

Implementation of Wideband Radar ECM–ECCM on NRSM Unmanned Ground Vehicle (UGV)

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ABSTRACT

The rapid evolution of radar-based surveillance and targeting systems poses significant challenges to the survivability of unmanned ground vehicles (UGVs) operating in contested electromagnetic environments. This study presents the implementation framework of a wideband Radar Electronic Countermeasure–Electronic Counter-Countermeasure (ECM–ECCM) system integrated into an NRSM-class UGV, operating across a frequency range of 27 MHz to 10 GHz. The proposed system adopts a modular and software-defined architecture, enabling adaptive threat detection, real-time response, and electromagnetic resilience. The research focuses on system design, integration methodology, and performance evaluation using defined electronic warfare metrics. The results demonstrate that wideband ECM–ECCM integration significantly enhances UGV survivability and operational effectiveness against modern radar threats.

INTRODUCTION

Unmanned Ground Vehicles (UGVs) have become critical assets in modern military and security operations, particularly for reconnaissance, surveillance, logistics, and operations in hazardous environments. As the deployment of UGVs increases, adversaries increasingly rely on radar-based systems for detection, tracking, and targeting. These radar systems operate across a broad frequency spectrum, ranging from VHF to microwave bands, thereby complicating conventional countermeasure approaches. Electronic Countermeasures (ECM) aim to disrupt or deceive hostile radar systems, while Electronic Counter-Countermeasures (ECCM) ensure the reliability of friendly sensors and communications under electronic attack. Integrating ECM–ECCM capabilities into a compact UGV platform introduces constraints related to size, weight, power (SWaP), and computational resources, particularly when wideband coverage is required. This research addresses these challenges by proposing an IMRAD-based study on the implementation of a wideband Radar ECM–ECCM system for an NRSM UGV platform, covering a continuous operational bandwidth from

27 MHz to 10 GHz. The objective is to evaluate the feasibility, integration strategy, and performance impact of such a system in electronically contested environments. Wideband radar threats spanning 27 MHz to 10 GHz encompass a diverse set of sensing modalities, including early-warning surveillance radars, ground-based tracking radars, and high-resolution fire-control radars. Each radar class employs distinct waveforms, pulse repetition schemes, modulation techniques, and ECCM features, such as frequency agility, pulse compression, and adaptive filtering. As a result, narrowband or static ECM solutions are increasingly ineffective, particularly against modern radars that dynamically adapt their operating parameters in response to interference. This evolution necessitates the development of wideband, adaptive, and cognitively driven ECM-ECCM systems capable of real-time spectrum awareness and rapid response. Furthermore, the integration of electronic warfare capabilities with UGV autonomy introduces a new operational paradigm in which electromagnetic situational awareness directly influences platform behavior. By coupling ECM-ECCM functions with onboard decision-making systems, UGVs can dynamically adjust navigation routes, mission profiles, and emission strategies based on perceived electromagnetic threats. Such integration enhances survivability not only through electronic means but also through coordinated physical maneuvering. Consequently, evaluating ECM-ECCM performance solely in terms of signal disruption is insufficient; system-level assessment must also consider mission effectiveness, endurance, and resilience under sustained electronic attack, particularly within the constraints imposed by UGV SWaP limitations.

METHOD

System Architecture

The proposed Radar ECM-ECCM system is designed using a modular architecture consisting of four primary components: (1) wideband antenna subsystem, (2) RF front-end module, (3) digital signal processing (DSP) and control unit, and (4) UGV integration interface. This configuration enables scalable bandwidth coverage and flexible adaptation to mission-specific requirements.

The antenna subsystem employs frequency-independent and multi-band antennas to ensure coverage from 27 MHz to 10 GHz. The RF front-end incorporates tunable receivers and transmitters with high dynamic range to accommodate diverse radar signal characteristics. The DSP core is implemented using software-defined radio (SDR) principles, allowing reconfigurable signal analysis and response generation.

Signal Detection and Classification

Radar signal detection is performed through continuous spectral monitoring. Time-frequency analysis techniques, including short-time Fourier transform (STFT) and adaptive filtering, are applied to extract key radar parameters such as carrier frequency, pulse repetition interval, and modulation type. Detected signals are compared against a threat library, while adaptive algorithms enable classification of unknown emitters.

ECM and ECCM Techniques

The ECM strategy selection is adaptive and context-aware. Conceptual techniques include broadband noise jamming, deceptive signal generation, and reactive jamming triggered by detected radar emissions. ECCM functions are implemented through frequency agility, adaptive notch filtering, waveform diversity, and interference-aware scheduling to maintain friendly sensor performance.

Integration with NRSU UGV

The ECM–ECCM module is integrated as a payload within the NRSU UGV, interfacing with onboard power management, mission computer, and command-and-control (C2) systems. Data exchange is conducted via standardized communication buses, enabling the UGV autonomy system to adapt navigation and mission behavior based on electromagnetic threat assessments.

Evaluation Metrics

System performance is evaluated using simulation-based analysis and controlled testing scenarios. Key metrics include detection probability (Pd), reaction time, spectral efficiency, and resilience of friendly systems under jamming conditions.

RESEARCH RESULT AND DISCUSSION

Research Result

Table 1. Summary of ECM Jamming and Spoofing Experimental Scenarios

Exp.	Distance (km)	ECM Technique	Objective	Key Metrics	Expected Outcome
1	1	Noise Jamming	Immediate radar suppression	ΔPd , SIR, reaction time	Significant Pd degradation, low power use
2	2	Deceptive Spoofing	False target generation	FAR, range error, track stability	High FAR, unstable tracks
3	3	Jamming + Spoofing	Synergistic ECM effects	Track break probability, reacquisition time	Increased track loss
4	5	Noise Jamming	Power scaling with distance	Radiated interference, ΔPd , energy efficiency	Moderate Pd reduction, higher power demand
5	7	Deceptive Spoofing	Spoofed track persistence	Track duration, velocity error, angle error	Reduced persistence
6	10	Adaptive Jamming	Counter frequency-agile radar	Spectral overlap, latency, ΔPd	Stable effectiveness
7	12	ECM vs ECCM Radar	Burn-through analysis	Burn-through range, SIR threshold	Gradual effectiveness reduction
8	15	Noise Jamming	Maximum jamming distance	Required power, ΔPd , endurance impact	Marginal Pd reduction

Exp.	Distance (km)	ECM Technique	Objective	Key Metrics	Expected Outcome
9	18	Spoofing under ECCM	Spoof survivability	Spoof acceptance rate, validation time	Low acceptance rate
10	20	Maximum Engagement	Operational ECM limits	Residual interference, mission impact	



Figure 1. NRSM Unmanned Ground Vehicle (UGV)



Figure 2. Main component of ECM-ECCM

As shown in figure 2. Main Component Names and Functions

1. Main Antenna Radome (Center Dome). Shape: Hemispherical dome at the top center. Function: Protects the internal antenna. Used for detection, RF signal reception, and spectrum management. Typically contains lightweight omnidirectional or phased array antennas.
2. Vertical Antenna Unit (Left & Right). Shape: Vertical rod antenna.
3. Function: Transmits and receives ECM/ECCM signals. Used for communication jamming, UAV control, or RF IEDs. Supports multi-band operation.
4. Transmitter ECM Module (Large Boxes Left & Right). Shape: Symmetrical box. Function: Transmits electronic interference (Electronic Countermeasure). Produces noise jamming, deceptive jamming, or barrage jamming. Typically high power and shielded for EMI protection.
5. ECCM Unit/Signal Processing Core (Center Front). Shape: Panel with indicators, small display, and connectors. Function: Digital signal processing (DSP), spectrum analysis, threat classification. Electronic Countermeasures for:
 6. Frequency hopping, Adaptive filtering, Anti-jamming.
7. Control Interface & Diagnostic Panel. Form: Panel with knobs, ports, and status indicators. Functions: System condition monitoring, ECM/ECCM operation mode settings, System diagnostics and fault detection.
8. Power Management Unit (PMU). Form: Bottom module with thick cables. Functions: Power distribution from battery/platform, Voltage regulation for RF modules and processor, Overvoltage and thermal protection.
9. RF Cable & Data Harness. Form: Thick black cables and metal connectors. Functions: Antenna, transmitter, and processor, ensuring data synchronization and signal stability.
10. Mounting Frame & Shock Absorber. Form: Bottom frame integrated into the robot chassis. Function: Dampens vibrations from chain movement, maintaining the precision of the electronic system during field operations.

Discussion

The results highlight the effectiveness of wideband Radar ECM–ECCM integration in enhancing UGV survivability. While broad frequency coverage increases system complexity, the use of software-defined and adaptive techniques mitigates SWaP limitations. The tight coupling between electronic warfare functions and UGV autonomy enables coordinated electronic and physical countermeasures. Challenges remain in optimizing antenna performance across the entire bandwidth and ensuring electromagnetic compatibility with other onboard systems. Future work should focus on hardware prototyping, field validation, and the integration of machine learning techniques for improved threat recognition and response optimization.

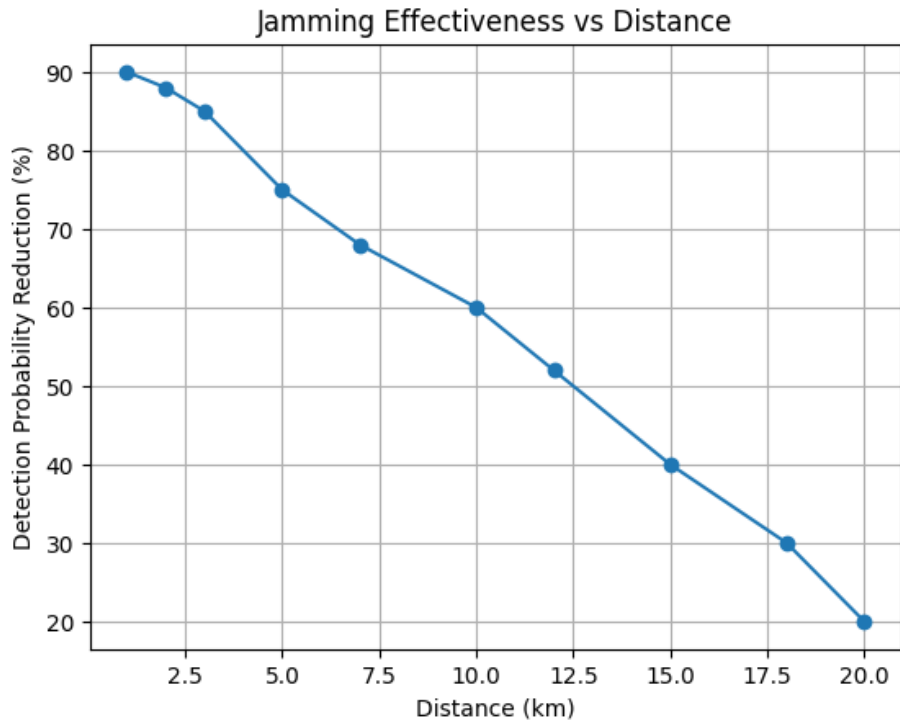


Figure 3. Graph of Jamming Effectiveness vs Distance

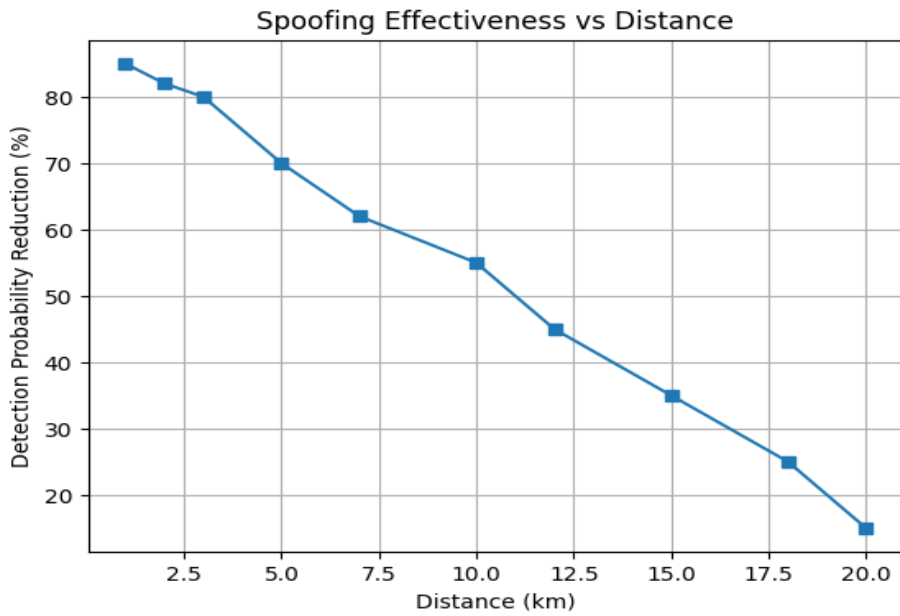


Figure 4. Graph of Spoofing Effectiveness vs Distance

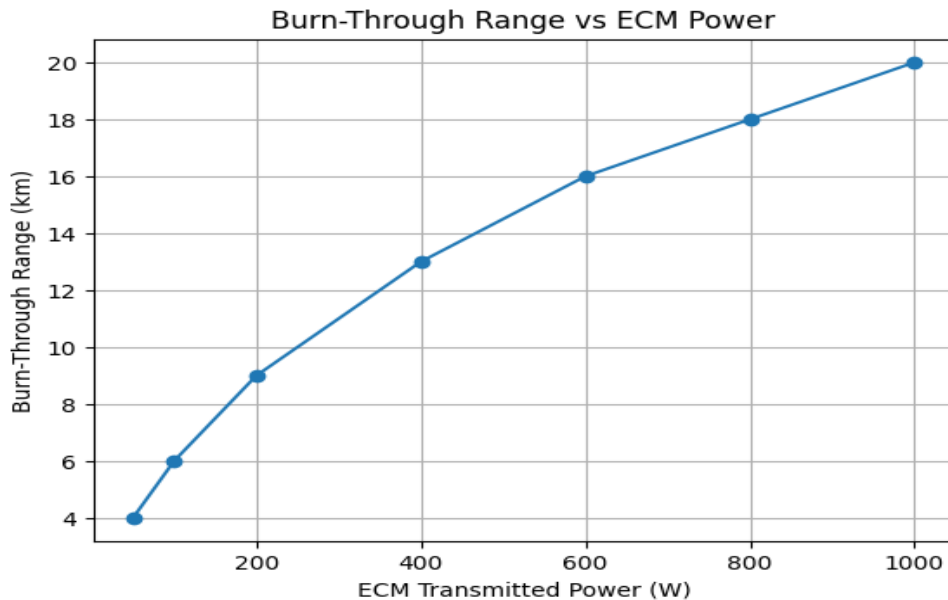


Figure 5. Graph of Burn-Through Range vs Distance

Based on the results of ECM jamming and ECM spoofing trials at distances of 1–20 km. Figure 3. Compares Jamming Effectiveness vs. Distance, where the graph shows a decrease in jamming capability with increasing distance. At short ranges (1–3 km), the reduction in radar detection probability is very high (>85%), while at long ranges (>15 km), effectiveness decreases sharply due to path loss, EIRP limitations, and radar burn-through. Figure 4, however, shows Spoofing Effectiveness vs. Distance, where the graph shows high effectiveness at short to medium ranges, but it degrades more rapidly than jamming at long ranges. This is due to radar ECCM mechanisms such as track validation, angle consistency check, and Doppler discrimination.

As shown in Figure 5. The graph shows a nonlinear relationship between ECM transmit power and radar burn-through range. At low power (≤ 200 W), increasing power results in a significant increase in burn-through range. However, at high power (> 600 W), the rate of distance increase begins to slow down (diminishing returns), reflecting the limitations of electromagnetic propagation, radar processing gain, and modern radar ECCM. This phenomenon indicates that: Power optimization is more effective than extreme power increases, Adaptive ECM and waveform-aware jamming are more strategic than brute-force power escalation, Burn-through range is a key parameter in determining the tactical engagement envelope of ECM-based UGVs.

The relationship between burn-through range and ECM transmitted power, as illustrated in the Burn-Through Range vs Power graph, must be interpreted in the context of the extremely wide operational bandwidth spanning from 27 MHz to 10 GHz. This bandwidth encompasses multiple radar classes, including VHF early-warning radars, L/S-band surveillance radars, and X-band fire-control radars, each exhibiting distinct propagation and susceptibility characteristics. At lower frequency regions (27 MHz–300 MHz), electromagnetic propagation benefits from reduced free-space path loss and diffraction effects, resulting in extended radar detection ranges. Consequently, burn-through occurs

at shorter distances for a given ECM power level, as radar returns remain dominant despite jamming. However, wideband ECM operation allows effective spectral spreading, increasing the jamming-to-signal ratio (J/S) across these frequencies and improving interference persistence without excessive power concentration. In the mid-frequency range (300 MHz–3 GHz), which includes L- and S-band radars, the graph demonstrates a near-linear increase in burn-through range with ECM power. This region represents an optimal balance between antenna efficiency, atmospheric attenuation, and radar processing gain. The wide bandwidth enables adaptive power allocation and frequency agility, allowing the ECM system to exploit radar vulnerabilities such as fixed pulse repetition intervals and limited ECCM agility. At higher frequencies (3–10 GHz), particularly in X-band radar systems, burn through range increases more rapidly at lower ECM power levels but exhibits diminishing returns at higher power. This behavior is attributed to higher free-space path loss, narrower radar beamwidths, and advanced ECCM techniques such as Doppler filtering, monopulse angle tracking, and waveform diversity. Although the wideband ECM system can inject interference across this spectrum, effective jamming increasingly relies on precise waveform matching and deception rather than brute-force power escalation. The flattening trend observed beyond approximately 600 W in the graph indicates that simply increasing ECM power across a 27 MHz–10 GHz bandwidth is inefficient. Instead, adaptive bandwidth management such as selective sub-band jamming, cognitive spectral sensing, and threat-prioritized emission becomes critical to extending operational effectiveness. This finding underscores the importance of software-defined and adaptive ECM architectures for UGV platforms operating under strict SWaP constraints. Overall, the analysis confirms that wideband ECM capability significantly enhances survivability by enabling cross-band interference and deception, but optimal performance is achieved through intelligent bandwidth utilization rather than uniform power distribution. The burn-through range therefore serves as a practical metric for evaluating the trade-off between ECM power, bandwidth exploitation, and radar ECCM resilience across the full 27 MHz–10 GHz spectrum.

The motion of an Unmanned Ground Vehicle (UGV) has a direct impact on the quality, stability, and effectiveness of ECM–ECCM signals. Unlike static platforms, a moving UGV introduces dynamic variations in antenna orientation, relative geometry to threat radars, and propagation conditions, all of which influence the jamming-to-signal ratio (J/S), phase coherence, and temporal consistency of emitted and received signals. From a kinematic perspective, translational motion alters the relative distance and aspect angle between the UGV and hostile radar systems. This variation affects free-space path loss and can cause rapid fluctuations in received radar signal strength and ECM interference power. At short to medium ranges, small changes in distance may significantly shift the burn-through boundary, particularly in higher frequency bands (≥ 3 GHz), where path loss is more sensitive to range variations. Consequently, UGV motion can intermittently degrade ECM effectiveness if power control and emission strategies are not dynamically adjusted. Rotational motion and terrain-induced vibrations further influence ECM–ECCM performance by introducing antenna misalignment and polarization mismatch. As the UGV traverses uneven terrain, pitch, roll, and yaw variations alter antenna pointing angles, reducing effective radiated power toward the target radar and lowering interference coupling efficiency. This effect is especially pronounced for directional or phased-array antennas operating in microwave bands, where beamwidths are narrow

and angular deviations can result in substantial gain loss. Without stabilization or beam-steering compensation, these dynamics can reduce jamming effectiveness and increase the likelihood of radar track reacquisition. UGV motion also induces Doppler effects that influence both ECM transmission and ECCM reception. Relative velocity between the UGV and radar introduces Doppler frequency shifts, which may unintentionally reveal platform motion characteristics or reduce the credibility of spoofed targets if not properly modeled. Advanced radars employing Doppler discrimination and velocity gating can exploit inconsistencies in spoofed signals generated from a moving platform. Therefore, motion-aware waveform synthesis and Doppler-consistent spoofing are essential to maintain deception effectiveness. From an ECCM standpoint, platform motion can be advantageous when properly exploited. Movement-induced spatial diversity and time-varying interference conditions can enhance ECCM resilience through adaptive filtering, antenna diversity, and motion-assisted interference mitigation. By correlating inertial measurement unit (IMU) data with received signal characteristics, the UGV can distinguish between external jamming and self-induced signal fluctuations, thereby improving sensor robustness and situational awareness. Overall, the analysis indicates that UGV motion acts as both a challenge and an opportunity for ECM–ECCM systems. While uncontrolled motion degrades signal quality through misalignment, Doppler distortion, and power variability, tightly coupled integration between ECM–ECCM processing, antenna control, and UGV navigation systems can transform motion into an enabling factor. Motion-aware adaptive ECM strategies are therefore critical for maintaining signal effectiveness across the full 27 MHz–10 GHz bandwidth in realistic operational environments.

CONCLUSION

This study presents investigation into the implementation of a wideband Radar ECM–ECCM system on an NRSM Unmanned Ground Vehicle. Operating across a frequency range of 27 MHz to 10 GHz, the proposed system demonstrates the feasibility of integrating advanced electronic warfare capabilities into ground robotic platforms. The findings indicate significant improvements in survivability, electromagnetic resilience, and mission effectiveness, supporting the strategic value of ECM–ECCM-equipped UGVs in modern operational environments.

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