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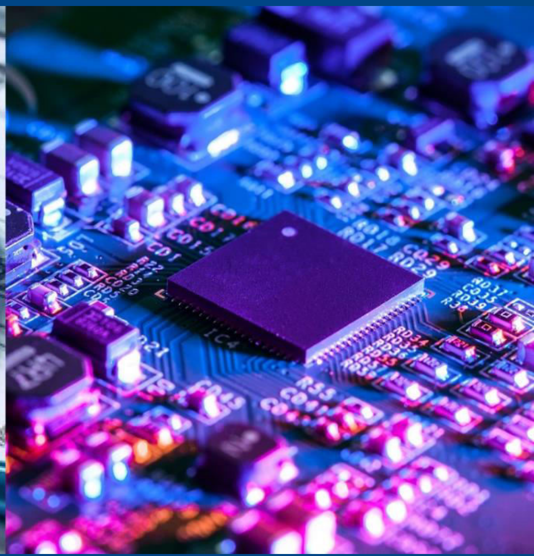

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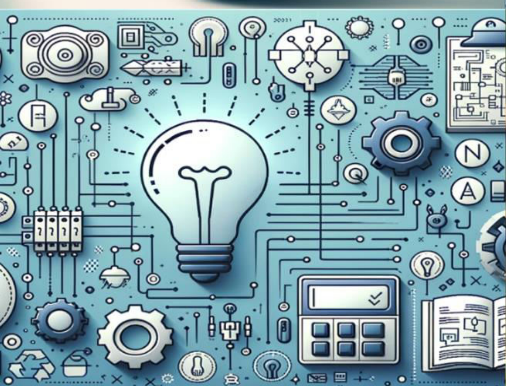

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Simulation of Underwater Target Detection and Tracking using Active Sonar

P.V.Krishna Kanth[1], Pinni Harshitha[2], Sriramula Mounika[3], Shaik Masthan Sadik[4], Vallepu Tejasri[5]

Assistant Professor, Department of ECE, R.V.R. & J.C College of Engineering, Chowdavaram, Guntur, A.P., India[1]

Under Graduate Students, Department of ECE, R.V.R. & J.C College of Engineering, Chowdavaram, Guntur, A.P., India[2-5]

ABSTRACT: In this work, a comprehensive simulation of an underwater active sonar system is presented, aiming to detect and track multiple moving targets within a bounded three-dimensional aquatic environment. The simulation models both the dynamic behavior of the targets and the physical phenomena involved in sonar wave transmission, reflection, and reception. A sinusoidal pulse at 20 kHz is transmitted from a stationary sonar located at the center of a 100×100×100-meter volume. Targets initialized with random velocities undergo free motion, with reflection at environmental boundaries to simulate realistic underwater behavior. Signal propagation delays are calculated based on the range to each target, and amplitude attenuation is incorporated to model spreading loss. Noise is added to the received signals to mimic real-world underwater acoustic conditions. The simulation results include target trajectories, distance evolution over time, and detailed plots of transmitted and received signals, with and without noise. The system successfully identifies and tracks targets despite noise interference, demonstrating the practical viability of active sonar techniques for underwater detection. The developed model provides a foundation for further research into more advanced sonar processing algorithms such as matched filtering, Doppler processing, and multi-target tracking systems.

KEYWORDS: Active Sonar, Target Detection, Underwater Simulation, Multi-Target Tracking, Signal Processing, Acoustic condition, Noise Interference

I. INTRODUCTION

Sonar (Sound Navigation and Ranging) technology has been extensively utilized in various underwater applications, including naval operations, marine biology research, and offshore engineering. It serves as a critical tool for detecting, localizing, and tracking objects submerged in aquatic environments where optical sensors are limited by light attenuation. Active sonar systems function by transmitting acoustic pulses into the medium and analysing the echoes reflected from targets.

However, underwater environments present numerous challenges for sonar operation. Signal attenuation due to geometric spreading and absorption, ambient noise, multipath reflections, and target-induced Doppler shifts complicate the detection and tracking processes. Therefore, realistic simulation of sonar systems is essential for studying their performance and developing robust signal processing algorithms.

This paper focuses on simulating an active sonar system operating in a constrained three-dimensional underwater volume. The sonar is stationary, while multiple targets move dynamically within the environment, subjected to boundary reflections to simulate an enclosed aquatic space. The transmitted sonar pulse, a 20 kHz sinusoidal waveform, propagates through the medium, reflects off targets, and returns to the sonar receiver with time delays and amplitude attenuation based on the target distances. Noise is added to emulate real-world conditions, and the resultant received signals are analysed for target detection feasibility.

Importance of Sonar in Underwater Applications

Sonar is indispensable in various applications:

- **Military/Naval**: Submarine detection, mine tracking, and torpedo defence systems.
- **Commercial**: Underwater pipeline inspection, fishery monitoring, oil exploration.
- **Research**: Bathymetry, marine biology, and climate change studies involving ocean dynamics.
- **Autonomous Systems**: Underwater drones, ROVs (remotely operated vehicles), and AUVs (autonomous underwater vehicles) rely heavily on sonar for navigation and obstacle avoidance.

The primary objectives of this simulation are:
- To model the dynamic motion of multiple underwater targets.
- To simulate sonar signal transmission, propagation, and reflection realistically.
- To evaluate the system's ability to detect targets in the presence of noise.
- To provide a visualization of target tracking and signal behaviour over time.

Through this simulation, foundational insights into sonar system behaviour are obtained, providing a stepping stone for future advancements in underwater sensing technologies.

Software Requirements: MATLAB

Tool Used: Phased Array System tool box

II.METHODOLOGY AND SYSTEM DESIGN

This section outlines the framework and design used to simulate the underwater sonar detection and tracking system.

Environment Setup

The simulation operates in a three-dimensional underwater volume measuring 100 meters along each axis (X, Y, Z). A stationary sonar unit is placed at the centre position (50, 50, 50). The speed of sound is set to 1500 meters per second, reflecting average seawater conditions. A fixed random seed ensures reproducibility of target initialization.

Target Initialization and Motion Modelling

Three targets are randomly positioned within the volume, between 10 and 90 meters along each axis to prevent immediate boundary collisions. Each target receives a random velocity vector ranging from -1 to 1 meters per second along each axis.

At each timestep:
- Target positions are updated based on their velocities.
- Boundary reflections are handled by inverting the velocity component upon collision and clamping the position within the environment limits.

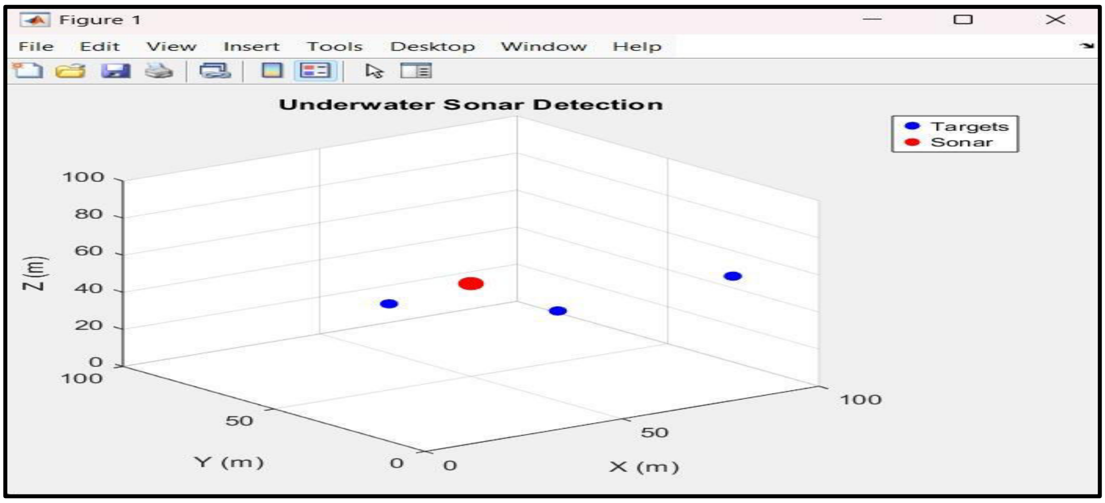


Figure 1: 3D Environment with sonar and targets in it

This approach mimics bounded underwater environments, such as experimental tanks or shallow marine regions.

Sonar Transmission and Echo Reception Modelling

The sonar system emits a sinusoidal acoustic pulse characterized by:

- Carrier Frequency: 20 kHz
- Pulse Duration: 5 milliseconds
- Sampling Frequency: 1 MHz

The received signal accounts for:

- **Propagation Delay**: Based on the round-trip distance to each target.
- **Amplitude Attenuation**: Modelled as inversely proportional to the square of the distance.
- **Noise Addition**: Additive White Gaussian Noise (AWGN) is introduced at a 20 dB signal-to-noise ratio to simulate environmental disturbances.

Echoes from multiple targets are delayed appropriately and superimposed at the receiver to represent realistic multi-target returns.

Target Tracking and Signal Analysis

Throughout the simulation:

- The Euclidean distance between sonar and each target is computed.
- Velocity components and speeds are recorded.
- Movement directions are estimated and categorized using compass-based orientation.

Visualization includes:

- A 3D plot showing real-time motion of targets and the sonar.
- Distance vs. time plots for each target.
- Clean and noisy received sonar signals for detectability assessment.

Individual Signal Transmission and Reception

In addition to combined echoes, the transmission and reception paths for each target are individually modelled:

- The transmitted pulse is compared against the delayed received signal.
- Delays are calculated based on final distances.
- Comparative plots display transmitted and received signals, highlighting the impact of distance-induced delays.

III.RESULTS

The simulation provides a comprehensive set of results, analysing the motion of targets, the behaviour of transmitted and received sonar signals, and the impact of underwater acoustic noise on detection performance. The key observations are presented below:

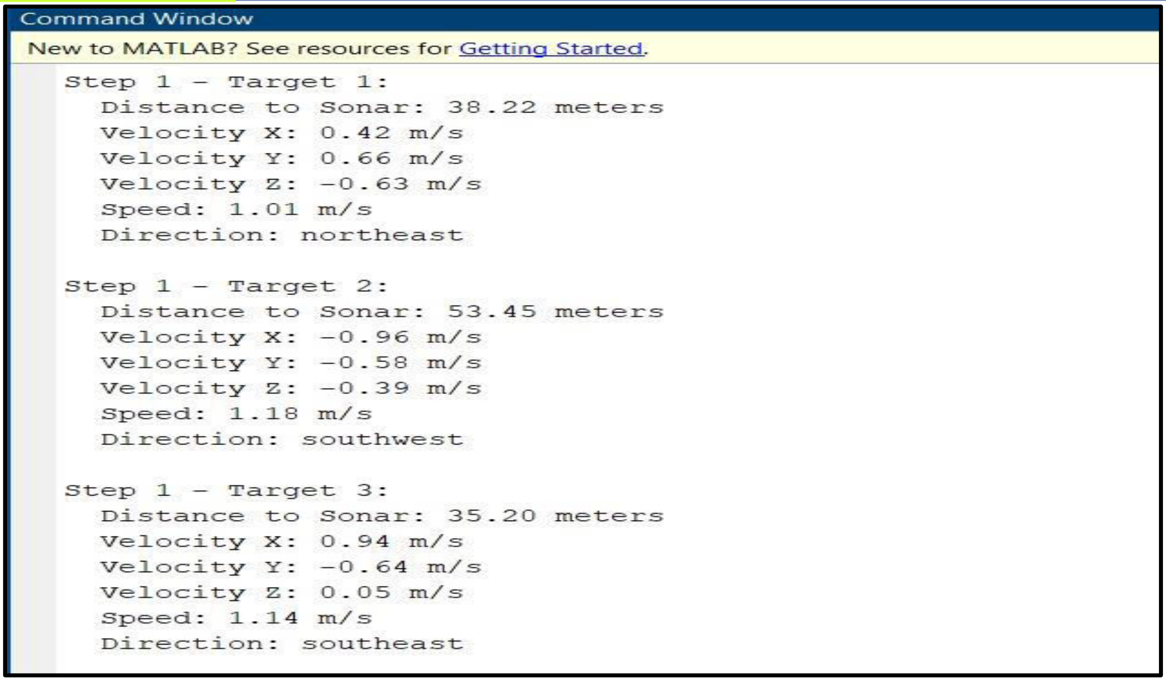
1. Target Motion and Distance Analysis

Throughout the simulation, the three initialized targets move within the 3D underwater environment. Their trajectories are visualized in a 3D plot, showing continuous motion with reflections off the boundaries, emulating realistic behaviour within a constrained aquatic volume.

The Euclidean distance from each target to the stationary sonar is tracked over time:

- For all three targets, the distance varies dynamically, demonstrating periods of approach and recession relative to the sonar location.
- Distance-versus-time plots reveal smooth, continuous changes, without abrupt discontinuities, validating the correctness of motion modelling and boundary reflection logic.
- Periodic distance variations correlate with boundary reflections, as expected when targets reverse direction after hitting a wall.

Periodic distance variations correlate with boundary reflections, as expected when targets reverse direction after hitting a wall. These plots are critical in assessing when a target might be optimally detectable based on range.



```
Command Window
New to MATLAB? See resources for Getting Started.
Step 1 - Target 1:
  Distance to Sonar: 38.22 meters
  Velocity X: 0.42 m/s
  Velocity Y: 0.66 m/s
  Velocity Z: -0.63 m/s
  Speed: 1.01 m/s
  Direction: northeast

Step 1 - Target 2:
  Distance to Sonar: 53.45 meters
  Velocity X: -0.96 m/s
  Velocity Y: -0.58 m/s
  Velocity Z: -0.39 m/s
  Speed: 1.18 m/s
  Direction: southwest

Step 1 - Target 3:
  Distance to Sonar: 35.20 meters
  Velocity X: 0.94 m/s
  Velocity Y: -0.64 m/s
  Velocity Z: 0.05 m/s
  Speed: 1.14 m/s
  Direction: southeast
```

Figure 2: Output command window

2. Velocity and Direction Estimation

At each timestep, the velocity components (Vx, Vy, Vz) and overall speed for each target are calculated. Using the velocity vectors, the system estimates the movement direction categorized into one of the eight principal compass directions (North, Northeast, East, Southeast, South, Southwest, West, Northwest).

The directions dynamically change over time, as targets bounce off boundaries, reflecting realistic unpredictable target motion in underwater environments.

This real-time estimation capability could form the basis for future work on predictive tracking and trajectory estimation.

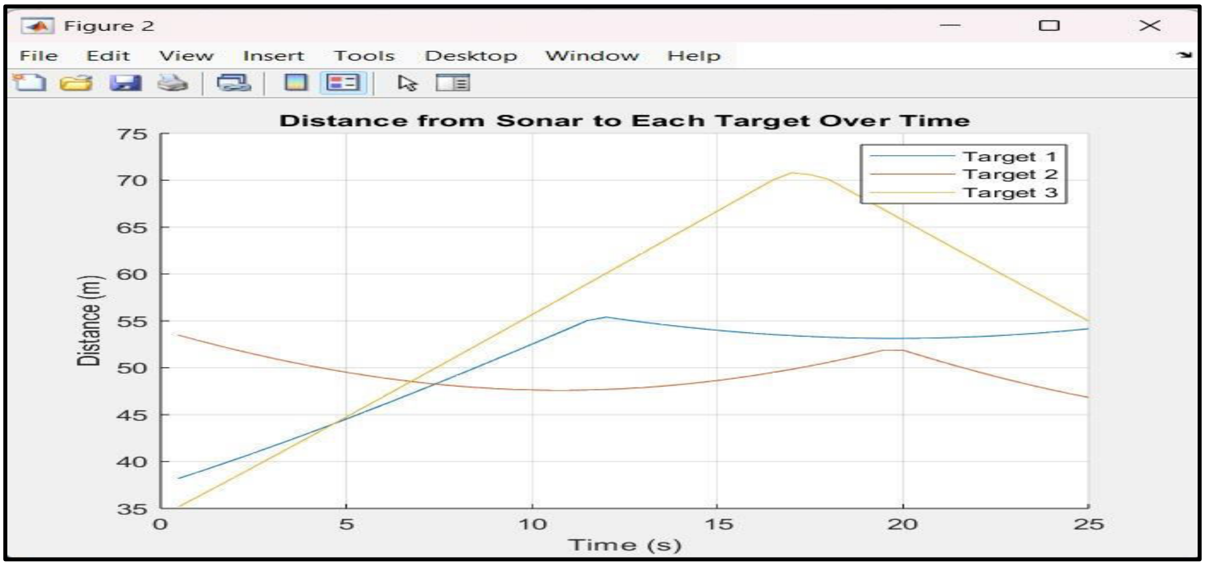


Figure 3: Direction from sonar to each target over time

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3. Sonar Signal Transmission and Reception

The transmitted sonar pulse, a clean 20 kHz sinusoid with a 5 ms duration, was successfully generated and plotted.

A zoomed-in view of the first 0.5 ms clearly shows the sinusoidal nature and high temporal resolution achieved by the 1 MHz sampling frequency.

At the receiver:

- The combined echoes from all targets were reconstructed based on two-way propagation delays and amplitude attenuation.
- The **clean received signal** shows distinct returns corresponding to different target ranges, although they are partially overlapping due to close distances.
- The **noisy received signal** still maintains identifiable echo peaks, indicating that at an SNR of 20 dB, the sonar system can reliably detect the presence of targets.

Comparison of clean and noisy signals highlights the robustness of simple sonar processing under moderate noise conditions.

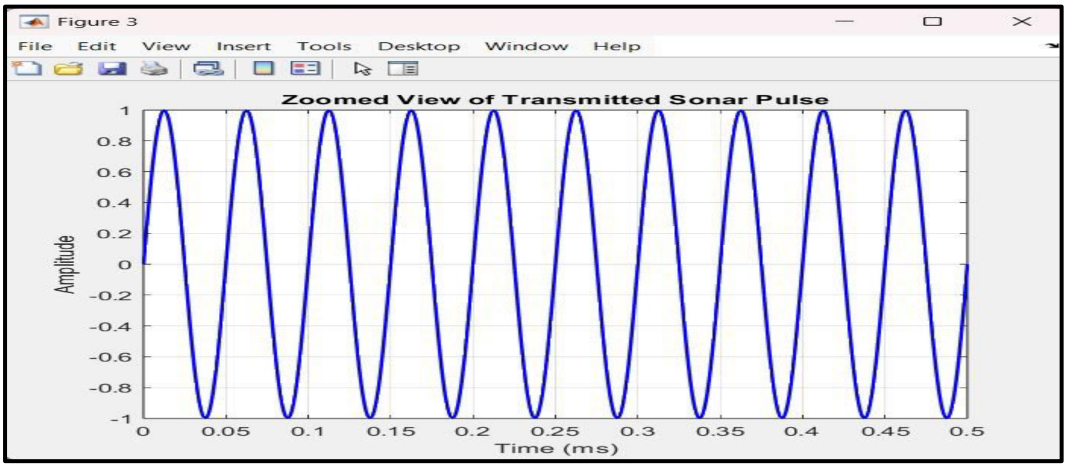

Figure 4: Zoomed view of transmitted sonar pulse

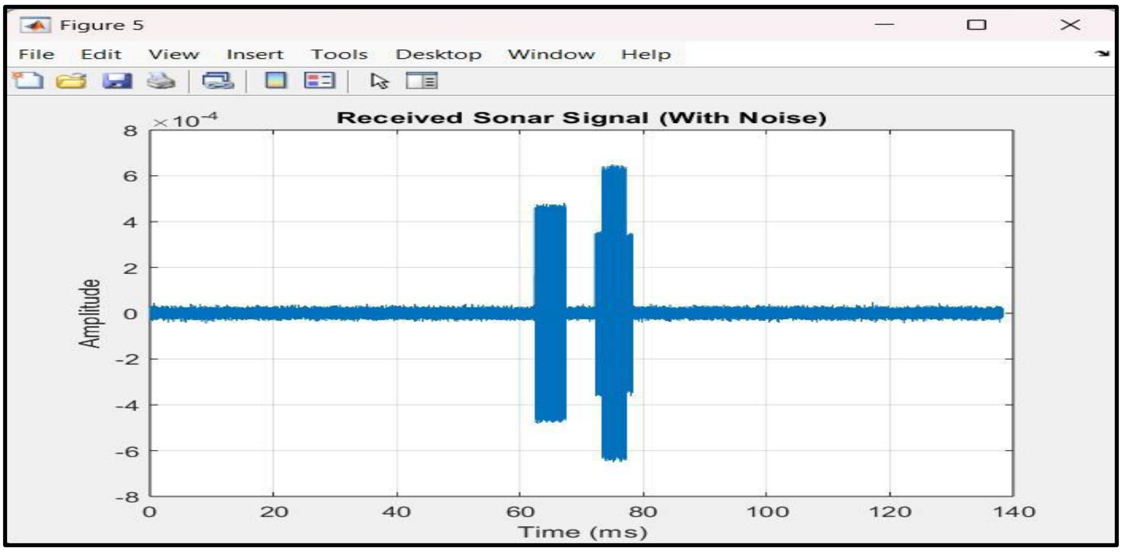

Figure 5: Received sonar signal with noise.

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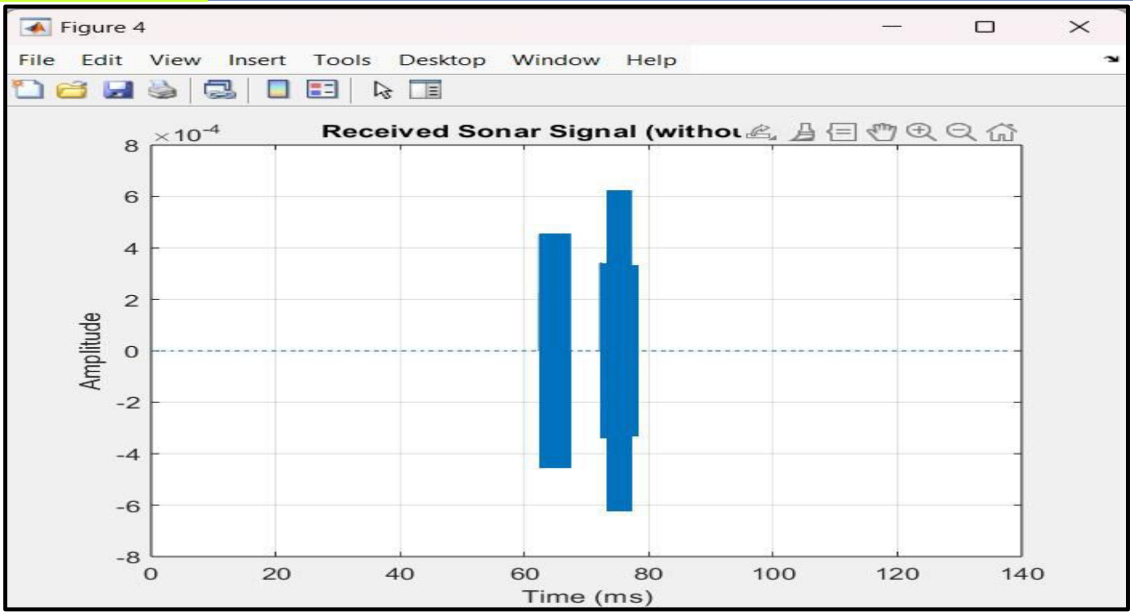


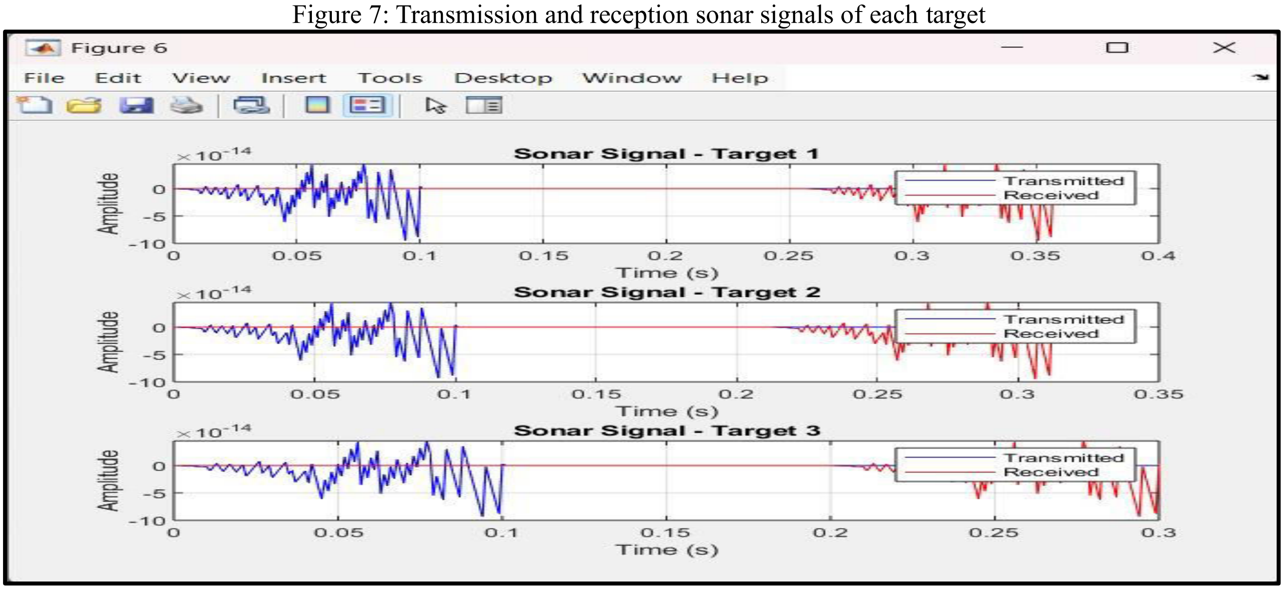
Figure 6: Received sonar signal without noise.

4. Individual Target Echo Analysis
The signal transmission and reception were separately modelled for each target:

- For each target, the delayed received pulse matches the transmitted pulse shape but shifted according to the distance-induced delay.
- Longer distances result in greater time delays, as clearly shown in the time-domain plots.
- Despite delay and minor amplitude changes, the pulse remains recognizable, suggesting that target detection and range estimation are feasible even in basic scenarios without sophisticated signal processing.

These individual plots reinforce the system's validity and help in understanding the effects of distance and signal attenuation separately for each target.

Figure 7: Transmission and reception sonar signals of each target



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Required Formulae

1. Distance between Sonar and Target:

$$\mathbf{d} = (\mathbf{xtarget} - \mathbf{xsonar})\mathbf{2} + (\mathbf{ytarget} - \mathbf{ysonar})\mathbf{2} + (\mathbf{ztarget} - \mathbf{zsonar})\mathbf{2}$$

2. Two-way Travel Time (Delay):

$$\mathbf{tdelay} = \mathbf{c2d}$$

where c=1500 m/sc = 1500 \, \text{m/s}c=1500m/s (speed of sound in water).

3. Signal-to-Noise Ratio (Linear Scale):

$$\mathbf{SNRlinear} = \mathbf{10}(\mathbf{SNRdB}/\mathbf{10})$$

4. Compass Direction (based on velocity components):

$$\boldsymbol{\theta} = \arctan\mathbf{2}(\mathbf{vy}, \mathbf{vx})$$

(Converted to degrees)

V. CONCLUSION

This study successfully developed a simulation of an active sonar system for detecting and tracking multiple targets in a dynamic 3D underwater environment. By modelling key aspects such as acoustic attenuation, propagation delay, and environmental noise, the simulation offers a realistic framework for analysing sonar performance and target behaviour under varying conditions.

The system serves as a valuable tool for understanding fundamental sonar principles and the challenges of underwater detection, such as signal degradation and noise interference. Future improvements, like incorporating Doppler effects, could further enhance realism by simulating frequency shifts caused by relative motion between the sonar and the targets.

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