A Framework for Integrating the Development of Swarm Unmanned Aerial System Doctrine and Design

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ABSTRACT

Unmanned Aerial System doctrine has been lacking, latent, or ignored as a prescribing design element in the emerging field of swarm technology. In this paper, an integrated methodology for designing a swarm unmanned aerial system (UAS) in parallel with swarm UAS mission doctrine is discussed. The structure of this methodology is derived from heuristics from the model-based systems engineering, robotics, human systems integration, biology, and computer science disciplines. The methodology provides a standard approach for designing and operating swarm UAS that seeks to meet the performance and doctrine requirements for any intended mission.

1.0 INTRODUCTION

There has been an increased interest in swarm technology over the last two decades. Much of this can be attributed to the dynamic field of unmanned systems technology, which has been rapidly developing in both the government and private sector. Unmanned system technology has expanded from physically hazardous, high-altitude, extended-endurance military missions to agriculture, mining, search and rescue, and environmental research civilian and commercial missions (USDOD 2013). Unmanned systems provide many advantages over manned systems. In the case of UAS, they are less constrained by human factors such as crew rest, G-tolerance, environmental conditions, and comfort. Unmanned systems can be expendable and could have lower life-cycle costs than manned systems; however, low system reliability (Finn 2010), low technology readiness levels, large logistical footprints, and an ironic increased manpower requirement have marginalized cost advantages. Likewise, unmanned systems' test and evaluation struggles, and poor track record for meeting operational effectiveness and suitability requirements have historically also contributed to higher system lifecycle costs.

To produce mission-effective systems, system architects must consider the doctrine, design, and planned assessment methodologies when developing a swarm UAS. Swarm technology is evolving faster than the techniques and test scenarios used to assess them. There will be an increased dependency on modeling and simulation for testing these systems that was not as critically vital in manned aircraft or single UAV system testing. Previously used rapid fielding strategies for remotely piloted UAS incur too much risk for swarm UAS, which may, by design, exhibit stochastic emergent behavior. The applications of swarm technology to unmanned systems are in the infancy of realization, although clear benefits from the enhanced capabilities can be envisioned for military missions: persistent search, long-term monitoring, sensor data collection, distributed networks, object retrieval, and offensive attack missions. How these swarmed unmanned systems will be integrated with singular unmanned systems and manned systems, and for which missions they are best suited is not well established. The revolutionary impact to future military capabilities maybe beyond imagination at this point, but not beyond the technological horizon enabling them.

2.0 BACKGROUND

Swarm robotics is the "study of how large numbers of relatively simple, physically embodied agents can be designed such that a desired collective behavior emerges from the local interactions among agents and between the agents and the environment" (Sahin 2005). Swarm technology derives impetus from biology. Large numbers of individuals such as birds, fish or insects may collectively work together to accomplish useful tasks that cannot be completed by an individual or any group of non-cooperative individuals. Members of the swarm may be non-intelligent and inefficient on an individual scale, yet emergent behavior arising from interactions between the individual agents enables advantages such as robustness, flexibility, and scalability (Sahin 2005). It is the local interactions among the agents and between the agents and their environment that may elicit beneficial collective behavior (Sahin 2005). When a multiple agent system performs a task that increases the total utility of the system, it has then accomplished cooperative behavior, which is a subset of collective behavior (Cao 1997). For the purpose of this paper, a swarm will be defined as a group of at least 50 individual, self-organized, homogeneous unmanned air vehicles (UAVs) that perform a mission through local interactions (Beni and Wang 1993, Beni 2005).

Key enabling technologies to swarm UAS development include improved communication networks, cost effective miniaturization of electronics, and automation. Swarm UAS must communicate for safety (sense-and-avoid, intra-swarm collision avoidance), managing the sensor payload, and monitoring health status. Communication must be timely. Meshed ad-hoc network architectures, where the network nodes self-organize their forward-relay capabilities, have shown promise in minimizing frequency spectrum and bandwidth conflicts and providing reliability and flexibility in swarm UAS communication (Frew 2008, Chung et al. 2013). Miniaturization of electronics including radio receivers, GPS, video cameras, and autopilot processors has made UAS swarm agents smaller, lighter and more capable. The dramatic drop in cost and increase in availability of these components have made swarm UAS affordable. These trends are likely to continue.

To progress from remotely piloted UAS to remotely directed swarm UAS, automation must be incorporated into the design architecture. Automation allows offloading tasks previously accomplished by humans, to the mechanical vehicle, or agent. Human Swarm Integration (HSwI), an application of Human Systems Integration (HSI) to swarms, is an amalgamation of robotics, biology, computer science, and experimental psychology. The way in which humans supervise, control, and intervene with swarms may be different from how they can interact with just one or two agents (Harriott 2014). Swarm operation demands the operator to assume a supervisory role at the macroscopic level, yet selectively focus some awareness at the individual vehicle level. There have been many studies (Cummings 2004, Cummings and Mitchell 2006, 2007) conducted regarding HSI for operating a single directed UAV and multiple directed UAVs, which show automation is usually advantageous for vehicle control and navigation. Cummings and Mitchell (2007) characterize unmanned supervisory control as a "nested control loop problem" where the critical inner loop covers basic vehicle guidance, the middle loop represents navigation, and the outer loop encompasses the payload and mission management. Incorporating automation into the inner and middle loops reduce workload of piloting and allows for more mission level management and decision-making. There has been little automation or HSwI research conducted on large numbers (50) of vehicles.

In response to the urgent needs of military Combatant Commanders to support operations in the war on global terrorism over the past two decades, unmanned systems have been rapidly acquired. Bypassing traditional acquisition processes has reduced requirements development and resulted in reduced mission effectiveness. Until 2003, every UAV system that completed operational testing was deemed “operationally unsuitable” (Carr et al. 2003). Some reasons for the shortcomings included imprecise maintainability, reliability, and availability metrics focused on technical specifications rather than metrics which describe how the system is expected to perform missions in operationally representative environments (Carr et al. 2003). A system doctrine, and its integration into the development process, is critical to synthesizing operationally meaningful and testable requirements.

Since 2003, UAV system performance under operational testing has continued to struggle. In 2007, the Air Force Operational Test and Evaluation Center (AFOTEC) Operational Utility Evaluation of the RQ-4 Globalhawk Block 10 found the system operationally effective at imagery intelligence missions, but not operationally suitable (DOT&E 2007). The MQ-9 Reaper was declared operationally effective and suitable by AFOTEC and the Office of the Director, Operational Test and Evaluation in 2008 (DOT&E), but this was after a long-delayed test program. Because it was fielded as an Advanced Concept Technology Demonstrator, its sole objective was to *demonstrate* military utility, not produce an operationally suitable or effective system. Significant engineering retrofits from the original Predator which first flew in 2001, were required (DOT&E 2009). In 2015, the Navy’s RQ-21A Blackjack was deemed neither operationally effective nor operationally suitable by DOT&E, even though it was the first Navy UAV system to undergo a traditional acquisition process (DOT&E 2015). This trend in test and evaluation is an indicator that the design architectures receive insufficient requirements development, and will likely continue to do so as UAS technology develops faster than prescribing doctrine.

3.0 SWARM DOCTRINE

Military doctrine is a prescriptive guide for how the military should conduct major campaigns and operations. It provides a standardized conceptual framework for connecting strategy, operations, and tactics, and is influenced by technology, the enemy’s capabilities, organizational structure, and geography. Doctrine shapes how missions should be accomplished in terms of roles, functions, and tasks. Doctrine development is guided by past experience, current concepts of operations, and experimentation using modeling and simulation, war-gaming, and field exercises. NATO defines doctrine as “fundamental principles by which the military forces guide their actions in support of objectives. It is authoritative but requires judgement in application” (NATO 2010).

Military historians have used the term “swarming” to describe one of the four general engagement patterns for military land, sea, and air operations: melees, massing, maneuver, and swarming (Arquilla 1997). Disordered melees were characterized by individuals fighting on their own, massing involved mainly fixed, controlled, inflexible formations, and eventually maneuver patterns offered the most flexibility. From a network-centric warfare perspective, swarming doctrine has been described as “an offensive action generated in pulses by highly dispersed forces that do not employ traditional hierarchical command and control structures” (Hart 2004). This progression of engagement patterns was enabled by the extent and efficiency of information processing, and each engagement pattern has been built upon foundations of the earlier patterns (Arquilla 2000). Looking through this lens, many conflicts throughout history could be characterized as swarming warfare: the British versus the Spanish Armada in 1588, the British against the swarming German U-boat wolf packs in the North Atlantic, the British Fighter Command exercising defensive swarming against the German Luftwaffe, the

Japanese kamikaze attacks against the US Navy, the US military in the Battle of Mogadishu, typical operations of non-governmental organizations, and Al Qaeda's strikes on multiple US targets on September 11, 2001 (Hart 2004, Arquilla 2000).

This historical characterization of swarming as pulsed attacks from traditional units under a decentralized command structure is likely different from what the future swarm UAS doctrine will look like. In the historical cases, while each individual unit (whether a submarine or Al Qaeda operative) operated somewhat autonomously using a decentralized command and control structure, each was commanded by an individual human. They did not exhibit true local communication and sensing capabilities, they were not exhibiting cooperative behavior, and the individual units exhibited too much variation to be considered homogeneous. The future modern swarming doctrine should expansively cover operations using agents to perform missions with much less human supervision than previously seen in historical military swarming examples.

What will the modern swarming doctrine look like? Swarming doctrine may include a centralized strategy, but focus on more widely distributed, smaller units executing pulse-like tactics. As a result, the organizational structure will be flatter than a traditional military organization's hierarchy and there will be a transition from “few and large” forces to “many and small” units (Arquilla 2010). As highlighted in Arquilla (2000), militaries looking to use swarming capabilities will need to consider close-in strategies after decades of primarily using standoff strategies shaped by precision-guided munitions. Otto Heilbrunn's concept of “concentric dispersion,” in which small groups of forces are amassed together to make quick strikes before dispersing is applicable to swarm UAS tactics which will involve continuous changes in unit size over the course of a mission (Arquilla 2000). Future wars are expected to be characterized by “astute use of communications, cyberspace, and technology, such that their impact extends regionally and globally” (USDOD 2010). The robustness, scalability, and non-deterministic behavior of swarm UAS make it compatible with missions that involve wide-area search and surveillance (especially when there is minimal cueing data), widely distributed attacks, diversion tactics, and suppression of enemy attacks (Clough 2002).

A key enabler for supporting a flatter hierarchy, greater elusiveness, and increased situational awareness is the communication network on which the swarm operates. Swarms can thrive on distributed communication and sensor networks for coordination, task allocation, and information sharing. An appropriately engineered communication network can enable the swarm to operate using decentralized control. Automation engineering will enable effective task allocation between agents, and between agents and humans. Militaries have traditionally been hierarchical and organized in large groups such as air wings, divisions, expeditionary units, and aircraft carriers, while swarms may benefit from a much flatter organizational structure. Resistance to organizational change will be a non-trivial challenge in developing military swarm doctrine.

4.0 SWARM ARCHITECTURE

The swarm architecture should be designed to support a “few and small,” widely dispersed, highly networked, pulsing attack style doctrine. In general, there are three main, overall command and control (C2) architectures used in swarm systems: orchestrated, centralized or hierarchical, and distributed or decentralized control (Dekker 2008). In *orchestrated control*, one agent is selected as a temporary leader based on specified transient factors (e.g., location, state, mission scenario). The leader receives sensor data from the other agents and broadcasts the fused, common, integrated picture. If the leader is disabled, a replacement is selected to continue in that role. This architecture is somewhat robust, but is not scalable to larger swarms or geographically dispersed swarms, and places a significant processing burden on one agent. A *centralized control* architecture resembles a traditional military command and control structure where agents are organized in a hierarchy and detailed tactical information is fed up the chain of command. While this hierarchical design simplifies data flow, it is not robust, and is inflexible in dealing with dynamic scenarios that require rapid reactions from agents. Centralized control of a swarm requires a hub-and-spoke communication architecture that presents several disadvantages: it limits the autonomous behavior of the swarm, it does not enable communication between agents, and it allows for a single point of failure in the design (Chung et al. 2013). A *distributed architecture* is characterized by the absence of a leader; rather swarm decisions are made via collective consensus among agents. This type of architecture is robust and scalable, but requires a communication network that will support potentially increased data traffic. As with other elements of swarm system design, a hybrid of C2 architectures can be used to take advantage of the strengths of each. The US Navy's Cooperative Engagement Capability anti-air warfare system utilizes a distributed architecture for situational awareness data and an orchestrated architecture for selecting targets (Dekker 2008). Decentralized control architectures, including market-based (or auction) methods, and implicitly derived single-agent solutions have been successfully demonstrated in swarm UAS (Chung et al. 2013). For these reasons, wireless mesh communication networks have been found as a potentially critical enabling form of swarm UAS communication architecture (Frew 2008).

Finite State Machines (FSM) (or finite state automata) have been shown to be effective in modeling multi-vehicle autonomous, unmanned system architectures (Weiskopf et al., 2002). Within an FSM architecture, each agent operates within one of several defined states at a given time. The trigger events that cause the agent to transition between states are precipitated by environmental conditions it senses or events it encounters. This type of structure is applicable in developing military swarm systems as the states and triggers can be defined deterministically (like a traffic light), which is necessary for high risk mission events such as target attacks. Conversely, there may be other mission events, such as searching, where some bounded degree of unpredictability is desired. In those cases, probabilistic finite state machines (PFSM) (or probabilistic finite state automata) can be used by allowing for different behaviors within a state or by offering multiple transitions between states (Paranuk 2003).

4.1 Taxonomies and Design Methods of Swarm Robotics Systems

A swarm UAS taxonomy should describe and classify the system using standardized nomenclature. Some swarm taxonomies focus on physical or functional architectures and levels of automation, while others characterize swarm systems based on problems or tasks (Gerkey and Mataric 2004). Dudek et al. (1993) formulated a pivotal taxonomy of swarm robotics based on seven different design variables: swarm size, swarm range, communication topology, communication bandwidth, collective re-configurability, and collective composition. While Dudek's taxonomy provides an organized and useful collection of design parameters for building a physical system, it does not provide the mission-oriented insights necessary for designing a system architecture specific to military swarm operations.

Behavior-based design, where the individual behavior of each agent is developed iteratively until the desired swarm behavior is acquired, is a typical design method. This bottom-up development method is counter to traditional systems engineering top-down design. In their review of design methods, Brambilla et al. (Brambilla 2013) noted that there is not a standardized method for designing individual agent behavior to create the desired swarm collective behavior; rather the design is mainly influenced by the perspicacity of the designer. The focus of this research is to use the mission and doctrine as the primary influencers of the design. Another commonly used behavior-base design is Brooks' subsumption architecture which uses a layering approach for controlling systems, and incorporates augmented FSM processors for managing inputs and outputs (Brooks 1985).

Top-down design methods. As previously mentioned, most swarm systems have been developed using bottom-up development methods where an individual agent's behavior is iteratively fine-tuned until the desired collective behavior is achieved, commonly called "code and fix." Brambilla et al. (2012) proposed a property-driven, top-down design method that formally describes the features of the system the designer wants to realize. Their method has four phases:

- Phase 1: formally state system requirements by specifying the intended properties;
- Phase 2: create an abstract macroscopic model and model checker to verify the properties;
- Phase 3: use the macroscopic model as a guide for implementing the system (macroscopic to microscopic transition);
- Phase 4: test the system using real robots.

4.2 Proposed Swarm UAS Mission Taxonomy

The intent of the proposed swarm UAS mission taxonomy is to create an overarching, modular "playbook" of swarm behaviors that can be assembled and sequenced to enable a swarm UAS to perform a variety of missions. Playbooks have been used by others to catalogue pre-defined behaviors or action plans for simplifying user control and synchronizing agent tasking in unmanned systems (Coppin and Legras 2012, Goldman et al. 2005, Simmons et al. 2000). The objective of this taxonomy is to support a swarm UAS architecture that can operate at an autonomous level that is acceptable in terms of risk to the unit commander, and may vary by mission. Likewise, the design supports operation of the swarm system at the tactical level, rather than by dictating each move via plays. The following terms will be used throughout the presented research to describe the composition of the swarm UAS mission architecture (Chung 2015):

- *Swarm mission* describes the overall task and purpose delineating the action assigned to the swarm UAS. Example swarm UAS missions include: intelligence, surveillance, reconnaissance (ISR), humanitarian assistance/disaster relief (HADR), search and rescue (SAR), and counter drug operations. A swarm mission is the parent of several swarm tactics.
- *Swarm tactic* is the employment and ordered arrangement of agents in relation to one another for the purpose of performing a specific task. Swarm tactics include searching, patrolling, localizing, tracking, and attacking. A swarm tactic can consist of different subtypes, for example a swarm search can be performed using a ladder search pattern, an expanding square search or a constricting, containment square search. A swarm tactic is the child of a swarm mission.
- *Swarm play* describes the maneuvers and behaviors of the swarm as a collective of agents. Artificial intelligence and robotics communities use the term "behavior" to describe "a regularity in the interaction dynamics between the agent and the environment" (Mataric 1995). Swarm plays can be described as behaviors with specific triggers and temporal constraints, and are the building blocks for swarm tactics. Example swarm plays include launch, recovery, transit, split, join, and orbit. A swarm play is the child of a swarm tactic.
- *Swarm algorithms* are the step-by-step procedures used by the controlling software to solve a recurrent task such as sorting, path planning or foraging. Swarm algorithms are the mechanisms used to build

swarm plays, and are the children of swarm plays.

- *Swarm data* are the quantities used by the swarm algorithms to perform calculations, including: position, heading, velocity, altitude, attitude, health status, and state.

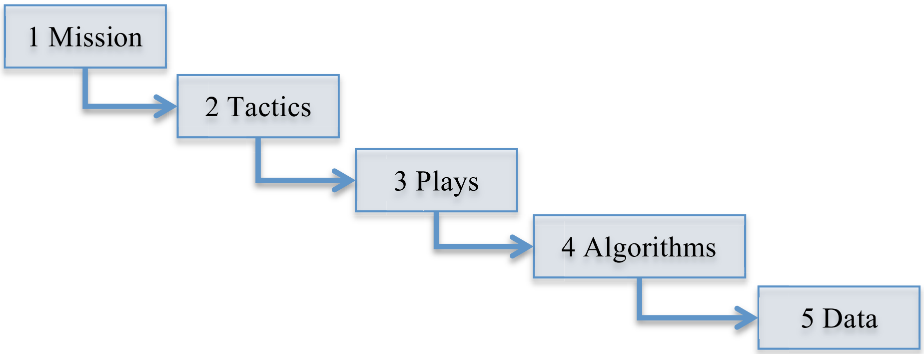

Figure 1: Proposed Overall Swarm UAS Mission Taxonomy

Figure 2 illustrates an example of a simple ISR mission, shown as a series of level two tactics built with *Innoslate*, an online model-based systems engineering software tool. For model conciseness, the level three plays comprising the tactics are modeled separately, but linked to their parent plays. All missions begin with the "Swarm ingress" tactic, which comprises a series of plays (

Figure 3), and conclude with the "Swarm egress" tactic. In the basic ISR mission, the search commences and progresses to "Swarm track" if a target is detected. The swarm continues executing the "Swarm search" tactic if no targets are detected. If an attack is authorized (via human intervention), the swarm proceeds to attack the target. If not, the swarm continues to patrol the search area until the battery levels of the UAVs require them to egress.

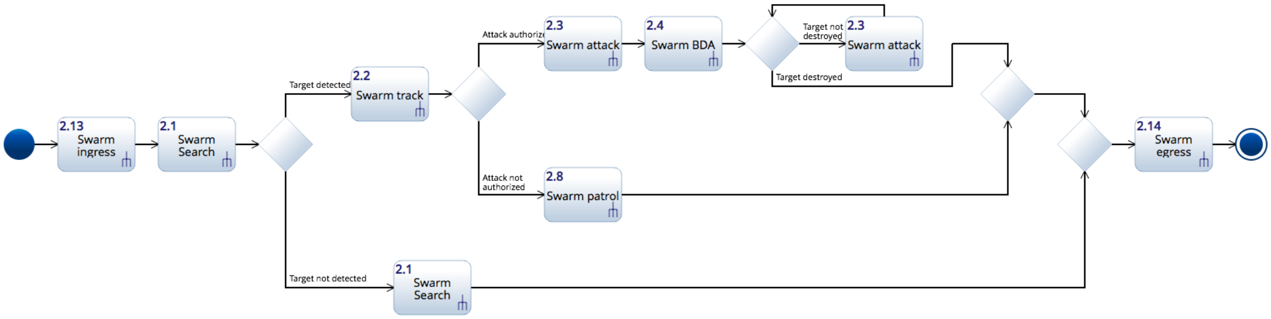

Figure 2: Swarm UAS Basic ISR Mission at Tactics Level

Figure 3 and Figure 4 are examples of two swarm UAS tactics - ingress and egress - decomposed into their requisite level three plays and respective play alternative options. Both tactics are standard tactics used in every swarm mission, and are shown as a sequence of plays with different mission-dependent alternatives. The objective of this approach is to pre-program these tactics into a mission playbook during the mission planning phase so that the swarm UAS operator only has to execute a tactic rather than a time-intensive series of plays. Specific alternatives can then be set as defaults for different mission types (i.e. for a covert mission the default settings would be “Min time to launch swarm,” “Evasive transit,” “Multiple terminal approach,” “Min time to land swarm”, and “Specified dimensions of landing”).

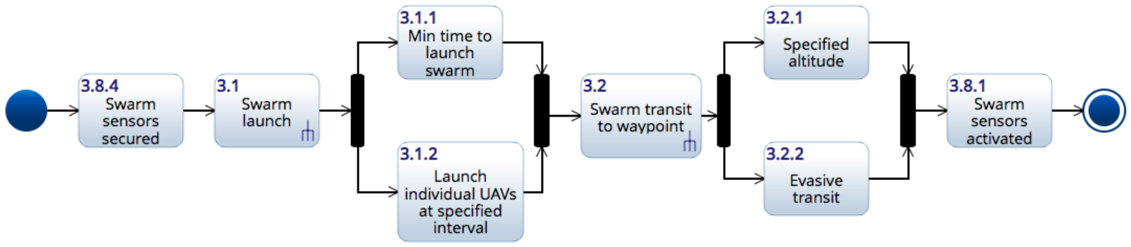

Figure 3: Swarm Ingress Tactic

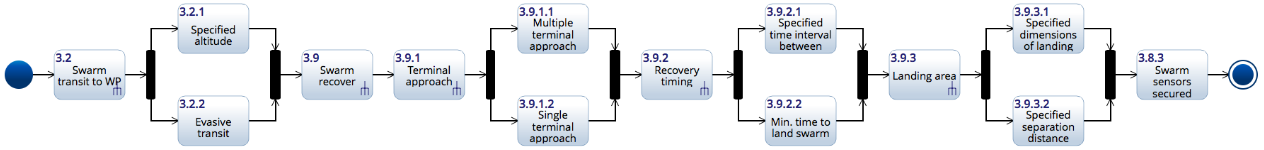

Figure 4: Swarm UAS Egress Tactic

4.3 Proposed Swarm UAS Mission Architecture

The proposed swarm UAS mission architecture should be modular, robust, and scalable. For those reasons, the control architecture should be decentralized and the mission architecture should be managed by FSMs in a layered approach. For instance, each swarm will be engaged in a single mission such as a swarm vs. swarm scenario (Figure 5). As illustrated, at any given time, the swarm should be operating in one of eight different mission states. The progression between the tactics should be controlled by the transitions shown in Figure 5. For example, after the pre-flight checks have been completed, the swarm has been launched and has arrived at the designated ingress waypoint; the swarm reaches the swarm-ready state where it is available for mission tasking. The first state of this mission is the search state, where the swarm remains until a target is detected. If the swarm feels threatened during the search or track states, it will transition to an evade state. Agents in each of the mission states, except for attack state, will transition to the egress state when a low battery condition is reached.

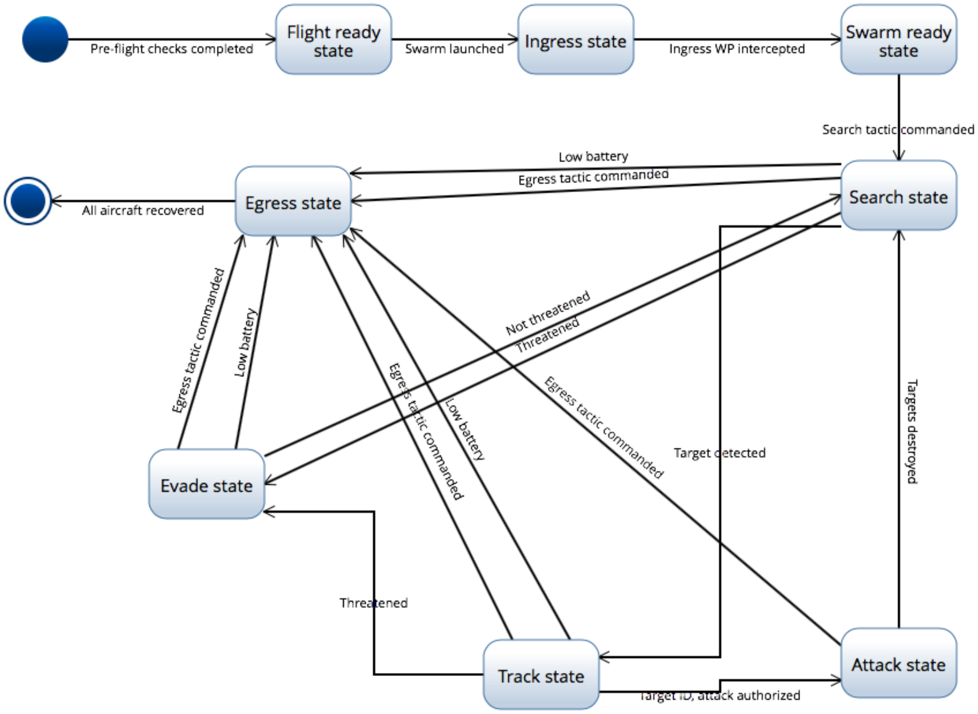

Figure 5: Swarm vs. Swarm State Diagram at Tactics Level

Table 1 shows the swarm vs. swarm example mission decomposed into tactics, potential plays designed to support the tactics, examples of algorithms that may be used to execute the plays, and data that permit algorithm computation. Three general categories of algorithms applicable for swarm UAS include: reactive, deliberative, and evolutionary algorithms. The class of *reactive* algorithms comprise sense and act, pheromone-based and other biologically inspired algorithms such as bee colony, ant colony, and particle swarm optimization (Senanayake et al. 2015). *Deliberative* describes algorithms that require information trading and solution deliberations, while *evolutionary* covers genetic algorithms and other fitness-based optimization functions (Mitchell 2009). Flocking algorithms simulate the behavior of a flock of birds in flight and compel each agent to steer itself based on three simple rules: separation (avoid other agents), alignment (align heading with other agents), and cohesion (steer toward center of agents). Physicomimetic algorithms model agents and obstacles as carrying the same “charge” with targets carrying the opposite charge, creating an artificial potential field. Collisions are avoided by repulsive forces between agents or between agents and obstacles, while attractive forces between opposite charges draw the agent toward the target (Dudek and Jenkin 2010, Senanayake et al. 2015). The example algorithms listed in Table 1 can be interchangeable for several cases, and more complex missions may compel a shift to evolutionary algorithms in the future.

Table 1: Swarm vs. Swarm Mission Architecture Example

1 Mission	2 Tactics	3 Plays	4 Algorithms	5 Data
Air Battle: Swarm vs. Swarm	Swarm Ingress	Swarm launch (Min time to launch)	Sorting	Agent state and pose
				Number of agents
				Number of launchers
		Swarm transit to WP (Specified altitude)	Flocking	Agent state and pose
				Number of agents
				Ingress waypoint
		Swarm sensors activated	Sorting	Agent state and pose
				Number of agents
				Sensor range
	Swarm Search	Swarm random pattern	Biologically inspired	Agent state and pose
				Number of agents
				Reference positions
				Search area
	Swarm Track Target	Swarm distributed sensing	Nearest neighbor	Agent state and pose
				Target pose
	Swarm Attack	Swarm weapon fire	Greedy selection	Agent state and pose
				Target pose
				Weapon envelope
	Swarm Evade	Swarm disperse	Physicomimetic	Agent state and pose
				Number of agents
				Reference positions
		Swarm join	Physicomimetic	Agent state and pose
				Number of agents
				Reference positions
	Swarm Egress	Swarm transit to WP - Specified altitude	Flocking	Agent state and pose
				Number of agents
				Egress waypoint
		Swarm recover	Sorting	Agent state and pose
				Number of agents

5.0 CONCLUSION AND FUTURE WORK

Within the field of unmanned systems, swarm UAS research has grown considerably for military as well as commercial applications. Despite the progression in research, UAS doctrine has been ignored as a specifying design factor in the field of swarm technology. Much of the research has focused on developing, testing, and varying individual agent behavior until the desired collective behavior is achieved. This bottom-up approach will most likely not provide the most efficient approach for designing a swarm UAS to meet mission requirements. The proposed swarm UAS mission taxonomy is designed to provide building blocks for an overall top-down design methodology, influenced by Brambilla et al., using iterative feedback loops from the bottom up. A decentralized control architecture and layered approach using FSMs will integrate military doctrine as a design element for developing swarm UAS technology.

Future research entails developing a model-based systems engineering method to design swarm UAS architecture from an initial doctrine. The next step involves inputting the proposed swarm UAS mission architecture into an integrated framework that will use design reference missions (Whitcomb et al. 2015) to build models of various specific swarm missions. Such models encompass physical and functional architectures, using Lifecycle Modeling Language (LML) and Systems Modeling Language (SysML) diagrams such as: state machine, activity, sequence, and use cases. The use cases generated by the models will then be compared to the results of live field exercises conducted with fixed-wing swarm UAS (Chung et al. 2013). The models will be iteratively modified to achieve the desired behavior of the system. Future objectives of this integrated swarm UAS framework are to: develop swarm UAS tactics, reduce the number of humans operating the system, design appropriate levels of autonomy for different mission and tactics states (i.e. human should be required to authorize weapon use, or operations involving close engagements), and develop operationally suitable and effective systems.

REFERENCES

U.S. Department of Defense. 2013. “Unmanned Systems Integrated Roadmap.”

Finn, Anthony, Scheding, Steve. 2010. *Developments and Challenges for Autonomous Unmanned Vehicles*. Springer. doi:10.1007/978-3-642-10704-7.

Sahin, Erol. 2005. “Swarm Robotics: From Sources of Inspiration to Domains of Application,” no. 631.

Cao, Y.U., A.S. Fukunaga, A.B. Kahng, and F. Meng. 1997. “Cooperative Mobile Robotics: Antecedents and Directions.” *Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots* 23: 226–34. doi:10.1109/IROS.1995.525801.

Beni, Gerardo, and Jing Wang. 1993. “Swarm Intelligence in Cellular Robotic Systems.” *Robots and Biological Systems: Towards a New Bionics? NATO ASI Series Volume 102*, no. 2: 703–12. doi:10.1007/978-3-642-58069-7_38.

Beni, G. 2005. “From Swarm Intelligence to Swarm Robotics.” *Swarm Robotics, Lecture Notes in Computer Science, 3342*, no. December. doi:10.1007/978-3-540-30552-1.

Frew, E.W., and T.X. Brown. 2008. “Airborne Communication Networks for Small Unmanned Aircraft Systems.” *Proceedings of the IEEE* 96 (12). doi:10.1109/JPROC.2008.2006127.

Chung, Timothy, Kevin Jones, Michael Day, Marianna Jones, and Michael Clement. "50 vs. 50 by 2015: Swarm vs. Swarm UAV Live-Fly Competition at the Naval Postgraduate School." *2013 Proceedings of AUSVI* (50).

Harriott, Caroline E, Adriane E Seiffert, Sean T Hayes, and Julie A Adams. 2014. “Biologically-Inspired Human-Swarm Interaction Metrics,” 1471–75.

Cummings, Mary L. 2004. “Human Supervisory Control of Swarming Networks.” … *Annual Swarming: Autonomous Intelligent Networked …*, 1–9. http://web.mit.edu/aeroastro/labs/halab/papers/cummingsswarm.pdf.

Cummings, Mary L., and Paul Mitchell. 2006. “Automated Scheduling Decision Support for Supervisory Control of Multiple UAVs.” *Journal of Aerospace Computing, Information, and Communication* 3 (6): 294–308. doi:10.2514/1.19599.

Cummings, M, S Bruni, S Mercier, and Pj Mitchell. 2007. “Automation Architecture for Single Operator, Multiple UAV Command and Control.” *The International C2 Journal* 1: 1–24. http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA478338.

Carr, Lee, Project Leader, Kristen Lambrecht, and Greg Whittier. 2003. “Unmanned Aerial Vehicle Operational Test and Evaluation Lessons Learned,” no. IDA Paper P-3821.

Director Operational Test & Evaluation. 2007. “Air Force Programs: Global Hawk High Altitude Endurance Unmanned Aerial Vehicle, RQ-4.” http://www.dote.osd.mil/pub/reports/FY2007/pdf/other/2007DOTEAnnualReport.pdf.

Director Operational Test & Evaluation. 2008. “Air Force Programs: MQ-9 Reaper Hunter Killer Armed Unmanned Aircraft System (UAS).” http://www.dote.osd.mil/pub/reports/fy2011/pdf/af/2011mq9reaperuas.pdf.

Director Operational Test & Evaluation. 2015. “FY15 Navy Programs: RQ-21A Blackjack Unmanned Aircraft System (UAS).” http://www.dote.osd.mil/pub/reports/FY2015/pdf/navy/2015rq21a_blackjack.pdf.

NATO Standardization Organization. "Allied Administrative Publication–6 (AAP-6): NATO Glossary of Terms and Definitions." (2010).

Arquilla, John, Ronfeldt, David. 1997. “In Athena’s Camp: Preparing for Conflict in the Information Age.” Rand Corporation.

Hart, D.M., and P.A. Craig-Hart. 2004. “Reducing Swarming Theory to Practice for UAV Control.” *2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720)* 5: 3050–63. doi:10.1109/AERO.2004.1368111.

Arquilla, John, Rondfeldt, David. 2000. “Swarming and the Future of Conflict.” *Defense*.

Arquilla, John. 2010. “The New Rules of War.” *Foreign Policy* 24. February (178): 60–67. doi:10.2307/20684990.

US Department of Defense. 2010. “Irregular Warfare : Countering Irregular Threats Joint Operating Concept.”

Clough, Bruce T. 2002. “Metrics, Schmetrics! How The Heck Do You Determine A UAV’s Autonomy Anyway.” *2002 Performance Metrics for Intelligent Systems Workshop*. http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA515926.

Dekker, Anthony. 2008. “A Taxonomy of Network Centric Warfare Architectures.” *Systems Engineering/Test and Evaluation*, 1–14. http://members.ozemail.com.au/~dekker/SETE.Dekker.final.pdf.

Weiskopf, Frank, Tim Gion, Dale Elkiss, Harold Gilreath, Jim Bruzek, Robert Bamberger, Ken Grossman, and Jordan Wilkerson. "Control of Cooperative, Autonomous Unmanned Aerial Vehicles." In *Proceedings of First AIAA Technical Conference and Workshop on UAV, Systems, Technologies, and Operations*. 2002.

Parunak, H. Van Dyke. 2003. “Making Swarming Happen.” In *Conference on Swarming and C4ISR, Tysons Corner, VA 3JAN2003*.

Gerkey, Brian P., Mataric, Maja J. 2004. “A Formal Analysis and Taxonomy of Task Allocation in Multi-Robot Systems.” The International Journal of Robotics Research 23 (9): 939–54.

doi:10.1177/0278364904045564.

Dudek, Gregory, Michael R M Jenkin, Evangelos Milios, and David Wilkes. 1993. “A Taxonomy for Multi-Agent Robotics.” *Autonomous Robots* 29.

Brambilla, Manuele, Eliseo Ferrante, Mauro Birattari, and Marco Dorigo. 2013. “Swarm Robotics: A Review from the Swarm Engineering Perspective.” *Swarm Intelligence* 7 (1): 1–41. doi:10.1007/s11721-012-0075-2.

Brooks, Rodney A. "A robust layered control system for a mobile robot. "*Robotics and Automation, IEEE Journal of* 2, no. 1 (1986): 14-23.

Brambilla, Manuele, Carlo Pinciroli, Mauro Birattari, and Marco Dorigo. 2012. “Property-Driven Design for Swarm Robotics.” *AAMAS 2012 International Conference on Autonomous Agents and Multiagent Systems*, no. June: in – press. http://iridia.ulb.ac.be/~mbrambilla/pdf/Bra-aamas2012.pdf.

Coppin, Gilles, and Francois Legras. 2012. “Autonomy Spectrum and Performance Perception Issues in Swarm Supervisory Control.” *Proceedings of the IEEE* 100 (3): 590–603. doi:10.1109/JPROC.2011.2174103.

Goldman, Robert P, Christopher A Miller, Harry B Funk, and John Meisner. 2005. “Optimizing to Satisfice : Using Optimization to Guide Users 1 Introduction.” *Interfaces*, no. January: 18–20.

Simmons, Reid, Apfelbaum, David, Fox, Dieter, Goldman, Robert P., Zita Haigh, Karen, Musliner, David J., Pelican, Michael, Thrun, Sebastian. 2000. “Coordinated Deployment of Multiple, Heterogeneous Robots.” *Proceedings of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 127–40. doi:10.1007/978-3-319-10969-5.

Chung, Timothy H. 2015. “Dr. Chung Directed Study Notes1.”

Matarić, M J. 1995. “Issues and Approaches in the Design of Collective Autonomous Agents.” *Robotics and Autonomous Systems* 16(2-4) (January 1994): 321–31.

Senanayake, Madhubhashi, Ilankaikone Senthooran, Jan Carlo, and Hoam Chung. 2015. “Search and Tracking Algorithms for Swarms of Robots : A Survey.” *Robotics and Autonomous Systems*. Elsevier B.V. doi:10.1016/j.robot.2015.08.010.

Dudek, Gregory, and Michael Jenkin. *Computational principles of mobile robotics*. Cambridge university press, 2010.

Mitchell, Melanie. 2009. *Complexity: A Guided Tour*. Oxford University Press.

Reynolds, Craig W. 1987. "Flocks, herds and schools: A distributed behavioral model." In *ACM SIGGRAPH computer graphics*, vol. 21, no. 4, pp. 25-34.

Whitcomb, C., Giammarco, K. and Hunt, S., 2015. *An instructional design reference mission for search and rescue operations*. Monterey, California. Naval Postgraduate School.