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BULLFROG: AI POWERED COUNTER UNMANNED AERIAL SYSTEM

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ABSTRACT

The proliferation of small unmanned aircraft systems (sUAS) presents an asymmetric threat to ground maneuver forces operating in contested and gray-zone environments. The Bullfrog Autonomous Weapon Station (AWS) addresses this operational gap through a passive, AI-powered counter-UAS system employing computer vision and machine learning for autonomous detection, tracking, classification, and engagement. Field testing at Technology Readiness Experimentation (T-REX) 26-1 demonstrated 100% probability of defeat against Group 1 UAS targets with a mean engagement time of 6 seconds and 10 rounds per kill at ranges exceeding 160 meters. Operating in both autonomous and human-in-the-loop modes, Bullfrog achieved 99.45% operational availability while leveraging service-common M240B weapons and Modular Open Systems Architecture for rapid integration with Joint All-Domain Command and Control (JADC2) networks. At $300,000 per unit with $10 cost-per-engagement, Bullfrog demonstrates operational relevance, speed-to-field, and alignment with Army and Marine Corps autonomy priorities.

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1. INTRODUCTION

1.1 Operational Context and Motivation: Modern C-UAS

Military forces worldwide face an unprecedented rise in adversary employment of small unmanned aircraft systems. From reconnaissance and targeting to direct kinetic attack and swarm tactics, Group 1-3 UAS platforms have fundamentally altered the tactical landscape for ground maneuver units [1]. The 2025 operational environment—characterized by multi-domain operations, distributed forces, and persistent "gray-zone" pressure—demands counter-UAS (C-UAS) capabilities that can autonomously protect forward-operating bases, convoy routes, critical infrastructure, and maneuver elements without imposing unsustainable operator burdens or logistical footprints.

Existing C-UAS solutions suffer from several critical limitations: active RF sensors that reveal friendly positions, complex operator interfaces requiring extensive training, high cost-per-engagement using missile effectors, and limited interoperability with emerging C2 architectures. Joint Interagency Task Force (JIATF) 401 has identified the urgent need for mobile, rapidly deployable C-UAS systems capable of both standalone and layered defense operations [2].

1.2 Prior Work and Technology Gaps

Traditional short-range air defense (SHORAD) systems such as Avenger and Stinger provide capabilities against aircraft but lack the precision, cost-effectiveness, and automation required for small UAS threats. Recent efforts including the Army's Interim Maneuver-SHORAD (IM-SHORAD) and Marine Corps Ground/Air Task-Oriented Radar (G/ATOR) have advanced layered defense concepts, but gaps remain in close-in, passive detection and low-cost kinetic defeat at the tactical unit level [3]. Academic research in computer vision for aerial target tracking [4] and real-time ballistic solution algorithms [5] has matured sufficiently for operational prototyping, yet few systems have demonstrated autonomous kill-chain execution in operationally relevant conditions.

1.3 Bullfrog Overview

This paper presents the Bullfrog AWS as a practical demonstration of integrated autonomous C-UAS capability aligned with Army and Marine Corps ground vehicle development missions. Section 2 describes the system architecture, autonomous algorithms, and multimodal sensor integration. Section 3 analyzes T-REX 26-1 field experimentation results demonstrating effectiveness, suitability, and producibility. Section 4 discusses operational applications including mobile ISV integration, fixed-site defense, and JADC2 interoperability. The paper concludes with recommendations for transition to operational forces and future capability enhancements.

2. System Architecture and Autonomous Capabilities

2.1. Hardware Design & Modularity

The Bullfrog AWS integrates a precision robotic turret, multimodal sensor suite, fire control computer, and service-common crew-served weapons into a compact, transportable package weighing 311 lbs (with M240B, no ammunition). The system employs a Modular Open Systems Approach (MOSA) architecture with line-replaceable units enabling rapid field maintenance and weapon/sensor swapping [6].

Key subsystems include:

- **Sensor Suite:** Electro-Optical (EO), Infrared (IR), and Laser Range Finder (LRF) manufactured by Allen Control Systems, providing passive detection from 50-900 meters with 30+ pixel target resolution requirements for CV/ML classification

Table 1: Optical Performance Reference

UAS Group	Detection Range
Group 1 UAS	985 m (0.612051 miles)
Group 2 UAS	3,041 m (1.89 miles)
Group 3 UAS	4,257 m (2.65 miles)
Group 4 UAS	19,465 m (12.1 miles)

- **Cradle and Turret Base:** ACS-manufactured precision gimbal achieving <1 MOA pointing accuracy, 360-degree traverse in ~4 seconds with no mechanical limits (software-configurable safety stops)
- **Effector:** FN Herstal M240B (current configuration) with planned integration of M2 .50 caliber, laser dazzler soft-kill systems, and APKWS for extended-range Group 2-3 UAS engagement
- **Fire Control:** UXV Technologies operator interface with game-controller-style layout requiring only 40-hour train-the-trainer course

The hardware modularity directly supports the Army's Modular APS Framework (MAF) and integration with platforms including Infantry Squad Vehicles (ISVs), Joint Light Tactical Vehicles (JLTVs), and fixed-site installations [7].

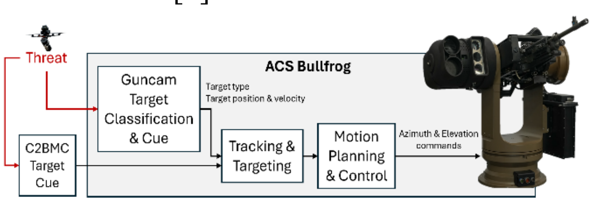

Figure 1: Bullfrog System Diagram

2.2. AI/ML Autonomous Kill Chain

Bullfrog executes a complete autonomous kill chain—detect, track, classify, engage, assess—through integrated computer vision and machine learning algorithms operating on EO/IR sensor feeds.

Detection and Tracking: Wide-angle EO/IR cameras continuously scan 360 degrees, employing aerial object detection neural networks trained on Group 1-3 UAS signatures. Upon detection, narrow-angle "GunCam" sensors acquire high-resolution tracking, with state estimation algorithms predicting target trajectory at 30 Hz update rates. The system demonstrated 100% detection rate (13/13 targets) at T-REX 26-1 with zero false positives [8].

Classification and Threat Assessment: CV/ML models classify detected objects using shape, size, motion characteristics, and thermal signatures. Threat confidence thresholds are operator-adjustable in the field, enabling mission-tailored rules of engagement while maintaining autonomous decision support.

Ballistic Solution and Engagement: Upon operator authorization (autonomous or human-in-the-loop modes), the fire control computer fuses LRF range data with target velocity, environmental conditions, and weapon ballistics to compute a precision firing solution. Recent integration of the Armaments Command Gunslinger ballistics computer promises sub-MOA accuracy and theoretical indirect-fire capability [9].

Battle Damage Assessment: Post-engagement sensor tracking assesses target defeat, triggering re-engagement if necessary or cueing operators for follow-on actions.

This autonomous architecture reduces operator cognitive load while enabling rapid response to time-sensitive threats—critical for protecting maneuver forces operating in high-threat UAS environments.

2.3. Multimodal Sensor Fusion and C2 Integration

Bullfrog's passive sensor suite eliminates electromagnetic signatures that compromise force positions, while WebSocket API interfaces enable integration with external sensors and C2 networks. Demonstrated integrations include:

Anduril Lattice C2: Real-time threat data sharing and cooperative engagement

Ground Vehicle Systems Center (GVSC) MAF: Platform-agnostic integration for ground vehicle Active Protection System (APS) architectures

JADC2-compatible interfaces: Standards-based data models for joint sensor-to-shooter networks

The system operates standalone or as a cued asset within layered defense architectures, receiving external sensor alerts while contributing local air picture data to Common Operating Picture (COP) systems [10]. This interoperability directly addresses JIATF 401 CMO-C2 objectives for breaking down C-UAS stovepipes and enhancing collective situational awareness.

Figure 2: C2 Interface

3. Field Experimentation Results: T-REX 26-1

3.1. Test Design and Methodology

T-REX 26-1 was conducted at Camp Atterbury, Indiana, from December 4-12, 2025, under the Office of the Under Secretary of War for Research and Engineering (OUSW(R&E)) Technology Readiness Experimentation program. The objective was to demonstrate Bullfrog's ability to autonomously scan, identify, track, engage, and destroy adversary Group 1 UAS with an M240B machine gun at ranges up to 300 meters [8].

Test scenarios included:

- Hovering targets
- Crossing patterns at 150 meters
- One-way attack profiles
- Swarm engagements (multiple simultaneous targets)
- Target velocities: 12-22 m/s
- Engagements above and below horizon

Ten engagement sequences were executed against thirteen Group 1 UAS targets in both autonomous and human-in-the-loop modes, generating effectiveness, suitability, and producibility data.

3.2. Performance Assessment

Detection Performance: Bullfrog detected all 13 targets with 100% detection rate (80% CI: 0.84, 1.00) at a mean detection distance of 132 meters (80% CI: 108-155 meters). Zero false positives demonstrated high-fidelity CV/ML algorithms suitable for rules of engagement compliance [8].

Engagement Performance:

- Probability of Defeat: 100% (13/13 kills, 80% CI: 0.84, 1.00)
- Mean Engagement Time: 6 seconds after track establishment (80% CI: 4-7 seconds) for single targets; longer initiation times for swarm engagements
- Mean Engagement Distance: 160 meters (80% CI: 130-190 meters)
- Rounds per Kill: 10 rounds (80% CI: 7-12 rounds), equating to <$10 per engagement using M240B ammunition

These results demonstrate operationally effective autonomous performance against realistic UAS threat profiles, with engagement timelines and cost-per-kill metrics that enable sustained defensive operations without prohibitive ammunition expenditure.

3.3. Suitability and Reliability

Availability: Bullfrog operated for 9 hours with only one ammunition stoppage causing 3 minutes downtime (operator-cleared without tools), achieving:

- Operational Ready Rate: 99.45% (80% CI: 0.91, 1.00)
- Operational Availability: 99.45%

Maintainability: No maintenance or repair actions required during the experiment. Modular design supports Line Replaceable Unit (LRU) field service.

Controllability: Game-controller interface enabled rapid operator familiarization. The 40-

hour train-the-trainer course includes both classroom and field instruction, supporting distributed training at unit level.

Adaptability: Software-adjustable parameters (safety limits, confidence thresholds) and hardware modularity (weapon/sensor swapping) enable mission-tailored configurations without depot-level modifications [8].

3.4. Producibility and Technology Readiness

The T-REX analysis team assessed Bullfrog at Technology Readiness Level (TRL) 6 and Manufacturing Readiness Level (MRL) 6, indicating a fully functional prototype demonstrated in an operationally relevant environment with production processes in place [8]. Since the testing, systems have performed in real-world applications moving the TRL level to 8, and updates to the manufacturing line increase the MRL to 8.

Production Metrics:
Current Production Rate: >20 units/month
Unit Cost: $300,000 (1-99 units), scaling to $255,000 (500+ units)
Production Footprint per Unit: 800 sq ft, 3 technicians, 3 support staff, 1 CNC machine
Lead Time: <6 months from order to delivery
The system leverages mature Commercial Off-The-Shelf (COTS) components (FN Herstal M240B, UXV fire control) integrated with ACS proprietary sensors and structures, mitigating supply chain risks. Low-Rate Initial Production (LRIP) is underway with demonstrated scalability to meet surge requirements [9].

4. Operational Applications and Transition Pathways

4.1. Mobile Ground Vehicle Integration

JIATF 401 Area of Interest (AoI) 26-004 specifically requires mobile Infantry Squad Vehicle (ISV) C-UAS kits for Task Force East operations [2]. Bullfrog's 311 lb weight (with M240B) and 18"H x 48"L x 20"W packaged envelope enable rapid integration on ISVs, JLTVs, and similar platforms without degrading mobility or payload capacity.

Mobile Employment Concept of Operations:

- Convoy Protection: Bullfrog-equipped ISVs provide organic C-UAS overwatch during movement, autonomously defeating reconnaissance and attack UAS without convoy halts
- Expeditionary Basing: Rapid emplacement at patrol bases, forward arming and refueling points (FARPs), and command posts provides immediate air defense capability during maneuver force transitions
- Reconnaissance and Security Operations: Scout elements equipped with Bullfrog maintain focus on ground threats while autonomous systems provide air defense, reducing requirement for dedicated air defense detachments

Self-deployment capability (demonstrated at T-REX via flatbed transport and autonomous movement to range) eliminates material handling equipment requirements, critical for expeditionary Marine Corps and light infantry operations [8].

4.2 Fixed-Site and Layered Defense Integration

Fixed-site applications address homeland defense, critical infrastructure protection, and forward operating base defense requirements identified in JIATF 401 AoI 26-002 [2].

Layered Defense Architecture:

- Long-Range Cueing Layer: External radars, acoustic sensors, or networked air picture data cue Bullfrog to sectors of interest.
- Mid-Range Detection Layer: Bullfrog passive EO/IR sensors provide surveillance and classification without RF emissions.
- Close-In Engagement Layer: Autonomous or HITL kinetic/soft-kill engagement within 50–600-meter envelope.

The system's WebSocket API and demonstrated Lattice/MAF integrations enable plug-and-play operation within Joint Force and interagency C-UAS networks. Standalone capability ensures mission continuation even with communications disruption—critical for contested electromagnetic spectrum environments [10].

4.3 Counter-Swarm Capabilities

T-REX results noted "longer initiation times during multitarget engagements," highlighting current limitations against coordinated swarm attacks [8]. Ongoing development efforts address this through:

- Multi-target tracking algorithms: Simultaneous track-while-engage capability for sequential target prosecution
- Cooperative engagement: Networked Bullfrog systems sharing target assignments to maximize magazine depth
- Hybrid effector integration: Laser dazzler soft-kill systems for lower-priority threats, preserving kinetic ammunition for high-value targets

These enhancements align with emerging counter-swarm doctrine emphasizing networked, multi-layered responses rather than single-system solutions [11].

4.4 Alignment with Military Priorities

Bullfrog directly supports Department of Defense autonomy and AI priorities articulated in the 2023 Data, Analytics, and Artificial Intelligence Adoption Strategy and 2024 Replicator Initiative [12]:

- Human-Machine Teaming: Operator-in/on-the-loop modes enable mission-appropriate autonomy levels from fully autonomous to advisory-only
- AI/ML Safety and Ethics: Zero false positives at T-REX demonstrates algorithmic fidelity; software-adjustable confidence thresholds enable rules of engagement compliance
- Rapid Fielding: TRL 6/MRL 6 maturity and LRIP capability support immediate procurement under Other Transaction Authority (OTA) or Middle Tier of Acquisition (MTA) pathways
- Commercial Technology Adaptation: COTS integration and industry-standard interfaces facilitate technology refresh and competitive sustainment

4.5 Transition Recommendations

Based on T-REX findings, recommended transition actions include [8]:

Near-Term (FY26):

- Limited procurement (10-20 units) for operational evaluation by Army and Marine Corps tactical units
- Integration testing with L-SHORAD C2 architectures and JADC2 testbeds
- Expanded envelope testing against Group 2-3 UAS to validate full system capability

Mid-Term (FY27-28):

- MIL-STD-810 environmental qualification for global deployment
- Formal System Safety Hazard Analysis (SSHA) per MIL-STD-882E for autonomous function certification
- Vendor Quality Management System (QMS) audit to support production scaling

Long-Term (FY29+):

- Program of Record establishment with full-rate production decision
- Fleet-wide integration across BCTs, MEUs, and critical infrastructure protection forces
- Continuous software updates for evolving threat libraries and capability enhancements

5. CONCLUSIONS

The Bullfrog Autonomous Weapon Station represents a mature, operationally relevant solution to the asymmetric UAS threat facing ground maneuver forces. T-REX 26-1 field experimentation validated the system's autonomous kill chain execution with 100% effectiveness against realistic Group 1 threat profiles, while demonstrating >99% availability and <$10 cost-per-engagement. The system's passive sensors, service-common weapons, MOSA architecture, and demonstrated C2 integrations address critical gaps in tactical-level C-UAS capability.

Alignment with JIATF 401 mobile and fixed-site requirements, combined with TRL/MRL 8 maturity and active LRIP, positions Bullfrog for immediate transition to operational forces via rapid acquisition pathways. Future enhancements—including counter-swarm algorithms, extended-range effectors, and enhanced sensor fusion—will ensure the system paces evolving UAS threats while maintaining the speed-to-field and cost-effectiveness required for large-scale Army and Marine Corps adoption.

As adversaries continue to proliferate small UAS across all operational domains, autonomous C-UAS capabilities like Bullfrog will prove essential to protecting ground forces, enabling freedom of maneuver, and maintaining overmatch in contested environments.

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9. ACRONYMS

A&R – Autonomy & Robotics
ACS – Allen Control Systems
AI – Artificial Intelligence
AoI – Area of Interest
APS – Active Protection System
AWS – Autonomous Weapon Station
BCT – Brigade Combat Team
C2 – Command and Control
C-UAS – Counter-Unmanned Aircraft Systems
CI – Confidence Interval
CMO – Common Mission Operations
CNC – Computer Numerical Control
COP – Common Operating Picture
COTS – Commercial Off-The-Shelf
CSO – Commercial Solutions Opening
CV/ML – Computer Vision/Machine Learning
DEVCOM – U.S. Army Combat Capabilities Development Command
DoD – Department of Defense
EO – Electro-Optical
FARP – Forward Arming and Refueling Point
FY – Fiscal Year
G/ATOR – Ground/Air Task-Oriented Radar
GVSC – Ground Vehicle Systems Center
GVSETS – Ground Vehicle Systems Engineering & Technology Symposium
HITL – Human-In-The-Loop
IM-SHORAD – Interim Maneuver-Short Range Air Defense
IR – Infrared
ISV – Infantry Squad Vehicle
JADC2 – Joint All-Domain Command and Control
JIATF – Joint Interagency Task Force
JLTV – Joint Light Tactical Vehicle
LRF – Laser Range Finder
LRIP – Low-Rate Initial Production
LRU – Line Replaceable Unit
MAF – Modular APS Framework

MEU – Marine Expeditionary Unit
MIL-STD – Military Standard
ML – Machine Learning
MOA – Minute of Angle
MOSA – Modular Open Systems Approach
MRL – Manufacturing Readiness Level
MTA – Middle Tier of Acquisition
OASW-MC – Office of the Assistant Secretary of War for Mission Capabilities
ODASW(P&E) – Office of the Deputy Assistant Secretary of War for Prototyping and Experimentation
OTA – Other Transaction Authority
OUSW(R&E) – Office of the Under Secretary of War for Research and Engineering
PEO – Program Executive Office
QMS – Quality Management System
RF – Radio Frequency
SHORAD – Short Range Air Defense
SSHA – System Safety Hazard Analysis
sUAS – Small Unmanned Aircraft Systems
T-REX – Technology Readiness Experimentation
TRL – Technology Readiness Level
UAS – Unmanned Aircraft Systems
USMC – United States Marine Corps