SWARM-IQ: Autonomous Cognitive Mapping Mesh for DDIL Operations

Jason L. Lind & Jack R. Driscoll

jason@groundbreaker.solutions jack@groundbreaker.solutions

Executive Summary

SWARM-IQ is a fully autonomous indoor drone swarm and fog computing mesh designed to provide *cognitive 3D mapping* and real-time threat detection in environments with denied or degraded GPS and communications (DDIL). This proposal addresses DTRA SBIR topic DTRA254-002 by integrating small unmanned aerial vehicles (UAVs) and intelligent anchor nodes into a self-organizing network that can explore complex structures, map them in three dimensions, and detect Weapons of Mass Destruction (WMD) threats without human teleoperation. The system leverages commercial off-the-shelf (COTS) hardware – including agile micro-drones (e.g. Crazyflie-based UWB anchors) and autonomous scout UAVs (e.g. Skydio X10 or Freefly Astro) equipped with advanced sensors (LiDAR, thermal IR, chemical detectors) – coordinated by a robust autonomy layer running on distributed fog computing nodes (NVIDIA Jetson-class onboard computers). By combining state-of-the-art algorithms for multi-agent exploration and SLAM (Simultaneous Localization and Mapping) with a resilient mesh communication network, SWARM-IQ enables warfighters to rapidly obtain "cognitive maps" of dangerous indoor environments and identify WMD threats from standoff distances.

The SWARM-IQ approach directly supports DTRA's mission to counter WMD threats by providing warfighters and CBRN responders a tool for safe, fast reconnaissance of denied spaces. The key innovations include:

- **Cognitive Mapping & Frontier Exploration**: Each drone builds a semantic-rich 3D map (a "cognitive map") of the environment, using frontier-based exploration to efficiently cover unknown areas. Environmental features and sensor cues (e.g. gas concentrations, radiation levels) are fused into the map, providing situational awareness beyond geometry.
- **Autonomous Multi-Agent Coordination**: A decentralized task allocation algorithm (Consensus-Based Bundle Algorithm, CBBA) assigns exploration and sensing tasks across the drone team in real time. This ensures efficient coverage, with agents negotiating which frontier to scout or which sensor reading to verify, even under intermittent communications.
- **GPS-Denied Navigation via SLAM**: Drones navigate reliably without GPS by using LiDAR-inertial odometry (FAST-LIO2) for accurate localization and mapping. FAST-LIO2 provides robust real-time SLAM, achieving high accuracy with low computational load on small onboard computers.
- **Mesh Network with Anchor Nodes**: The system establishes a self-healing mesh communication network using both mobile drones and static *anchor* nodes. Ultra-wideband (UWB) anchor nodes (e.g. Crazyflie LPS nodes) are placed or dropped in the environment to extend communication range and serve as navigation reference points. The swarm monitors the geometric dilution of precision (GDOP) of anchor geometry and automatically deploys additional anchors when needed to maintain localization accuracy. *[Figure 1: Anchor Layout and GDOP Contours]*
- **Advanced WMD Sensors and Edge Processing:** Each scout drone carries lightweight WMD detection payloads such as a FLIR MUVE C360 multi-gas detector for chemical threats (sensing CO, Cl_2, O_2, NO_2, H_2S, SO_2, etc.), a FLIR Boson thermal infrared camera for heat or radiological anomaly detection, and potentially miniaturized radiation detectors. Sensor data is processed on-board (fog computing) to immediately flag threat indicators, which are tagged in the map and relayed over the mesh network. This minimizes reliance on continuous comm links and reduces raw bandwidth needs.

In Phase I, SWARM-IQ will be developed and demonstrated at a proof-of-concept level, emphasizing technical feasibility. We will build a prototype swarm (3–5 small UAVs and 2–3 anchor nodes) and validate autonomous mapping and threat localization in a representative GPS-denied, communication-limited indoor environment (e.g. a warehouse or mock urban structure). By project end, we expect to generate a 3D map with overlaid hazard detections (a "cognitive map") and demonstrate that the system can localize radiation/chemical sources within a cluttered building using only on-board sensing and computation. Phase I results will quantify mapping accuracy, detection rates, communication robustness, and inform refinements.

Phase II will expand on this foundation, optimizing the system for austere operational environments and integrating into end-user workflows. We will ruggedize the hardware for field deployment, increase swarm size and autonomy, and conduct larger-scale demonstrations (e.g. multi-room or subterranean facilities). A key Phase II goal is delivering a MACO interface (Mapping & Awareness for Counter-WMD Operations) that seamlessly connects SWARM-IQ output to operator devices such as ATAK. In alignment with DTRA's MACO concept, SWARM-IQ will feed real-time mapped threat data to warfighters through an intuitive situational awareness interface. The final deliverable will be a TRL-6 prototype ready for operational evaluation, with a clear pathway to transition.

In summary, SWARM-IQ offers a transformative capability for counter-WMD and tactical reconnaissance missions: a deployable kit of intelligent drones that map, sense, and share critical indoor data without requiring infrastructure or risking personnel. This proposal details our technical approach, work plan, team qualifications, and commercialization strategy to develop SWARM-IQ under the SBIR program. The innovation is rooted in current research and COTS technology, maximizing the chances of Phase I success and rapid transition to warfighter use.

Identification and Significance of the Problem

Operations in complex indoor or subterranean environments — such as buildings, tunnels, or bunkers — are a critical challenge for the Department of Defense, especially when facing Weapons of Mass Destruction (WMD) threats. DTRA's mission underscores the need to counter and deter WMDs (chemical, biological, radiological, nuclear) and improvised threats. A key part of that mission is safely mapping and surveying dangerous interiors where WMDs or their precursors might be manufactured, stored, or deployed. Examples include searching a suspected chemical lab in a dense urban block, scouting a tunnel network for radiological dispersal devices, or assessing a bombed facility for residual CBRN hazards. In all cases, warfighters and CBRN responders require timely situational awareness of the environment ("Where are the rooms, corridors, choke points?") and of potential threats ("Is there toxic gas, radiation, or bio-agent present, and where?").

However, these missions typically occur in GPS-denied and communication-degraded settings. Indoors, satellite navigation is unavailable, removing the primary source of positioning for conventional drones or robots. Adversaries or structural conditions may further produce a DDIL environment (Denied, Degraded, Intermittent, or Limited communications) where radio links are sporadic or jammed. Human warfighters entering such environments must contend with poor visibility, complex layouts, and the constant risk of ambush or exposure to hazardous substances. Current technology for remote reconnaissance in these scenarios is limited. Ground robots (like small UGVs) have been used, but they can be slow, have difficulty with obstacles (stairs, rubble), and often still require manual teleoperation over a reliable radio link. Autonomous drones offer speed and vantage advantages, but most off-the-shelf drones rely on GPS for navigation and a strong radio link for control, making them unreliable in contested indoor spaces.

The significance of the problem is evident: without a means to rapidly and safely map and sense inside these environments, commanders lack critical information. This can lead to mission delays, increased risk to personnel (sending soldiers in "blind"), or incomplete threat neutralization (missing hidden WMD materials). A tragic example is the clearing of improvised chemical labs or weapon storage sites in urban combat – troops must wear full protective gear, moving slowly and methodically, which still exposes them to danger if an unknown hazard or booby trap exists. If instead a team of robots could autonomously explore the site first, build a 3D map, and pinpoint any chemical leaks or radiation hotspots, the "cognitive load" on the human team would be greatly reduced and their safety enhanced. The map would serve as a *cognitive aid*, allowing them to virtually inspect the environment and plan accordingly. In effect, a solution is needed to provide "eyes and noses" for our forces in places where they cannot safely go initially.

Several technical challenges must be overcome to enable this capability:

- **Navigation and Mapping without GPS**: The robots must determine their own location and map the environment using on-board sensors alone. This calls for advanced SLAM algorithms that fuse lidar, camera, and inertial measurements to produce accurate maps and localization in real time.

- **Exploration of Unknown Areas**: The system must decide how to explore efficiently. Unlike a single robot, a *swarm* can cover more ground, but it requires coordination. The solution must incorporate strategies for frontier exploration, where each robot seeks out the boundary between known and unknown space, to incrementally build the map. Multi-robot frontier allocation is a complex problem, especially under communication constraints.

- **Communication in DDIL Conditions**: In a GPS-denied structure, RF signals (e.g., Wi-Fi, UHF) are attenuated by walls and distance. If multiple drones go deep inside, maintaining a link to the operator or between drones is hard. The system needs a way to self-establish a communications relay network. A promising approach is using some agents as mesh network nodes or dropping relays as they progress. This problem is analogous to what DARPA's Subterranean Challenge teams faced, where robots became nodes in a mesh and even dropped radio repeaters to extend underground comms.

- **WMD Sensor Integration and Cognitive Mapping**: Detecting threats is not just a matter of carrying a sensor; the data must be interpreted in context. For example, a spike in a gas detector reading should be correlated with the drone's location and the map geometry to mark a likely source zone on the map. The concept of a "cognitive map" in this context means a map that not only shows spatial layout but also embeds *meaningful information* about the environment (hazard locations, points of interest, annotations). This requires data fusion and perhaps semantic mapping techniques to ensure the output is readily understandable to operators. The system must also filter sensor data to avoid false positives (e.g., distinguish a benign heat source from a dangerous one).

- **Autonomy and Decision-Making**: In a denied environment, the robots must operate with a high degree of autonomy. They cannot rely on continuous human teleoperation. This means the onboard AI has to handle obstacle avoidance, path planning, target search, and possibly adapt to new objectives (such as focusing more search in an area where a hazard is detected). Ensuring robust autonomy in unknown, cluttered spaces is a significant challenge.

Addressing these challenges will fill a crucial capability gap for DoD. A solution like SWARM-IQ will *significantly reduce risk to personnel and time on target* in counter-WMD missions. It will enable:

- Faster mission completion: Autonomous drones can clear a building or cave for hazards in a fraction of the time a manual team would require, especially when encumbered by protective gear.

- Improved intelligence: High-fidelity 3D maps with embedded hazard data provide commanders with actionable intel (e.g. exact location of a toxic gas pocket) before committing people.

- Reduced communication load: By using onboard processing and mesh relays, the system can function with minimal external comms, which is vital in DDIL and also reduces detectability (electromagnetic emissions) to adversaries.

- Force multiplication: One operator can oversee a team of drones doing the work of many personnel, allowing scarce CBRN experts to cover more sites or focus on analysis.

In summary, the problem of *autonomous cognitive mapping and WMD sensing in DDIL environments* is of high significance to national security. Solving it will directly support DTRA's objectives and enhance warfighter capabilities in counter-WMD operations. SWARM-IQ is designed to be that solution, combining multiple cutting-edge technologies into a cohesive system to meet this urgent need.

Technical Objectives

The Phase I technical objectives for SWARM-IQ are as follows:

1. **Design and Demonstrate Autonomous Cognitive Mapping**: Develop the software and algorithms for a multi-UAV system to perform *Simultaneous Localization and Mapping (SLAM)* in a 3D indoor environment without GPS. This includes implementing FAST-LIO2 LiDAR-inertial odometry for real-time mapping, and demonstrating the creation of a coherent 3D map (point cloud or occupancy grid) of an unknown indoor area. Accuracy objective: achieve mapping errors <0.5 m over 50+ m traversal, demonstrating higher accuracy at lower computation load than traditional methods.

2. **Implement Frontier-Based Multi-Agent Exploration**: Enable the swarm to efficiently explore unknown spaces using frontier exploration strategies. Each drone should autonomously identify unexplored frontiers (boundaries between known and unknown space) and navigate to map new areas. In Phase I, we will develop a coordination logic (leveraging CBBA or similar) so multiple drones divide exploration tasks without collision or duplication, even with minimal communications.

3. **Integrate WMD Sensing and Threat Detection**: Incorporate WMD sensor payloads on the drones (e.g., FLIR MUVE C360 for chemical detection, FLIR Boson for thermal imaging of radiological sources, etc.) and develop onboard data processing to detect anomalies. The objective is to demonstrate the ability to detect at least one simulated threat signature (e.g., a chemical gas source or a heat source representing a radiation emitter) and mark its location on the map. Sensor integration will be calibrated so that the system can localize a source within 2 m accuracy in a cluttered environment.

4. **Establish a Robust Communication & Localization Mesh**: Develop the mesh networking capability using a combination of mobile drones and static anchor nodes. We will set up small UWB anchors (Crazyflie LPS nodes or equivalent) that can be deployed to create a local positioning system and act as comm relays. The objective is to maintain >90% uptime of communications between the swarm and an operator station in an environment with at least 2 concrete walls separation, by autonomously relaying through anchor nodes. We will also quantify the improvement in localization when anchors are used (target: 50% reduction in drift or error vs SLAM alone). This involves implementing a GDOP-monitoring algorithm to trigger deployment of additional anchors when position geometry becomes poor.

5. **Demonstrate Phase I Feasibility in Relevant Environment**: Conduct an end-to-end demonstration in a representative DDIL indoor scenario. The demonstration success criteria are: (a) team of ≥3 drones explores ≥3 rooms (~3000 sqft area) autonomously, (b) a 3D map is generated covering >90% of traversable space, (c) at least one "threat" is detected and correctly pinpointed on the map, and (d) the operation is completed within a 15-minute flight session without human intervention. Achieving these will TRL-raise the concept from roughly TRL-3 to TRL-5 by end of Phase I.

6. **Plan Transition and Integration Path**: Although primarily a Phase I planning objective, we will identify integration points for Phase II such as the MACO interface (e.g., formatting our map and sensor data output to feed into ATAK or similar command-and-control systems). The objective is to define how SWARM-IQ

would be used by operators in the field, ensuring our technical approach aligns with end-user requirements and can transition to a program of record or dual-use application.

Each of these objectives will be addressed through specific tasks in the Phase I Work Plan, described below. Collectively, they aim to prove the core functionality of SWARM-IQ and prepare the groundwork for a fuller Phase II system.

Work Plan

The work plan is organized into a series of technical tasks corresponding to the objectives above. The Phase I effort (assumed ~6 months duration) will progress from design and simulation through subsystem development to an integrated prototype demonstration. The tasks and schedule are structured to systematically reduce risk and demonstrate feasibility.

Task 1: System Architecture & Design (Month 1-2)

We begin by designing the overall SWARM-IQ system architecture. In this task, the team will select and specify the hardware and software components and define how they interact. Key subtasks include:

- **Hardware Selection**: We will procure COTS platforms for both drones and anchors. For scout drones, we anticipate using platforms such as *Skydio X2/X10* or *Freefly Astro* which offer autonomous navigation capabilities and payload capacity. For example, Skydio X10 features on-board autonomy and a FLIR Boson thermal camera, making it suitable for our needs. Freefly Astro (or similar) can carry heavier sensors like the MUVE C360 gas detector. For micro-anchors, we use the Bitcraze Crazyflie 2.1 with UWB Loco Positioning decks as stationary nodes; these are palm-sized and can be easily transported by a drone and placed in the environment. We will also select an edge computing module (e.g., NVIDIA Jetson Orin NX) to run our fog computing tasks either on the drones or as part of a base station that interfaces with the mesh.
- **Sensor Suite Definition**: We outline the sensor payloads for each node. Each scout drone will be equipped with a 3D LiDAR (e.g., *Livox Avia* or *Ouster OS0-32*), IMU, a downward or front-facing camera for visual context, the FLIR Boson thermal IR camera (for heat sources), and the FLIR MUVE C360 multi-gas detector (for chemical threat detection). The Crazyflie anchors will have UWB transceivers for localization and a simple radio (2.4 GHz) for mesh networking; they may also carry environmental sensors (e.g., temperature, or a small radiation sensor) if weight allows, to augment sensing when static.
- **Architecture Diagram**: We will create a system block diagram showing how components communicate. The architecture will follow a distributed fog computing model: compute tasks such as SLAM and frontier selection run on each drone's Jetson, while a lightweight coordination node runs on either one "leader" drone or an edge computer that drones connect to intermittently. The communication architecture will use a multi-tier approach: UWB for localization pings, a mesh radio network (likely using a protocol like 802.15.4 or a MANET radios) for data exchange between drones/anchors, and a base station link (likely at 900 MHz or 2.4 GHz) that connects to the operator when possible. The diagram will highlight data flows: e.g., LiDAR data -> SLAM module -> map; gas sensor data -> onboard detection algorithm -> hazard map layer; inter-drone comms -> CBBA task allocation.
- **Simulation Environment Setup:** In parallel, we will set up a high-fidelity simulation environment (using ROS2 and Gazebo or Unity-based simulator) to prototype algorithms before field testing. We will incorporate a sample indoor map (like a floorplan with rooms, hallways) and simulate sensor data (lidar scans, etc.), as well as a simple model for communication range. This will help in early testing of exploration and mapping logic under controlled conditions.

This task results in a complete system design and requirements baseline. A System Design Review (SDR) milestone at end of Month 2 will confirm that the chosen components and architecture meet the objectives. At SDR, we will deliver design documents including the architecture diagram, interface definitions, and a bill of materials of the selected COTS components.

Task 2: Autonomy Core Development – SLAM and Frontier Exploration (Month 2-4)

This task develops the core autonomy software for mapping and exploration on each drone:

- **SLAM Implementation (FAST-LIO2):** We will integrate the FAST-LIO2 algorithm for LiDAR-Inertial Odometry on our target hardware. Using the open-source implementation, we will optimize it for our drone's LiDAR (tuning it for Livox or Ouster sensor characteristics) and ensure it runs in real-time (at least 10 Hz pose update) on the Jetson. We will test the SLAM in the lab by carrying the sensor rig through a small course and verifying map accuracy against ground truth. Key performance metrics (drift, CPU usage) will be recorded. FAST-LIO2's ability to operate without explicit feature extraction and to support both spinning and solid-state LiDARs is valuable for our heterogeneous sensor approach.

- **Frontier Detection & Navigation**: We will implement a module to identify exploration frontiers from the partially built map. Using techniques from Yamauchi's frontier-based exploration, the algorithm will mark unexplored open boundaries in the occupancy grid. We will leverage existing ROS2 exploration packages as a starting point, adapting them for multi-robot use. Each drone will regularly compute frontiers in its local map (which, in a multi-agent scenario, could be merged via occasional data exchange or kept separate with tasks deconflicted – see Task 3).

- **Local Autonomous Navigation:** Develop the local planner for drones to navigate to goal frontiers while avoiding obstacles. We will use a combination of LiDAR-based obstacle avoidance (e.g., Voxblox or Rapidly-exploring Random Tree (RRT) planners) and the drone's native autonomy (Skydio's platform, for instance, has built-in obstacle avoidance using vision). The navigation stack will be tested in simulation first, then on a single drone in a controlled indoor course (e.g., flying down a hallway, turning into a room).

- **Cognitive Mapping Layer**: We will design the data structures to hold the *cognitive map*. In practice, this may be an annotated 3D occupancy map or point cloud. We will define how to embed sensor readings into the map. For example, we might maintain a 3D grid where each cell holds not only occupancy probability but also vectors of sensor observations (e.g., gas ppm readings, temperature from IR). A threshold exceedance can mark a cell as "hazard" which can then be presented distinctly. This data architecture is crucial for later exporting to the user interface (MACO). We will implement simple versions of this: e.g., if gas > threshold at a location, flag that voxel.

- **Single-Agent Dry** Runs: By mid-Phase I (around Month 3), we plan to have a single drone autonomously mapping a simple room in our lab. This will be a dry run of the full pipeline: takeoff, SLAM running, frontier chosen, drone moves to frontier, maps new area, etc., until area is covered or battery is low. This also tests autonomous takeoff/landing which we will incorporate (drones will start on the ground at entry point, and ideally return to start or at least land safely if battery low or mission complete). Any issues (e.g., SLAM loss in feature-poor areas) will be identified and mitigated (adding more loop closure, using visual-inertial fusion if needed from a camera, etc.).

The deliverable from Task 2 is a functioning autonomy core on a single platform, demonstrated in a controlled environment, and logs/maps to show performance. We expect to demonstrate an initial *cognitive map* (with perhaps one type of sensor annotation) by the end of Task 2.

Task 3: Multi-Agent Coordination and Communication (Month 3-5)

In Task 3, we expand the solution to multiple agents and implement the mesh network and anchor deployment strategies:

- **Consensus-Based Task Allocation (CBBA):** We will implement a decentralized coordination algorithm so that drones can assign frontiers among themselves. We have chosen the Consensus-Based Bundle Algorithm (CBBA) as a foundation due to its proven efficacy in multi-agent task allocation. In our context, "tasks" are exploration goals (frontier locations) or specific sensing tasks (e.g., one drone might be tasked to loiter and take additional readings if another detected a possible hazard). CBBA will allow each drone to bid for tasks based on its utility (distance, remaining battery, sensor capability) and reach consensus through local communication. We will implement a simplified CBBA in simulation first to verify that, for example, two drones will naturally split up to explore two different rooms rather than both going to the same room.

- **Mesh Networking Setup:** Using small radios (likely the NRF radios on Crazyflie or an external ESP32 radio for each device), we will establish a mesh network protocol. We will likely use an existing MANET routing protocol (such as OLSR or BATMAN) on a lightweight embedded Linux that runs on the Jetson and possibly a Pi Zero attached to anchors. The aim is that any node (drone or anchor) can route data to any other, even if not in direct range, by multi-hop. We will test the mesh by placing anchors and drones in various building locations and measuring latency and packet loss. This network will carry both coordination messages (for CBBA and map sharing) and telemetry back to the base station (when connected).

- **Anchor Deployment Logic:** We develop the strategy for when and where a drone should deploy an anchor node. Criteria may include: (1) signal strength/throughput dropping below a threshold as it moves away from entry, (2) localization uncertainty increasing (e.g., SLAM covariance rising) which could be improved by a known reference point, or (3) a preset interval (e.g., drop a node every 10 m or every two rooms). The concept of GDOP (Geometric Dilution of Precision) from positioning is useful: if the drone's current set of anchors yields a high GDOP (poor geometry) for its location, that could trigger deploying a new anchor to improve geometry. We will simulate GDOP by treating anchors like "satellites" in a local positioning scenario and computing the value; when GDOP > X, drop an anchor and incorporate it. We will implement a simple behavior: a drone carries a couple of coin-sized UWB anchor nodes in a hopper; on trigger, it will hover and release (or place) an anchor on the ground or a ledge. If physical deployment in Phase I is risky, we will simulate it by manually placing anchors beforehand at roughly where the algorithm would have dropped them. The anchor then becomes part of the UWB localization network and comm mesh.

- **Multi-Agent Mapping & Data Fusion:** We will create a mechanism for merging maps and sharing sensor information among drones. Given limited bandwidth, a full real-time map merge may be impractical, so we will adopt a distributed mapping approach. Each drone keeps its map, but when in communication, they exchange key data – e.g., loop-closure signals if they see each other, or frontier info to not duplicate effort. If bandwidth permits, we can periodically send summarized map data (like frontier locations or downsampled point clouds) to a central node which merges them. At minimum, by mission end, the maps can be merged offline. In Phase I, a full decentralized SLAM is beyond scope, but we will ensure the system design supports eventual tighter integration in Phase II.

- **Communication-Denied Fail-safes:** We will implement behaviors to handle comms loss. If a drone loses contact, it will continue its local mission (because it's autonomous) but also attempt to regain link by either returning toward known anchors or elevating (if possible) to reconnect. Alternatively, after a time, it may return to base. This ensures a robust system that doesn't get irrevocably lost if comms fail. Testing this will involve intentionally turning off an anchor or blocking signals and observing system behavior.

By the end of Task 3 (around Month 5), we expect to demonstrate in a simple indoor scenario two drones working together: for example, starting at the same entry, then splitting into two areas, each dropping an anchor along the way, and maintaining a mesh network that relays data back to the operator. A mid-term demonstration will be given to DTRA sponsors showing two UAVs collaboratively mapping a small area with one or two anchors improving comms.

Task 4: Integrated Demonstration and Testing (Month 5-6)

This task focuses on the end-to-end integration of all components and the final Phase I demonstration:

- Hardware Integration: We will integrate the sensors and compute payload on the drones physically and ensure flight-worthiness. By Month 5, all drones and anchors will be assembled: LiDAR and cameras mounted, Jetson installed with our software stack, and anchor nodes packaged to be easily deployable. We'll conduct safety test flights (teleoperated) to verify drones can carry the payload and to tune flight parameters if needed (especially for any custom platform).

- Dry-run and System Tuning: In our testing facility (e.g., an indoor high-bay area or a set of offices after hours), we will conduct full system dry-runs. We'll start with a small area with full team, then scale up scenario complexity. We will fine-tune parameters such as frontier gain (how aggressively to seek new area vs solidify map), anchor placement thresholds, communication ping intervals, etc., based on these tests. We will also evaluate system performance against objectives: e.g., measure how long mapping takes, what percent of area is mapped, did we correctly identify our test "hazards" (we may use a safe alcohol vapor or CO_2 source for gas and a warm object for thermal).

- MACO Interface Prototype: Although a full interface is more of a Phase II deliverable, we will prepare a simple prototype of how data will be presented to users. Likely, we will run an instance of ATAK (Android Team Awareness Kit) or a laptop-based GUI that receives the map and sensor alerts from the swarm. If possible, we'll create a plugin or script for ATAK to display our generated map overlays (e.g., as a KML file or custom map layer). This will allow us to show the sponsor an operator's view: e.g., a floorplan with colored markers where gas was detected, etc. This step ensures we keep the transition to MACO in mind.

- Final Demonstration: We will conduct the final demo, fulfilling the criteria in the technical objectives. The scenario will involve an indoor structure (could be a warehouse with partitions or a multi-room lab space). We will introduce one or more simulated WMD threats: for instance, a benign gas source emitting a detectable tracer gas, and a heated object to mimic a radiation source. The SWARM-IQ system (Phase I prototype) will be deployed from the building entrance: the drones will take off and explore the building fully autonomously. Some will deploy anchors to maintain comms deeper inside. They will map the rooms and corridors. Upon detecting the gas leak or hot spot, the respective drone will flag it; another drone may be tasked to get a confirming reading or take a closer look (to simulate multi-agent confirmation). At mission end, the operator should have a map that clearly shows the building layout and the locations of the detected hazards. We will monitor the mission live via the mesh network (perhaps getting telemetry on a base station) and record all data for analysis. The entire run will be timed to ensure it meets operational needs (target <15 minutes).

- Success Criteria and Evaluation: After the demo, we will analyze whether objectives were met (as listed: mapping completeness, detection accuracy, comms performance, etc.). Any shortfalls will be documented along with planned improvements for Phase II.

Task 5: Reporting and Phase II Plan (Month 6)

In the final weeks, we will focus on documentation and planning:

- Prepare Phase I Final Report: Summarize all findings, results, and developed technology. This report will include the final 3D maps, photographs of the hardware, performance metrics, and an honest assessment of technical risk going forward.
- Phase II Work Plan Development: Using the knowledge from Phase I, we will outline the Phase II approach in detail. This will emphasize how we will go from the Phase I prototype to a deployable system. Key Phase II additions may include ruggedizing drones (e.g. shielding electronics from contaminants), adding more sensor types (perhaps a neutron/gamma detector for radiological detection), scaling up swarm size, and extensive field trials in realistic environments (maybe at a military operations in urban terrain – MOUT – site or subterranean test facility). We will also plan the MACO interface full integration and involvement of end-users for feedback.
- Commercialization Plan: We will refine the pathway to transition (further elaborated in the commercialization section of this proposal). In Phase I we will have identified likely DoD stakeholders (e.g., DTRA J10, SOCOM, Army CBRN units) and possibly commercial partners (drone manufacturers or defense primes) to engage in Phase II. We will line up letters of support or interest if possible, to demonstrate demand for the Phase II/III capability.

Deliverables for Task 5 include the final technical report, a Phase II proposal draft/outline, and all required financial and administrative reports for the SBIR program.

Schedule: The tasks above overlap partly for efficiency. A summary timeline:

- Months 1-2: Complete system design, start coding SLAM and sim (Task 1).
- Month 3: Single-drone mapping demo in lab (Tasks 2 done, Task 3 starts).
- Month 4: Multi-drone sim tests, initial dual-drone run (Task 3 mid).
- Month 5: Full integration, multi-drone field test with anchors, iterate (Tasks 3 & 4).
- Month 6: Final demo and reporting (Task 4 & 5).

This phased approach ensures that by the end of Phase I, all major components of SWARM-IQ have been proven at least in a basic form, reducing risk for a Phase II prototype build-out.

Related Work

SWARM-IQ builds upon and extends recent advancements in autonomous robotics, multi-agent systems, and counter-WMD sensor integration. We acknowledge the following related work as influencing our approach:

- DARPA Subterranean Challenge (SubT): The SubT Challenge (2018-2021) spurred development of multi-robot systems for underground search and mapping. Leading teams (CERBERUS, Explorer, etc.) deployed a mix of drones and ground robots that autonomously explored tunnels, caves, and urban underground environments. Notably, teams used techniques like *droppable communication nodes* to maintain networks in GPS-denied subterranean spaces. SWARM-IQ leverages similar ideas but tailors them to smaller drones and adds dedicated WMD sensing. The key difference is our focus on a *swarm of entirely airborne units with a fog network* (most SubT teams had primarily UGVs and a few UAVs) and the integration of CBRN sensors. The success of SubT teams in mapping unknown terrains and locating artifacts validates the feasibility of our core approach (autonomous exploration, mesh networking) in DDIL environments.

- Mapping & Awareness for Counter-WMD Operations (MACO): DTRA's MACO initiative exemplifies the user need for integrated mapping and sensing tools. For example, Draper Laboratory's work with DTRA on MACO provided robotic mapping capabilities and interfaced them with ATAK for real-time CBRN situational awareness. Their solution integrated CBRN sensors on a robotic platform and delivered a "mapped-out view" of hazards to the user. SWARM-IQ aligns with this vision but aims to advance it by using *multiple cooperating robots* instead of a single platform, and achieving fully autonomous operation (MACO as demonstrated relied on a single UGV or UAV providing data). We intend to remain compatible with and possibly contribute to the MACO framework, for instance by exporting our cognitive maps in a format suitable for ATAK/TAK interfaces.

- Multi-Robot Exploration Research: Frontier-based exploration originally proposed by Yamauchi (1997) remains a popular approach for multi-robot mapping. Numerous academic works (e.g., Benkrid et al. 2016) have studied strategies for coordinating robots to cover unknown areas efficiently. Our use of CBBA for task allocation is informed by research from MIT ACL and others showing that market-based algorithms can achieve near-optimal task division with low communication overhead. We improve on prior art by coupling task allocation tightly with communications awareness (i.e., our system will avoid sending a drone beyond comm range without an anchor) – a pragmatic twist needed for real-world deployment.

- SLAM and Navigation in GPS-denied environments: State-of-the-art SLAM systems such as Google's Cartographer, ORB-SLAM, and the more recent LIO-SAM and FAST-LIO2 have demonstrated reliable mapping in indoor scenarios. FAST-LIO2 in particular has proven robust and computationally efficient for drone applications. Additionally, commercial systems like *Skydio 3D Scan* now offer autonomous indoor scanning for industrial use, showing that vision-based and LiDAR-based autonomy has matured to handle large-scale indoor mapping. Skydio's system is a single drone system primarily for scanning construction sites, but it validates the capability of autonomous navigation and mapping in GPS-denied indoor environments using onboard cameras and LiDAR. SWARM-IQ takes inspiration from these systems and pushes the envelope by adding collaboration among multiple drones and specialized sensing.

- WMD Detection Technologies: On the sensing front, integrating CBRN sensors into robotic platforms has been explored by organizations like the Army's CBRN School and DHS. For example, lightweight chemical sensors (e.g., multi-gas detectors, photoionization detectors) and radiation sensors (like miniature scintillators or Geiger-Muller tubes) have been mounted on UGVs such as iRobot PackBot or drones in experimental efforts. The FLIR MUVE C360 is one of the first COTS drone-specific gas detection payloads and has been deployed on UAVs for hazmat response. Similarly, FLIR's Black Hornet PRS (Personal Reconnaissance System) integrated a radiation sensor into a tiny drone for military survey missions. These efforts indicate a clear trend and demand for remote CBRN detection. Our system will use these proven sensor payloads but focus on the data fusion and automation aspect that is less developed in current offerings.

In summary, SWARM-IQ stands on the shoulders of previous work in multi-robot exploration, SLAM, and CBRN sensing, but its novelty lies in the *synthesis* of these elements into an integrated system optimized for immediacy and autonomy in tactical scenarios. We combine advanced algorithms (many of which are at Technology Readiness Level 4-5 individually) and mature COTS hardware to create a new capability that, to our knowledge, does not currently exist in DoD or commercial inventory: a ready-to-deploy indoor swarm kit for cognitive mapping and threat detection.

Technical Risk and Mitigation

While the feasibility is high, as with any cutting-edge development, there are technical risks to be managed in Phase I and beyond. The major risks and our mitigation strategies are:

Risk 1: SLAM Failure or Degeneracy in Complex Environments. The indoor environments of interest could be cluttered (many obstacles) or feature-sparse (long uniform corridors) which can challenge SLAM algorithms. If the LiDAR returns or visual features are insufficient (e.g., smoke-filled room or dark tunnels for visual sensors), the drone might lose pose track. *Mitigations:* We address this by using a multi-sensor SLAM approach: FAST-LIO2 (LiDAR + IMU) is quite robust to darkness and gives precise odometry. We will add loop closure detection (possibly via a lightweight scan context or visual fiducial if needed) to correct drift. The drones can also exploit the anchor network: if a drone has UWB ranging to 3+ anchors, it can use that as a position reference to bound SLAM drift (similar to GPS aiding). In case of SLAM loss, the drone can pause and attempt to relocalize either by returning to a last known good area or by using the map from other drones (if available). We also keep an inertial dead-reckoning fallback such that even if mapping fails, the drone can backtrack along its last known trajectory to reestablish position.

Risk 2: Communication Blackout and Coordination Loss. In the worst-case, a drone might go out of range before deploying a relay, leading to loss of connection. This could result in multiple drones exploring the same area redundantly or, worse, a drone not returning. *Mitigations:* Each drone is endowed with a degree of independence – if cut off, it will follow a fail-safe to either return to a known anchor or complete a limited local search then return to base. To prevent blackouts, we simulate and plan the anchor deployment carefully (estimating radio range and signal propagation in typical structures, using lower frequency comms that penetrate walls better). We may also configure a *time-triggered rendezvous*: drones periodically come near the entry or an anchor to offload data and get new instructions, rather than roam indefinitely. The CBBA algorithm is naturally robust to asynchronous comms (there are variants like A-CBBA that handle intermittent links). If comms degrade, the system will degrade gracefully to more autonomous behavior with less team coordination, rather than failing entirely.

Risk 3: Limited Flight Endurance of Small Drones. Most small UAVs have flight times on the order of 20-30 minutes (less when carrying heavy payload). Covering a large building might strain battery life, especially if multiple passes or slow exploration is needed. *Mitigations:* We mitigate this by using multiple drones to parallelize the search (so each covers less area) and by choosing efficient trajectories (via frontier strategy). Also, our use of "fog" computing offloads some heavy computation (map merging perhaps) to a base station or to anchors, saving drone battery for flight. In Phase II, we can explore tethered drones as anchors (one idea: use a tethered drone as a comms hotspot at the entry with unlimited endurance, like a relay balloon). For Phase I, we will constrain demos to manageable size or optionally allow a mid-mission battery swap (land one drone, launch a fresh one to continue). This risk is moderate given our focus on small-scale Phase I demo, but must be watched for larger deployments.

Risk 4: Sensor False Positives/Negatives and Data Interpretation. The chemical sensor might alarm due to benign substances or miss a subtler hazard; thermal readings might be confused between a weapon and a hot pipe. If not properly interpreted, this could either cause false alarms (wasting time) or missed detections (danger to troops). *Mitigations:* We will calibrate sensors in realistic conditions and use a sensor fusion approach for confidence. For example, if a gas reading is detected by one drone, a second drone could be dispatched to double-check (two independent measurements reduce chance of false reading). For thermal detection, we can use thermal-video analytics to differentiate shapes (a large diffuse heat might be fire vs. a point source for device). Additionally, in Phase II, we can incorporate *machine learning* models for anomaly detection across sensor modalities (trained on known signatures of dangerous materials). During Phase I, we keep thresholds conservative and will clearly mark confidence levels on the map (so operators know if something is a weak indication or a strong one).

Risk 5: Integration and Weight Management: There is a risk that by integrating all these components (LiDAR, cameras, Jetson, sensors, battery) on a small drone, we may exceed payload capacity or cause stability issues.

Mitigations: We will select drones with sufficient payload (the Freefly Astro, for instance, is designed to carry a mirrorless camera and lidar, so ~1-2 kg payload). If needed, we can distribute sensors among the swarm (not every drone needs every sensor: e.g., one carries the MUVE C360, another carries a radiation sensor, and they share data). This reduces per-drone weight. Our anchor nodes are small (tens of grams) and should not impact the carrying drone significantly. We will also test the weight and balance on ground before flight. In worst case, we might use slightly larger drones or reduce the number of sensors for Phase I demo (e.g., use just one type of WMD sensor to prove concept, then add more in Phase II when we can use a larger platform or improved battery tech).

Risk 6: Regulatory and Flight Safety Risks: Flying drones indoors autonomously has safety considerations – risk of collision with environment or between drones. *Mitigations:* We will use platforms with proven obstacle avoidance (Skydio's vision system is very good at avoiding collisions automatically). We will also enable geofencing in software to keep drones within a virtual boundary. And during development tests, a safety pilot will be ready to take manual control or hit an e-stop if needed. All flights are indoors or in controlled space, so FAA regulations are not a major issue, but we will still follow best practices for airworthiness. Redundancies like propeller guards and soft mounting of anchors (so if they fall, no damage) will be in place.

Overall, our approach intentionally uses COTS components and existing algorithms to lower development risk. Many individual pieces (SLAM, drones, sensors) are at high TRL, so the main challenge is in integration and cooperation, which is manageable in the SBIR scope. Each risk has one or multiple mitigation pathways identified. Phase I will also serve to empirically discover any unknown risks, which we will document and address in Phase II (for example, human factors risk: ensuring the interface is actually useful and not overwhelming – we will gather user feedback if possible).

By rigorously testing in Phase I's limited scope, we aim to retire the highest risks early. The Phase I demonstration itself is a risk reduction step for the eventual operational system. With the planned mitigations and iterative test-driven development, we are confident that no single risk is "show-stopping," and a successful Phase I feasibility demonstration will pave the way to a robust Phase II prototype.

Potential for Commercialization

The SWARM-IQ technology has strong commercialization potential in both military and civilian markets. The dual-use nature of autonomous mapping and hazard detection means our solution can transition not only to DoD programs but also to homeland security, public safety, and industrial applications. Below we outline the primary transition pathways and commercialization strategy:

DoD and Government Transition Pathways:

- DTRA and Military CBRN Units: The immediate intended transition is to DTRA or other DoD components responsible for WMD reconnaissance and site exploitation. Upon successful Phase II, SWARM-IQ could be fielded as a kit for *Technical Support Groups (TSGs)* or combat units tasked with WMD disablement. We envision the technology feeding into programs like the U.S. Army's CBRN defense modernization. For instance, Army and Marine Corps CBRN reconnaissance platoons could carry SWARM-IQ in their Stryker NBCRV vehicles to deploy at suspected chemical weapon sites. Our plan is to engage with the Joint Program Executive Office for CBRN Defense (JPEO-CBRND) during Phase II to align our product with their requirements, paving a way for Phase III funding or acquisition. Additionally, SOCOM units (such as Nuclear Disablement Teams or Special Forces Chemical units) could rapidly deploy SWARM-IQ in sensitive missions – we will seek a CRADA or similar in Phase II with a relevant group to pilot the system.
- Integration with MACO/ATAK: By adopting the MACO interface standards from the outset, we facilitate integration into existing soldier systems. This significantly eases transition, as units are already using ATAK for situational awareness. In Phase II we will refine our ATAK plugin such that any unit with ATAK

can use SWARM-IQ's outputs on their Android device in the field. This interoperability can attract programs like the Army's IVAS (Integrated Visual Augmentation System) in the future, wherein 3D maps and hazard overlays from SWARM-IQ could be fed into soldier goggles or command post systems.

- DHS and First Responders: Beyond DoD, the Department of Homeland Security (DHS) is a major potential customer. DHS's first responders (e.g., FEMA Urban Search & Rescue teams, or Hazmat teams under FEMA and state agencies) could use SWARM-IQ for disaster response. For example, after an earthquake or industrial explosion, a SWARM-IQ drone team could swiftly survey a damaged building for people (via thermal) and hazardous leaks. We plan to seek DHS S&T (Science & Technology) Directorate contacts or SBIR programs for follow-on funding. The technology also aligns with needs of the FBI WMD Directorate and National Guard Civil Support Teams (CSTs) who respond to domestic WMD incidents.
- Defense Industry Partnerships: We recognize that transitioning to programs of record often requires partnering with established defense contractors who have manufacturing and support capabilities. We will engage companies like FLIR (Teledyne FLIR), which not only produce many sensors we use but also have existing products in reconnaissance drones and UGVs for CBRN (e.g., PackBot, FirstLook robots with sensors). A partnership or licensing deal with such a company could fast-track SWARM-IQ to a broader market. Similarly, drone manufacturers (Skydio, Shield AI, or even larger UAV integrators like L3Harris) might see value in incorporating our multi-agent cognitive mapping AI into their systems. During Phase II, we will actively demonstrate our prototype to these potential transition partners and solicit their feedback or investment (letters of interest can be obtained to support our commercialization claims).

Commercial and Dual-Use Applications:

- Industrial Inspection and Asset Management: The autonomous mapping mesh can be marketed to industries that need to inspect large indoor facilities (without GPS). This includes power plants, chemical plants, oil & gas refineries, and underground mines. Currently, such inspections are done by humans or single drones; SWARM-IQ could provide a faster, automated solution, especially in hazardous conditions (to inspect for gas leaks or structural issues). For example, an oil refinery turnaround could deploy SWARM-IQ drones to map internal structures of large processing units and sniff for volatile compound leaks, improving safety and reducing downtime. We will explore partnerships with companies in industrial inspection services (like those that already use drones for flare stack or tank inspections) to adapt our tech for their needs (perhaps removing some military-specific components and focusing on mapping + gas detection).
- Security and Law Enforcement: SWARM-IQ could be used by police or security forces for building clearance and hostage rescue scenarios. The system could map a building and locate adversaries (by detecting human heat signatures via thermal camera) or hazards (improvised traps, flammable gas) before officers enter. This is a natural extension of how SWAT teams currently use throwable robots or surveillance drones, and leveraging a swarm can cover more ground quickly. We anticipate interest from specialized law enforcement units and will market to them via homeland security trade shows and existing contracts vehicle (some of our team members have relationships in the law enforcement tech community).
- Construction and Building Information Modeling (BIM): A peacetime application of our cognitive mapping is automated creation of 3D models for buildings, akin to what commercial drones do with photogrammetry but indoors. Construction companies often need to produce as-built drawings of complex interiors. A system of drones that can cooperatively scan a building could drastically speed up the process. Companies like Skydio are already pushing in this direction; our differentiator is multi-drone coordination which can save time on very large sites, and perhaps being able to operate in environments without any existing comms or lighting (since we have our own lighting and comms network). We could license the multi-agent

exploration software to such companies or spin off a product variant focused on scanning (without the WMD sensors).

- Academic and R&D Markets: The technologies in SWARM-IQ (multi-UAV SLAM, mesh networking) will be of interest to research labs and universities. We can offer a *SWARM-IQ developer kit* comprising drones, anchors, and software, to laboratories for their own research (for instance, testing new multi-robot algorithms). Open-sourcing parts of our software (non-sensitive components like frontier exploration code) might also generate community adoption and improvement, which we can then incorporate (this open innovation approach has worked well for robotics frameworks like ROS).

Business Model and Marketing: Our primary business model will likely start with direct sales or leases of SWARM-IQ systems to government customers. This includes providing the hardware (or integration instructions for specified COTS parts) plus our proprietary software, along with training and support services. We anticipate initial low-volume, high-value sales for specialized units. Over time, as we refine and prove the system, we could pursue volume manufacturing via a larger partner or license the tech.

To market the product, we will leverage demonstration events and trials. Getting SWARM-IQ into high-visibility exercises (for example, a CWMD field training exercise or a civilian disaster drill) will attract stakeholders. We will attend relevant conferences: NDIA CBRN Conference, AUVSI Xponential, DHS S&T showcase, etc., to present results from Phase I/II. We have allocated effort in Phase II to refine the product's user experience and to ensure we meet certification standards (airworthiness, safety) required for adoption.

Intellectual Property (IP): We are developing unique algorithms and integration know-how which we will protect as needed. We may file patents on the anchor deployment method and cognitive map data fusion techniques. However, since we rely on many open-source components, our value is in the system integration and trade secrets in tuning the swarm behaviors. We will carefully manage IP so as not to impede transition – for DoD usage, we will offer government purpose rights as required under SBIR data rights rules, enabling the DoD to use and modify the system. For commercial sales, we will maintain proprietary rights to the software and provide licenses.

Revenue Projections and Funding Needs: If Phase II is successful, by the end of Phase II we could have a MVP (minimum viable product) that a military customer could start using experimentally. Phase III (out-of-SBIR) funding might come from an agency like DTRA or JPEO-CBRND to conduct larger pilots or procurement of limited quantities. We estimate the addressable defense market (including DHS) for a product like this to be in the order of tens to hundreds of units (each unit being a swarm kit) over a few years, with each unit perhaps costing $200k (including multiple drones, sensors, etc.). That implies a potential revenue of $20M+ if widely adopted. On the commercial side, applications like industrial inspection have a large global market (the drone inspection market is projected to be billions by mid-2020s). If we capture even a niche for hazardous indoor inspection, that could mean a few million in annual sales or licensing.

To realize these opportunities, we may seek additional investment after Phase II (either private or via programs like DIU or In-Q-Tel funding, given the national security angle). Our goal is to bootstrap via SBIR through prototype stage, then either scale organically with early sales or secure strategic partnerships to go into production.

In conclusion, SWARM-IQ is positioned not just as a one-off SBIR prototype, but as a sustainable product that addresses a critical capability gap in defense while also offering commercial value. Our team is committed to transitioning this technology out of the lab and into the hands of users who need it. The SBIR funding will de-risk the core technology, after which our commercialization strategy will ensure the government's investment yields an operational product. Immediate COTS component usage and interoperability with existing systems (like ATAK) mean that, once proven, SWARM-IQ could be rapidly deployed in real-world scenarios – potentially within 1-2 years for pilot use, rather than a protracted development cycle. This agility further bolsters the attractiveness to defense and commercial customers alike.

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