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Radar Signal Processing for UAV Detection

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Abstract*—The increasing use of small Unmanned Aerial Vehicles (UAVs) in surveillance and tactical operations has created new challenges for airspace security. Detecting these UAVs using conventional radar systems is difficult because such systems are mainly designed for large aircraft with high radar cross sections (RCS). In contrast, small UAVs are often built using lightweight composite materials, which produce weak radar reflections and make reliable detection challenging. This paper presents a MATLAB-based pulse radar signal-processing framework to improve UAV detection in noisy environments. The system generates a rectangular pulse signal, models the UAV echo as a delayed and attenuated return signal, and introduces noise using an Additive White Gaussian Noise (AWGN) model. A matched filter is then applied to enhance the signal-to-noise ratio (SNR), followed by peak detection to determine the time delay of the received signal. Using this delay, the range of the UAV is estimated. Simulation results show that matched filtering significantly improves detection performance and helps reduce range estimation errors even under low SNR conditions. In the simulation, the UAV is detected at an approximate range of 1500 m with minimal error. These results demonstrate that the proposed approach provides an effective and reliable basis for radar-based UAV detection and monitoring systems.

Index Terms*—UAV detection, pulse radar, matched filter, radar signal processing, SNR, range estimation, AWGN, MATLAB simulation.

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have seen rapid growth in both military and civilian applications in recent years. They are widely used for tasks such as reconnaissance, surveillance, and other tactical operations. However, the increasing availability of small UAVs has also created new challenges for airspace monitoring and security. If misused, these drones can pose serious risks to restricted areas, national borders, and important infrastructure.

Traditional radar systems are mainly designed to detect large aircraft with high radar cross sections (RCS). In comparison, small UAVs have compact sizes and are often made from lightweight composite materials, which results in very weak radar reflections. Because of this, detecting them using conventional radar techniques becomes difficult. To address this issue, this work develops a signal-processing framework based on pulse radar principles and matched filtering to improve the detection of small UAVs.

II. PROBLEM STATEMENT

Detecting small UAVs using radar presents several technical challenges, mainly due to their size, weak signal reflections, and the presence of noise in radar systems.

A. Low Radar Cross Section

Small UAVs generally have a very low Radar Cross Section (RCS) because of their small physical size and the use of lightweight, non-metallic materials in their construction. Their geometry also reduces electromagnetic reflection. Since the received signal power depends directly on the RCS, radar systems designed for large aircraft often struggle to detect these smaller targets.

B. Received Power Fall-Off

The received signal power decreases rapidly as the distance between the radar and the target increases. This relationship follows the inverse fourth-power law:

$$Pr \propto R^{-4}$$

Because of this strong attenuation, echoes from distant UAVs can become extremely weak and may approach the noise level of the receiver.

C. Noise and Clutter

Radar signals are affected by several sources of interference, including thermal noise, electromagnetic interference, and environmental clutter. In this work, these disturbances are modeled using an Additive White Gaussian Noise (AWGN) model with zero mean and constant power spectral density. Under low Signal-to-Noise Ratio (SNR) conditions, reliable target detection becomes difficult.

D. False-Alarm Rate

When a fixed detection threshold is used, random fluctuations in noise can sometimes be interpreted as valid target signals. This leads to false alarms, especially when the SNR is low. Reducing false alarms often requires improved filtering or adaptive threshold techniques.

E. Range-Estimation Error

The range of a target is estimated from the round-trip time delay (τ) of the radar signal. However, noise and distorted signal peaks can make it difficult to accurately determine the correct delay. This introduces errors in the calculated distance:

$$R = c\tau / 2$$

Reliable peak detection methods are therefore needed to improve range estimation accuracy.

III. BACKGROUND AND EXISTING APPROACHES

Traditional radar systems typically use fixed-threshold detection methods based on expected noise levels. While this approach works well for large targets with high RCS, it is less effective for detecting small UAVs. Fixed thresholds cannot easily adapt to changing noise conditions, and the absence of matched filtering limits the improvement in signal-to-noise ratio.

More advanced radar systems use techniques such as Constant False Alarm Rate (CFAR) detection and Doppler processing to improve performance. However, these methods are often complex and may not be suitable for low-cost radar surveillance systems.

IV. PROPOSED SYSTEM

The proposed system comprises four processing stages designed to overcome the limitations identified in Section III.

A. Pulse Generation

A rectangular pulse with a duration Tp is generated using MATLAB:

$$s(t) = A \cdot rect(t/Tp)$$

Where A represents the peak amplitude of the pulse. The pulse width Tp determines the range resolution. A shorter pulse width improves resolution, but it also reduces the energy contained in each transmitted pulse.

B. Echo Modelling

The UAV is modeled as a point target that reflects the transmitted signal with attenuation α and a time delay $\tau = 2R/c$. The received signal can be written as:

$$r(t) = \alpha\, s(t - \tau) + n(t)$$

Where n(t) represents noise modeled as Additive White Gaussian Noise (AWGN) with zero mean and variance σ^2. To simulate a realistic radar scenario, a pulse train consisting of three pulses with a Pulse Repetition Interval (PRI) of 15 µs is used.

C. Matched Filter

A matched filter is used to improve the signal-to-noise ratio of the received signal. It is designed using the time-reversed conjugate of the transmitted pulse:

$$h(t) = s(Tp - t)$$

The filter output is formed by convolution:

$$y(t) = r(t) * h(t)$$

This process produces a strong peak at $t = \tau$, which helps identify the delay of the received signal even when noise is present.

D. Peak Detection and Range Estimation

A peak detection algorithm is applied to the filtered signal y(t). The algorithm searches for peaks that exceed 50% of the maximum amplitude. The first detected peak corresponds to the estimated delay τ. The range of the UAV can then be calculated using:

$$R = c\tau / 2$$

V. THEORETICAL ANALYSIS

A. Radar Range Equation

The power received from a target depends on several parameters, such as transmitted power, antenna gain, wavelength, and the target's radar cross section (RCS). It is given by the radar range equation:

$Pr = (Pt \cdot Gt \cdot Gr \cdot \lambda^2 \cdot \sigma) / ((4\pi)^3 \cdot R^4)$

For a small UAV located at R = 1500 m with a small RCS value σ, the received power becomes very weak. Because of this, signal processing techniques such as matched filtering are required to improve the signal-to-noise ratio and enable reliable detection.

B. *Range Resolution*

Range resolution represents the minimum distance between two targets that a radar system can distinguish. It is expressed as:

$\Delta R = cTp / 2$

For a pulse width Tp = 1 µs and speed of light c = 3 × 10^8 m/s, the calculated range resolution is:

$\Delta R = 150\ m$

This means the radar system can distinguish two targets only if they are separated by at least 150 meters.

C. *Matched-Filter Output SNR*

The matched filter improves detection by maximizing the output signal-to-noise ratio (SNR). The theoretical SNR at the output of the matched filter is given by:

$SNR\_MF = 2Es / N_0$

where Es = $\int|s(t)|^2$ dt represents the transmitted pulse energy and $N_0/2$ is the two-sided noise power spectral density. One important advantage of the matched filter is that its optimal performance does not depend on the exact pulse shape.

D. *Neyman–Pearson Detection*

Radar detection can be modeled as a binary hypothesis testing problem:

$H_0 : r(t) = n(t)$ *(target absent)*

$H_1 : r(t) = \alpha\, s(t-\tau) + n(t)$ *(target present)*

For Gaussian noise, the detection rule compares the matched filter output with a threshold γ:

$|y(\tau)| > \gamma$

The probability of detection and probability of false alarm are given by:

$Pd = Q((\gamma - \mu_1) / \sigma)\ Pfa = Q(\gamma / \sigma)$

where Q (·) represents the complementary Gaussian cumulative distribution function. Increasing the threshold reduces the false alarm probability, but it may also reduce the probability of detecting the target

VI. MATLAB IMPLEMENTATION

A. *Simulation Environment*

The proposed system is implemented using MATLAB R2023b. The Signal Processing Toolbox is used for generating the radar pulse and performing signal operations. Noise is introduced using the awgn() function, while matched filtering is implemented using the conv() function. The simulation results and signal waveforms are visualized using MATLAB's built-in plotting tools.

B. *System Parameters*

TABLE I: Simulation Parameters

Parameter	Value
Speed of Light (c)	3 × 10^8 m/s
Sampling Freq. (fs)	20 MHz
Pulse Width (Tp)	1 µs
UAV Distance (R)	1500 m
No. of Pulses	3
PRI	15 µs
SNR	0 dB
Noise Model	AWGN

C. *Processing Pipeline*

The signal processing procedure followed in the simulation is summarised below:

1. Initialize parameters: speed of light c, pulse width Tp, sampling frequency fs, target range R, and SNR.
2. Generate transmitted signal: create a three-pulse rectangular pulse train with a pulse repetition interval (PRI) of 15 µs.
3. Model the echo: introduce a time delay τ = 2R/c and attenuation factor α = 0.7 to represent the UAV reflection.
4. Add noise: apply AWGN to the received signal at the specified SNR level.
5. Construct matched filter: h = fliplr(ref pulse).
6. Perform filtering: compute the convolution y = conv (rnoisy, h, 'same').
7. Detect peaks: identify locations where |y| > 0.5 × max(|y|).
8. Estimate range: compute the estimated range using R = c × t (locs (1)) / 2.

VII. SIMULATION RESULTS

A. Effect of SNR on Detection

The system performance was evaluated under three different SNR conditions. When the SNR is −10 dB, the received signal is strongly affected by noise. Even in this case, the matched filter is able to detect peaks corresponding to the three transmitted pulses, showing that detection is possible even under very noisy conditions.

At SNR = 0 dB, a clear and distinct peak appears at the correct delay, allowing reliable detection of the UAV echo. When the SNR increases to +10 dB, the peak becomes much stronger, and the peak-to-sidelobe ratio exceeds 20 dB. This enables more accurate identification of the target delay and improves range estimation.

B. Range Estimation Accuracy

The target range in the simulation is set to R = 1500 m, corresponding to a true delay of τ = 10 μs. At SNR = 0 dB, the estimated range obtained from the simulation is 1575 m, resulting in an absolute error of 75 m (about 5%).

This error mainly occurs due to sampling quantisation. With a sampling interval of Δt = 1/fs = 50 ns, the corresponding range resolution becomes ΔR = 7.5 m per sample.

The range estimation error is calculated using:

$e_r = |R - \hat{R}|$

As the SNR increases, the estimation error gradually decreases and approaches the theoretical limit determined by the sampling resolution.

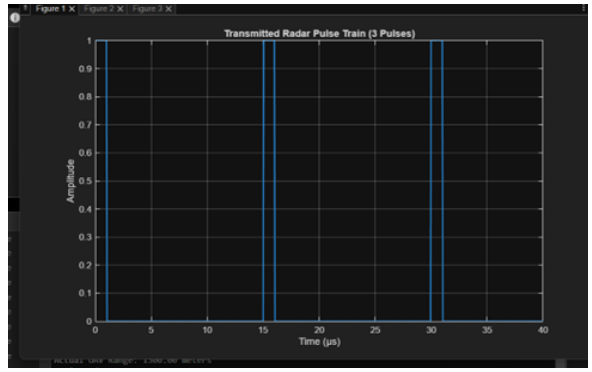
C. Summary of Advantages

The proposed approach offers several advantages:

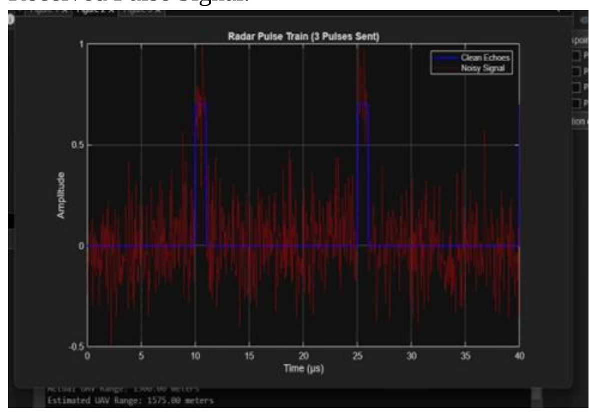
1. Improved SNR through matched filtering (proportional to $2E_s/N_0$)
2. Ability to detect targets even under low SNR conditions
3. Range accuracy is mainly limited by sampling resolution
4. Simple implementation using MATLAB
5. A flexible framework that can be extended for more advanced radar processing

VIII. OUTPUT

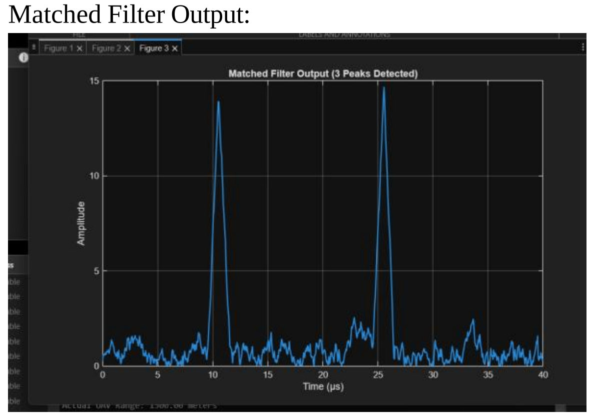
Transmitted Pulse Signal:



Received Pulse Signal:



Matched Filter Output:



IX. CONCLUSION

This paper presented a MATLAB-based pulse radar signal processing framework for detecting and estimating the range of small UAVs. The key idea is the use of matched filtering, which improves the output signal-to-noise ratio and enables reliable detection even in noisy environments.

Simulation results show that the proposed method can successfully detect UAV echoes in a three-pulse radar signal and estimate the target range with an error of about 5% at moderate SNR levels. These results demonstrate that the approach can be useful for small UAV detection applications.

Future work can extend this framework by including Doppler processing for velocity estimation, adaptive threshold techniques such as CFAR, and more advanced radar waveforms like FMCW for combined range and velocity estimation. In addition, implementing the system on hardware platforms such as SDR or FPGA could enable real-time deployment.

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