Special Issue: Dynamic Large-Scale Swarm Systems in Urban Environments: Results from the DARPA OFFSET Program

Regular Article

DARPA OFFSET: A Vision for Advanced Swarm Systems through Agile Technology Development and Experimentation

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Abstract: As robotics and autonomous technologies continue to see breakthrough innovations, specifically in the areas of large-scale multi-robot teams, their alignment with operationally relevant applications in fielded contexts has been necessary to both obtaining valuable user feedback as well as informing and refining the use cases themselves, i.e., co-evolving the concepts of operations alongside technology maturation. The Defense Advanced Research Projects Agency (DARPA) OFFensive Swarm-Enabled Tactics (OFFSET) program[1] was a four-year program which actively embraced this iterative, mission-focused development approach, coupling technology innovation with field experimentation activities to rapidly advance capabilities for large-scale, heterogeneous robotic teams in complex and adversarial urban environments. This vision paper highlights the motivation for the OFFSET program; provides descriptions of the technical objectives and outcomes; and offers insights into the program structure designed to facilitate and inject technology innovations through an ambitious campaign of field tests and learning.

Keywords: military applications, robot teaming, human robot interaction

1. Introduction

In October 2017, the Defense Advanced Research Projects Agency (DARPA) kicked off the OFFensive Swarm-Enabled Tactics (OFFSET) program, selecting two Swarm Systems Integrators (SSIs) to design, develop, and deploy an open architecture for swarm technologies in both physical and virtual environments. Each system would include an extensible game-based architecture for enabling the design and integration of swarm tactics, a swarm tactics exchange to foster community interaction, immersive interfaces for collaboration among teams of humans and swarm systems, and a physical testbed to validate developed capabilities. Throughout the program, the developed swarm systems

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*This work was conducted while this author served as the OFFSET Program Manager at the Defense Advanced Research Projects Agency (DARPA), Tactical Technology Office.

[1]More information can be found at https://www.darpa.mil/work-with-us/offensive-swarm-enabled-tactics.

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architectures were made accessible to a wider swarm technology developer audience referred to as Swarm Sprinters, selected by DARPA to integrate their respective innovative swarm technologies. Technical progress of the stand-alone swarm systems architecture and capabilities offered by the SSIs and their respective collaborative integration efforts with the Swarm Sprinters were periodically assessed at approximately six-month intervals at a series of operationally relevant field experiments, each with increasing scale and complexity. The main contributions of this program overview paper encompass the detailing of the vision and execution of the DARPA OFFSET program, as well as sharing the lessons learned over the rigorous campaign of swarm systems field experiments for future field robotics researchers.

DARPA's motivation for exploring and advancing applied swarm systems technologies was to address and overcome many of the operational gaps in prior research efforts conducted largely in isolated or controlled (e.g., laboratory or simulation) settings by developing the necessary components for "in-the-wild" swarm systems capabilities. Focusing specifically on enabling these future capabilities, DARPA identified the development of "swarm tactics" to capitalize on the unique attributes of swarm systems to effect tactical advantage (Arquilla and Ronfeldt, 2000; David and Nielsen, 2016; Scharre, 2018). Swarm size (i.e., the number of elements in the swarm) had often been the prevailing (albeit limiting) consideration when identifying advantages of swarm technologies; however, the underlying premise of the OFFSET program was that the potential of swarm systems had yet to be fully explored and realized. Indeed, swarm tactics that could fully utilize the richness of swarm systems beyond swarm size, to include agent and collective complexity, heterogeneity in the swarm's composition, and collaborative interactions between humans and the swarm, would lead to disruptive swarm capability advantages of interest to the Department of Defense (DoD).

The paper is organized by first introducing the DARPA OFFSET program in Section 2, including the program's operational context and motivations, OFFSET's canonical swarm capabilities framework, and the program's overall technical approach. Section 3 offers a summary description of the OFFSET program structure, which highlights the context and inspiration for OFFSET's unique program design. The field experimentation details provided in Section 4 represent the primary focus of this paper and showcase the evolution of the lessons learned from OFFSET's agile swarm technology development approach. These field tests offer numerous insights for swarm systems in the real world, shared in Section 5, followed by a series of informed recommendations for future applications and expanded development of swarm capabilities presented in Section 6. The paper concludes by highlighting diverse contributions of the OFFSET program and its newly minted swarm systems ecosystem and summarizing closing remarks in Sections 7 and 8, respectively.

2. OFFSET: A Swarm Systems Framework

2.1. A Vision for Operationally Relevant Swarm Systems

DARPA's OFFSET program envisioned future small-unit infantry forces using hundreds of small uncrewed aerial vehicles (UAVs) and or uncrewed ground vehicles (UGVs) to accomplish diverse missions in challenging urban environments. By utilizing and combining emerging technologies in swarm autonomy and human-swarm teaming, the program sought to enable rapid development and deployment of breakthrough capabilities.

OFFSET Vision
To discover innovative technologies to enable **large-scale teams of air and ground robots** to support **small-unit forces** operating in **complex urban environments**

The OFFSET vision consisted of these three core concepts:

1. **Large-scale teams of air and ground robots.** Through both the swarm size (number of agents) and the heterogeneity (types of platform and payload capabilities), OFFSET aimed to unlock the potential advantages for swarm systems in operational settings. Within OFFSET,

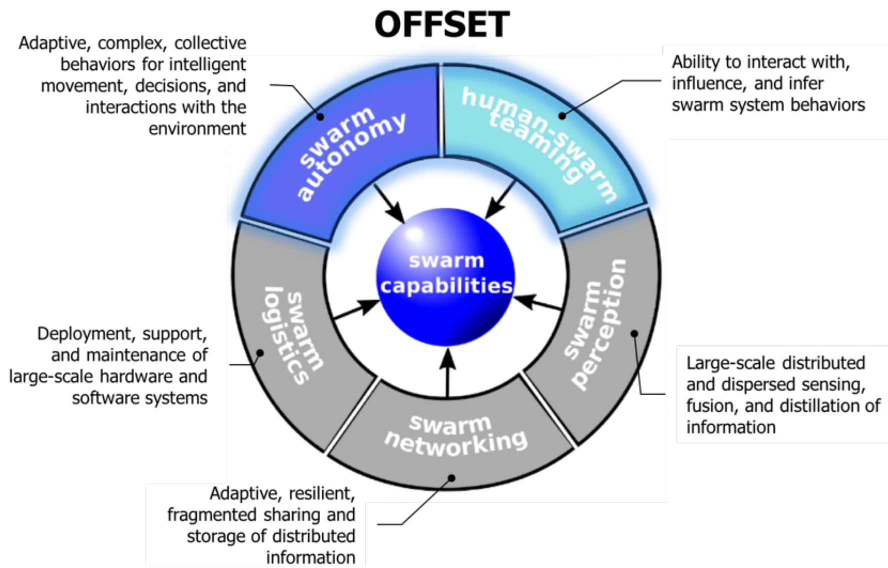


Figure 1. The confluence of five technology elements enable future swarm capabilities. While **swarm perception**, **swarm networking**, and **swarm logistics** are important problems for researchers in industry and academia to address, DARPA focused OFFSET's priorities on the core pillars of **swarm autonomy** and **human-swarm teaming**.

"large scale" was defined as a threshold swarm size of 100 robots, with an objective of 250 combined aerial and ground autonomous systems.

2. **Small-unit forces.** Recognizing the limitations of overtasked personnel, OFFSET sought to empower and equip a single "swarm commander" individual with innovative human-swarm teaming approaches and immersive swarm interfaces to best manage the complexity of the swarm.
3. **Complex urban environments.** Given the challenges of the urban setting, OFFSET set out to discover innovative opportunities for swarm systems to overcome, if not actively utilize, the features of urban environments through the swarm systems' abilities to conduct distributed and dispersed operations.

2.2. Motivation and Technical Objectives

The increasing availability of distributed, large-scale, autonomous systems has renewed and reinvigorated the exploration and acceleration of swarm capabilities. These technological advances have converged to give rise to five key areas for swarm systems capabilities, as illustrated in Figure 1:

1. **Swarm autonomy** encompasses adaptive, complex, collective behaviors for intelligent movement, decisions, and interactions with the environment.
2. **Human-swarm teaming** highlights the need and ability to interact, influence, and infer swarm system behaviors.
3. **Swarm perception** involves large-scale, distributed and dispersed sensing, fusion, and distillation of information.
4. **Swarm networking** pertains to adaptive, resilient, fragmented sharing and storage of distributed information.
5. **Swarm logistics** addresses both hardware and software deployment, support, and maintenance of large-scale systems.

The OFFSET program's focus was to advance key elements of these enabling swarm technologies, focusing on the swarm autonomy and human-swarm teaming components of swarm system

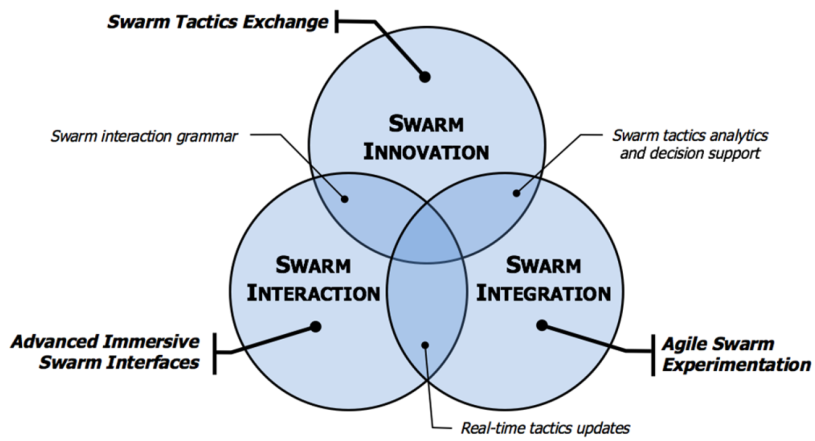


Figure 2. The three key facets for the envisioned OFFSET Swarm Systems Architecture, unifying synergies in the innovation, interaction, and integration of swarm tactics.

capabilities. OFFSET designed, developed, and demonstrated two extensible swarm systems architectures, both of which were encoded in a realistic game-based environment and embodied in physical swarm autonomous platforms. The objective of these swarm architecture reference implementations was to advance the *innovation*, *interaction*, and *integration* of novel swarm tactics, as illustrated in Figure 2. At this level of abstraction, the program sought to synergistically invent and/or implement swarm tactics, e.g., in virtual settings, alongside the rapid iterations on actual swarm technologies, i.e., using physical testbeds, to maximize insights obtained throughout the program.

2.2.1. OFFSET Swarm Systems Architecture

The general swarm systems architecture model, as offered by OFFSET, represents the interagent capabilities as well as swarm interactions with command elements. Specification of such a system-of-systems architecture requires definition of network configurations and communication protocols; identification of standard data structures, information sharing methods for world models, and shared awareness of the state of the swarm system; and the specification of transparent swarm software interfaces that enable design and implementation of swarm tactics.

A key consideration in the realization of swarm tactics arose from the need to compose multiple swarm "building blocks" comprising of swarm algorithms, swarm primitives, and even other swarm tactics. Swarm algorithms form the foundation of simple functions or "skills" that the swarm is capable of executing collectively. While these functions (e.g., maneuver forward, measure signal strength, sense obstacles) may not individually offer actionable operational value, the combination of these swarm algorithms into swarm primitives, or collective behaviors, can represent more integrated swarm capabilities. For example, such swarm primitives may encode behaviors to locate points of interest in an area, identify ingress points to a building, or define and secure a perimeter. As the central focus of OFFSET, swarm tactics catalyze operationally relevant swarm system capabilities via the composition of swarm primitives, conducted in sequence and/or concurrently, to address tactical objectives in support of the mission.

These "building blocks" were designed to be potentially created and contributed to by disparate third-party developers. Clear specification and documentation of the pertinent interfaces, including those relevant to intraswarm as well as potential interswarm (e.g., when subswarms are present) configurations for swarm tactics, was desired. As such, the OFFSET framework for the layers of swarm autonomy, depicted in Figure 3, offered a top-down, swarm mission-driven perspective to guide the development, integration, and demonstration of swarm systems capabilities.

Of significant interest to DARPA were swarm systems architectures which could flexibly adapt, i.e., either prior to or in the midst of current collective swarm tactics execution, in the face of system uncertainty, dynamic environments, and adversarial conditions. Development of entirely new

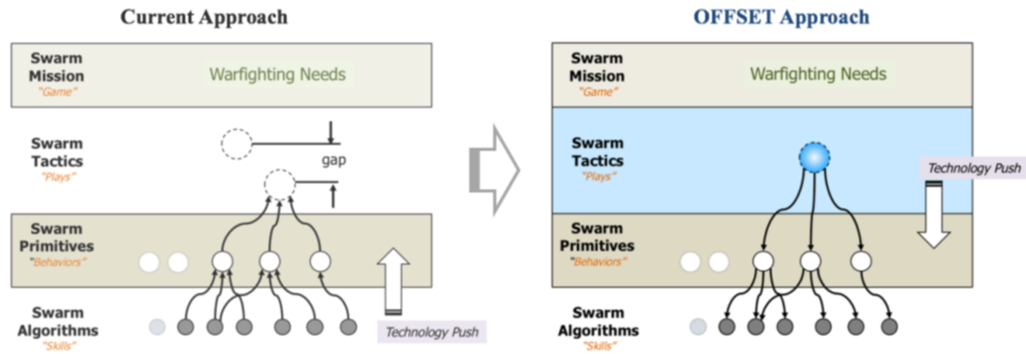


Figure 3. The OFFSET framework for exploring the layers of swarm autonomy, deriving requisite swarm tactics, swarm primitives, and swarm algorithms form the top-down (right) swarm mission definition. The conventional bottom-up approach (left) leaves a gap between warfighter needs and the swarm tactics developed, whereas the swarm tactics–focused top-down approach addresses warfighter needs as the driver of advances in swarm capabilities.

technologies in the areas of resilient communications and distributed computation were outside the scope of this effort. Instead, OFFSET encouraged the use of existing state-of-the-art capabilities and open standards (e.g., established extensible message formats, public-domain algorithms, open-source distributed systems libraries).

Support for extensible access and tools for collecting, processing, and analyzing swarm systems, such as data logging, playback, and visualization, were also considered essential for the swarm system architecture, with an emphasis on enabling both evaluation and exploration of swarm systems capabilities through simulation and experimentation.

2.2.2. Urban Operations

The OFFSET program's operational focus was military operations in urban terrain. Particular challenges in these environments include the increasingly vertical, occluded, and channelized contexts in which small-unit ground forces must maneuver, defend, and engage both dynamic environments and adversaries. Such impediments are exacerbated by the fact that such operations must often be conducted in areas where knowledge, access, and/or control of factors like infrastructure, supply chains, local conditions, and potential threats are severely limited. The very nature of these urban settings calls for advances in distributed and dispersed autonomous system capabilities organic to company-level-and-below ground units of the future.

To envision an OFFSET-empowered future operational backdrop, one may consider the scenario where the swarm systems form the "tactical swarm vanguard," which serve the role of an advance party ahead of the main operating force (e.g., an infantry company or platoon). In this context of "recce" or "armed recon," the swarm vanguard conducts surveillance of the area of operations, provides tactical situational awareness, prepares the battlespace, and/or initiates relevant activities to support the main unit's mission objectives. The main force elements may advance to augment the swarm's present activities, offering occasions for combined actions involving both human and autonomous swarm forces, as well as enabling the swarm to continue pressing forward as appropriate or necessitated by the mission.

Referencing United States Marine Corps (USMC) Reference Publication (MCRP) 12-10B.1 (U.S. Marine Corps, 2018), an offensive urban operation can be divided into a series of four phases: reconnoiter the objective, isolate the objective, secure a foothold, and seize the objective, which can be described as follows.

- **Reconnoiter the objective:** Gather intelligence such as avenues of approach, supply routes, ingress and egress points, infrastructure and utilities, locations of enemy combatants, and other information that may not be apparent in existing databases or maps.

Figure 4. The OFFSET vignettes represented a progression of operationally relevant urban missions to drive swarm systems development.

- **Isolate the objective:** Deny the enemy the ability to maneuver or reinforce by impeding the flow of manpower, supplies, weapons, and communications.
- **Secure a foothold:** Provide the attacking force with a position from which they can assault through the objective area.
- **Seize the objective:** Push forces to clear or control the objective area, including consolidation of the objective area and reorganization for future tasking.

These phases provided the context for how OFFSET teams would ultimately envision, design, and implement the necessary swarm tactics and their composition to accomplish each of the respective operational objectives. In this manner, DARPA designed the OFFSET program phases to align with operational vignettes, as illustrated in Figure 4.

This progression of mission-focused objectives—from gathering information and intelligence through reconnaissance and isolating specific buildings; to then positioning teams of robots to conduct movements towards, around, and within urban structures; culminating with wider-area operations to seize and maintain awareness of key geographical locations within the urban environment—ensured that each phase of the OFFSET program would yield meaningful and "minimally viable" swarm capabilities.

3. OFFSET Program Structure

This section highlights a model, shown to be successful in the OFFSET program, for fostering an iterative and collaborative ecosystem to drive (swarm) technology innovation.

3.1. Swarm Systems Integrators

OFFSET solicited[2] and selected two Swarm System Integrator teams to develop the overarching open-source swarm systems architecture, including the game-based environment, the interactive human-swarm interface technologies, and the definition of software interfaces enabling modular swarm tactics development. Swarm System Integrators were selected to perform throughout the duration of the OFFSET program across three phases. Each phase, aligned with the operational

[2] Proposals were requested through the DARPA OFFSET Broad Agency Announcement (BAA) #HR001117S0011 (DARPA, 2017).

Table 1. Objective capabilities of interest for autonomous swarm systems.

Operational Context	Vignette 1	Vignette 2	Vignette 3
Representative Mission	Isolate an urban objective	Conduct an urban raid	Seize key urban terrain
Mission Duration	15-30 minutes	1-2 hours	4-6 hours
Area of Operations	Approx. two square city blocks	Approx. four square city blocks	Approx. eight square city blocks
Swarm Size	50	100	250

vignettes described in Section 2.2.2, were designed to demonstrate progressively larger swarm sizes over longer mission durations and larger areas of operation. The desired capabilities for each vignette are summarized in Table 1.

The three vignettes highlight the mission-oriented nature of OFFSET, where capabilities of the collective swarm are not defined by system or platform specifications but rather by their ability to execute one or more swarm tactics in support of the mission. The key attributes of the associated missions centered around

- **Mission duration**, which describes the time during which the swarm is actively employed, potentially including transit and deployment times;
- **Area of operations**, which describes the physical size of the urban sector, including the vertical dimension, in which the swarm agents are conducting the mission; and
- **Swarm size**, which describes the desired number of combined total air and/or ground agents involved in the current mission.

Given the expansive scope of technical expertise required, each of the two Swarm Systems Integrators composed a highly multidisciplinary team to address the anticipated need for robust systems integration, robotic systems engineering, simulation development, field testing and operations, and DevOps-based software development skill sets.

3.2. Swarm Sprinters

DARPA further solicited proposals for Swarm Sprinters in approximately six-month intervals through BAAs. The purpose of these Swarm Sprints was to engage with a wider developer and user audience and to conduct rapid technology development efforts. An additional benefit of this sprint-driven solicitation structure was to allow DARPA to refine the trajectory of swarm systems development based on continuously emerging needs of the program as well as newly available insights and technology offerings external to the program.

These Swarm Sprints each focused on one or more key thrust areas or high-level research areas of interest to OFFSET, so as to offer each cohort of thematically aligned Swarm Sprinters the potential opportunity for shared development experiences and mutual benefit. The thrust areas included Swarm Tactics, Swarm Autonomy, Human-Swarm Teaming, Virtual Environment, and Physical Testbed, described further below, by associated Swarm Sprint:

Swarm Sprint 1
Swarm Tactics for Vignette 1
Design and implement one or more swarm tactics of operational relevance for a heterogeneous swarm isolating an urban objective.

Swarm Sprint 2
Systems Enablers for Enhanced Swarm Autonomy
Develop and integrate systems enablers for enhanced swarm autonomy, including both hardware and software along with associated swarm tactics, swarm primitives, and swarm algorithms.

Swarm Sprint 3

Interactions and Interfaces for Human-Swarm Teaming

Design, develop, and demonstrate novel interaction and interface modalities for enhanced human-swarm teaming.

Swarm Tactics for Vignette 2

Design and implement one or more swarm tactics of operational relevance for a heterogeneous swarm conducting an urban raid.

Swarm Sprint 4

Swarm Systems Advances through Synthetic Technologies

Develop and implement synthetic capabilities in simulation representing potential future technologies to enable and demonstrate novel swarm tactics.

A.I. for Accelerating Swarm Tactics Design

Discover and learn novel swarm tactics through application of artificial intelligence (AI) and machine learning using enhancements of OFFSET virtual environments.

Swarm Sprint 5

Enhancements and Enablers for Swarm Physical Testbeds

Prototype and integrate innovative component technologies into physical testbeds for swarm systems to create new swarm-focused capabilities.

Swarm Tactics for Vignette 3

Design and implement one or more swarm tactics of operational relevance for a heterogeneous swarm seizing key urban terrain

Selected Swarm Sprinters were expected to expeditiously deliver and integrate their capabilities with the open-source architectures provided by the Swarm Systems Integrators. Figure 5 illustrates the schedule of the Swarm Sprints with their associated thrust areas and durations.

Furthermore, highlighting that innovative technologies can arise from diverse performer types, Swarm Sprinters comprised small businesses and startups, large businesses, research laboratories, and academic institutions, as illustrated in Figure 6. These Swarm Sprinters were able to design swarm tactics and/or requisite supporting elements and integrated them according to the specifications set forth by the architectures developed by the Swarm Systems Integrators.

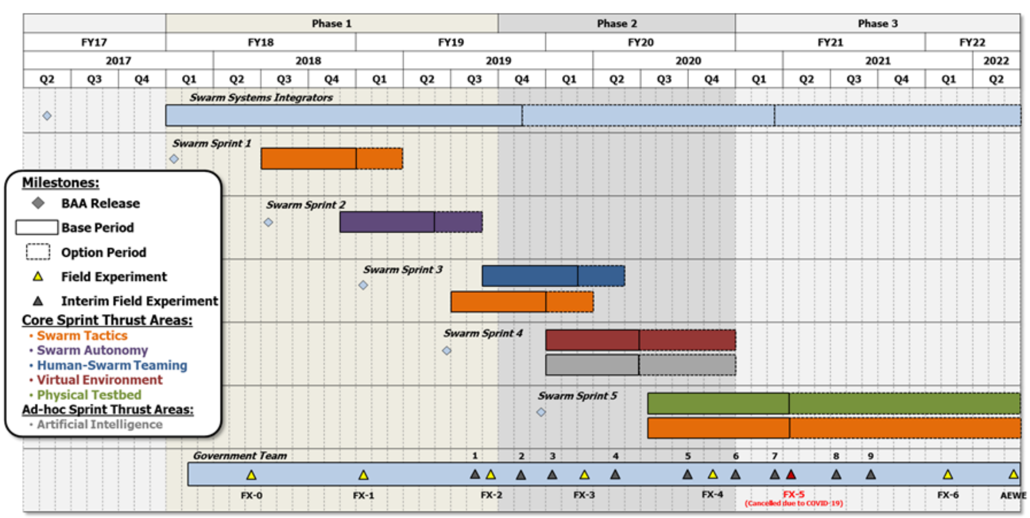


Figure 5. The OFFSET Swarm Sprint schedule, representing the staggered solicitation and execution of the six-to-nine-month periods of performance aligned with one or more thrust areas.

Figure 6. Illustration of Swarm Sprinters across five Swarm Sprint efforts, representing diverse organization types and technical approaches and contributions to the OFFSET Swarm Systems Architecture(s).

Swarm Sprints provided critical enhancements to the overall OFFSET program. Each Swarm Sprint offered novel features and/or new capabilities for one or both of the Swarm Systems Integrators' respective architectures. The Integrators were inclined to adopt and showcase the most compelling and innovative Swarm Sprinter–developed contributions as part of their integration efforts. Further, the Swarm Sprinters helped inform and shape the evolution of the swarm technologies of interest to OFFSET, both through their close interactions and feedback with the Swarm Systems Integrator teams and also via their active contribution of feature requests, bug reports, and updates to the OFFSET code and knowledge base.

3.3. Government-Led Field Experimentation Team

OFFSET also established a government-led field experimentation team responsible for the design, planning, and execution of the field experimentation events (see Section 4) and evaluation of the developed Swarm Systems Integrators technologies and Swarm Sprinter contributions. The field experimentation team continuously engaged with operational stakeholders to develop and refine representative mission scenarios, and further developed highly configurable and scalable digital infrastructure and tools to enable next-generation autonomy test and evaluation capabilities.

The infrastructure developed by the field experimentation team consists of a U.S. government–developed (now publicly available[3]) swarm experiment management software suite called Mole that facilitates execution of the experiment, provides orchestration over the experimental components, monitors the experimental infrastructure, and hosts analysis and reporting tools. Additional experiment infrastructure comprised physical entities for robots to explore, field nodes to allow interactions, sensors measuring environmental conditions, and hard-wired networking to allow for data transmission and communications between the field nodes and the experimentation management suite. Together, these components represented an agile "experimentation-in-a-box" capability by providing a highly configurable and scalable infrastructure for test and experimentation of swarm systems.

[3] Repository can be found at https://github.com/niwcpac/mole.

4. OFFSET Field Experimentation Campaign

To further reinforce the mission-focused approach described in Section 2.2.2, in the early inception stages of the OFFSET program, the OFFSET government team attended and observed live USMC urban operations training exercises at Twentynine Palms, California, to experience firsthand the nature of the operating environment and flow of urban operations. These observations significantly informed and positively influenced the philosophy, design, and execution of the OFFSET field experimentation events and scenarios described in this section.

4.1. OFFSET Experimentation Philosophy

Diversifying Swarm Test Environments. In contrast to traditional test campaigns, the OFFSET program intentionally sought out new venues at different military testing and training locations to host and conduct its field experimentation events. This somewhat burdensome approach required both OFFSET performer and government teams to overcome learning new range procedures and personnel and to expend nontrivial effort to redesign swarm mission scenarios and implementations to each new venue. However, testing at different locations for each test event directly aligned with and benefited from the agile and iterative nature of the OFFSET program. The overwhelmingly positive impacts included mitigating the effects of “overfitting” the resulting technology solutions to a given venue; exercising fluency of field operations and planning associated with new test sites; and encouraging new insights for all teams in constructing and executing compelling swarm test scenarios.

Enabling “Physical Simulation”. While crafting the OFFSET swarm mission scenario for field experimentation, AprilTag visual fiducials (Olson, 2011) were used as surrogate elements in the test scenario to allow teams to focus on swarm-level autonomy capabilities, rather than agent-level component technologies. Each AprilTag represented “game pieces” within the scenario (e.g., human intelligence (HUMINT) sources, hostile combatants, improvised explosive devices (IEDs), etc.). OFFSET progressed from using the AprilTag 2 series (`Tag36h11` family) (Wang and Olson, 2016) to AprilTag 3 (`TagCustom48h12` family) (Krogius et al., 2019), enabling increased scenario complexity by using nested AprilTags, i.e., a smaller inner AprilTag within a larger outer AprilTag, as shown in Figure 7. The nested AprilTags allowed swarm agents to perform detection at stand-off ranges, but required interrogation by getting physically closer and/or calling in teammates (e.g., rovers) to recognize or identify the surrogate elements.

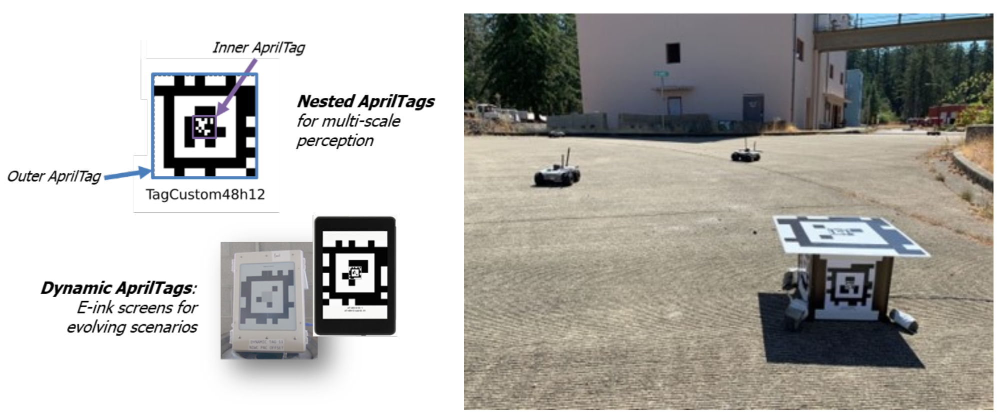


Figure 7. OFFSET field tests leveraged AprilTag (Krogius et al., 2019; Olson, 2011; Wang and Olson, 2016) fiducial markers (left) to represent various scenario elements, such as benign objects and hostile threats, which incorporated networked Raspberry Pi–based edge nodes (right) to directly interact with fielded robots for diverse surrogate effects throughout the scenario.

Coupled with the AprilTags encoding the various surrogate scenario elements, the experimentation venue was further instrumented extensively with networked Raspberry Pi nodes equipped with Bluetooth beacons (shown in Figure 7). These field nodes allowed for direct "at-the-edge" interactions with similarly Bluetooth-equipped swarm agents, thereby enabling a "physical simulation" of actual dynamic scenario evolutions, orchestrated digitally in real time by the OFFSET government team.

Accelerating Swarm Testbed Evolutions. A primary objective for OFFSET was to integrate the developed swarm tactics in a physical swarm testbed comprising various aerial and ground autonomous systems. Such field testing of swarm capabilities was intended to validate assumptions as well as expose real-world challenges. The goal was to bring swarm technologies to a level of maturity that would enable extensive experimentation to then drive concept generation; develop increased familiarity with autonomous swarm systems; inspire new swarm tactics, techniques, and procedures (TTPs); and identify new mission trade spaces and technology gaps for swarms in practice.

OFFSET challenged performers to go well beyond previously existing capabilities and physical realizations of swarm systems—largely limited to laboratory or indoor-only settings—to create two instantiations of physical testbeds to demonstrate large-scale, heterogeneous swarms. Further, rather than specifying platforms to be used, the OFFSET program invited the teams to conduct their own market surveys, determine suitability (e.g., cost, availability, maintainability), and select their choice of surrogate platforms capable of collaboratively employing swarm tactics. This flexibility required periodic assessments of commercially available platforms while still highlighting the need to have dependable and familiar platforms for rapid fielding. Figure 8 shows the various air and ground robot platforms used by the different OFFSET performer teams, illustrating the heterogeneity of the vehicle types and configurations (and thus, the extensibility of the underlying swarm systems architectures.)

4.2. Overview of OFFSET Field Experiments

In this section, we provide brief overviews of each OFFSET field experimentation event, including scenario descriptions and key takeaways. A deeper exploration of results for FX-6 is also provided as an exemplar of the types of analysis conducting and reporting provided to teams as feedback to inform and accelerate their technology development efforts. Table 2 summarizes the cadence and diversity of OFFSET field experiments.

Figure 8. Gallery of OFFSET swarm platforms, including the 3DR Solo (quadcopter), Uvify IFO-S (quadcopter, two configurations), Aion R1 (rover, two configurations), Edge 540XL (fixed-wing), Aion VTOL (VTOL fixed-wing), and ModalAI m500 (quadcopter). (Not shown are multiple platforms deprecated over the course of the OFFSET program.)

Table 2. Summary of the schedule and venues for OFFSET field experimentation, highlighting the frequency, diversity, and intensity of each test event.

Field Experiment	Location	Date
FX-0	Randalls Island, NY	9-11 March 2018
FX-1	Camp Roberts, CA	22-25 October 2018
FX-2	Fort Benning, GA	5-13 June 2019
FX-3	Camp Shelby, MS	7-19 December 2019
FX-4	Joint Base Lewis-McChord, WA	20 July - 12 August 2020
FX-5	canceled	January 2021
FX-6	Fort Campbell, KY	2-19 November 2021

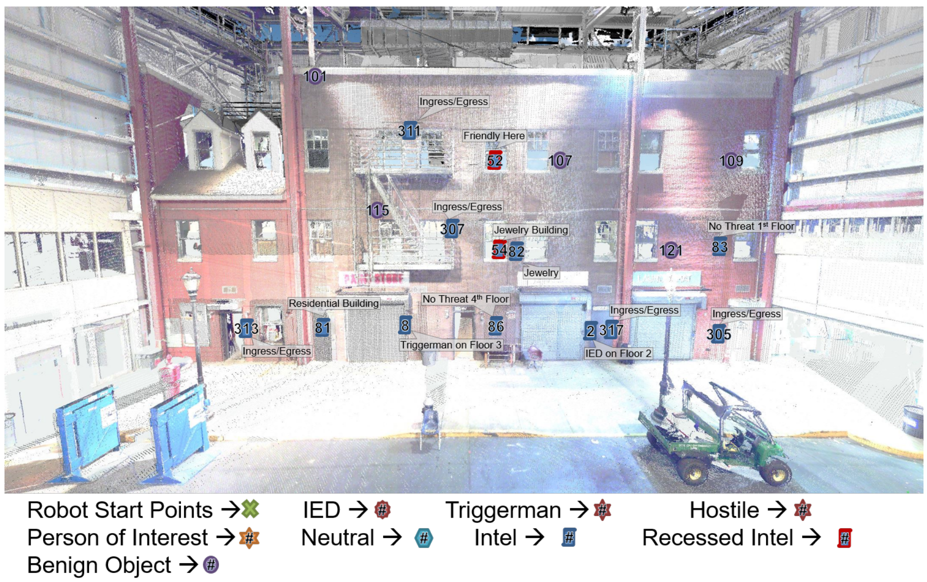


Figure 9. Overlay of the FX-0 scenario on a colorized 3D point cloud depicting an FDNY training facility at Randalls Island, New York. FX-0 was conducted 9-11 March 2018.

4.2.1. FX-0: Randalls Island, New York

This event was designed to be an integration activity (as opposed to capability testing) and offered all teams their first opportunity to observe the scope and magnitude of a representative OFFSET field test, taking place in the training facilities for the Fire Department of New York (FDNY). The facsimile of a neighborhood street with ground-level storefronts and multistory buildings with varying levels of clutter or collapsed interiors posed significant challenges for the initial deployment of robots. This event also helped set the tone for the types of operational settings of interest to the OFFSET program, e.g., urban rescue and first response missions as related to military urban combat contexts. Figure 9 shows a colorized 3D point cloud of one of the facades within the wholly enclosed training facility, with annotations for where OFFSET scenario elements (approximately 20 AprilTags) were emplaced for robot interactions.

Key FX-0 Takeaways. This integration event demonstrated the significantly challenging nature of urban environments, including street curbs, stairwells, nontrivial clutter in rooms, variability in door and window dimensions, issues with dust and lighting, etc. Despite the critical reliance on GPS-based guidance for all robots, which limited the reliability of the deployments of the robots, teams exercised other field skills and collected valuable initial data. These insights were critical for informing considerations such as minimum crew sizes for fielding and transporting robots and test event scheduling requirements.

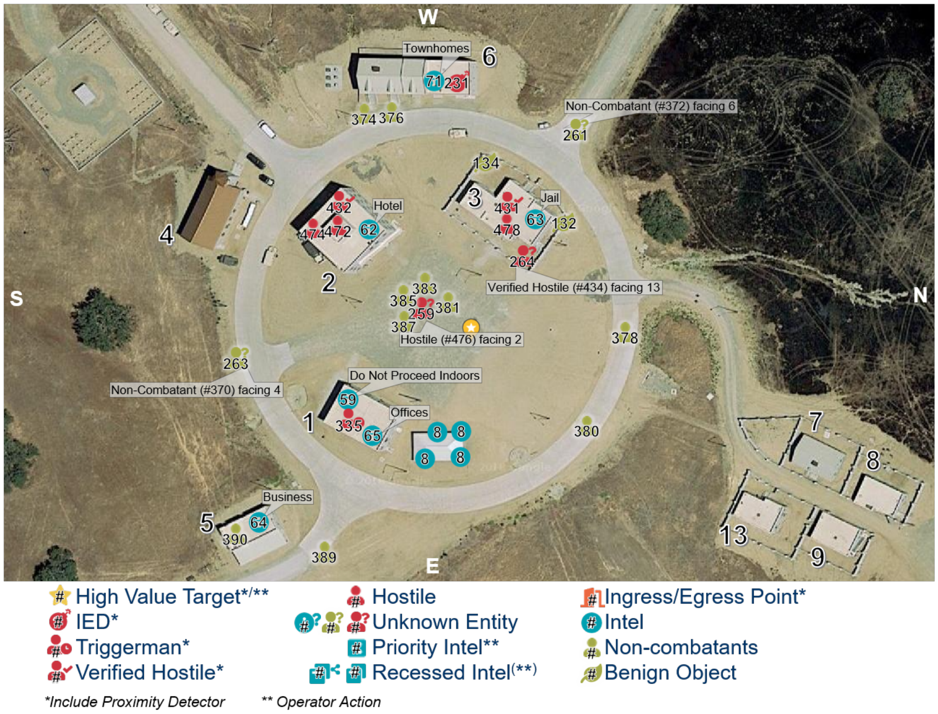


Figure 10. Overhead view and overlay of the FX-1 scenario at Camp Roberts, CA. FX-1 was conducted 22-25 October 2018.

4.2.2. FX-1: Camp Roberts, California

This inaugural capability test event occurred at the Combined Arms Collective Training Facility (CACTF) at Camp Roberts, California, and introduced the urban mission—isolating an urban objective—for Phase 1 of the OFFSET program, encompassing various wide-area surveillance and reconnaissance tasks. The test environment comprised 13 building structures, ranging from one to three stories, and offered a relatively compact area of operations (see Figure 10). The scenario comprised approximately 200 AprilTags with several hostile threats represented.

Key FX-1 Takeaways. This event accentuated the difficulty in operating in the real world, i.e., without validated ground truth data such as accurate elevation or detailed building geometry data, which impacted not only the configuration and fielding of the physical testbeds but also the fidelity of the virtual environments. In the former sense, the field test exposed the necessity and challenges of conducting field calibrations, with ramifications for safety systems (e.g., geofencing and building collision offsets). In the latter, teams had developed initial versions of their respective graphical user interfaces, but did not yet bring together sufficiently accurate geospatial models that could minimize disparity between the real and simulated environments. The teams realized that the ability to rapidly create, ingest, and integrate real-world representations in both field mission tools (e.g., swarm interfaces) and synthetic environments, as envisioned by the program, would greatly accelerate their field test readiness levels.

4.2.3. FX-2: Fort Benning, Georgia

This capability test event, conducted at the Selby CACTF at Fort Benning, Georgia, represented an expanded instance of the Phase 1 mission for isolating an urban objective. As visible in Figure 11, the scenario progressed from east to west, with the swarms required to transit and explore the full length of the test range to reach the primary mission objectives (i.e., western-most building with high concentration of representative hostile threats). With 15 buildings at this site and 315

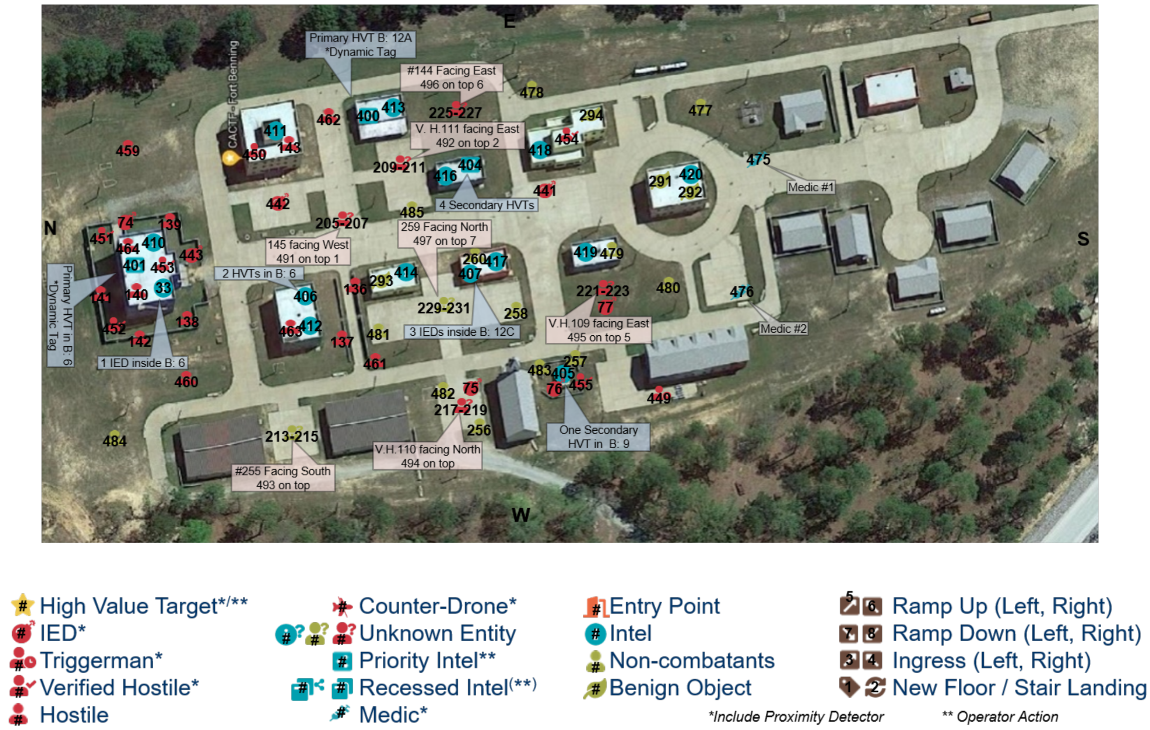


Figure 11. Overhead view and overlay of the FX-2 scenario at Fort Benning, GA. FX-2 was conducted 5-13 June 2019.

AprilTags emplaced throughout the area of operations, this test environment represented a slightly larger setting, which further demonstrated variability in the layout of the scenario objectives, leading to opportunities to explore alternative swarm deployment concepts.

Key FX-2 Takeaways. The increasing number of platforms accentuated known limits and unveiled new challenges of scaling to larger field operations, from logistics of transport and configuration to early lessons in swarm mission management and field safety procedures. Although initial concepts of operations deploying robots in a sequence of waves eased the observation and tracking of active platforms on range, subsequently having nearly all of the vehicles return home simultaneously (e.g., after collective return-to-launch (RTL) signals were sent at the end of the runs) showcased the increasing congestion of large-scale flight operations. The unpredictability of weather conditions, e.g., intermittent rain, also highlighted the need for agility and flexibility in the field for both the technologies, e.g., ability to rapidly change mission plans to accommodate uncertain test windows, and the field operations, e.g., ability to rapidly set up and/or recover deployed swarm platforms. Based off lessons learned from FX-0 to FX-2, the teams developed standard operating procedures for mission management, platform readiness checklists, and safety communication workflows to ensure consistency across the field operations team, which allowed them to operate with greater agility and flexibility.

4.2.4. FX-3: Camp Shelby, Mississippi

The initial test event for OFFSET Phase 2 represented the next evolution in urban missions, namely of conducting an urban raid, which required more precisely locating individual targets of interest within buildings and incentivizing both outdoor and indoor operations. This event took place at Camp Shelby, Mississippi, presenting 25 buildings in two sections (annotated in Figure 12) that offered teams a sequential progression of advancing their robotic teams through two distinct geographical styles of urban terrain. The scenario stressed the ability to conduct multiple phases of

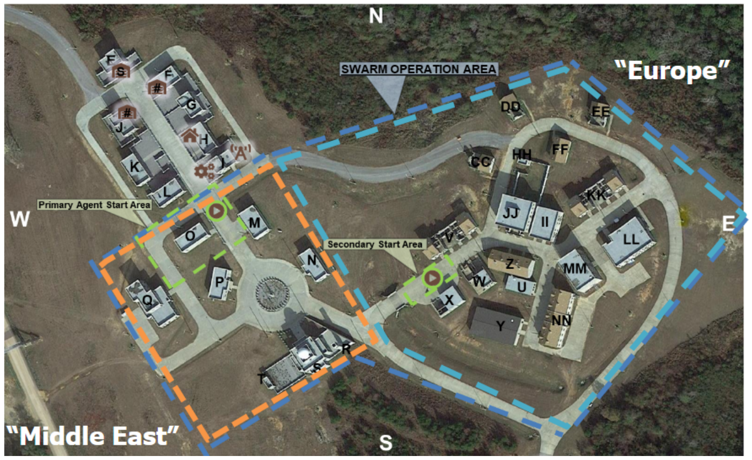


Figure 12. Map of the FX-3 area of operations at Camp Shelby, MS. The two distinct regions offered differing characteristics for building configurations and layout.

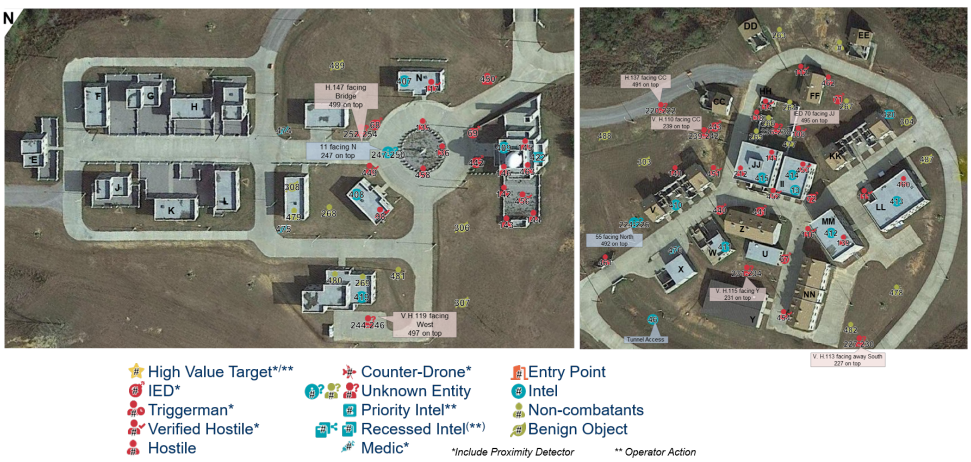


Figure 13. Overlay of the FX-3 scenario at Camp Shelby, MS. FX-3 was conducted 7-19 December 2019.

operations, either sequentially or concurrently, from reconnaissance to targeted operations around and within a building to route clearance activities (see Figure 13).

Key FX-3 Takeaways. The larger area of operations exacerbated the challenges of swarm networking, where limited connectivity drastically constrained the ability to execute, manage, and deploy collaborative behaviors. Inconsistent communications, in addition to the logistics of even larger fleet sizes, forced teams to consider alternative approaches to deployment and mission execution, including restaging vehicles to locations with known connectivity and allowing for coordination among subswarm members to happen even in the absence of connectivity back to the swarm commander. The scenario also reinforced the envisioned advantages of swarm systems, namely the ability to partition the swarm to simultaneously address different tasks to parallelize the operations. Highlighting the impact of environmental conditions for field robotics, the unexpectedly low temperatures substantively impacted field operations, such as increased variability in battery endurance, leading to further development of energy-aware considerations for designing swarm behaviors and conducting swarm missions. By this experiment the teams had personnel operating in the rapid field experimentation cadence for a year, which was a strength as area of operations, swarm size, and mission duration all increased.

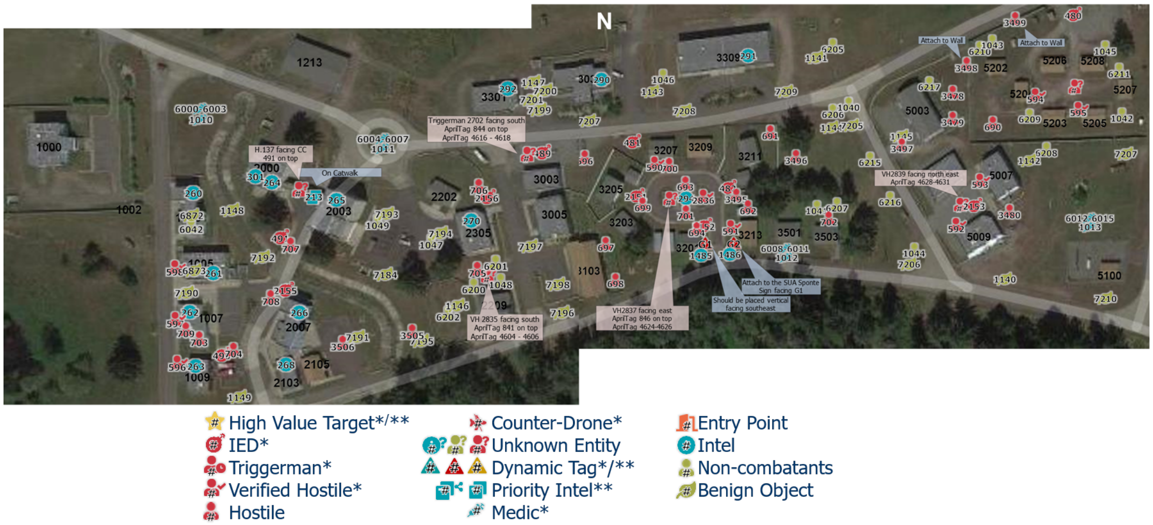


Figure 14. Overhead view and overlay of the FX-4 scenario at Joint Base Lewis-McChord, WA. FX-4 was conducted 20 July–12 August 2020.

4.2.5. FX-4: Joint Base Lewis-McChord, Washington

Conducted with safety considerations in mind, due to the nascent but concerning pandemic conditions, this fourth field test was conducted at the Leschi Town CACTF at Joint Base Lewis-McChord, Washington, which comprised 39 buildings and showcased overpasses and other unique structures (see Figure 14). As the culminating event for Phase 2, the teams demonstrated modified concepts of operations involving two distributed launch zones to aid in both expediting the setup of increasingly larger fleet sizes as well as promoting sufficient area coverage. This event also introduced fixed-wing aircraft capable of aggressive flight profiles in urban settings; dynamic AprilTags displayed on E-ink screens that could be time or event triggered; and synthetic technologies implemented in the live-virtual environments, e.g., swarm tactics leveraging models for see-through-wall sensors. These novel contributions informed further iteration of the swarm systems architectures.

Key FX-4 Takeaways. The performance of teams at FX-4 represented substantive improvements and better test readiness, despite teams having to learn how to develop and test remotely due to the pandemic. As expected, the personnel footprint necessary for conducting large-scale field operations was impacted by pandemic safety precautions, including spatially isolating different teams while still enabling successful test execution and communications. The teams' investments into their respective networking solutions, including the use of tactical LTE cellular base station and modems and commercially available mesh radios, allowed both teams to focus more on the swarm autonomy necessary to engage the mission scenario more substantively. This progression to a more mission-focused demonstration of swarm capabilities, aligned with the OFFSET program vision, allowed for teams to tie their specific technologies to swarm mission effects, such as enhanced persistent surveillance, increased detections of artifacts, and interplay between locating high-value artifacts and the swarm commander's decision-making processes.

4.2.6. FX-5: Canceled due to COVID-19

Given worsening pandemic conditions, and in the interest of the safety of all team members, FX-5 was canceled, and instead the focus was placed on increasing the capabilities of the virtual environment (described further in Section 4.3) to enable mission rehearsals and simulation analysis. The additional time also enabled further investments into reducing the accumulated technical debt due to the ambitious development schedule of the program.

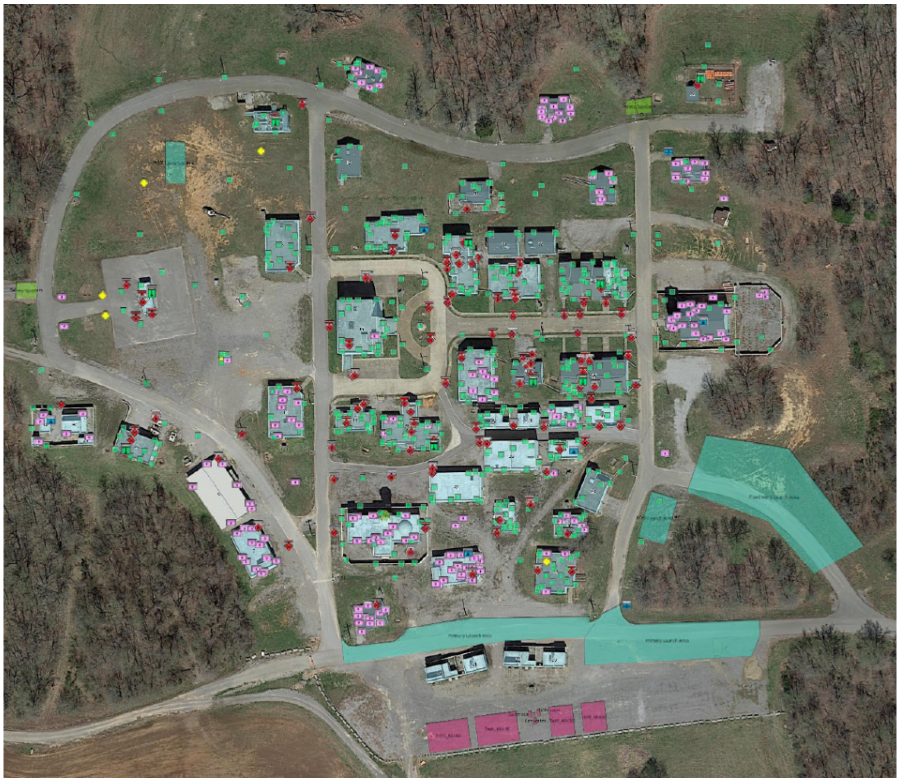


Figure 15. Overhead view and overlay of the FX-4 scenario at Cassidy CACTF, Fort Campbell, KY/TN. FX-6 was conducted 2-19 November 2021.

4.2.7. FX-6: Fort Campbell, Kentucky

As the culminating event for Phase 3 and the OFFSET program as a whole, the sixth field test was conducted at the Cassidy CACTF at Fort Campbell, Kentucky/Tennessee. Since it had been over a year since the teams last demonstrated their technologies, both teams were able to demonstrate both new and hardened swarm technologies. FX-6 served as a "capstone event" for the OFFSET program, which many government stakeholders and active-duty personnel attended to observe the state of the art in swarm systems capabilities. The operational environment at the Cassidy CACTF included 49 buildings, which provided both verticality and constrained spaces to install 1190 AprilTags, which can be seen in Figure 15. FX-6 also introduced the Swarm Sprinter–developed Hive-XL, a "drone carrier" trailer enabling up to 80 drones to be transported, charged, and automatically launched and recovered, and the introduction of live, virtual, constructive (LVC) simulation capabilities to further extend OFFSET capabilities.

FX-6 Results. As with all prior field test events, the OFFSET field experimentation team collected large volumes of swarm data, such as swarm telemetry and scenario interactions, and generated quantitative results of interest for swarm systems technology development. Figure 16 illustrates a summary plot for all experiment runs conducted for both Swarm Systems Integrators over the nearly two weeks of experimentation activities at FX-6. Shown in this chart, by team and by experiment run, are (a) the total number of swarm agent deployments (which includes agents that were recovered mid-run and redeployed) and (b) the number of unique agents deployed. As seen, teams were able to conduct swarm missions with consistent deployments of many dozen swarm platforms simultaneously, all under the management of the single swarm operator.

Figure 17 illustrates a time-evolution plot of the total number of swarm agent deployments for two representative experiment runs (one for each Swarm Systems Integrator team). Whereas one

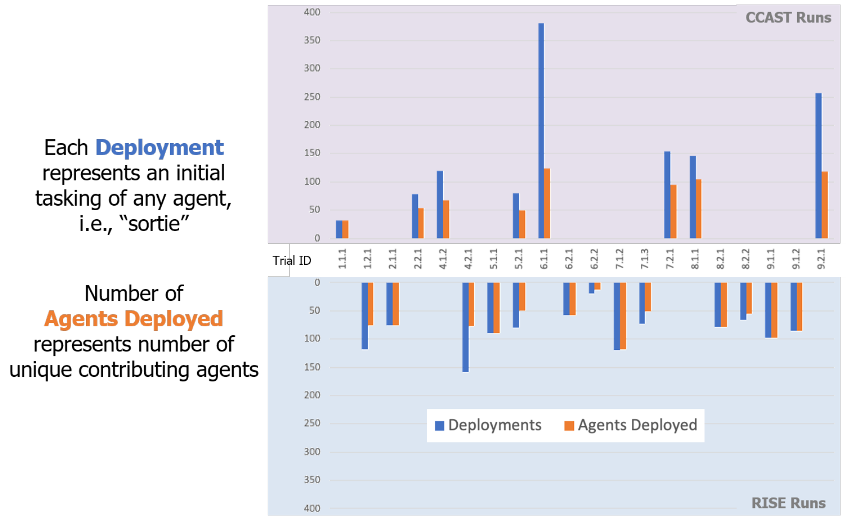
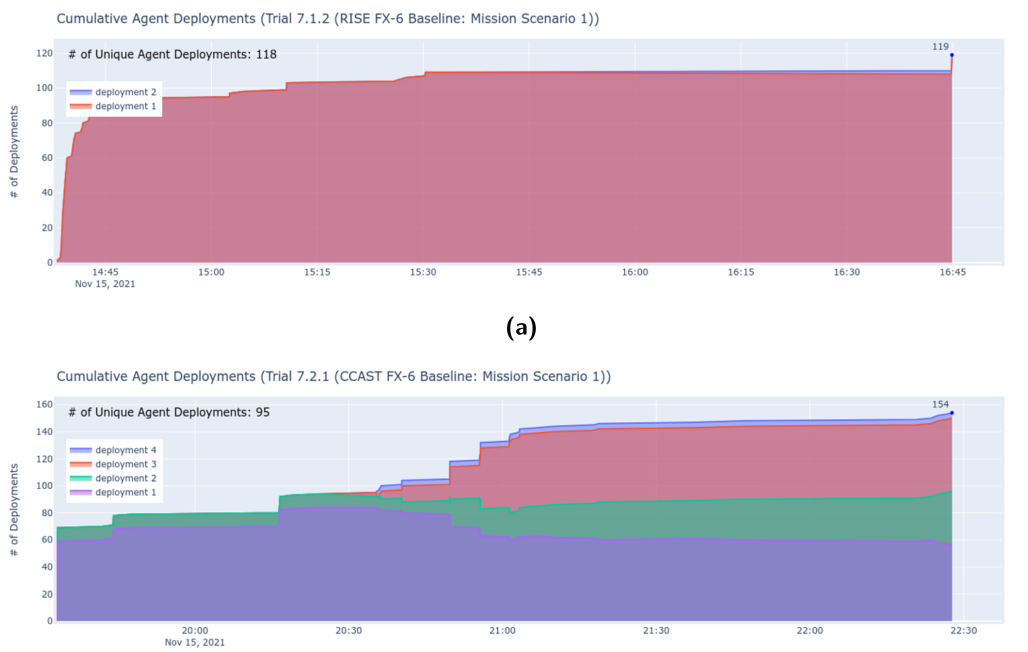


Figure 16. FX-6 experiment summary of the total number of swarm agent deployments and unique agent deployments, for each experiment run (indicated by trial id) for both Swarm Systems Integrators.



(a)

(b)

Figure 17. Exemplar plots of the total number of swarm agent deployments as a function of time. The number of unique swarm agent deployments is also indicated. These plots illustrate the differences in operational concepts, including (a) massive instantaneous launch at the start of the run, versus (b) phased launches with recovery and relaunch of swarm platforms.

team opted to rapidly launch en masse at the beginning of the run and conducted the mission with their fixed set of deployed swarm platforms, the other team conducted a staggered approach with waves of deployments, including the recovery and subsequent redeployment of swarm assets.

One metric that can be extracted from these charts is a team's *swarm power generation rate*, which addresses how quickly a swarm can be amassed. Pertinent to the swarm commander's mission priorities, such a metric can inform how long the swarm can be sustained at a given force strength level, as well as how many platforms are needed in reserve to meet those numbers to replenish depleted and/or attrited swarm assets.

One of the highlights of FX-6 occurred on the final day of experimentation runs, where both teams operated their swarms *simultaneously* for collaborative execution of the mission scenario. The area of operations was divided into two sections, allowing for both teams' respective swarms to deconflict their operations. Additional enhancements to the field experimentation infrastructure enabled shared situational awareness where, despite different message formats and software interfaces, swarm telemetry could be translated and provided to each other's swarm commander interfaces. This ad hoc success further highlighted both the extensibility of the swarm systems architectures to address a novel use case, but also suggested a future mode of operations where multiple swarms could potentially be employed concurrently.

Of the 301 platforms ready and available for use during the Joint Exercise Shift, the results of the deployments are shown in Figure 18. As visualized in the heatmap in Figure 19, the number of swarm agents effectively covered the entire area of operations.

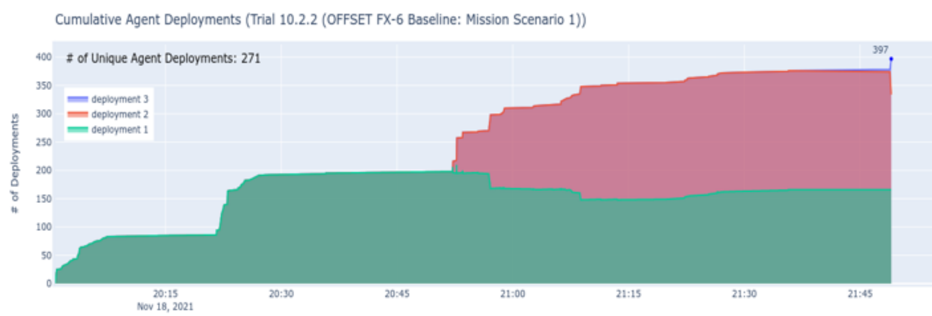


Figure 18. Swarm deployments over time during joint shift.

Figure 19. Heatmap of swarm activity and area coverage during joint shift.

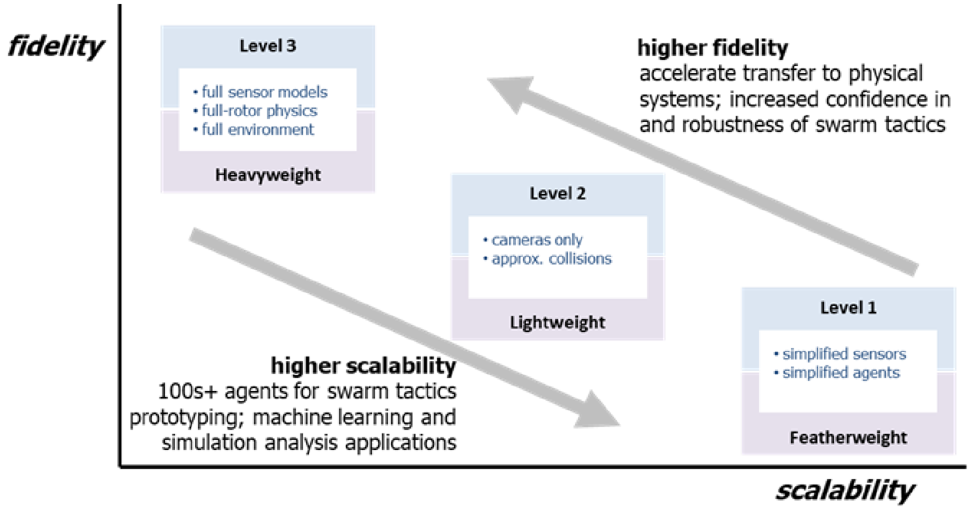


Figure 20. Multiple levels of fidelity are required to enable sufficient fidelity and scale for swarm simulation. The OFFSET teams had similar approaches to levels of fidelity, with one team denoting the various levels as heavyweight, lightweight, and featherweight (shown in purple), and the other team denoting their levels as Level 1, Level 2, and Level 3 (shown in blue).

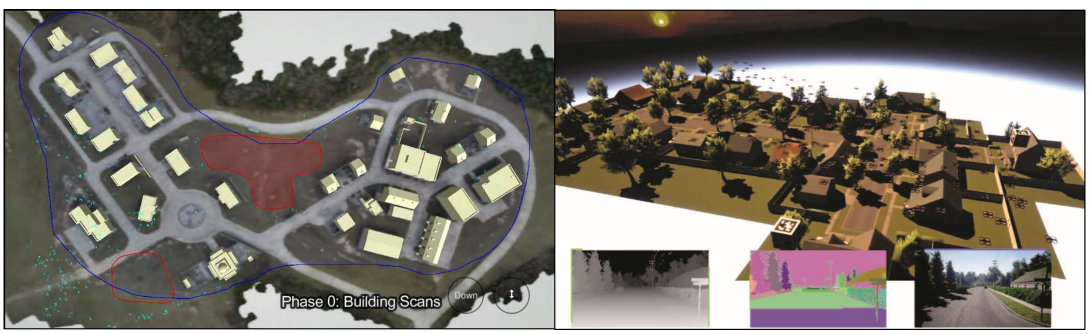


Figure 21. Screenshots of OFFSET scalable swarm simulation environments, implemented by the two Swarm Systems Integrators in Unity3D (left) and UnrealEngine-based Microsoft AirSim (Shah et al., 2018) (right).

4.3. Role of Virtual Capabilities

Both teams invested in the development of game-based virtual environments with multiple levels of simulation fidelity in order to test, debug, and evaluate swarms at scale (Clark et al., 2021). Both teams had developed simulators with varying levels of fidelity (i.e., allowing higher fidelity, or higher scalability). These levels of simulation, and their associated tradeoffs, are depicted in Figure 20.

An example use case for using a high-fidelity simulation would be to leverage simulated sensor streams at the agent level. A low-fidelity simulation would opt to bypass the sensor-level data, reducing the computation resources required, allowing for an increased number of simulated swarm agents. Screenshots of each team's simulation are shown in Figure 21.

At FX-6, the virtual environments allowed teams to rehearse missions, interact with the test environment by using preexisting map models and/or 3D meshes derived from photogrammetry scans, and simulate the mission scenario to develop new and optimized strategies for execution. Another benefit was the ability of the field experimentation team to provide a virtual version of the mission scenario in advance (i.e., for integration and practice prior to physical experimentation) and as a mirror (i.e., status of scenario elements in the real world to match the simulated "digital twin") to the physical experiment.

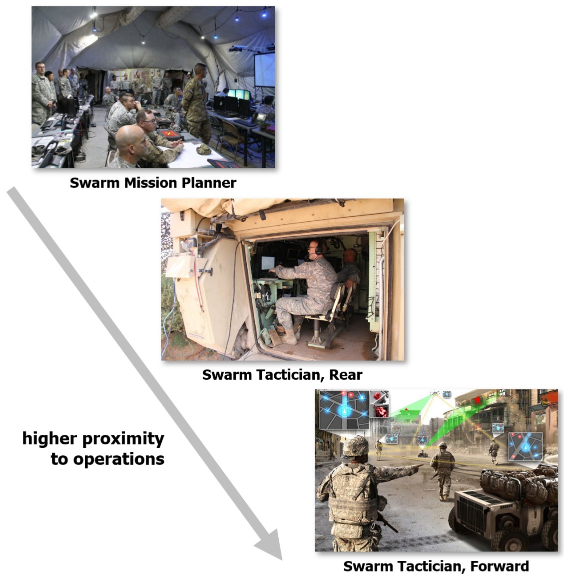


Figure 22. OFFSET identified three different "swarm personas" that could require different interactions (e.g., swarm tactics) and interfaces (e.g., input devices for command and output devices for swarm feedback) based on proximity to operations.

4.4. Human-Swarm Teaming at Scale

Both teams designed intuitive and immersive swarm interfaces by leveraging multimodal, mixed-reality, and interactive technologies to address the complexity of the swarm systems as well as the cognitive, physical, and contextual needs of human teammates or tacticians when conducting urban operations. Early in the program, the two teams each identified a primary swarm interface; one team designed an immersive virtual reality environment, whereas the other team designed a lightweight sketch-based interface for tablet or laptop. As the program progressed and based on iterative engagements with stakeholders and end users, it became more evident that there would not be a "one-size-fits-all" solution. To further refine the diverse needs in operationally relevant human-swarm interaction, the OFFSET program identified and defined three different "swarm personas" (see also Figure 22) that are relevant for human-swarm teaming considerations:

- **Swarm mission planner.** This user composes and assesses swarm tactics for execution of a future mission, utilizing available intelligence and using simulations to inform and explore anticipated evolutions of the mission and their likelihoods of achieving desired mission objectives.
- **Swarm tactician, rear.** This user is engaged in real-time and dynamic execution of swarm tactics during actual operations, and is situated in a protected and/or remote location (e.g., battalion headquarters or inside an armored command vehicle) away from the area of operations.
- **Swarm tactician, forward.** This user is engaged in real-time and dynamic execution of swarm tactics during actual operations, and is physically present in the area of operations amidst units and the autonomous swarm conducting the mission, and is thereby required to interact with the swarm from within the combat environment.

While a swarm mission planner could benefit from a top-down view with complete command of all swarm assets, a swarm tactician, forward, might need to have more contextual situational awareness and command over a smaller subswarm. Teams developed and expanded the use of different swarm interfaces that operate seamlessly with the OFFSET architecture, a sample of which is shown in Figure 23. Teams also ensured their systems could operate with widely used

Figure 23. Examples of the immersive swarm interfaces developed in the OFFSET program.

government-off-the-shelf (GOTS) products such as the Android Team Awareness Kit (ATAK). By FX-6, OFFSET demonstrated the feasibility for a single swarm operator to simultaneously manage a swarm of over 200 robots though the use of advanced, interactive, and immersive swarm interfaces. Both teams collected quantitative (e.g., operator workload statistics) and qualitative data (e.g., end-user feedback) on their interfaces for further analysis and respective insights.

5. OFFSET Lessons Learned

The OFFSET program demonstrated numerous novel swarm technologies and capabilities, and also showcased the payoffs (and challenges) of an unconventional program structure designed to foster rapid iteration and innovation for such advances. Over the course of the program, several consistent themes emerged and were repeatedly validated through the field experimentation events, Swarm Sprint integration activities, and research and development processes. This section summarizes those lessons learned as a potential framework for future investigations or investments into advancing swarm systems capabilities.

Lesson 1: Collaborative autonomy is contingent on agent autonomy

The advantage of swarm systems arises from the collective capabilities aggregated across multiple agents and, as such, the extent to which sophisticated or advanced swarm autonomy can be achieved is tied to the capabilities and autonomy levels of the individual agents. In other words, while the primary premise for swarm systems is that the whole is greater than the sum of its parts, it is also true that if the "parts" (i.e., the individual agents) are more capable, then the upper bound of what the "whole" (i.e., the swarm) is capable of will also be greater.

For example, many of the early demonstrations of swarm tactics largely focused on spatial area coverage and sensor placement, decomposing the area of operations and deconflicting trajectories to primarily maximize exterior (i.e., outdoor) situational awareness. However, the urban missions of interest to OFFSET intentionally required directed interactions with representative threats in the scenario as well as deliberate decision making and maneuver in confined spaces. These complex logical and physical tasks were challenging due to the limitations of individual robots' capabilities.

Difficulties with basic navigation over uneven terrain or GPS-less maneuver into and within buildings at the individual-robot level impeded deeper explorations of the collective benefits of having teams work collaboratively in those settings.

Lesson 2: Hardware integration at swarm scales is especially a challenge

The astonishing pace of turnover in commercially available robotics technologies, including platforms, sensors, and computation, as well as rapid advances in autonomy algorithms available through open-source software, were found to be challenging, even having been anticipated and embraced by the OFFSET program structure. In particular, numerous platforms (e.g., 3DR Solo, Intel Aero) that were available at the start of OFFSET were ended by their manufacturers mid-program, leading to shortages of both replacement drones and parts and requiring continuous search for alternatives. It was thus imperative that both the field teams and swarm systems architectures were flexible enough to (a) integrate new hardware (i.e., provisioning, check-out testing) as seamlessly as possible, and (b) incorporate the resulting heterogeneity in platforms and capabilities into the design and execution of swarm tactics.

Additionally, given the swarm scales of interest, the sustainment and maintenance requirements were difficult, especially for prototype research and development teams, since any single modification, fix, or update would likely necessarily need to be promulgated to large numbers of swarm vehicles. Similarly, due to supply chain limitations for large-quantity requirements, teams faced challenges in sourcing sufficient numbers of components from otherwise small-sized vendors, leading to different hardware configurations or setup procedures as well as the need for configuration management tracking. These lessons were instrumental for not only incentivizing and innovating efficient solutions, but also exposed teams to the anticipated challenges faced when designing for (large-scale) production systems (in contrast to their more familiar one-off research and development activities).

Lesson 3: Having a program structure that specifically requires frequent and varied integration touch points is critical but hard

Agile swarm experimentation requires agile program management. In order to establish the six-month design-build-test-learn cycle, the OFFSET program team was challenged to maintain a tightly coordinated project plan while remaining flexible to address unforeseen disruptions, e.g., a global pandemic.

As a lesson learned, one of the most demanding elements of this program structure was the coordinated management of Swarm Sprinter activities. While one set of Swarm Sprinters was integrating into the OFFSET swarm systems architectures as part of the current Swarm Sprint, the next cohort of performers was commencing their contract periods of performance, and prospective Swarm Sprinters were seeking information in anticipation of the upcoming Swarm Sprint solicitation.

Lesson 4: Swarm field logistics plays an outsized role in defining swarm concepts of operations

When envisioning autonomy development for small-unit use cases, research and development efforts for single- or few-robot systems have largely focused on tactical employment, given the nominally smaller logistics footprint. However, with the advent of swarm systems employed at small-unit (i.e., fewer personnel) tactical levels, the concepts of operations of how the swarm systems are deployed and employed are significantly impacted by logistical considerations, perhaps more typical of larger operations, e.g., at higher echelons of command such as brigade levels and above. The manner in which swarm field logistics dramatically influences mission planning and execution also necessarily alters the modeling and algorithmic approaches for developing new swarm tactics. Said another way, the classes of swarm tactics designed for the OFFSET program were coupled with and optimized under particular field logistics constraints, such as small field operations teams, (aerial) platform endurance limits, and minimalist onboard capabilities (e.g., achievable GPS precision). New approaches for fielding swarm systems (e.g., self-servicing and/or -recovering robots, “mothership” mobile host delivery platforms, novel energy solutions) could unlock innovation of entirely new categories of swarm tactics, given the outsized influence of the swarm logistics. For example, OFFSET explored the mobile host delivery platform concept with the Hive-XL developed by Sentien Robotics under the Swarm Sprint 5 effort. The standard OFFSET swarm field logistics and deployment methodology was to stage all platforms simultaneously, which allowed the swarm to rapidly generate mass and support surge operations (e.g., over 100 platforms deployed in less than five minutes). The Hive-XL, which enabled centralized launch, charge, and recovery of 80 heterogeneous UAVs, provided sustainment support over longer missions (over 2 hours) to the swarm while requiring a smaller logistics footprint. While the swarm field logistics and deployment tradeoffs were explored, there remain significant opportunities to expand the initial work conducted within the OFFSET program into broader potential mission settings.

6. Recommendations

A positive outcome of the OFFSET program has been the distillation of various experiences and insights, as summarized in Section 5, to inform near-term future opportunities to further accelerate the development of swarm systems technologies. We provide a number of recommendations in this section to highlight areas for investment and/or partnerships (e.g., with the government) that would help overcome existing constraints to achieve the next level of swarm capabilities.

Recommendation 1: Identify and/or increase access to at-scale physical test environments to enable and enhance field-hardened swarm systems technologies

The tightly intertwined nature of field operations and swarm logistics with the design and implementation of swarm autonomy, e.g., swarm deployment and employment concepts, significantly illustrates the value of conducting field tests in representative environments at operationally relevant scales and settings. Whereas using this active feedback loop of in-the-field experience would greatly accelerate the early design of swarm tactics and swarm mission capabilities, failing to do so, i.e., designing swarm algorithms in the absence of frequent and realistic field contexts, would significantly exacerbate downstream fielding of these technologies. Recognizing the general difficulty in gaining access to military test facilities such as those utilized during the OFFSET field tests, opportunities to establish closer partnerships between government and research organizations (e.g., universities, small businesses) would offer immense value to the expedited development of these advanced technologies.

Recommendation 2: Invest in expanding the operational utility of commercially available ground and aerial robots

The OFFSET program afforded the opportunity to establish and calibrate a baseline of achievable swarm capabilities with the available aerial and ground platforms utilized. This point of departure demonstrates the extent of the missions that could be addressed with existing low-cost systems, but, more importantly, OFFSET's extensible swarm systems architecture and scalable swarm simulation environments can directly offer insights into how more capable systems can dramatically enhance future swarm capabilities.

However, in order to achieve the next available level of platforms with increased autonomy, perception, and mobility capabilities, there is a significant cost and complexity increase, which may limit the viability of large-scale teams. In this manner, future investment in the design of a middle class of platforms, tailored for large-rate production but with more capable features, would offer a potential opportunity to enable enhanced swarm capabilities currently absent from the commercial market.

Recommendation 3: Investigate novel software and hardware solutions to enhance swarm fleet reliability and to streamline swarm logistics

The ability to rapidly provision, diagnose, and register swarm agent(s) to provide reliable fleet awareness, e.g., to alert swarm commander or field personnel and/or to automatically identify impacts to swarm mission plans and update alternate courses of action, would offer significant speedups in preparing for and addressing issues with swarm systems status. While present-day IT solutions, e.g., internet-of-things-style software, may offer some limited capabilities for monitoring, the intermittent and unreliable communications with swarm assets poses additional difficulty. Further, the ability to collectively troubleshoot among members of the swarm, e.g., using a teammate's sensors to automatically identify any visual indicators or issues or mismatches in expected behaviors or trajectories to determine anomalies in swarm logic, could be a future enabler for reliable swarm operations. Additional explorations into novel hardware-based solutions to enhance swarm logistics, including remote battery charging or mobile servicing robots to emplace or recover swarm assets in predesignated launch zones, could offer creative ways to alleviate the personnel and/or time burden, which would all improve and influence the utility of these swarm systems technologies.

7. The OFFSET Ecosystem

Swarm systems, including experimental testbeds and simulation-based studies, have long fascinated the robotics and autonomous systems community, leading to significant research efforts and resources invested to explore, model, and understand the complexity in the design and application of swarm robotic systems. This increasingly maturing body of swarm systems research, as well as significant advances in available technologies, continues to accelerate advances in swarm autonomy as well as further accentuate the role of human-swarm interaction. Opportunities in field robotics to extend these efforts to complex unstructured environments (as opposed to indoor, laboratory, or instrumented settings) and challenging multifaceted mission scenarios (such as urban combat operations) will continue the progression towards highly resilient, more capable, and field-hardened technologies and capabilities.

As Swarm Systems Integrators and multiple cohorts of Swarm Sprinters collaborated significantly to advance the state of the art in swarm systems capabilities, many valuable contributions have arisen from the myriad of performers involved in the OFFSET program. The diversity of these contributions is noteworthy, highlighting both the breadth and depth of opportunities. An exemplar (not exhaustive) list of OFFSET contributions includes the following:

- **Formal methods-based approaches for collective behaviors** (Moarref and Kress-Gazit, 2017). Developed software for the automated synthesis and verification of high-level autonomy specifications by utilizing recent work and advances in linear temporal logic (LTL) formulations for collective systems.
- **Ergodic control approaches for enhanced human-swarm interactions** (Prabhakar et al., 2020). Demonstrated successful integration with SSIs at FX-3 by executing commands on their novel haptic tablet interface, which sent commands to swarm agents based on decentralized ergodic coverage trajectories.
- **Neuroevolutionary approaches for learning swarm tactics** (Behjat et al., 2021). Developed a novel multistage AI framework using neuroevolution, driven by flexible learning mechanisms and environment enhancements that together enabled systematic escalation of robustness in designing and evaluating swarm tactics.
- **Scalable simulation and algorithms for collision avoidance in urban scenes** (Arul et al., 2019). Addressed realistic considerations for conducting wide-area surveillance in urban areas, such as collision avoidance, and developed an approach to efficiently compute collision avoidance for large-scale swarms.
- **Wireless emitter localization swarm algorithms** (Sauter et al., 2020). Developed swarm algorithms for multiple agents equipped with radio-frequency (RF) receivers to efficiently search and collaboratively maneuver to identify and locate RF emitters, such as Bluetooth beacons.
- **RF modeling and simulation for aerial robots** (Kitchen et al., 2020). Developed exterior building scanning patterns using emulated onboard radar to conduct see-through-wall sensing search of multifloor buildings for human presence and/or moving human detection.

- **Swarm battery management** (Diehl and Adams, 2021). Provided an automated agent-swap tactic based on battery life, which tasked agents at low battery levels to be automatically relieved by an agent with full battery on standby to complete a given swarm task.
- **Transformable wheel and leg ground mobility design** (Lee, 2021). Developed a proof-of-concept prototype for OFFSET-scale UGVs with novel passive transformable wheel designs for agile and versatile locomotion.
- **Agile fixed-wing flight with onboard sensing** (Polevoy et al., 2022). Demonstrated aerobatic fixed-wing aircraft conducting onboard flight control, navigation, and perception, integrated into the larger OFFSET swarm at FX-6 to conduct high-speed aggressive maneuvering around urban structures.
- **Multi-UAS transport, stowage, deployment, and recovery platform** (Sentien Robotics, 2022). Constructed a Hive-XL prototype capable of automated launch, recovery, and recharge of 80 heterogenous UAVs. Three additional Hive-ISO units, with the form factor of standard shipping containers, were also developed and demonstrated at FX-6.
- **Human factors for swarm control applications** (Miller et al., 2020). Investigated the complexity and challenges in human-swarm teaming, including design of visual markers and other tools to address the increased scale of swarm operations of interest to OFFSET.

At its conclusion, OFFSET produced two complementary exemplars of advanced swarm systems, each comprising a demonstrated swarm software architecture with implementation of swarm tactics and advanced swarm interfaces, a physical swarm system testbed for substantive experimentation and operationalization, and a deep understanding of how to foster a robust developer and user community for enduring engagement in the advancement of swarm system capabilities. Additional specific contributions of the OFFSET program are further detailed in and deferred to respective papers by the extensive family of OFFSET performers.

The aggregate impact of OFFSET is highlighted by the insights derived from the OFFSET program that have informed not only the technological trade spaces of swarm systems design, but also, and more broadly, the scalability of human-machine teaming constructs, test and evaluation for autonomous systems, and open system architectures for distributed, networked capabilities.

8. Conclusions

While many technical challenges remain to fully realize the envisioned benefits of swarm systems in operational contexts, the OFFSET program offered both development and demonstration opportunities in novel ways, including tightly coupling physical and virtual experimentation and introducing new "third-party" technologies through the program's Swarm Sprint integration model. Future collaborators and stakeholders will and have already benefited from the program incorporating integration of these technologies. The prioritization of frequent real-world testing, with the progression of more challenging and larger-scale mission-focused objectives, was successful in developing "minimally viable" swarm capabilities that can be demonstrated in complex urban environments. As such, the OFFSET program offered significant insights and transitioned technologies into nearer-term capabilities of interest to the Department of Defense while also cultivating an ecosystem for future development.

Numerous opportunities for continued advances exist in developing more resilient swarm systems capabilities, including the additional areas of swarm logistics, swarm perception, and swarm networking (as referenced in Figure 1). The ability to rapidly provision, diagnose, and register swarm agents to provide reliable fleet awareness would greatly enhance pre-mission readiness, and further explorations into novel hardware-based solutions, such as wireless battery charging or mobile servicing robots to emplace or recover agents, could offer creative ways to alleviate the logistical personnel and/or time burden. Future abilities to aggregate heterogeneous sources of information to provide a "swarm-based" common operational picture could utilize emerging machine learning–based approaches for situational inference; alternatively, considering introspective applications of swarm perception may enable collective troubleshooting among members of the swarm, e.g., using a teammate's sensors to automatically identify any indicators or mismatches in expected behaviors or trajectories to self-heal any anomalies. Further, while present-day networking technologies, e.g., commercially available mesh radios or LTE-based cellular modems, may offer interim solutions, future swarm networking capabilities for secure, private, and resilient information sharing among swarm agents will undoubtedly be critical for operating in disrupted or denied environments.

Given DARPA's mission to anticipate technological surprise, the OFFSET program accelerated and demonstrated the viability and effectiveness of swarm systems technologies. OFFSET will continue to provide an impactful platform for the development of future swarm systems capabilities, but, perhaps even more importantly, OFFSET's programmatic and technical approach can further serve as a valuable resource and model for the Department of Defense and the broader robotics community.

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References

Arquilla, J. and Ronfeldt, D. (2000). *Swarming and the Future of Conflict.* RAND Corporation, Santa Monica, CA.

Arul, S. H., Sathyamoorthy, A. J., Patel, S., Otte, M., Xu, H., Lin, M. C., and Manocha, D. (2019). LSwarm: Efficient collision avoidance for large swarms with coverage constraints in complex urban scenes. *IEEE Robotics and Automation Letters*, 4(4):3940–3947.

Behjat, A., Manjunatha, H., Kumar, P. K., Jani, A., Collins, L., Ghassemi, P., Distefano, J., Doermann, D., Dantu, K., Esfahani, E., et al. (2021). Learning robot swarm tactics over complex adversarial environments. In *2021 International Symposium on Multi-Robot and Multi-Agent Systems (MRS)*, pages 83–91. IEEE.

Clark, S., Usbeck, K., Diller, D., and Schantz, R. E. (2021). CCAST: A framework and practical deployment of heterogeneous unmanned system swarms. *GetMobile: Mobile Computing and Communications*, 24(4):17–26.

DARPA (2017). OFFensive Swarm-Enabled Tactics (OFFSET) Broad Agency Announcement. BAA# HR001117S0011.

DARPA (2021a). OFFensive Swarm-Enabled Tactics (OFFSET) Program Website. https://www.darpa.mil/program/offensive-swarm-enabled-tactics.

DARPA (2021b). OFFensive Swarm-Enabled Tactics (OFFSET) Work-with-Us Website. http://www.darpa.mil/work-with-us/offensive-swarm-enabled-tactics.

David, R. A. and Nielsen, P. (2016). Defense science board summer study on autonomy. Technical report, Defense Science Board, Washington, DC.

Diehl, G. and Adams, J. A. (2021). Battery variability management for swarms. In *International Symposium on Distributed Autonomous Robotic Systems*, pages 214–226. Springer.

Kitchen, S., Chase, R., Sauter, J., and Bixler, K. (2020). Simulated RF environments for UAV-mounted Bluetooth 5.0 receivers. In *Unmanned Systems Technology XXII*, volume 11425, page 114250C. International Society for Optics and Photonics.

Krogius, M., Haggenmiller, A., and Olson, E. (2019). Flexible layouts for fiducial tags. In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 1898–1903. IEEE.

Lee, K. (2021). Transformable wheel and leg assembly. U.S. Patent App. 17/233,754.

Miller, C. A., Adams, J., Clark, S. S., Kane, S., Roundtree, K., and Walker, P. (2020). Human factors issues and challenges in research on "many-agent" control applications. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 64, pages 324–328. SAGE Publications: Los Angeles, CA.

Moarref, S. and Kress-Gazit, H. (2017). Decentralized control of robotic swarms from high-level temporal logic specifications. In *2017 International Symposium on Multi-robot and Multi-agent Systems (MRS)*, pages 17–23. IEEE.

Olson, E. (2011). AprilTag: A robust and flexible visual fiducial system. In *2011 IEEE International Conference on Robotics and Automation*, pages 3400–3407. IEEE.

Polevoy, A., Basescu, M., Scheuer, L., and Moore, J. (2022). Post-stall navigation with fixed-wing UAVs using onboard vision. *arXiv preprint arXiv:2201.01186*.

Prabhakar, A., Abraham, I., Taylor, A., Schlafly, M., Popovic, K., Diniz, G., Teich, B., Simidchieva, B., Clark, S., and Murphey, T. (2020). Ergodic specifications for flexible swarm control: From user commands to persistent adaptation. In *Robotics Science and Systems 2020*.

Sauter, J. A., Bixler, K., Kitchen, S., and Chase, R. (2020). RF emitter localization with robotic swarms. In *Unmanned Systems Technology XXII*, volume 11425, page 114250D. International Society for Optics and Photonics.

Scharre, P. (2018). How swarming will change warfare. *Bulletin of the Atomic Scientists*, 74(6):385–389.

Sentien Robotics. (2022). Sentien Robotics HIVE-XL UAS Fleet Launch, Recovery, and Recharge. https://www.sentien.com/hive-xl.

Shah, S., Dey, D., Lovett, C., and Kapoor, A. (2018). AirSim: High-fidelity visual and physical simulation for autonomous vehicles. In *Field and Service Robotics*, pages 621–635. Springer.

U.S. Marine Corps. (2018). Military operations on urbanized terrain (MOUT) MCRP 12-10b.1 (formerly MCWP 3-35.3). https://www.marines.mil/Portals/1/Publications/MCRP%2012-10B.1%20GN.pdf?ver=2020-02-12-121429-267.

Wang, J. and Olson, E. (2016). AprilTag 2: Efficient and robust fiducial detection. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 4193–4198. IEEE.

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