variations, including satellite-based localization (i.e., GPSS, GLONASS), Bluetooth Low Energy (BLE), IMU, camera, infrared sensor, and even RF-based localization. In this work, we present an accurate localization technique via battery-less passive RFID tag-UAV integration. We have employed two low-complexity methods: generalized cross-correlation with phase transformation (GCC-PHAT) algorithm and triangulation technique. By simulation, we have validated that an accurate antenna array-based dynamic localization can be realized. For the sake of simplicity, we only demonstrate two-dimensional movement. However, the identical method can also be used in the three-dimensional movement. While this paper considers only two antenna arrays and one RFID tag, the proposed concept can be expanded to a more extensive system with a larger number of antenna arrays and RFID tags.**

***Index Terms*—radio frequency identifiers (RFID), drone, antenna array, localization, MATLAB**

I. Introduction

Radio Frequency Identifiers (RFID) have become one of the fastest growing commodities of networked devices. In 2019 alone, at least 20 billion RFIDs were produced worldwide [1]. RFID is a technology that allows data to be encoded in a small form (tag). The data contained inside the RFID tag can be captured wirelessly by the RFID reader through electromagnetic (EM) waves. A typical RFID tag weighs only around 1 gram [2] and can be produced in various forms (e.g., keychain, stickers, flexible card). An RFID tag is available on the market at a price as low as 0.05 to 0.1 USD [3], while the RFID reader can be fabricated with a production cost as low as 9.35 USD [4]. Due to these factors, RFID has gained huge popularity. In accordance with its name, RFID has mainly been used as an identifier to identify and track various ranges of items such as books, groceries, electronic devices, pets, and even livestock.

Despite its popularity, the RFID system has a major limitation. A typical passive RFID tag can only be readable within a few meters of distance in a line-of-sight (LoS) situation [5], [6]. In the non-line-of-sight (nLoS) situation, when the RFID tag surface is covered by a wall, furniture, or even a thick book, for example, the readability of the RFID tag becomes worse. In fact, [7] has revealed that in a room with densely-populated RFID readers, there still remains up to 80% of RFIDs lie in a blind spot.

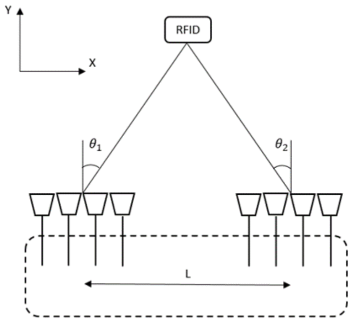

Fig. 1. Antenna Array-Based Localization System.

The researcher has proposed various approaches to combat this problem. One of the approaches is to integrate the RFID system into unmanned aerial vehicle (UAV) technology [8]–[10]. In the last decade, UAVs have attracted massive interest from both academia and the industry. UAV promises a new paradigm to the future wireless network by offering a mobile RF console. To this date, UAVs have been employed to serve as a dynamic access point [11], repeater [12], and even mobile base station [13].

On the other hand, localization techniques have achieved significant developments in the last decade. There is a wide range of localization tool variations, including satellite-based localization (e.g., GPS, GLONASS, and Galileo) [14]–[16], Bluetooth Low Energy (BLE) [17], IMU [18], camera [19], infrared sensor [20], and even RF localization [21]. Therefore, in this work, we present an accurate localization technique via battery-less passive RFID tag-UAV integration. This work aims to demonstrate the possibility of employing low-complexity techniques to realize the dynamic antenna array-based localization of passive RFID tag-equipped drones. To achieve our objective, we have considered multi-antenna arrays, each of which is capable of transmitting and receiving EM waves from-and-to the RFID tag. Based on the MATLAB simulation, it is observed that an accurate RFID Tag-equipped antenna array-based localization concept can be achieved.

Finally, the rest of this paper is organized as follows. Section II comprises the system model of the localization system.

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Then, in Section III, we present the step-by-step MATLAB simulation along with the simulation results. Lastly, the conclusion of this work is presented in Section IV.

II. System Model

Fig. 1 illustrates the overall model of the antenna array-based localization system. Let us assume that there are a set of antenna arrays, each of which is separated by L distance. The antenna array is located on the ground and is equipped with an RFID reader. Then, an RFID tag is attached to a moving object (e.g., drones) with unknown dynamic locations. For simplicity, the system model is confined to a two-dimensional scenario with two antenna arrays and one RFID tag. Each antenna array comprises four antennas. The objective of the proposed localization system is to estimate the location of the moving RFID tag by using the signals received by the antenna arrays. To acomplish that, there are two steps to determine the location of the RFID tag, which are explained as follows.

- DoA Estimation: In the first stage, the direction of the RFID tag toward each antenna array is determined by using the direction of arrival (DoA) technique. To do that, one can exploit the difference in the signal's time of arrival among the antenna elements. By utilizing the time difference, the DoA is determined. Indeed, there are too many accurate methods to determine the DoA. However, in this work, we employed a generalized cross-correlation with the phase transformation (GCC-PHAT) algorithm to illustrate the DoA estimation stage. GCC-PHAT is chosen for its simplicity and its availability inside the MATLAB system toolbox.
- RFID Tag Position Calculation: In this stage, the RFID tag position is calculated by using the triangulation technique. To do that, first, we need to draw a straight line from each antenna array along the arrival direction. Note that in this work, we only consider two antenna arrays and one RFID tag. Then, by calculating the intersection of the two straight lines, the RFID tag position can be estimated.

A. Triangulation Formula

Basically, the triangulation formula is just a simple trigonometric formula. Let us consider the system model in Fig. 1 as a two-dimensional scenario. Assuming that the first antenna array is located at the coordinate $(0, 0)$ and the second antenna array is placed at $(L, 0)$. Then, the RFID tag location is located at (x, y). After the DoA estimation, we obtain the direction of arrival toward the first antenna array as θ_1 and toward the second antenna array as θ_2. By using the triangulation formula, we can rewrite the L as

$$L = y \tan\theta_1 + y \tan\theta_2. \quad (1)$$

Then, the coordinate of the RFID tag (x, y) is obtained as

$$x = y \tan\theta_1 \quad (2)$$

$$y = \frac{L}{\tan\theta_1 + \tan\theta_2} \quad (3)$$

III. MATLAB Simulation

In this section, let us briefly explain the step-by-step MATLAB tutorial for simulating the RFID tag-equipped drone for the antenna array-based localization system.

A. RFID Tag and Antenna Array Setup

For the first step, we have to define the RFID and the antenna array setup. As aforementioned, for simplicity, let us consider two antenna arrays. Each antenna array comprises four antennas and is separated by L from the other antenna array. For the demonstration purpose, let us consider crossed dipole antenna element. The antenna setup can be easily configured by using `phased.ULA` function as follows.

```
L1 = 0;

L2 = 30;

N_Ant = 4;

Ant_ULA = phased.ULA('Element',phased.CrossedDipoleAntennaElement,'NumElements',N_Ant);
```

After the antenna arrays are initialized, we have to determine the position of the first and second antenna arrays. Since the simulation only considers a two-dimensional setup, let us initialize the position of the first antenna array as $(0, 0)$. Then, the second antenna array is placed at $(L, 0)$. With this condition, the two antenna arrays are 30m separated from each other in the x-axis direction.

```
Ant_pos1 = [L1;0;0];

Ant_vel1 = [0;0;0];

Ant_ax1 = azelaxes(90,0);

Ant_pos2 = [L2;0;0];

Ant_vel2 = [0;0;0];

Ant_ax2 = Ant_ax1;
```

Besides the antenna array position, we also have to declare the RFID tag position as well. The actual RFID tag location, indicated by `rfid_pos`, will be the ground truth to be compared with the estimation result from the localization algorithm. As an example, let us set the actual coordinate of the RFID tag as $(15, 100)$.

```
rfid_pos = [15;100;0];

rfid_vel = [0;0;0];

rfid_ax = azelaxes(-90,0);

rfid_ULA = phased.CrossedDipoleAntennaElement;
```

B. Radio Wave Setup

For the next step, let us configure the radio wave parameters. In this simulation, we set the carrier frequency as 300 kHz and the bandwidth as 100 kHz. The radio wave parameters are configured into the `phased.LinearFMWaveform` function.

```
fc = 300e3;             % 300 kHz

bw = 100.0e3;           % 100 kHz

fs = 2*bw;

waveform = phased.LinearFMWaveform('SampleRate',fs,'SweepBandwidth',bw,'PRF',5,'PulseWidth',0.02);

signal = waveform();

n_sub = 128;
```

C. Radiation, Propagation, and Receive Signal Modeling

In this step, we specify the parameters for radiation, propagation, and receive signal modeling by using the functions that are already available in the toolbox, such as `phased.WidebandRadiator` and `phased.WidebandCollector`.

```
radiator = phased.WidebandRadiator('Sensor',
rfid_ULA,'PropagationSpeed',c,'SampleRate',fs,
CarrierFrequency',fc,'NumSubbands',n_sub);

collector1 = phased.WidebandCollector('Sensor',
Ant_ULA,'PropagationSpeed',c,'SampleRate',fs,'
CarrierFrequency',fc,'NumSubbands',n_sub);

collector2 = phased.WidebandCollector('Sensor',
Ant_ULA,'PropagationSpeed',c,'SampleRate',fs,'
CarrierFrequency',fc,'NumSubbands',n_sub);
```

Then, we call the `phased.WidebandFreeSpace` function to realize the wideband signal propagation paths between the RFID tag and the antenna arrays.

```
channel_1 = phased.WidebandFreeSpace('
PropagationSpeed',c,'SampleRate',fs,'
OperatingFrequency',fc,'NumSubbands',n_sub);

channel_2 = phased.WidebandFreeSpace('
PropagationSpeed',c,'SampleRate',fs,'
OperatingFrequency',fc,'NumSubbands',n_sub);
```

Besides the propagation paths, we also have to determine the propagation directions between the RFID tag and the antenna arrays. These propagation directions are determined concerning the location of the RFID tag.

```
[~,ang1t] = rangeangle(Ant_pos1,rfid_pos,
rfid_ax);

[~,ang2t] = rangeangle(Ant_pos2,rfid_pos,
rfid_ax);
```

After the parameters are set, we need to radiate the signals from the antenna arrays to the RFID tag, which will then be re-radiated back toward the antenna arrays.

```
sigt = radiator(signal,[ang1t ang2t]);

sigp1 = channel_1(sigt(:,1),rfid_pos,Ant_pos1,
rfid_vel,Ant_vel1);

sigp2 = channel_2(sigt(:,2),rfid_pos,Ant_pos2,
rfid_vel,Ant_vel2);
```

In this simulation, we need to compute the DoA of the received signal at the antenna arrays. Since the collector response is a function of the DoA in the antenna array coordinate system, we need to pass the local coordinate axes matrices to the `rangeangle` function. The `rangeangle` function returns the path distance and angles in the local or global coordinate systems.

```
[~,ang1r] = rangeangle(rfid_pos,Ant_pos1,
Ant_ax1);

[~,ang2r] = rangeangle(rfid_pos,Ant_pos2,
Ant_ax2);
```

Then, the signals are collected at the antenna arrays as:

```
sigr1 = collector1(sigp1,ang1r);

sigr2 = collector2(sigp2,ang2r);
```

D. DoA Estimation and RFID Tag Position Calculation via Triangulation

At this point, let us explain the implementation of the localization algorithm. To estimate the location of the RFID tag using DoA estimation and triangulation formula, first, we have to call the estimator using `phased.GCCEstimator` function.

```
doa1 = phased.GCCEstimator('SensorArray',
Ant_ULA,'SampleRate',fs,'PropagationSpeed',c);

doa2 = phased.GCCEstimator('SensorArray',
Ant_ULA,'SampleRate',fs,'PropagationSpeed',c);
```

Then the DoA from the collected signal at the receive antenna arrays can be estimated as:

```
theta_1 = doa1(sigr1);
theta_2 = doa2(sigr2);
```

After obtaining the DoA for each antenna array, we calculate the coordinate of the RFID tag using a triangular formula. Once again, since this simulation only consider two-dimensional coordinate (i.e., x-axis and y-axis), we have set the z-coordinate value to zero.

```
y_coor = L2/(abs(tand(theta_1)) + abs(tand(
theta_2)));

x_coor = y_coor*abs(tand(theta_1));

z_coor = 0;

rfid_coordinate = [x_coor;y_coor;z_coor]
```

E. Estimated Coordinate Result

By running the example code, we will get the estimated coordinate of the RFID-tag at $(15.0041, 99.6409)$ (See. Fig. 2). This result is matched with the actual coordinate of the RFID tag, which has been defined before in the `rfid_pos`. Recall that we define the actual location of the RFID tag as $(15, 100)$. It is observed that the difference between the actual and estimated coordinates is relatively small.

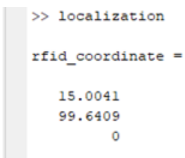

Fig. 2. Estimated Coordinate from the Localization Simulator.

F. Mobile Drone Simulation

The objective of this paper is to simulate a dynamic localization technique to estimate the location of a moving object. However, to this point, we have only demonstrated the localization for the static RFID tag. Hence, in this subsection, we present the simulation for dynamic localization. Assume that the RFID tag is attached to a flying drone that is dynamically moving around the room. The antenna arrays need to gather all of the received data to localize the RFID tag. In order to simulate this kind of scenario, we have employed the previous code and run it repeatedly, with the gradual changes of the x-axis and y-axis coordinates. These gradual changes are analogous to the drone movement.

As an example, assume that the drone is stationary at the coordinate of $(10, 100)$. Then, as time goes by, the drone

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is started moving in a circular manner toward the $(12, 100)$ coordinate, then moving to the $(13, 250)$ coordinate. The illustration of this scenario is depicted in Fig. 3.

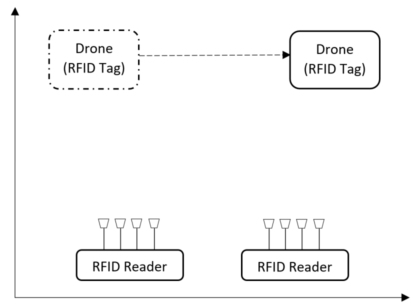

Fig. 3. Dynamic Localization of the RFID Tag Attached to a Moving UAV.

As can be seen in Fig. 4, the estimated RFID tag location is in line with the simulation scenario. Several circles are located around the $(10, 100)$ point, indicating that the drone is stationary at the $(10, 100)$ position. Then, the other circles indicate the movement of the drone. Note that there are imperfections in the estimated location results. The imperfections between the actual coordinate and the estimated coordinate are caused by the error in the calculation of the DoA due to the drone movement. The error of the DoA estimation affects the triangulation calculation, which then leads to the error in the RFID tag coordinate estimation.

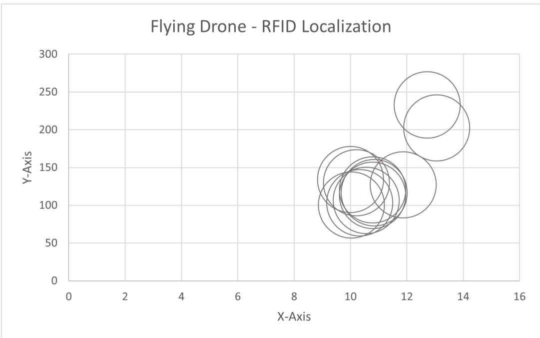

Fig. 4. Flying Drone Localization Simulation Result.

IV. Conclusion

In this article, we present a step-by-step MATLAB simulation tutorial for the RFID tag-equipped drone for the antenna array-based localization system. We have employed two low-complexity methods, namely generalized cross-correlation with phase transformation (GCC-PHAT) algorithm and triangulation technique. By simulation, we have validated that an accurate antenna array-based dynamic localization can be realized. For the sake of simplicity, we only demonstrate two-dimensional movement. However, the identical method can be used in three-dimensional movement as well. While this paper considers only two antenna arrays and one RFID tag, the proposed concept can be extended to a larger system with a bigger number of antenna arrays and RFID tags. Lastly, the MATLAB code in this work can be reproduced and used freely for localization-related research and development.

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