Multi-target method for small unmanned vehicles parameters remote determination by microwave radars

V D Kuptsov, S I Ivanov, A A Fedotov and V L Badenko

Peter the Great St. Petersburg Polytechnic University, 29, Polytechnicheskaj st., St. Petersburg, 195251, Russia

E-mail: vdkuptsov@yandex.ru

Abstract. This article explores the properties of the multi-target method for small unmanned vehicles parameters remote determination by microwave radars, which allows to expand significantly the range of unambiguously determined speeds of unmanned vehicles. The reasons of occurrence of false targets and their number in the mode of the parameters simultaneous measurement for the set of unmanned vehicles are identified. Using a computer experiment in LabVIEW, the probability of the unmanned vehicles true parameters determination at various ratios of the signal to noise at the input of the radar receiver in multi-target mode was investigated.

1. Introduction

The technologies of the “smart city” involve the creation, development and improvement of parameters remote sensing means for land and flying unmanned vehicles (UV). Flying UV in the “smart city” monitor important urban industrial facilities, highways for traffic jams, the condition of housing and communal services, deliver mail and parcels, and participate in servicing the tourism sector. At the same time, flying UVs can also pose a threat to the normal functioning of the “smart city”, which requires determining the parameters of unmanned aerial vehicles (UAVs) to counter it.

Ground-based UVs, mainly vehicles, use radars to automatically control the distance between moving vehicles, to warn of cross traffic, to help change lanes, park and detect obstacles, pedestrians and blind spots. In addition, radars use traffic police services to ensure traffic safety using administrative measures.

Among the remotely determined parameters of ground and airborne UVs, the most important are: range, radial speed, direction of movement, effective dispersion area (EPR), azimuth and elevation. Various methods can be used to determine the location and radial velocity of objects: ultrasonic, optical lidar, use of video cameras, and microwave. The first three of these principles have a significant drawback - they are highly dependent on weather conditions (precipitation, fog), have a small detectable range to the object (ultrasound and video), and have a high cost (optical lidar). To a certain extent, the listed methods are complementary, but due to these reasons, the microwave radar method is universally recognized as the preferred method.

Despite the rapid progress in the development of technologies of the “smart city”, some fundamental aspects of the remote determination of the parameters of small ground unmanned vehicles (UVs) and unmanned aerial vehicles (UAVs) by microwave radars remain unclear. Among them: search and study of new forms of radio frequency signals of a special form, solving the problem of ambiguity in
determining speeds in a wide range, identifying the causes of false targets and their number in the multi-target mode of the parameters simultaneous measurement, studying the effect of noise on the probability of target parameters unambiguous determination in multi-target mode.

The microwave and ground-based unmanned vehicles radars for the simultaneous measurement of speed and range use the generation and emission of a special shape signals, which include: frequency-modulated continuous wave (FMCW), frequency shift keying (FSK) continuous wave. In [2], a waveform with very short $T_{\text{chirp}}$ chirp durations was proposed, which has become a classic FMCW. The output signal of the mixer, which transfers the spectrum of the received signal to the difference frequency of transmission and reception, is digitized by the ADC with a sampling frequency $f_s$ on each chirp. A number of the samples of each chirp is converted to the frequency domain using the Fast Fourier Transform (FFT) and written to the Beat-Doppler frequency matrix in columns. The maximums contained in the resulting table determine the speed and range of targets. The proposed waveform has advantages such as high measurement accuracy, high resolution and reliable performance. The disadvantage is that the maximum unambiguously measured speed is limited by the interval of chirp repetition. The problem of Doppler ambiguity arises when the target’s speed exceeds the maximum measurable speed in the first Nyquist zone. In [3], for a radar with a sequence of 64 chirps with a duration of 1 ms each, a sweep bandwidth of 150 MHz at a radio frequency of 24 GHz, a maximum detectable speed of only 22.5 km / h was determined, which is insufficient for use in remote control networks by small unmanned vehicles in various environments amid moving objects of wildlife.

To overcome the problem of ambiguity in determining high target speeds, several modified signals of the chirp sequence have been developed. The earliest developed signal with an LFM sequence is a signal consisting of several segments with an LFM sequence with different chirp repetition intervals [4, 5] multiple chirp sequence segments with different chirp repetition intervals. Based on this signal, the Chinese remainder theorem is applied to resolve Doppler ambiguities. However, in the case of multi-target, the waveform requires at least three segments of the chirp [5]. As a result, this type of signal always requires a long measurement time. [6] proposed a new type of modified waveform called the interlaced chirp sequence (ICS). This type of signal allows you to easily and flexibly adjust the unique range of distance and speed in accordance with the requirements of a particular application, regardless of the limited minimum chirp interval. However, for higher uniquely measured speeds, the maximum measurable range decreases. [7] proposed a random pulse repetition interval (PRI) technique applied in pulse Doppler (PD) radar for anti-interference and ambiguity-resolving purposes. It should be noted that this method is quite difficult to implement.

In [3,8], a modified signal of the chirp sequence was developed by adding an additional frequency shift between each two adjacent chirps. Doppler ambiguities can be resolved using additional phase information introduced by the frequency shift. However, the authors [3,8] use a simplified mathematical model of the echo signal of the radar, which becomes inadequate at high target speeds. In [9] we considered a strict mathematical model of the input microwave signal that takes into account a wide range of velocity changes of the target. Based on this model [9], the operability limits of the algorithm for unambiguous estimation of speed and range have been analyzed.

The use of phase signal processing methods in [3,8] significantly reduces the noise immunity of signal processing in radars. Preferred are methods based only on processing the amplitude spectrum of the FFT. Such methods are considered in [10,11,12]. To solve the multi-target problem, in [10, 11] 4 different waveform segments were used, in [12] 5 segments were used.

This article explores the properties of the multi-target method for small unmanned vehicles parameters remote determination by microwave radars, which we proposed in [New2An] and which allows us to significantly expand the range of unambiguously determined UVs speeds. The causes of false targets and their number in the mode of simultaneous measurement of the parameters of multiple targets (multi-target) are identified, and the influence of noise on the probability of a true determination of the UVs parameters in multi-target mode is investigated.
2. Multi-target Detection Algorithm for FMCW Radar
The algorithm for estimating speeds and distances to targets in multi-target mode proposed by us in [1] is based on the form of the probe signal of the radar transmitter shown in figure 1. Waveform consists of three segments: a constant frequency segment and two linear frequency modulated signals (chirps) with various deviations. The total frame length is $T = T_0 + T_1 + T_2$.

\[ f_{R1} = \frac{\Delta f_1}{T_1} \tau_0 - \frac{2V_R}{c} f_0, \quad f_{R2} = \frac{\Delta f_2}{T_2} \tau_0 - \frac{2V_R}{c} \left( f_0 - \frac{3\Delta f_2}{2} \right) \]

Fig. 1. Proposed Waveform [1].

The mathematical model of the intermediate frequency signal under noise conditions is determined in [9]. Beat frequencies $f_{R1}$ and $f_{R2}$, i.e. the frequency of the signal at the mixer output in the channels $I$ and $Q$ of the intermediate frequency of the radar receiver for chirps, respectively, with numbers $k=0$ and $k=1$ are defined by expressions

The problem of determining the target parameters in multi-target mode is that for each speed from the set of speeds of all targets, it is necessary to match the true range to the target from the set of all ranges to the targets. The most difficult task in the multi-target mode is the problem of “pairing” the beat frequency $f_R$ belonging to the same target at first and second chirp with Doppler frequency $f_D$. We found [1] that the minimum of functional $\Xi(f_{R1}, f_{R2})$ correspond to a true pair of speed-distance of targets

\[ \Xi(f_{R1}, f_{R2}) = f_{R1} \frac{T_1}{\Delta f_1} - f_{R2} \frac{T_2}{\Delta f_2} - f_D \left( \frac{T_1}{\Delta f_1} - \frac{T_2}{\Delta f_2} \right) \rightarrow \min \]

Thus, the algorithm for processing the received signal includes a one-dimensional fast complex Fourier transform, an estimate of the frequencies of the maxima of the amplitude spectrum, calculation of ranges and speeds of targets for estimating the frequencies of maxima, and the application of a pairing algorithm for the ranges and speeds of targets. In the interval where the frequency of the emitted signal is constant ($T_0$) the speed of all targets is determined by the maxima of the amplitude spectrum. Each Doppler target frequency corresponds to a 2D beat frequency matrix for the $T_1$ and $T_2$ intervals. The choice of the minimum matrix values according to algorithm (3) determines the Doppler frequency (speed) and two beat frequencies corresponding to the target $R$.

3. The appearance of false targets in the multi-target algorithm
Multi-target algorithms of parameters remote determining have an inherent feature, consisting in the possibility of false targets with virtual (not corresponding to real) values of the radial velocity $V_R$ and distance $R$. The reason for the appearance of false targets is the situation when the beat frequencies $f_{R1}$
and $f_{R_2}$ corresponding to two different speeds $V_{R_1}$ and $V_{R_2}$ of two distinguishable targets coincide with the beat frequencies $f_{R_1}$ and $f_{R_2}$ of the third target having a speed of $V_{R_3}$. A false target has a speed corresponding to one of the real targets, but the distance is determined erroneously. The maximum possible number of false targets $n_f$ with the total number of observed targets $N$ with distinct speeds in proportion to the number of placements without repetitions of $N$ elements of 2

$$n_f = N \cdot A^N_2 = N \cdot (N-1) \cdot (N-2)$$

(4)

The value of $n_f$ increases rapidly with increasing $N$. So for the number of targets observed $N = 9$ with distinct $V_{R_k}$ speeds, the maximum possible number of false targets is 504, which can be comparable to the number of resolvable points in range $N_R$, determined by the formula

$$N_R = \frac{R_{MAX}}{\delta R}$$

(5)

It is of practical interest to calculate the probability $P_f(N, m)$ of the occurrence of $m$ false targets with a total number of monitoring targets equal to $N$ for the case when the targets have different radial velocity. This probability is a special case of hypergeometric distribution [13].

$$P_f(N, m) = \frac{C^m_{n_f} \cdot C^{N-n_f}_{N-n_f}}{C^N_{n_f}}$$

(6)

where $C^n_r$ – binomial coefficient. 3D graph of a function $P_f(N, m)$ is presented in figure 2. The graph shows that the probability of the absence of false targets ($m = 0$) drops sharply with increasing $N$. So for $N = 8$ it is about $10^{-4}$, and for $N = 3$ it is more than 0,096. The dependence of $P_f(N, m)$ on its arguments $N$ and $m$ is not monotonic. For observed targets $N > 5$, there is the most likely value of false targets $m$.

![Figure 2. The probability $P_f(N, m)$ of the appearance of $m$ false targets with their total number equal to $N$.](image)

The most effective method for eliminating false targets in radars is to track the path of targets with subsequent filtering algorithms, for example, using filters on surface acoustic waves matched by noise parameters to the receiving-amplifying path [14].

4. Results of a computer experiment

False targets in the algorithms of remote determining of parameters arise when the distance-speed pair does not match the true values of the target when pairing range values with target speeds. Using a computer experiment in the LabVIEW environment, we investigated the probability of determining the
true parameters of unmanned vehicles (targets) for various signal-to-noise ratios (SNR) at the input of the radar receiver in multi-target mode. The simulation parameters are shown in table 1.

| Table 1. Simulation parameters. |
|---------------------------------|
| Constant frequency | First chirp | Second chirp |
|---------------------|-------------|--------------|
| Modulation Period, ms | 8,192 ($T_0$) | 8,192 ($T_1$) | 8,192 ($T_2$) |
| Sampling Frequency, MHz | 1.0 | 1.0 | 1.0 |
| FFT point | 8192 | 8192 | 8192 |
| Carrier Frequency $f_0$, GHz | 76.5 | 76.5 | 76.5 |
| Sweep Bandwidth, MHz | 0 | 450 ($\Delta f_1$) | 1000 ($\Delta f_2$) |

The signal-to-noise ratio was determined in accordance with the expression

$$SNR = 10\log \frac{P_{\text{beat}}}{2\sigma^2}$$

(7)

where $P_{\text{beat}}$ – beat signal power, $\sigma^2$ – Gaussian noise variance. Noise was determined by integration over the entire frequency band of the fast Fourier transform.

The speed and range of targets in computer experiments were set by the values presented in figure 3 for 12 targets. Reducing the number of targets was carried out by excluding from the set of two targets with maximum values of speed and range.

The computer experiment was as follows. For the given simulation parameters from table 1 and the number of targets $N$, 500 experiments were conducted for each SNR value. If the parameters of at least one of the targets were determined incorrectly in the experiment, the result was recorded as negative. If the parameters of all $N$ targets were determined without errors, the result was recorded as positive. The criterion for distinguishing between positive and negative experimental results was the condition that the standard deviation of the velocity value for five hundred experiments did not exceed 1 km/h and the standard deviation of the range did not exceed 1 m. Probability of target velocity and distance true estimation was calculated as the ratio of the number of experiments with positive results to the total number of experiments equal to 500. The obtained dependence of probability of target velocity and distance true estimation on the signal to noise ratio for various numbers of targets $N$ from 2 to 12 is shown in figure 4.
With an increase in the number of simultaneously evaluated targets, the probability of reliably determining the speed and range of targets, which is 98%, is achieved with a larger signal to noise ratio. For example, for 2 targets, probability of target velocity and distance true estimation 98% corresponds to \( SNR_{98\%} = -20 \text{ dB} \), and for 12 targets \( SNR_{98\%} = -10 \text{ dB} \). Thus, adding each target to the multi-target algorithm leads to the need to increase the \( SNR \) by approximately \( \Delta SNR = 1 \text{ - } 2 \text{ dB} \) for \( N \) values in the first ten and more than 4 dB for \( N \) in the second ten. As the number of targets increases, the \( \Delta SNR \) value increases.

The decrease in the probability of target velocity and distance true estimation near the \( SNR_{98\%} \) values occurs sharply, when the \( SNR \) changes by 4 dB the probability of target velocity and distance true estimation drops from one to zero. The identified dependencies of probability of target velocity and distance true estimation determine the need to take into account a significant margin in \( SNR \) when designing microwave radars in multi-target mode that remotely determine the parameters of small unmanned vehicles.

5. Conclusion
In this article, we assessed the effect of the receiver noise of the unmanned vehicles microwave radar on the probability of target velocity and distance true estimation in our proposed multi-target parameter estimation algorithm. Determined as a result of computer simulation patterns allow to estimate the required \( SNR \) value for the radars that determines the parameters of a multiple targets.

Acknowledgments
The reported study was funded by RFBR, project number 19-29-06034.

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