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REGULAR PAPER

Aerial Locating Method Design for Civil Aviation RFI: UAV Monitoring Platform and Ground Terminal System

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Abstract

A key open question in the aerial locating method is ensure that parameters that identify the location of the radio frequency interference (RFI) are monitored, and to make sure that the locating algorithm is unbiased. Furthermore, the transmission of parameters to the ground for real-time analysis and display of the RFI location is important as it provides insight into the performance advantages of the aerial location method. The main contributions of the article are four points: the first is the introduction of the angle of arrival (AOA) algorithm to civil aviation RFI location, and the integration of algorithm characteristics with unmanned aerial vehicle (UAV) operations proposing an aerial monitoring method for civil aviation RFI. Simulation results show that the two-point cross-location method obtains effective information on the location parameters of the RFI. The second is to build a UAV monitoring platform, which is as light as possible to make sure the direction finding and digital transmission devices meet the airworthiness requirements, so that the UAV can complete the data acquisition task within a safety margin. Thirdly, a ground analysis system was designed to receive information on the UAV's parameters, enabling software manipulation to ensure safe operation under non-visual conditions. In addition to this, the monitoring data is processed in real time and algorithms are used to resolve the location of interference sources and display them on a map. The fourth one is to verify the implementation of the aerial positioning method by setting up different test scenarios. Compared with portable direction-finding equipment and ground monitoring, the test results show that the UAV-based RFI monitoring method performances better in monitoring radius and positioning accuracy with a small direction-finding error, and the advantages of the ground analysis system are highly integrated and intuitive display.

Keywords RFI · AOA · UAV · Monitoring · Civil aviation

1 Introduction

In the field of aviation, " illegal broadcast", "pseudo-base stations" and other electronic devices, and their transmitting frequency is very close to that of very high frequency (VHF) [1–4], which generates serious intermodulation interference to civil aviation radio frequencies [5–7]. Radio interference can reduce or even interfere with ATC radio communications and important avionics equipment [8], which poses a serious threat to the safety and may lead to temporary airport closures. In recent years, the number of reported radio interference of airports around the world has increased significantly [9, 10]. According to the east China ATC bureau, there were 334 radio interference incidents in east China in 2015, since then, more than 300 interference incidents have been reported each year [11, 12]. Among them, the aerial interference events in 2019 accounting for 53%, the aerial interference become the main factor of civil aviation RFI. To prevent civil aviation RFI [13], in recent years, the International Civil Aviation Organization (ICAO), Ministry of Industry and Information Technology (MIIT) and Civil Aviation Administration of China (CAAC) issued several radio management regulations and normative documents [14]. In addition, the Supreme People's Court of the People's Republic of China (SPC) and Supreme People's Procuratorate of the People's Republic of China (SPP) issued

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a lot of legal documents, providing a powerful legal weapon to punish the illegal setting of radio stations [15]. Although all levels of the state have strengthened the protection of dedicated civil aviation radio frequencies, and the radio management and CAA departments have selected expensive professional equipment and employed professional personnel to detect, civil aviation radio interference incidents still occur frequently.

Thus, there is an urgent need for an efficient and low-cost way of RFI detection in civil aviation. The traditional way of RFI monitoring and locating generally needs to monitor and locate the interference source signal through more than two fixed monitoring stations to determine the approximate area first, and then send out the monitoring vehicle to approach the target area. After further narrowing the range, portable direction-finding equipment is used to locate the interference source and finally locate the actual location of the source [16]. In the above method of using portable equipment to approach and find the interference source, it is easy to encounter the situation of obstacle blockage or complex geographical environment, so that affects the monitoring accuracy and stability. In addition, this method costs too much labor and time and is difficult to monitor airborne interference [17]. Thereby, CAAC has prepared a draft regulatory standard system for the application of UAV communication and navigation surveillance technology, which is recommended to use UAV platforms to carry special equipment to carry out the RFI investigation in the area, especially in the airport area, by using an aerial-ground coordination method.

In this work, we propose a UAV-based RFI aerial monitoring method, which can avoid the multipath effect of radio waves caused by obstacles and improve the advantages of ground-based methods for detection. This method can not only monitor aerial interference, but also ground - aerial interference and ground interference well.In addition, we also designed an RFI ground analysis system to achieve real-time display of aerial monitoring system data while manipulating the UAV to determine the location of RFI.

This ground analysis system combines the UAV control with interference source analysis, which can be completed by one person at a time, reducing monitoring difficulty and manpower consumption. In order to verify the feasibility and availability of the aerial monitoring method, this paper experiments on the system's directional error, monitoring radius, and two-point cross-location accuracy. According to the result, compared with ground monitoring methods, the UAV-based monitoring method is highly mobile, inexpensive, easy to operate, and can quickly locate the location of civil aviation RFI, which is suitable for use in open areas around airports.

While the radio wave propagating on the ground, refraction, reflection, scattering, bypassing and other phenomena will occur, but it will not happen when the propagation is in the air. And the radio signal direct wave can be detected in the use of UAV monitoring platform in high altitude. In addition, small UAVs have the characteristics of mobility, flexibility, low-cost and simplicity of operation, etc. With the continuous development of communication technology and UAV technology, the reliability and safety of UAV monitoring systems will continue to be improved, and the airtime will continue to be extended. Meanwhile, the use of UAVs to monitor RFI could provide a fast and efficient solution to ensure civil aviation radio security. The use of Multi-rotor UAV as a tool for RFI monitoring offers several advantages:

(1) The change in pitch to produce a change in thrust and torque is not needed any more, which makes the mechanical design simplified and reduces the maintenance costs.
(2) The use of multiple rotors makes each rotor smaller in diameter, which reduces the chance of collision with external objects.
(3) The use of multi-rotors greatly enhances the maneuvering flexibility to work in harsh, complex mission environments with less risk.
(4) In the event of a failure of one of the power outputs, the airframe can still maintain attitude stability.

The rest of this paper is organized as follows: Section 2 reviews the current status of research on RFI localization methods; Section 3 describes the adopted RFI localization algorithm, the hardware components of the aerial monitoring system and the functional modules of the ground analysis system. Section 4 tests the over-the-air monitoring system and evaluates the results; Section 5 concludes the whole paper.

2 Related Works

Aeronautical CNS systems are increasingly dependent on radio and radio spectrum monitoring becoming increasingly important [18]. Many papers pointed out that intermodulation interference is the main cause of interference in navigation aids [19–23]. [24] evaluating the effect of third-order intermodulation distortion on very high frequency (VHF) omnidirectional range and instrument landing systems used by the Ghana Civil Aviation Authority (GCAA). These interferences can affect the exchanged signals integrity and cause communication errors, thus, rapid RFI elimination is critical to civil aviation safety [10]. To solve the low efficiency and difficulty of RFI eliminate in civil aviation, various researchers have done some studies on monitoring methods and monitoring approaches [25].

Ground-based monitoring methods are usually expensive and time consuming, and may not be able to detect aerial interference [26]. An array of large-aperture sensors mounting on an airship to transmit signals from the aerial to the ground could estimate the location of RFI and work out methods that could be calibrated in real time for internal errors [27]. [28] also using airships as aerial platforms carrying radio monitoring equipment to monitor RFI, when the flying height reaches 100 m, most of the monitoring signals could be monitored. However, the large size of the airship would threaten the safe operation of the aircraft and would not be flexible enough or easily controlled. Some researchers have used a more feasible approach, [29–31] developing a model which enables to detection of the potential RFI based on measurements of GPS carrier to noise (CNo) and helicopter attitude. A RFI reducing the CNo by only a few dB can be detected in this way. However, this method requires helicopters to collect data over a large area, and in China, where the development of aeronautics is slow [32], the number of helicopters that can operate is small and flight routes must be requested in advance [33], a complex approval process with long lead times that does not allow a rapid location of RFI. However, the airline route involves a wide geographical range. Thus, combining civil airliner automatic dependent surveillance-broadcast (ADS-B) messages with ground-based radio surveillance spectrum data was proposed to monitor potential RFI along the route promptly [34]. However, since radio monitoring agencies have not yet established links with airlines in this area, data availability is poor and difficult to implement. In addition, the civil aviation Global Navigation Satellite System (GNSS) interference management method has been proposed and the data recorded onboard the aircraft to locate RFI while implemented a function to warn of interference signals has been applied [35]. But this type of approach also fails to meet the availability of data and lacks the software for real-time processing simultaneous for jamming and spoofing. These problems can be avoided by using small UAVs. The possibility of using UAV in spectrum monitoring and radio interference detection was investigated by [36]. An RFI positioning system based on UAV has been proposed and the monitoring platform trajectory planning technique has been studied, but no prototype was applied to the actual scenario, and its reliability was debatable and it was not possible to achieve UAV monitoring [37]. At the same time, the visual condition operation could not meet the security requirements around the airport. Moreover, it is not possible to display the positioning results in real time.

RFI positioning technology is usually based on RSS [38, 39]. [40] combining with UAV by using a collection of signal strength measurements to determine the location of RFI. But the use of RSS is relatively simple and the actual positioning accuracy is low. This method is suitable for indoor positioning [41, 42], but not for the airport surroundings where the electromagnetic signal is complex. In addition, TOF [43, 44], TDOA [45–48], and AOA [49–53] are used to locate RFI. In addition to using a single method for positioning, there is also a joint positioning method. [54] explores the possibility of using AOA and TDOA observations to achieve particle filter positioning RFI. TOF positioning requires multiple sampling integrations and long measurement times [55], and the range of the UAV does not allow for a complete measurement. TDOA positioning is more accurate, but requires multi-machine collaboration with multiple operators working together [56]. Multiple methods combination positioning is more accurate than single method positioning, but the method is still in the theoretical stage and relies on interaction with ground stations, making it less independent than single machine monitoring. In contrast, the use of AOA for positioning is relatively accurate [57], and the complexity of a multi-UAV system and the interaction with ground stations can be avoided by operating a single UAV flying to different locations for measurements.

This study makes up the inability to monitor the direct radio waves by using the ground equipment. Compared to other aerial monitoring equipment, the use of Multi-rotor UAVs not only has an advantage in its structure, but also has an advantage in getting an official approval quickly. On this basis, we designed an aerial positioning method, including the construction of an UAV monitoring platform as well as the design of a ground analysis system. This study provides a solution for a rapid and effective identification of RFI monitoring in Chinese civil aviation, which is of practical significance to ensure the safe operation of aeronautical CNS systems.

3 Proposed Methodology

The main focus of this study is monitoring the RFI around civil aviation airports using the UAV-mounted radio direction-finding system, and analyzing the location information through its return data. To this end, an aerial monitoring scheme was proposed based on theoretical analysis and application scenarios. After determining its feasibility through simulation, an aerial monitoring system was built. However, the integration of the system is not high enough, and multiple people are required to complete it. To further improve the degree of automation, a set of matching ground analysis systems is also designed. The specific application scenarios of this research are shown in Fig. 1. The detailed methods, the hardware components and their functions will be described in detail in the rest of this section.

3.1 System Composition

The system which is the UAV-based RFI monitoring and analysis method consists of three parts, UAV, airborne direction-finding equipment and ground analysis system. UAV and airborne direction-finding equipment can be called

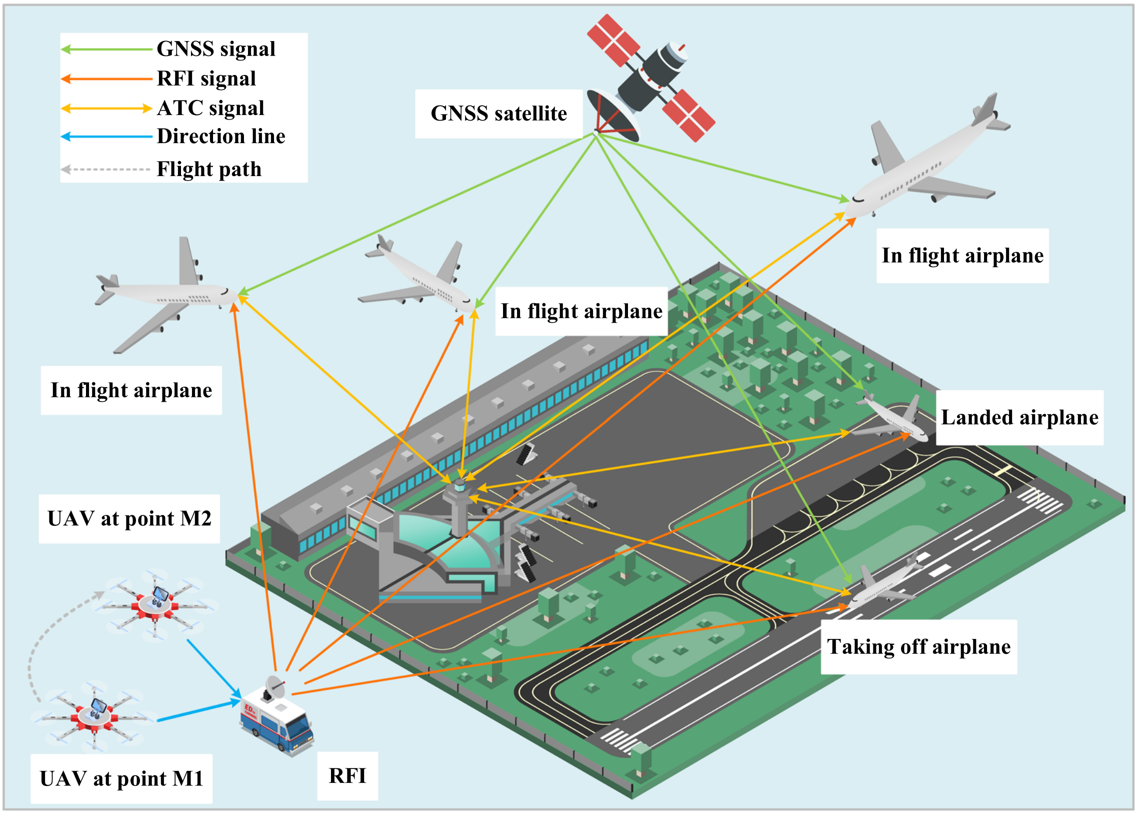


Fig. 1 UAV positioning civil aviation RFI application scenario

aerial monitoring systems. The composition of the entire system is shown in Fig. 2.

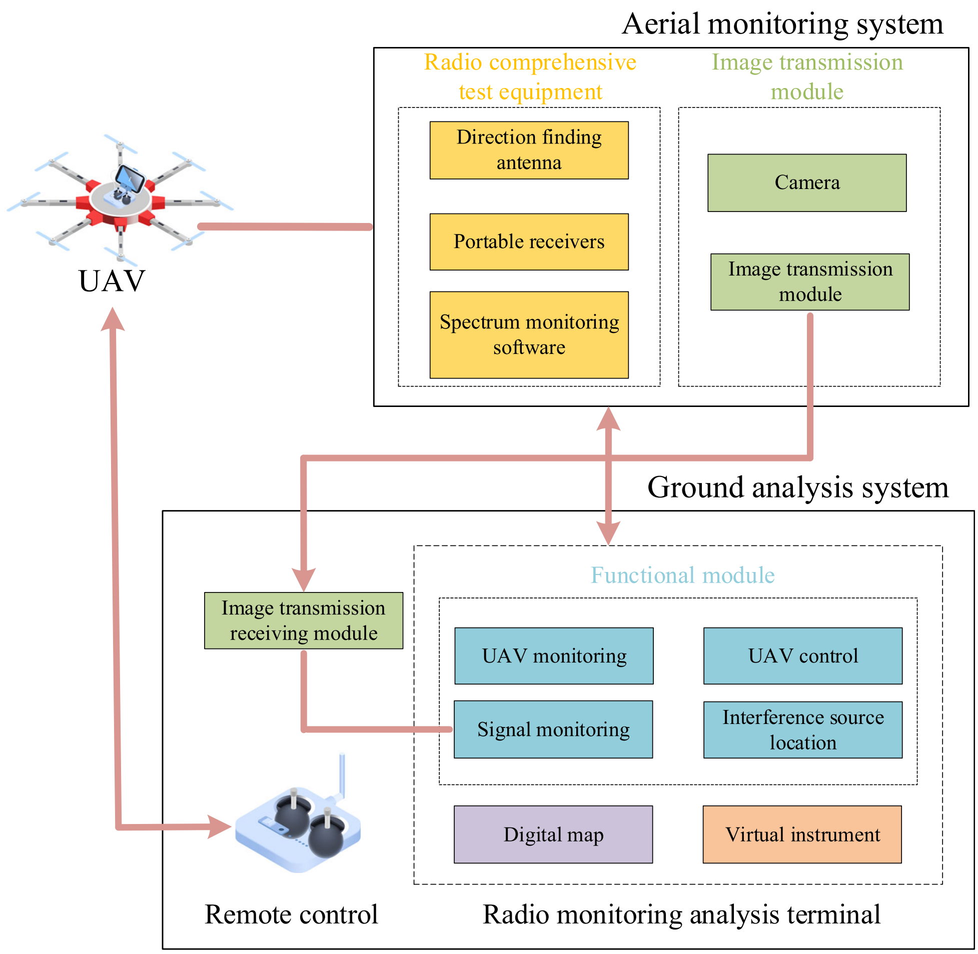
3.2 Aerial Monitoring System

This monitoring method uses a small UAV as a platform equipped with a radio direction-finding system to achieve aerial maneuverability. The model should meet the characteristics of long-lasting endurance, strong load and portability. D JI S100 adopts V-shaped 8-rotor design, which can provide sufficient power. When equipped with the battery model 6S 15000mAh, the endurance could be 15 min and the effective operation time can reach 12 min. The whole aircraft weighs about 4Kg, and the maximum takeoff weight is about 11Kg, which can carry radio comprehensive test equipment (0.2Kg), laptop computer (1.5Kg), and image transmission module (0.2Kg) easily. In addition, all the arms can be folded down by using type 1552 folding paddles to minimize the whole machine transport volume which makes it convenient for monitoring personnel to carry.

The radio aerial direction-finding equipment consists of three parts. The direction-finding antenna system is used to receive incoming signals. The direction-finding channel receiver is applied to process incoming signals, and the direction-finding terminal processor is operated to extract and display signal information. P9030 contains a direction-finding antenna, portable receiver, and supporting spectrum monitoring software, which integrates the above three parts. Comparing with the single device, the weight is significantly reduced, and the takeoff weight of the UAV could also be reduced at the same time. The directional antenna is used to monitor the orientation information of the radio signal, and its installation direction is the same as the UAV nose direction, so the incoming wave orientation information of the RFI signal can be determined by the UAV orientation information. The UAV platform is loaded with the APM flight control system, which has a built-in six-axis sensor, the MPU6000. Its integrated barometer named MS-5611 obtains altitude by measuring air pressure to aid GPS positioning. The D JI S100's three-axis magnetometer, the HMC5883, obtains the UAV's azimuth and the RFI's azimuth is used to measure the geomagnetic field. The Micro Air Vehicle Link (MAVLink) communication protocol is used within the APM to communicate between the UAV and the ground station, and the monitoring information collected by the UAV is sent to the ground analysis system using this protocol**.** The portable receiver is used to process the radio signals received by the direction-finding antenna. The spectrum monitoring software is installed on the laptop and is used to display the spectrogram of the received radio signals in real time.

Since the basic unit for MAVLink transmission is the message frame, it cannot transmit the radio signal spectrogram in

Fig. 2 System composition diagram of RFI monitoring and analysis based on UAV



real time, therefore, a set of an image transmission device is needed to transmit the over-the-air monitoring screen to the ground terminal. In this study, the image transmission module includes a camera RunCam Swift 2, and an image transmitter module AOMWAY tx001. The camera is used to capture the spectrogram of the radio signal displayed in real time by the laptop. The image transmitter module is used to transmit the spectrum monitoring images to the ground immediately.

The D JI S100 is used as an UAV platform, carrying P9030 radio comprehensive testing equipment, laptops, and image transmission modules to form an aerial monitoring system. The RFI aerial monitoring system is shown in Fig. 3.

Ground Analysis System During the RFI elimination, the current working model requires at least two technicians. One UAV operator, who is responsible for controlling the UAV. Another technician is responsible for radio monitoring tasks by operating software to set the frequency sweep range of the equipment, monitoring the radio signal parameters, storing the data and doing statistical analysis. In addition, UAV monitoring, radio spectrogram display, RFI location analysis, and RFI location display require different software to complete, and the automation of the ground system is low. To solve the above problems, we have developed a ground terminal. The functions of UAV control and radio monitoring can be realized at the same time by using it, and only one person is needed in operation.

The ground analysis system consists of the UAV remote control Futaba14SG, the image transmission receiver Eagle

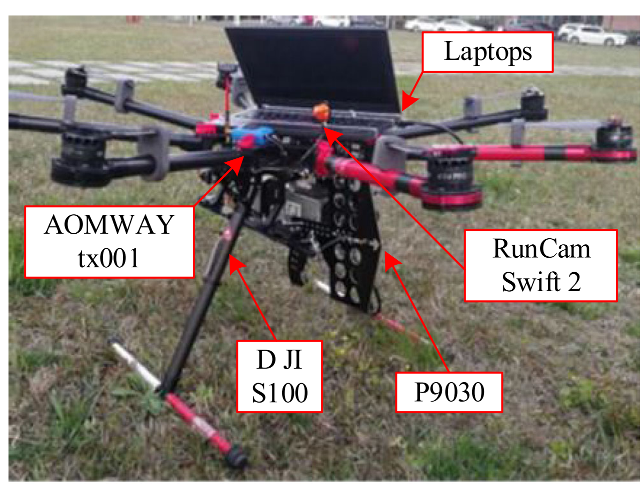


Fig. 3 Physical image of RFI aerial monitoring system

Eye all-in-one machine and a laptop computer with a ground terminal.

Among them, the UAV remote control is used for take-off, control and landing under visual conditions. The image transmission receiver used to receive the spectrogram transmitted from the image transmission transmitting module to the ground. The ground terminal is mainly composed of three modules, a virtual instrument module, an electronic map module and a function module. The interface of the ground terminal is shown in Fig. 4.

As shown in the picture, with the help of ActiveX virtual instrument plug-in, a lot of information such as yaw angle, pitch angle, altitude, etc. could be displayed on the virtual instrument module, so that it is possible for the operator to grasp the flying attitude of the UAV. The electronic map layers could be loaded by the electronic map module and the real-time position of the UAV could also be displayed by it. The four functions of UAV monitoring, including the UAV operation, interference source positioning, and signal monitoring can be realized by the operation module. The monitored information is flight data such as flight altitude, attitude angle, flight speed, etc., which shows the data changes in real time. The operator could send control instructions to the UAV aerial platform to achieve the control of the UAV and transplant the positioning algorithm in MATLAB to the ground terminal to avoid the process of manually reading data and entering data. The computer is connected to the image transmission receiving module, and the spectrum data graph transmitted to the ground is displayed in the signal monitoring function area through the interface.

3.3 Aerial Monitoring Method

In the airport, aircraft in various operating states will receive guidance signals from GNSS satellites, VHF omnidirectional radio range (VOR), Non-Directional Beacon (NDB) two-way communication with the tower and other air traffic control (ATC) seats and so on. At this time, if there is aerial interference, the location of the RFI cannot be quickly positioned by the ground monitoring equipment. For this situation, we propose an aerial monitoring method.

The UAV is equipped with a radio direction-finding system to inspect in areas with RFI interference, and its operations such as takeoff, landing and location switch are controlled by remote control under visual conditions or controlled by the ground terminal under non-visually conditions. The spectrum data collected by the UAV is transmitted to the ground terminal through a digital transmission receiver, while the UAV onboard data module transmits RFI monitoring data and UAV flight data to the ground terminal through the MAVLink protocol. The monitor selects the location of the monitoring point according to the spectrum image displayed in the ground terminal. The UAV flight control decodes attitude information in real time and transmits it to the ground terminal, including position information, angle information, speed information, etc. After acquiring the information, the ground terminal uses the positioning algorithm to resolve the coordinates of the RFI and then displays it on the map. The monitor eliminates RFI according to its positioning location on the map. The process of achieving RFI positioning is shown in Fig. 5.

In order to obtain the location of RFI with high accuracy in a short time, we adopts the AOA localization method in this study. AOA localization is used to set up directional antennas or array antennas at two or more location points to obtain the angular information of radio wave signals emitted by the target source, and then estimate the location of the target source by the intersection method.

Suppose the Space Cartesian Coordinate System (SCCS) of the RFI is $R(x, y, z)$, the SCCS of the monitoring point are $M_i(x_i, y_i, z_i)$, the UAV monitors the azimuth of R as α_i,pitch angle is β_i, $i = 1, 2 \ldots N$.

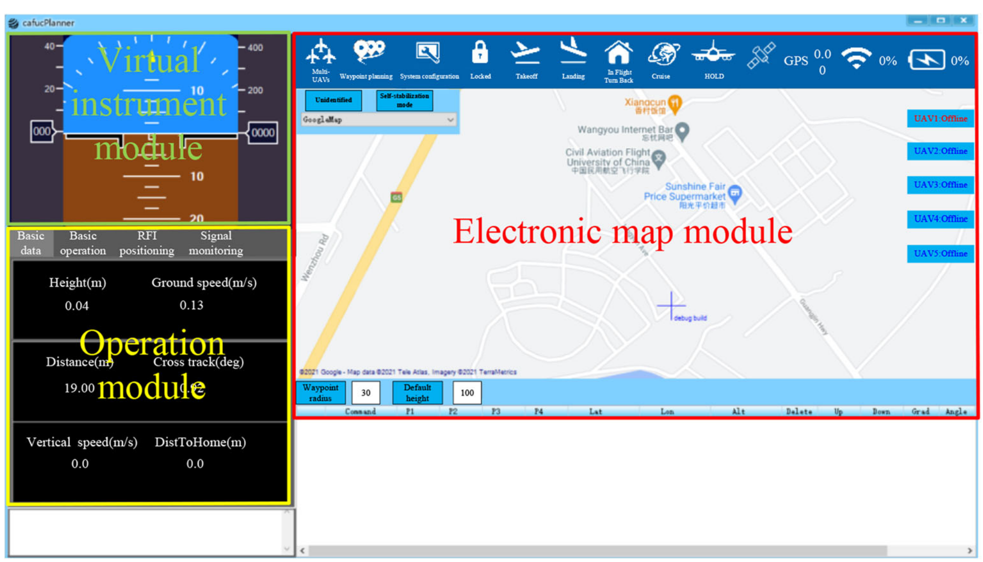


Fig. 4 Ground terminal diagram of RFI analysis system based on UAV

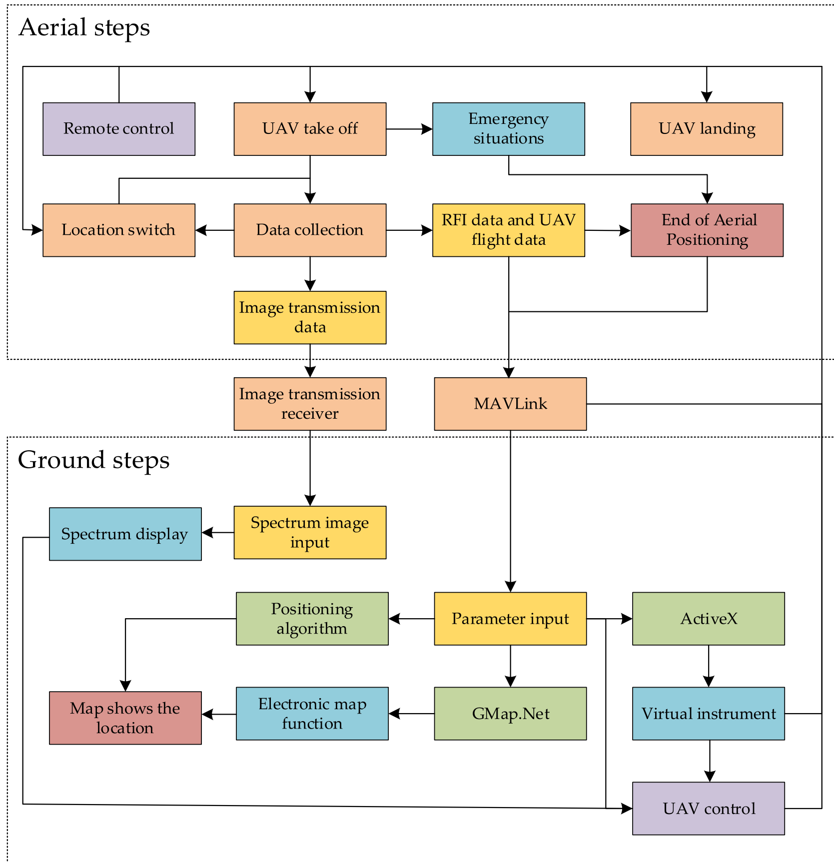


Fig. 5 Flowchart of UAV-based RFI localization

As shown in Fig. 6, the AOA method is used to locate the position of R, if the position of M_i is known and α_i and β_i can be obtained, it is deduced from the trigonometric theorem that:

$$\tan\beta_i = \frac{y-y_i}{(z-z_i)\sin\alpha_i}$$
$$\tan\alpha_i = \frac{y-y_i}{x-x_i}$$

According to the terrain around the airport and the received signal strength, if the UAV monitors the position of R at M_1 and M_2 successively, M_1 monitors the azimuth of R as α_1 and the pitch angle as β_1, M_2 monitors the azimuth of R as α_2 and the pitch angle as β_2, bring the coordinates of M_1, M_2 and α_1, α_2, β_1 into the formula:

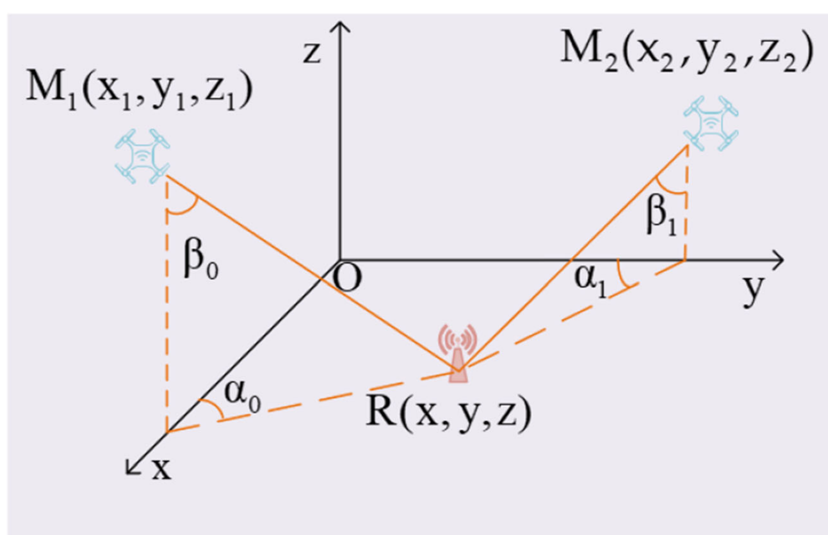


Fig. 6 Schematic diagram of UAV positioning RFI based on AOA method

$$\begin{cases} x\tan\alpha_1 - y + y_1 - x_1\tan\alpha_1 = 0 \\ y - z\sin\alpha_1\tan\beta_1 - z_1\sin\alpha_1\tan\beta_1 = 0 \\ x\tan\alpha_2 - y + y_2 - x_2\tan\alpha_2 = 0 \end{cases}$$

The conversion into a matrix of the form:

$$\begin{bmatrix} -\tan\alpha_1 & 1 & 0 \\ 0 & 1 & -\sin\alpha_1\tan\beta_1 \\ -\tan\alpha_2 & 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} y_1 - x_1\tan\alpha_1 \\ y_1 - z_1\sin\alpha_1\tan\beta_1 \\ y_2 - x_2\tan\alpha_2 \end{bmatrix}$$

Suppose $A = \begin{bmatrix} -\tan\alpha_1 & 1 & 0 \\ 0 & 1 & -\sin\alpha_1\tan\beta_1 \\ -\tan\alpha_2 & 1 & 0 \end{bmatrix}, X = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$, $B = \begin{bmatrix} y_1 - x_1\tan\alpha_1 \\ y_1 - z_1\sin\alpha_1\tan\beta_1 \\ y_2 - x_2\tan\alpha_2 \end{bmatrix}$ make $AX = B$, in that way $X = A^{-1}B$, the R position can be determined.

In the process of solving R coordinates, the coordinate information obtained from the UAV is Geodetic Coordinate System (GCS), so it is necessary to convert the GCS into SCCS. The coordinate conversion process is eq. (1).

$$\begin{cases} x = (N + H)\cos(B)\cos(L) \\ y = (N + H)\cos(B)\sin(L) \\ z = \left[N\left(1 - e^2\right) + H\right]\sin(B) \end{cases} \tag{1}$$

Where L, B and H are longitude, latitude and geodetic height, respectively. N is the radius of prime vertical, $N = a/\sqrt{1 - e^2 * \sin^2(B)}$, e is the first eccentricity of the earth.

After solving the position of the R coordinate of the earth cartesian coordinate system, in order to display it on google maps, it is necessary to convert the SCCS to the GCS. The coordinate conversion process is eq. (2).

$$\begin{cases} L = \arctan\left(\dfrac{y}{x}\right) \\ B = \arctan\left[\dfrac{z}{\sqrt{x^2 + y^2}}\left(1 - \dfrac{e^2 N}{N + H}\right)^{-1}\right] \\ H = \dfrac{\sqrt{x^2 + y^2}}{\cos B} - N \end{cases} \tag{2}$$

Among them, $e^2 = (a^2 - b^2)/a^2$, a is the length of the long radius of the earth's ellipsoid and b is the length of the short radius of the earth's ellipsoid.

We designed a positioning software in the MATLAB GUI environment based on the above positioning method, but the software requires a professional to read the data transmitted by the UAV and input it manually, which is a slightly complicated and labor-intensive process.

4 Results and Discussion

In order to test the aerial monitoring system, we set up an analog RFI in CAFUC, 2.1 km away from Guanghan airport tower. The geographical relationship between the airport and the school is shown in Fig. 7. We placed the analog RFI at different positions and set the aerial monitoring platform to different flight heights verifying the advantages of the system from three aspects, which were direction-finding error, monitoring radius and cross-location.

4.1 Direction-Finding Error

During the direction-finding error test process, the simulated interference sources were placed at five different non-line-of-sight test points, which were R1 (middle and low-rise buildings), R2 (middle and high-rise buildings), R3 (sparse forests and buildings), R4 (forest), R5 (low building complex). The five points varied in distance and degree of occlusion which could cover a wide range of RFI emission scenarios. The height of the aerial monitoring system was set to 0 m, 15 m, 21 m, 30 m separately. The direction-finding error of the aerial monitoring system varied with the height of the UAV platform as shown in Fig. 8.

As the Fig. 8 shown, when the UAV platform height was set in the range of 0 m to 15 m, the amplitude intensity of the analog RFI received by the aerial monitoring system increased due to the increasing height of the UAV platform, the direction-finding error decreased with the increasing height

Fig. 7 Relationship between analog RFI location and airport location

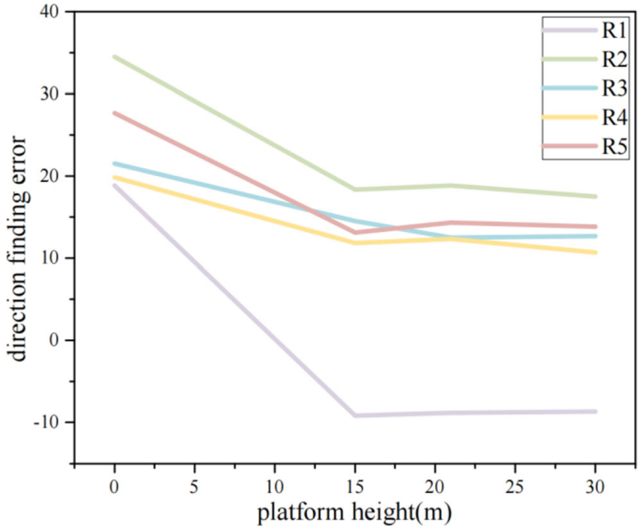


Fig. 8 The relationship between UAV platform height and direction-finding error

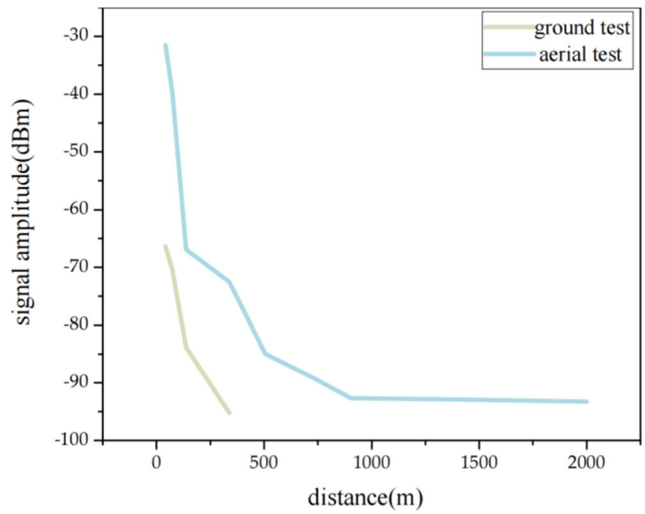


Fig. 9 The relationship between the height of the UAV platform and the direction-finding radius

of the UAV platform. When the height of the UAV platform exceeded 15 m, since the target signal was close to the line-of-sight propagation, the height of the UAV platform had little effect on the amplitude intensity of the analog RFI received by the aerial monitoring system, the direction-finding error did not change significantly.

4.2 Monitoring Radius

The monitoring radius test was divided into ground test and aerial test. During the ground test, the airborne monitoring system was placed at a fixed point on the ground, and a test member who rode a bicycle with the analog RFI started from the fixed point. During the ride, the test member transmitted signals at intervals until the signal was not received by the airborne monitoring system or the signal amplitude intensity did not change significantly. And if the height of the UAV platform was fixed at 30 m during the aerial test, the test process was the same as that on the ground. The test data is shown in Table 1.

T1-T7 indicate ground monitoring points, and T8-T16 express aerial monitoring points. Due to the ground signal propagation is hindered, when the ground radius exceeds 500 m, the signal from the analog interference source cannot be detected by ground monitoring. The relationship between the monitoring radius of the aerial monitoring system and the height of the UAV platform is shown in Fig. 9.

On the whole, as the distance between the aerial monitoring system and the analog RFI continues to increase, the signal

Table 1 Ground and aerial monitoring radius test

monitoring points	platform height(m)	distance(m)	signal amplitude(dBm)
T1	0	42	−66.35
T2	0	74	−70.45
T3	0	138	−83.85
T4	0	338	−95.21
T5	0	506	–
T6	0	736	–
T7	0	904	–
T8	30	42	−31.533
T9	30	74	−39.677
T10	30	138	−66.877
T11	30	338	−72.544
T12	30	506	−84.988
T13	30	736	−89.277
T14	30	904	−92.677
T15	30	1357	−92.877
T16	30	2000	−93.25

Table 2 Two-point cross-location test data

monitoring points	longitude(°)	latitude(°)	altitude(°)	azimuth(°)	pitch angle(°)
M1_1	104.30338	30.94917	441.63	43	13
M1_2	104.30336	30.94919	441.7	44	12
M1_3	104.30338	30.94913	441.54	50	13
M1_4	104.30334	30.9492	441.78	34	11
M1_5	104.30338	30.94921	441.95	49	15
M2_1	104.30272	30.94957	441.34	6	12
M2_2	104.30218	30.94982	442.61	12	13
M2_3	104.30345	30.94962	441.57	20	13
M2_4	104.30124	30.9497	441.21	2	12
M2_5	104.30211	30.9498	441.39	4	14

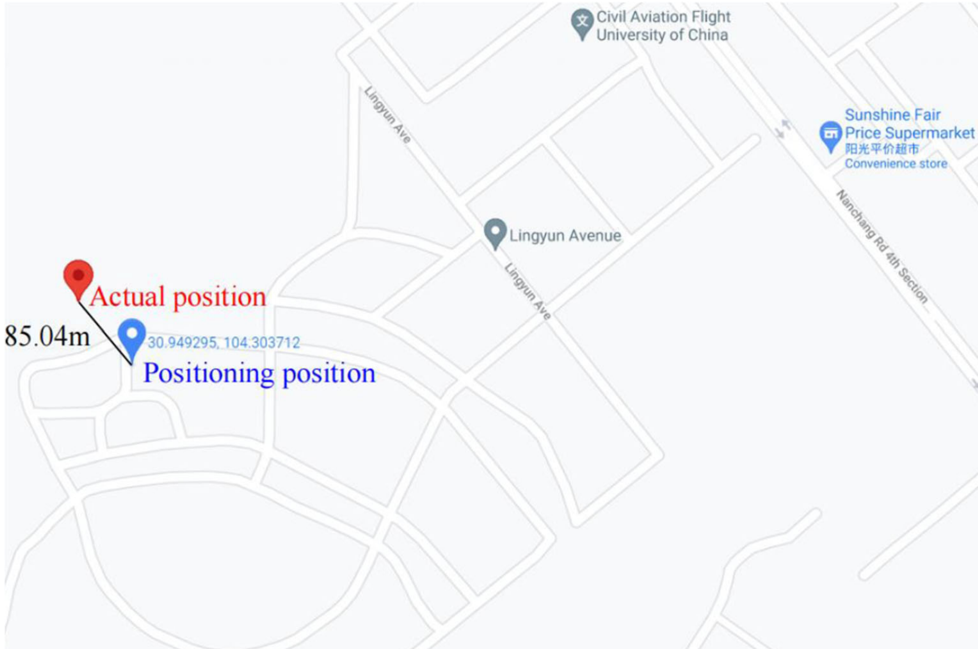


Fig. 10 The relationship between the actual location of the analog RFI and the positioning location

amplitude intensity will decrease. But aerial monitoring has special advantages compared with ground monitoring. On the one hand, when the monitoring radius is within 500 m, the signal strength received in the air is better than the ground. On the other hand, when the monitoring radius exceeds 500 m, the ground cannot receive the signal, but the signal can be monitored in the aerial within 2000 m.

4.3 Cross-Location

During the cross-location test, the analog RFI was placed at a fixed point, and the flying height of the UAV platform was higher than the height of the obstructions around the test point. M1 and M2 were selected as the monitoring points of the aerial monitoring system. The UAV equipped with monitoring equipment at M1 and M2 points monitored the simulated interference source, and the ground terminal recorded the monitoring information. In order to avoid the contingency of the test, five repetitions of the test were performed at each point for the analog RFI. The test data is shown in Table 2.

Take the average value of the angle information of the two points to have a look respectively. After calculation by the ground terminal, the earth coordinates of the simulated interference source obtained by AOA method cross-location are (104.3037, 30.9492, 420.0194), and the actual position coordinates of the analog RFI are (104.30321, 30.94984, 421.92), and the difference between the positioning position and the actual position is 85.04 m. Figure 10 shows the relationship between the two locations from the ground terminal.

Among them, the red anchor point is the actual location of the analog RFI, and the blue anchor point is the positioning location. The main reason for this error is that when the aerial monitoring system monitors the analog signal, the UAV cannot accurately measure the azimuth angle of the analog signal source. Based on the same reason, the non-parametric problems would also caused by the RFI itself, same as the obstacle blockage or complex geographical environment, return data, and data transmission [58]. But the direction-finding and positioning could be achieved by this system basically, on which the advantages are obviously compared with the ground equipment.

5 Conclusions

We proposed an aerial monitoring and analysis method to locate RFI around civil aviation airports in this work. And based on this method, the UAV was equipped with a radio direction-finding system to monitor the incoming wave azimuth information of the RFI signal at two different points. Meanwhile, information such as the coordinates of the UAV and the pitch angle is recorded and then transmitted to the ground for analysis using positioning algorithms. Moreover, we combined an aerial monitoring system with a ground analysis system. In addition, we also used this synthesized system to verify the monitoring and analysis methods from three aspects, including direction-finding error, monitoring radius and cross-location. From the actual test results, it could be claimed that the UAV-based RFI monitoring and analysis method is better than the ground investigation method, and the advantages are high automation and intuitive display. However, errors still exiting between the positioning position of the interference source and the actual position. In subsequent studies, we will consider adding an adaptive estimator to improve the location accuracy by optimising non-parametric factors. In addition, atmospheric disturbances have a significant impact on UAV flight safety and efficiency. To ensure the smooth operation of RFI monitoring solution, wind sensing and estimation will also be investigated in our future work.

Authors Contributions The overall study supervised by Chao Zhou; Methodology, hardware, software, and preparing the original draft by Renhe Xiong, Hongzheng Zeng and Jun Xiao; Review and editing by Yao Wang, Pingfa Jia and Jia Ye; The results were analyzed and validated by Tiantian Zhao and Kun Hu. All authors have read and agreed to the published version of the manuscript.

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Data Availability The data that support the findings of this study are available from the corresponding author, R.X., upon reasonable request.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

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Competing Interests The authors declare no conflict of interest.

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