Phased array radar system design based on single-send and multiple-receive for LSS-UAV target

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Abstract. In order to improve the precision of radar target positioning, the phased array frequency modulated continuous wave (FMCW) radar system based on single-send and multiple-receive is proposed for low altitude, slow speed, small Unmanned Aerial Vehicle (LSS-UAV) target. The much lower-cost passive electronically scanned array (PESA) radar technology has been employed for the azimuth electronically scanning. In addition, wide beam scanning beam of elevation direction is used to further expand the range of space coverage. Phase-comparison method is adopted to high-precision angle measurement of elevation direction in interferometer angle measurement system with dual distributed receivers. As a result, the novel radar system possesses the abilities of Doppler velocity measurement and linear FMCW distance measurement, as well as the high precision angle measurement at the same time. It can provide long distance, wide range, all-weather/time detection accurate target location information for optical system and electronic interception system to detect LSS-UAV targets for some more cost-sensitive applications in the homeland security market.

1. Introduction

In recent years, with the rapid development of the small unmanned aerial vehicle (UAV) market in the world, the LSS-UAV products have gradually moved to thousands of households. However, due to the lack of the rules regarding UAV, the uncontrollable phenomenon of the LSS-UAVs is seriously threatened the security of the society. Optical detection (visible light/infrared), radar detection [1,2] and passive detection are usually adopted to catch the LSS targets. Radar detection has been widely used in LSS-UAV security monitoring system because of its long range of function and all weather/time working ability [3,4].

In general, the radar is divided into two main systems, including the pulse radar system and the continuous wave (CW) radar system. The pulse radar possesses a remarkable advantage of long detection range, but there is an inherent distance blind area because of transceiver block, which the target in the close range (more than a few hundred meters) can’t be detected at all. However, the CW radar has no distance blind spot in theory, especially suitable for the close-range detection of LSS targets. At present, most of the detection radars for LSS targets use single-send and single-receive CW system [5]. Nevertheless, the radar is not able to supply the accurate elevation angle data without the proper conditions, so it can’t provide the accurate target location information to the photoelectric and strike system. In this letter, a kind of phased array radar system design based on single-send and multiple-receive is proposed to obtain the precise speed, distance and angle (azimuth and elevation angles) information [6,7] of LSS-UAV target. The system has many advantages of an affordable price,
install easy to use, high precision, adaptability, strong anti-interference ability, there is no blind spot at close range and so on.

2. System model and design method
Because of persistent surveillance and early warning capability with lower installation costs, lower costs and lower false-alarm rates, the newer and much lower-cost PESA (passive electronically scanned array) radar technology has been employed to detect LSS-UAV targets. The radar can work independently and communicates with the external control server through the Gigabit Ethernet interface (or wireless network). The control server sends control information to the radar through the network port to control the radar and receives the status information and target information returned by the radar. It can also be used as an important remote monitoring sensor to realize a multi-sensor system against LSS targets, as shown in Fig. 1.

Figure 1. The architecture diagram multi-sensor system against LSS targets.

The phased array radar based on single-send and multiple-receive adopts FMCW and PESA system for LSS-UAV targets. The whole radar system is made up of four subsystems: phased array antenna system, Radio Frequency(RF) transceiver module, processing module and power module, as shown in Fig. 2.

Figure 2. The schematic diagram of the radar composition.

The phased array antenna system consists of a total of three sub antennas, which the one of them mainly transmits the radiation signal and the two of them receive the target echo signal. The PESA antenna system is composed of waveguide antenna radiator, azimuth and elevation power dividers, large number of phase shifters and beam control network. In particular, the azimuth direction realizes ±45 degrees electronically controlled scanning coverage, the ultra-wide elevation beams (up to 17 degrees wide beam) coverage based on the phase weighting method can be achieved. This allows the radars to stand off from the area to be monitored, mounted on top of existing buildings.

The transceiver module mainly includes one transmitter channel and two receiving channels, low noise amplifier (LNA) module, frequency synthesizer and solid-state power amplifier(PA). It mainly completes the functions of signal generation, up-conversion, amplification, filtering, down-conversion and gain control. The power module transforms the 220V alternating current(AC) power to the +5V, +12V and +15V direct current(DC) power needed by each module of the radar. The processing module includes DSP, FPGA and so on. It mainly completes signal
After receiving the baseband echo signal from the transceiver module, analog-to-digital (AD) sampling, signal in-phase/quadrature (I/Q) calibration (CAL), channel correction, moving target indication (MTI), clutter suppression, fast Fourier transform (FFT), constant false alarm rate (CFAR) processing and target detection are carried out. The target is tracked stably to complete the detection of the distance, speed and angle of the targets. The radar principle block diagram based on single-send and two-receive is given in Fig. 3. From the cost and practical application of view, Ku band operation frequency, 2.8W solid state emission power, two receiving channels, ultra-wide elevation beams but not electronically controlled as azimuth beams are adopted to design the radar for LSS-UAV targets.

Figure 3. The radar principle block diagram based on single-send and two-receive.

The characteristics of LSS-UAV targets determines that the radar echo signal is coupled with the ground clutter signal seriously. The radar target distance and speed of the FMCW system are coupled with the velocity, which aggravates the influence of the ground clutter on the target detection. In order to minimize the ground clutter and improve the echo signal to clutter ratio (SCR) of small target, first of all, according to the characteristics of the surveillance radar and the ground fixed correspondingly, the fixed clutter cancellation is carried out by MTI technology. And the multi-pulse moving target detection (MTD) technology is used to carry out the energy accumulation of the echo signal. At the same time, the clutter is used in the CFAR detection. Graph cancellation technology can minimize the false alarm caused by clutter. In addition, the radar system uses joint probabilistic data association algorithm (JPDA) technology and Kalman filtering technology to reduce false alarm, improve the accuracy of multi-target association and achieve stable tracking of low and slow multi-target.

3. Phase comparision angle measurement method

The system structure of the single transmitter and the dual transceivers for FMCW phased array radar provides the hardware support for accurate measurement of target distance, speed and angle. The high precision angle measurement of LSS targets detection radar is based on the interference principle of phased array radar dual receiving antenna and the ambiguity resolution of the coprime wavelengths. The schematic diagram of the phase comparison angle measurement method is shown in Fig. 4.
Figure 4. The schematic diagram of phase comparison angle measurement method based on two receivers.

The phase comparison angle measurement method based on two receivers is used to measure the phase differences $\Delta \phi$ between the two receiving antennas to determine the angle $\theta$ of the target. Suppose the beam direction of the two sub arrays is the normal direction of the array. And the phase centre distance between the receiving antennas is $D$. There are the phase differences $\Delta \phi$ between the two sub arrays received from the directional signal.

$$\Delta \phi = \phi_1 - \phi_2 = \frac{2\pi}{\lambda} D \sin \theta$$

where $\phi_1$ and $\phi_2$ are the different phase values from two receiving antennas respectively, $\lambda$ is the wavelength at working band. Therefore, after measuring the phase differences $\Delta \phi$ of two receiving antennas, the angle $\theta$ of the target can be determined.

$$\theta = \arcsin \frac{\lambda \Delta \phi}{2\pi D}$$

The range of the phase values of the output signals of the two receivers $\phi_1$ and $\phi_2$ are both $(-\pi, \pi)$, and the range of the phase differences $\Delta \phi$ are $(-2\pi, 2\pi)$.

$$\Delta \phi = 2\pi N + \psi, \quad N = -1 \text{ or } 0, \psi \in (0, 2\pi)$$

where $\psi$ is the observation value of the phase differences between the two sub array antennas. However, because -1 or 0 can’t be determined by $N$, there is the phase ambiguity problem, which leads to the angular ambiguity. Therefore, in order to keep the phase unambiguous, the value range should be less than $(-\pi, \pi)$. Suppose the angle measurement range is set as $(-\theta_{\text{max}}, \theta_{\text{max}})$, so that the angle measurement is not ambiguous any more, it should be satisfied as follows:

$$\Delta \phi = \frac{2\pi}{\lambda} D \sin \theta_{\text{max}} < \pi$$

Therefore, the maximum unambiguous angle $\theta_{\text{max}}$ is as follows:

$$\theta_{\text{max}} < \arcsin \left(\frac{\lambda}{2D}\right)$$

In general, if the beam is not broadened by the phase weighting method, the 3dB beam width $\theta_{3\text{dB}}$ can be approximately expressed as follows:

$$\theta_{3\text{dB}} \approx \frac{0.88\lambda}{D \cos \theta_0}$$

In normal direction, select $\theta_0 = 0^\circ$, if the angle is measured within the range of the 3dB beam width, the maximum unambiguous angle $\theta_{\text{max}}$ can be expressed as follows:

$$\theta_{\text{max}} = \frac{\theta_{3\text{dB}}}{2} = \frac{0.44\lambda}{D} < \arcsin \left(\frac{\lambda}{2D}\right) \approx \frac{\lambda}{2D}$$
That is to say, if the beam is not broadened, the angle measurement within the 3dB beam width can always satisfy the condition that the angle is not ambiguous. However, when using the beam weighting algorithm, the elevation beam is extended to ultra-wide beam and the azimuth beam is kept a pencil shape, as showed in Fig. 5 (as mentioned above in the radar design), the angle ambiguity will appear even in the range of 3dB beam width.

\[
\theta_{3dB} = 17°
\]

Figure 5. Simulation results of antenna azimuth and elevation plane antenna pattern at 16GHz.

Aiming at the target of low speed flight, we use phased array radar's frequency agile characteristics to change the radar transmitting frequency quickly to achieve the ambiguity of the angle.

The FMCW phased array radar can change the radar transmitting frequency \( f \), that is, the radar working wavelength \( \lambda \) is easily changed. The wavelength of the two adjacent two radar beams is respectively \( \lambda_1 \) and \( \lambda_2 \), which are coprime with each other, and the measurement phase values caused by the target angle \( \Delta \phi_1 \) and \( \Delta \phi_2 \) at the two working wavelengths is measured as follows:

\[
\begin{align*}
\Delta \phi_1 &= 2\pi N + \psi_1 = \frac{2\pi}{\lambda_1} D \sin \theta \\
\Delta \phi_2 &= 2\pi N + \psi_2 = \frac{2\pi}{\lambda_2} D \sin \theta
\end{align*}
\]

(8)

The value of \( N \) is obtained by solving the two sets of equations at Ku band. And then the results of the high precision angle measurement are achieved unambiguously.

4. System integration and experimental results

The phased array radar system based on single-send and multiple-receive is integrated and tested under laboratory conditions, as shown in Fig. 6. In order to verify the high precision angle measurement capability based on phase comparison method with the coprime wavelength preliminarily, a simple experiment is set in the laboratory. The Ku band horn antenna is used to simulate the echo of the target on the stand bar marked with the scale. The horn launches the electromagnetic wave to simulate the target echo and it is set up on the stand bar marked with the scale. The radar fixed to a certain horizontal distance from the horn and receives the simulated signals at different height positions. The angle test information is extracted and compared with the actual installation elevation angle. Because the antenna's elevation beam width is 17 degrees and the antenna beam width is symmetrical, the elevation angle in the range of 0–14 degrees is enough by moving the height of the horn from 1.25 meters to 2.8 meters up to ground, as shown in Fig. 7. The comparison results of different elevation angles between the test values with the phase comparison method and the
set values are presented in Table 1. It can be seen from the table that the angle measurement accuracy is can be controlled in 0.4 degrees.

Figure 6. The phased array radar system tested under laboratory conditions.

![Figure 6](image)

Table 1. Comparison results of different elevation angles between the test values with phase comparison method and the set values.

| Name                              | the values of the elevation angles |
|-----------------------------------|-----------------------------------|
| the height of the mounting of the horn | 1.25m    | 1.8m    | 2m      |
| set value                         | 0°      | 5.2°    | 7.1°    |
| test value                        | -0.3°   | 5.5°    | 6.7°    |
| angle measurement accuracy        | 0.3°    | 0.3°    | 0.4°    |

Subsequently, the adjusted flight test, field test for grabbing LSS-UAV and multi-sensor system joint test with the photoelectric and interference haves been carried out to test the radar’s properties.

Figure 7. The phased array radar test system to verify angle measurement accuracy under laboratory conditions.

![Figure 7](image)
successively, as shown in Fig. 8. From the test flight data, it can be seen that the radar can accurately detect the speed, distance and angle of the LSS-UAV targets and carry out stable tracking. For the PHANTOM 3 and PHANTOM 4 UAVs from DJI-Innovations with the radar cross-section (RCS) at 0.01 m², the detection range of the radar is more than 2km, while the distance from the blind area is less than 20m. The minimum detection speed is about 1m/s and the angle measurement accuracy is less than about 0.5 degrees in wide beam range by comparing the set values with the test values in wide beam range in the flight tests, as shown in Fig. 9.

Table 2. Comparison results of different elevation angles between the test values with phase comparison method and the set values.

| distance (m) | successful guidance | Failure guidance | success rate |
|-------------|---------------------|-----------------|--------------|
| 0~100m      | 36                  | 0               | 100%         |
| 100~300m    | 128                 | 0               | 100%         |
| 300~400m    | 400                 | 0               | 100%         |
| 500~600m    | 240                 | 0               | 100%         |
| 600~700m    | 196                 | 0               | 100%         |
| 700~800m    | 198                 | 2               | 99%          |
| 800~1000m   | 416                 | 5               | 98.5%        |
| above 1km   | 168                 | 4               | 97.6%        |
| total       | 1878                | 11              | 99.4%        |

The radar works with the optoelectronic in collaboration efficiently because the distance, speed, azimuth and elevation angles of the target can be taken by the radar and the data are quickly and accurately sent to the photoelectric system. The test results show that the rate of the radar successfully guiding the photoelectric system has been more than 99% within thousands of flying experiments, as shown in Table 2. A total of 1878 tests were done in the multi-sensor system joint experiment. Only the accidental guidance failed around 1km far away, and most of the reasons for the failure were limited by the optoelectronic detection in bad weather conditions.

Figure 8. The field test scenario diagram of the radar for grabbing the LSS-UAV targets.
Figure 9. The curve of angle measurement accuracy comparing the set values with the test values in wide beam range by the flight tests.

5. Conclusion
The phased array radar system design method and test results based on single-send and multiple-receive for LSS-UAV target are presented in the letter. It can provide long distance, wide range, all-weather/time detection accurate target location information for optical system to detect LSS-UAV targets, especially with high precision angle measurement capability based on improved phase comparison angle measurement method. The test results show that the success rate of the radar guiding the photoelectric system is over 99% within lots of flying experiments by the design method. Thus, the accuracy of the radar design for LSS-UAV targets and improved angle measuring algorithm for ultra-wide beam is fully verified.

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