# Project Proposal: Create-X Capstone

## Executive Summary

**Mission:** Design, build, and demonstrate an autonomous counter-UAS (C-UAS) system using three high-speed quadcopter interceptors with dual-sensor fusion (radar + computer vision) in a coordinated layered defense to kinetically defeat Group 1/2 enemy drones. We're building an affordable Iron Dome that can protect any high-value target with unmatched agility and sensor reliability.

**Core Innovation:** A rapid-response perimeter defense system deploying three high-agility quadcopter interceptors in a coordinated pincer formation. Dual-sensor fusion (microwave radar + computer vision) provides validated target tracking with accurate range data. Upon detection, all three interceptors launch simultaneously from angled platforms, accelerating quickly to intercept speed. The primary interceptor attacks head-on while two flanking interceptors provide coverage from offset angles. If the primary interceptor successfully disables the target, flanking drones autonomously abort mission and return to base. If primary attack fails, flanking drones continue pursuit until target destruction is confirmed. Quadcopter design enables rapid direction changes to track evasive targets that fixed-wing aircraft cannot follow.

**Key Differentiators:**

- **Agility:** Quadcopter design enables sharp turns and hover capability, tracking evasive targets that change course abruptly (critical for 50-100 ft engagements at 25+ mph).
- **Dual-Sensor Fusion:** Radar provides accurate range and velocity data while CV provides precise angular tracking. Sensor handshake validates detections and eliminates false positives.
- **Cost:** Simple quadcopter airframe with waterjet-cut carbon fiber and 3D-printed parts keeps per-unit cost under $280, enabling scalable deployment.
- **Rapid Fabrication:** Waterjet manufacturing from 2D CAD files and 3D-printed components with parts sourced from McMaster-Carr, Home Depot, Amazon, and Walmart enable fast iteration and low-cost production.
- **Intelligence:** Ground station handles all processing and sensor fusion, eliminating expensive onboard compute while maintaining precision control through validated dual-sensor tracking.
- **Scalability:** Modular three-interceptor cells can be deployed to protect any high-value target: military bases, office buildings, data centers, energy plants, manufacturing facilities, airports, government buildings, and critical infrastructure.

**Objective:** This Create-X capstone project bridges the gap between engineering theory and practical application. Students will execute a complete hardware development cycle in 4 months, integrating mechanical, electrical, software, and controls engineering to demonstrate autonomous swarm intercept technology with dual-sensor fusion addressing a critical security challenge.

**Outcome:** A field-ready three-interceptor system demonstrating complete autonomous detect-track-engage capability using affordable components and validated dual-sensor tracking, proving layered kinetic intercept against Group 1/2 drone threats.

# Significance & Market Gap

## The Threat

Unauthorized drones threaten critical infrastructure across multiple sectors: military bases, corporate campuses, data centers, energy facilities, manufacturing plants, and airports. Group 1/2 drones (under 55 lbs) represent the vast majority of security incidents. At typical engagement distances (50-100 ft) and speeds (25+ mph / 37 ft/s), targets have only 2-3 seconds to maneuver evasively. Current C-UAS solutions lack the combination of agility, sensor reliability, and cost-effectiveness needed for widespread deployment.

## Our Solution: High-Agility Dual-Sensor Iron Dome

Nobody has successfully demonstrated a coordinated quadcopter interceptor system with dual-sensor fusion (radar + CV) that combines instant response, evasive target tracking, validated sensor data, and cost-effective scalability using rapid manufacturing techniques. We prove that three agile quadcopters with waterjet-cut frames, 3D-printed components, and dual-sensor ground guidance can provide layered kinetic defense faster and cheaper than any existing system.

## Distinction from Existing Solutions

**1. Quadcopter Agility:** Purpose-built for maneuverability with ability to track evasive targets through sharp direction changes. At 50-100 ft engagement distances with targets at 25+ mph, quadcopter design is essential for tracking targets that maneuver abruptly (typical of commercial drones). Fixed-wing interceptors would overshoot due to large turn radius.

**2. Dual-Sensor Fusion:** Microwave Doppler radar (HB100) provides velocity and range data, computer vision provides precise angular tracking. Sensor handshake validates detections (eliminates false positives), provides accurate range estimation, and enables tracking in degraded visibility. Single-sensor systems lack validation and accurate range data.

**3. Rapid Manufacturing:** Waterjet-cut carbon fiber frames from simple 2D CAD files enable low-cost, high-precision fabrication. 3D-printed mounts, brackets, and structural components allow rapid iteration. All hardware sourced from accessible suppliers (McMaster-Carr, Home Depot, Amazon, Walmart) enables fast prototyping and easy replacement.

**4. Intelligent Layered Attack:** Primary interceptor (center) attacks head-on. Two flanking interceptors provide coverage from offset angles. If primary succeeds, flankers abort and return (preserving assets). If primary fails, flankers continue pursuit (ensuring target destruction).

**5. Ground-Based Processing:** Ground station handles all sensor fusion, trajectory prediction, and guidance. Interceptors receive real-time commands via high-bandwidth telemetry, eliminating expensive onboard processing.

**6. Cost-Effective Scalability:** Simplified design with commodity components and accessible manufacturing (waterjet CF + 3D printing). Per-unit cost under $280 enables deployment of multiple defensive cells.

# Technical Architecture

## System Overview

**Ground Sentry Station:** Laptop-based control system running Python sensor fusion software. Microwave Doppler radar (HB100) provides velocity and range data. 1080p webcam provides angular tracking via computer vision. Kalman filter fuses both sensors for validated target state estimation. Multi-interceptor coordination via MAVLink. Antenna array maintains communication with 3 interceptors up to 1 km.

**Three High-Agility Interceptors:** Quadcopter design (450mm frame, 1-2 lbs loaded) with waterjet-cut carbon fiber arms and center plates. 3D-printed motor mounts, landing gear, and component brackets. Positioned yards apart on angled launch platforms (15-30 degrees) constructed from Home Depot plywood and PVC pipe. Each has four brushless motors, flight controller, and GPS. High thrust-to-weight ratio (>2:1) enables rapid acceleration and sharp direction changes to track evasive targets.

**Enemy Drone:** Cheap consumer quadcopter from Amazon/Walmart representing typical Group 1 threat capable of rapid evasive maneuvers.

## Interceptor Specifications

**Airframe:** Quadcopter 450mm frame with waterjet-cut carbon fiber arms (3mm thickness) and center plates (2mm thickness) from simple 2D CAD files. 3D-printed PLA/PETG motor mounts, landing gear, GPS mount, and electronics bay. Reinforced front section for impact (layered CF + 3D-printed bumper). Total weight: 1-2 lbs loaded. Optimized for agility and speed.

**Manufacturing Approach:**

- Carbon fiber sheets waterjet-cut from 2D DXF files (local waterjet service or university machine shop)
- 3D-printed structural components (Prusa or Bambu Lab printers, PLA/PETG material)
- Hardware (bolts, nuts, standoffs) from McMaster-Carr or Home Depot
- Assembly using standard tools (hex keys, screwdrivers from Home Depot/Amazon)

**Propulsion:** Four 2204 2300KV motors with 5-inch props. High discharge LiPo for maximum power. Max speed: 80-100 km/h, 6-8 min aggressive flight time.

**Flight Control:** Matek F405 flight controller running ArduCopter firmware, Beitian BN-220 GPS module.

**Communications:** FlySky 2.4 GHz RC (backup), ESP32 WiFi telemetry (primary command, 1 km range), MAVLink protocol. Each interceptor has unique SYSID.

**Power:** 4S 1500mAh high-discharge LiPo (75C+) for maximum thrust and agility.

### Ground Sentry Station

**Hardware:** User-provided laptop with GPU, 1080p webcam with optical zoom (Amazon), HB100 microwave Doppler radar module (Amazon/eBay), DIY antenna array (copper wire from Home Depot), pelican-style case (Amazon/Harbor Freight).

**Software Stack:** Python 3.10 with OpenCV for CV tracking and radar interface. Sensor fusion via Kalman filter (FilterPy library). Leverages open-source codebases: ArduPilot multi-vehicle control, YOLOv8 for detection, ROS navigation principles for intercept geometry. Sensor handshake validates detections. Collision avoidance coded into waypoint paths. Mission planner UI with PyQt6.

**Dual-Sensor Fusion Algorithm:**

1. Radar provides velocity and approximate range
2. CV provides precise angular position and track ID
3. Kalman filter fuses measurements with cross-validation
4. Sensor handshake confirms detection (both sensors must agree)
5. Fused state provides validated position, velocity, and range for intercept calculation

### Angled Launch Platforms

**Design:** Three platforms with 15-30 degree adjustable incline for gravity-assisted quick takeoff. Construction from Home Depot plywood (3/4" thickness), Home Depot/Lowe's PVC pipe for support structure, McMaster-Carr hardware (hinges, angle brackets). 3D-printed angle adjustment mechanism and drone retention clips. Simple assembly with basic tools. Quadcopters positioned on platforms, motors spin up to full power before release.

# Team Structure & Responsibilities

### Team 1: EE/CS (Command & Control) - 2-3 Students

**Primary Responsibilities:**

- Software: Dual-sensor fusion (radar + CV) using Kalman filter, trajectory prediction, intercept geometry calculator, sensor handshake validation, mission UI

- Firmware: ArduCopter configuration, multi-vehicle coordination using swarm examples, collision avoidance in waypoint generation
- Radar Integration: HB100 interface, signal processing, velocity/range extraction
- Electronics: Power distribution for high-current motors, radar module integration
- Communications: WiFi telemetry setup, MAVLink config using ArduPilot codebase

**Key Deliverables:** Ground station with dual-sensor fusion and live tracking, four programmed flight controllers with swarm firmware, validated sensor handshake algorithm, multi-interceptor coordination with collision avoidance.

### Team 2: AE/ME (Airframe & Flight Operations) - 2-3 Students

**Primary Responsibilities:**

- Airframe Design: CAD modeling (SolidWorks/Fusion 360) for waterjet-cut CF parts and 3D-printed components, structural analysis for impact loads
- Manufacturing: Coordinate waterjet cutting of CF sheets, 3D print structural components (motor mounts, landing gear, brackets), assembly
- Launch System: Design and fabricate three angled launch platforms from Home Depot materials (plywood, PVC), 3D-printed angle mechanisms
- Propulsion: Motor mounting, ESC installation, thrust testing, thermal management
- Part Sourcing: Coordinate hardware procurement from McMaster-Carr, Home Depot, Amazon (bolts, standoffs, PVC, plywood, adhesives)
- Flight Operations: Test piloting, aggressive maneuver testing, flight safety management, multi-aircraft coordination
- Enemy Drone: Purchase from Amazon/Walmart, maintenance, operation

**Key Deliverables:** 4 assembled quadcopter airframes optimized for agility (waterjet CF + 3D-printed parts), three angled launch platforms, validated propulsion system, flight operations manual, impact test data, documented part sourcing list with supplier links.

# Estimated Project Budget (4 Interceptors)

| Category | Item | Quantity | Unit Cost | Total Cost |
|---|---|---|---|---|
| **Airframe** | Carbon fiber sheets (3mm/2mm) | 2 sheets | $30 | $60 |
| | Waterjet cutting service | 4 sets | $15 | $60 |
| | 3D printing filament (PLA/PETG) | 3 kg | $20 | $60 |
| | Landing gear components | 4 sets | $8 | $32 |
| | Hardware (bolts, nuts, standoffs - McMaster) | 1 set | $40 | $40 |
| | Adhesives (epoxy, CA glue - Home Depot) | 1 set | $20 | $20 |
| | Plywood for launch platforms (Home Depot) | 2 sheets | $10 | $20 |
| | PVC pipe and fittings (Home Depot) | 1 set | $25 | $25 |
| **Propulsion** | 2204 2300KV motors (Amazon) | 16 | $12 | $192 |

| Category | Item | Quantity | Unit Cost | Total Cost |
|---|---|---|---|---|
| | 30A ESC (4-in-1) (Amazon) | 4 | $25 | $100 |
| | 5-inch props (Amazon) | 16 sets | $3 | $48 |
| **Flight Control** | Matek F405 controller (Amazon) | 4 | $45 | $180 |
| | Beitian BN-220 GPS (Amazon) | 4 | $15 | $60 |
| **Electronics** | 4S 1500mAh 75C LiPo (Amazon) | 8 | $25 | $200 |
| | FlySky FS-A8S receiver (Amazon) | 4 | $12 | $48 |
| | ESP32 WiFi telemetry (Amazon) | 4 | $8 | $32 |
| | Power distribution boards (Amazon) | 4 | $8 | $32 |
| | XT60 connectors, wire (Amazon) | 1 set | $20 | $20 |
| | Multi-battery charger (Amazon) | 1 | $45 | $45 |
| **Ground Station** | 1080p webcam with zoom (Amazon) | 1 | $60 | $60 |
| | HB100 Doppler radar module (Amazon/eBay) | 1 | $8 | $8 |
| | Copper wire for antenna (Home Depot) | 1 set | $15 | $15 |
| | Pelican-style case (Amazon/Harbor Freight) | 1 | $40 | $40 |
| | Cables and connectors (Amazon) | 1 set | $20 | $20 |
| **Enemy Drone** | Cheap quadcopter (Amazon/Walmart) | 1 | $40 | $40 |
| **Consumables** | Extra props, hardware, adhesives | 1 set | $60 | $60 |
| | **Total (est.)** | | | **$1,617** |
| | **Per additional unit (est.)** | | | **$280** |

*All components easily sourceable from Amazon, McMaster-Carr, Home Depot, Walmart, or eBay with 1-2 week delivery.*

# Development Timeline (January - April 2026)

## Month 1: January - Foundation

**Week 1-2:** Finalize specs and order components from Amazon, McMaster-Carr. (AE/ME) Complete CAD models for waterjet-cut CF parts and 3D-printed components, begin launch platform design, source plywood and PVC from Home Depot. (EE/CS) Set up development environment, begin dual-sensor fusion software.

**Week 3-4:** (AE/ME) Coordinate waterjet cutting, 3D print motor mounts and structural parts, assemble Interceptor 1, bench tests, motor thrust testing. Design and fabricate angled launch platform prototype using Home Depot materials. (EE/CS) Flash ArduCopter firmware, bench test controller. Integrate HB100 radar module, validate radar data acquisition. (All) Integrate ground station, begin sensor fusion testing with static targets.

**Milestone:** Interceptor 1 assembled with waterjet CF frame and 3D-printed components, launch platform prototype complete, ground station tracking with dual sensors functional, radar velocity data validated.

## Month 2: February - Demo 1

**Week 5-6:** (AE/ME) Test launches from angled platform, validate high-speed performance and aggressive maneuvers, coordinate waterjet cutting and 3D printing for Interceptors 2-3, fabricate remaining launch platforms from Home Depot materials. (EE/CS) Deploy dual-sensor fusion software with Kalman filter, implement sensor handshake validation, validate MAVLink. (All) Tune PID loops for aggressive flight.

**Week 7-8:** (AE/ME) Complete Interceptors 2-3 assembly (waterjet CF + 3D-printed parts) and all three launch platforms, individual test flights with aggressive maneuvers. (EE/CS) Deploy multi-vehicle software, implement engagement logic. (All) Formation flight tests, track enemy drone with dual sensors.

**Demo 1 (Week 8):** 3 flight-tested quadcopters with waterjet-cut frames, three launch platforms, ground station coordinating all aircraft using dual-sensor fusion and tracking enemy drone.

**Milestone:** Three interceptors flying under coordinated ground station command with validated dual-sensor tracking, all launch platforms operational, manufacturing workflow validated.

## Month 3: March - Sensor Fusion & Aggressive Flight

**Week 9-10:** (All) Aggressive maneuver testing, validate ability to track rapidly changing targets. Position all three launch platforms in deployment configuration. Validate simultaneous launch coordination from platforms. Test intercept approach angles with evasive enemy drone.

**Week 11-12:** (All) Test complete engagement sequence with evasive enemy drone. Validate sensor handshake eliminates false positives. Refine guidance algorithms for moving target with direction changes. Test engagement abort logic. Multiple evasion scenarios. (AE/ME) Print spare parts (motor mounts, landing gear) as needed.

**Milestone:** Aggressive intercept validated, dual-sensor fusion tracking evasive targets, engagement logic tested in flight, rapid repair capability demonstrated with 3D-printed spares.

## Month 4: April - Final Validation

**Week 13-14:** (All) Integrated tests: dual sensors detect enemy, validate with handshake, command simultaneous platform launch. Validate convergence geometry against evasive target. Test complete engagement sequence at high speed with direction changes. Optimize guidance for kinetic intercept.

**Week 15-16:** (All) Dress rehearsal with full mission profile. Final validation: dual sensors detect enemy with handshake, three interceptors launch from platforms, track evasive target through direction changes, converge using agile maneuvers, at least one achieves kinetic contact. Demonstrate intelligent abort.

**Final Demo (Week 16):** Live demonstration of three-interceptor coordinated platform launch with dual-sensor fusion tracking and high-agility intercept with intelligent engagement logic.

**Final Deliverable:** 4 flight-tested high-agility quadcopters with waterjet CF frames and 3D-printed components, three angled launch platforms (Home Depot materials), ground station with dual-sensor fusion system, documented successful coordinated kinetic intercept against evasive target, complete CAD files and part sourcing list.

# Success Criteria

## Minimum Viable Product (MVP)

1. Dual sensors (radar + CV) detect and track enemy drone with sensor handshake validation
2. Three quadcopter interceptors with waterjet-cut frames achieve stable high-speed autonomous flight (80+ km/h)
3. Simultaneous launch coordination from angled platforms (Home Depot construction)
4. Interceptors track evasive target through sharp direction changes using agile maneuvers
5. Ground station maintains continuous dual-sensor guidance throughout intercept
6. Intelligent engagement logic functions (abort when primary succeeds)
7. At least one interceptor achieves kinetic contact with evasive target
8. Manufacturing workflow validated (waterjet CF + 3D printing from accessible sources)

## Stretch Goals

1. Return-to-base capability for surviving aircraft
2. Successful kinetic destruction of moving enemy drone
3. System achieves less than 3 seconds from detection to launch
4. Successful engagement against enemy drone with aggressive evasive maneuvering
5. Validated 100+ km/h sprint capability
6. Sensor fusion operates in degraded visibility (fog/dusk)
7. Rapid field repair using 3D-printed spare parts

# Risk Mitigation

| Risk | Mitigation |
|---|---|
| Insufficient agility for evasive targets | High thrust-to-weight quadcopter design, extensive aggressive maneuver testing |
| Waterjet cutting delays | Order cutting early, maintain backup manual cutting option, buffer stock |

| Risk | Mitigation |
|---|---|
| 3D print failures | Print multiple copies of critical parts, maintain spare filament stock |
| Launch platform failure | Simple robust design from readily available materials, backup manual launch capability |
| Interceptor collision | Collision avoidance coded into waypoint paths, altitude offsets |
| Radar false detections | Sensor handshake requires both CV and radar agreement before engagement |
| GPS/telemetry loss | Failsafe return-to-base, geofencing, reduced range operations |
| Motor overheating | Thermal testing, proper ESC sizing, cooling airflow design |
| Complex quadcopter tuning | Leverage ArduCopter community PID profiles, extensive flight testing |
| Part sourcing delays | Order all Amazon/McMaster items in Week 1, maintain vendor alternatives |
| Regulatory compliance | Operate under FAA Part 107, obtain necessary waivers |

# Future Development (Post Create-X)

## Near-Term Enhancements

### Onboard Vision for Terminal Guidance

- Add Raspberry Pi Zero 2W for autonomous terminal tracking (+$30 per interceptor)
- Enables fully autonomous intercept when target leaves ground station sensor range

### Enhanced Radar

- Upgrade to 24GHz FMCW radar for precise range and angle data (+$50)
- Enables better tracking at extended ranges

### Munitions Integration

- Transition from kinetic impact to small explosive payload
- Enables guaranteed target destruction and larger threat engagement

### Advanced Manufacturing for Scale Production

- Automated waterjet cutting with nesting optimization for material efficiency
- Injection molding for high-volume 3D-printed component production
- Custom frame geometries for specialized threat profiles

# Further Studies & Research Extensions

## 1. Counter-GPS-Dependent Drones (Shahed-Type Long-Range Threats)

**Problem:** Long-range GPS-guided drones (e.g., Iranian Shahed-136) rely on GPS/GLONASS navigation for waypoint following. Current C-UAS solutions struggle with these threats due to extended engagement ranges and GPS-based guidance.

**Proposed Solution: GPS-Denied Interceptor with Onboard Jammer**

- **Payload:** Miniature GPS jammer (L1/L2/L5 frequency disruption) carried by interceptor
- **Effect:** Cuts enemy drone GPS lock, forcing navigation failure or drift-prone inertial guidance
- **Interceptor Navigation:** CV + radar + IMU + visual odometry (GPS-independent)
- **Advantage:** Neutralizes threat without kinetic contact, reusable interceptor, extended stand-off range
- **Technical Challenges:** GPS-denied SLAM, terrain reference navigation, jamming power vs weight trade-off

**Research Questions:**

- Effective jamming range and minimum power requirements for GPS disruption
- Visual SLAM and terrain-matching algorithms for GPS-denied navigation
- Integration with CV/radar sensor fusion for autonomous guidance
- Legal/regulatory framework for GPS jamming systems

## 2. High-Power Microwave (HPM) Offensive Interceptor

**Problem:** Soft-kill C-UAS (RF jamming, GPS spoofing) are defensive and reactive. No mobile offensive HPM systems exist for proactive threat neutralization.

**Proposed Solution: Miniaturized HPM Payload (Mini-Epirus Leonidas Concept)**

- **Approach:** Interceptor carries directed-energy HPM emitter for electronics disruption
- **Effect:** Disables enemy drone flight controller, GPS, telemetry, ESCs at stand-off range
- **Mode:** Seek-and-attack rather than static perimeter defense
- **Advantage:** Reusable interceptor, multiple engagements per sortie, no kinetic contact required
- **Technical Challenges:** HPM miniaturization, power/weight ratio, thermal management, directed beam control

**Research Questions:**

- Minimum effective HPM power for drone electronics disruption (kW-level pulses?)
- Lightweight capacitor bank and pulse-forming network design
- Thermal dissipation for repeated HPM shots
- Beam focusing and aiming mechanisms for mobile platform
- Safety protocols for HPM operations near friendly electronics

## 3. Advanced Launch Systems

### Pressurized Tube Launch with Folding Wings (Fixed-Wing Variant)

- **Concept:** Interceptor stored in pressurized launch tube, pneumatic ejection with spring-loaded wing deployment
- **Advantages:** Extremely fast launch (<1 second), protected storage, all-weather capability
- **Application:** Fixed-wing interceptor variant for extended range/endurance missions
- **Technical Challenges:** Folding wing mechanism reliability, tube sealing, pneumatic system design

### Rocket-Assisted Takeoff (RATO)

- **Concept:** Solid rocket motor booster for instant high-speed launch (0 to 100 km/h in 2 seconds)
- **Advantages:** Eliminates platform delay, maximizes closing speed, reduces reaction time to <3 seconds
- **Application:** Both fixed-wing and quad variants
- **Technical Challenges:** Rocket ignition reliability, transition from rocket to electric power, structural loads

### Catapult Launch Systems

- **Concept:** Electromagnetic or bungee catapult for rapid sequential launches
- **Advantages:** Reusable, no consumables, reliable
- **Application:** Fixed-wing variant for consistent high-speed launch
- **Technical Challenges:** Catapult design, acceleration loads, launch repeatability

## 4. Multi-Platform Swarm Architecture

### Multi-Interceptor vs Multi-Threat Scenarios

- **Concept:** Hybrid swarm of fixed-wing (endurance/range) and quadcopter (agility/close-in) interceptors
- **Application:** Simultaneous engagement of multiple threat types (e.g., multiple Shahed-type fixed-wing + commercial quad threats)
- **Advantages:** Optimized interceptor type to threat, swarm redundancy, extended coverage
- **Technical Challenges:** Heterogeneous swarm coordination, threat classification and assignment algorithms, communication bandwidth

### Research Questions:

- Optimal swarm composition ratio (fixed-wing : quad) for mixed threat environments
- Autonomous threat prioritization and interceptor assignment
- Coordination algorithms for heterogeneous platforms
- Scalability limits (10+ interceptor swarm coordination)

**Example Scenarios:**

- 6 fixed-wing interceptors vs 3 Shahed-type threats (extended range intercept)
- 6 quadcopter interceptors vs 3 commercial quad threats (close-in agile intercept)
- 4 fixed-wing + 4 quad hybrid swarm vs 2 Shahed + 2 commercial quad mixed threat

# Commercialization Potential

The global C-UAS market is projected to reach over $10B by 2030. This system addresses massive market need across military, commercial, and industrial sectors.

## Target Markets

**Military & Government:** Base perimeter defense, government buildings, sensitive installations.

**Commercial & Industrial:** Corporate campuses (IP security), data centers ($30B+ industry), energy facilities, manufacturing plants (industrial espionage prevention), airports, events/venues.

## Competitive Advantages

**Agility:** Quadcopter design provides superior maneuverability to track evasive targets through sharp direction changes, critical for close-range engagements (50-100 ft).

**Validated Tracking:** Dual-sensor fusion (radar + CV) with handshake validation eliminates false positives and provides accurate range data, improving reliability over single-sensor systems.

**Rapid Manufacturing:** Waterjet-cut carbon fiber frames from 2D CAD files and 3D-printed components enable fast iteration and low-cost production at scale (40-60% cost reduction vs traditional hand layup).

**Accessible Supply Chain:** All components sourceable from Amazon, McMaster-Carr, Home Depot, and Walmart enables rapid prototyping, easy field repairs, and distributed manufacturing.

**Cost:** Per-unit under $280, total system under $1,650 enables widespread deployment across commercial applications.

**Simplicity:** Ground station handles all sensor fusion and guidance, reducing onboard complexity while maintaining precision through validated dual-sensor tracking.

**Scalability:** Simple design with commodity components and accessible manufacturing enables rapid production. Modular cells can be networked for campus-wide protection.

**Intelligence:** Dual-sensor fusion with smart engagement logic maximizes effectiveness using open-source AI tools and sensor validation.