50 vs. 50 by 2015: Swarm vs. Swarm UAV Live-Fly Competition at the Naval Postgraduate School

Chung, Timothy H.

Curran Associates, Inc.

Chung, T.H., Jones, K.D., Day, M.A., Jones, M., and Clement, M. "50 VS. 50 by 2015: Swarm Vs. Swarm UAV Live-Fly Competition at the Naval Postgraduate School." AUVSI North

50 VS. 50 BY 2015: SWARM VS. SWARM UAV LIVE-FLY COMPETITION AT THE NAVAL POSTGRADUATE SCHOOL

Timothy H. Chung[a], Kevin D. Jones[b], Michael A. Day[c], Marianna Jones[c], and Michael Clement[d]

Aerial Combat Swarms is a swarm vs. swarm UAV live-fly competition, designed to inspire new concepts of operations and illuminate new tactics in unmanned systems employment, specifically in the swarm and counter-swarm robotics arenas. The competition scenario involves a tournament of "battles" where in each such battle two teams comprising many autonomous aerial robots vie for air superiority while simultaneously defending a high value unit on the ground and/or attacking that of the opponent's. The vision for the inaugural grand challenge event is for 50 vs. 50 UAVs by the year 2015.

The Aerial Combat Swarms competition further serves as an innovation testbed, providing the infrastructure and open architecture interface definitions for hardware/software/network connections between UAVs, ground command stations, observers, and the "Arbiter," which serves as an "autonomous referee." An additional element includes specifications for operating in a virtual battle arena for modeling and simulation experiments and hardware-in-the-loop flight validation. The overarching open design enables participants to leverage existing technologies available from the Aerial Combat Swarms open source community. The ambitious grand challenge competition effort described in this paper presents a novel and unique opportunity to explore advanced tactics for robotic swarms. Perhaps more increasingly and operationally relevant, this competition actively accelerates future concepts for also engaging and defeating adversarial unmanned systems.

INTRODUCTION

As unmanned system technologies continue to advance, so increases the likelihood of their use by adversaries of the future in capacities such as in swarm attacks. However, current approaches of expending high cost solutions to address these low cost threats is unsustainable in resource-constrained contexts. In these cases, innovation can help defeat inundation. The ambitious grand challenge competition effort described herein presents a novel and unique opportunity to explore advanced tactics for robotic swarms and, more specifically, for defeating these saturation attack scenarios. The *Aerial Combat Swarms* Swarm vs. Swarm UAV Challenge competition is de-

---

[a] Assistant Professor, Systems Engineering, Naval Postgraduate School, Monterey, CA 93943.
[b] Research Associate Professor, Mechanical and Aerospace Engineering, Naval Postgraduate School, Monterey, CA 93943
[c] Research Associate, Systems Engineering, Naval Postgraduate School, Monterey, CA 93943.
[d] Research Associate, Information Sciences, Naval Postgraduate School, Monterey, CA 93943.

signed to inspire new concepts of operations and illuminate new tactics in unmanned systems employment, specifically in the swarm and counter-swarm robotics arenas. The competition scenario involves a tournament of live-fly, large scale "battles," where in each such battle two teams comprising many autonomous aerial robots vie for air superiority while simultaneously defending a high value unit on the ground and/or attacking that of the opponent's. **The vision for the inaugural grand challenge event is for 50 vs. 50 UAVs by the year 2015.** The *Aerial Combat Swarms* grand challenge competition is envisioned to be staged as a two-week, tournament-style, live-fly outdoor event, where eight qualifying teams engage in a series of single-elimination matches. Points are scored by successful attacks on both the opponent's aircraft as well as its home base, awarded by an arbitrating virtual referee. Each match comprises advance preparation time, a specified launch window during which all battle-ready aircraft must be aloft, two half periods separated by an intermission, and recovery operations at the match's conclusion.

Motivation

Recent reports in the public domain identify the potential use of "saturation attacks," where dozens of kamikaze unmanned aerial vehicles (UAVs) execute precision strikes nearly simultaneously, as a serious threat to the U.S.'s military and information superiority. This "swarm" of UAVs, consisting of assets such as the "Harpy" UAV and its derivatives, can loiter autonomously for long durations while seeking radiating targets, thereby rendering vessels employing these systems virtually "blind" to imminent and subsequent threats. In this context, advanced technologies to defeat such threats are of vital interest to U.S. and allied forces around the world.

The above vignette highlights the explosive emergence of unmanned systems in military operations, but increasingly not limited to U.S. and allied employment. The increasing exploitation of low-cost technologies by adversaries has been witnessed in modern day irregular warfare contexts. Coupled with increasing nation-state development efforts in unmanned systems, these threats challenge defense researchers, technologists, and decision makers to study and develop *counter* unmanned systems tactics, that is, the employment of unmanned systems to defeat those of the adversary. Explicit emphasis on the generation of these tactics will directly enable translation of operational needs to mission specifications to technological requirements.

Further, as unmanned system technologies continue to advance, so increases the likelihood of the adversary's use of low cost saturation attacks as described above. However, given that current concerns for countering the rise of opponents' unmanned systems capabilities are largely focused on defeating single-platform unmanned threats, the presented challenge provides a venue to explore advanced capabilities to address future threats that may be faced in the technologically driven and rapidly changing battlespace.

Swarm vs. Swarm UAV Challenge as an Innovation Testbed

The *Aerial Combat Swarms* competition further serves as an innovation testbed, providing the infrastructure and open architecture interface definitions for hardware/software/network connections between UAVs, ground control stations, observers, and the "Arbiter," which serves as an "autonomous referee." An additional element includes specifications for operating in a virtual battle arena for modeling and simulation experiments and hardware-in-the-loop flight validation. The overarching open design enables participants – ranging from university teams, research laboratories and institutes, industry partners, to even hobby enthusiasts and high school clubs -- to leverage rapidly changing technologies available from the *Aerial Combat Swarms* open source community. For example, if one team wishes to emphasize its hardware platform designs, they may be able to use flight control and coordination algorithms from the community's library of autonomy algorithms. Alternatively, if another team excels at computational methods for, e.g., perception or flight formations, they could use the Naval Postgraduate School's UAV swarm fleet to validate their algorithms. In both arenas, the competition and the community benefit from these collaborative interactions and use of the testbed. As host and active participant of the *Aerial Combat Swarms* competition, the Naval Postgraduate School and its partners can engage in advanced research and development while also ensuring current and future DoD operational relevance. The nature of the *Aerial Combat Swarms* competition embraces trends in crowd-sourced innovation to accelerate technological development of robust, low-cost, and imaginative software and hardware. Such technological innovation, coupled with comprehensive scientific breakthroughs in swarm robotic command, coordination, and communication; human-robot team interfaces; embedded computational intelligence; and systems modeling of dynamic adversaries, offers significant and numerous high-risk, high-reward opportunities of interest to research and operational communities.

Relevant Research

Testbeds for outdoor, multi-UAV research: The testbeds and related research projects reviewed below are highlighted by their common focus on fixed-wing, multi-UAV systems developed for outdoor, field experimentation efforts. This survey is meant to be descriptive, rather than exhaustive, of the general scale and scope of existing testbeds to identify needs addressed by the proposed competition and associated infrastructure.

The Multiple AGent Intelligent Coordination and Control (MAGICC) Lab at Brigham Young University has led many initiatives in developing an integrated research program, including efforts in cooperative algorithms among several UAVs.[1,2]

MIT's Multi-UAV testbed emphasized simplified on-board electronics for their UAVs as much as possible in order to focus on higher-level tasks.[3] Their testbed consisted of eight Trainer ARF 60 aircraft with gasoline engines. The entire system was constructed using commercial-off-the-shelf (COTS) components.

The DragonFly project at Stanford University represents an early UAV testbed, which focused on control architecture and cooperative missions between two heavily modified model aircraft.[4] The ground control station (GCS) was designed around an open control platform developed by Boeing. Primary research objectives included mode selection, which was handled using a standalone microcontroller that monitored RF signal strength and switched between manual, autonomous and safety modes as appropriate.

The GRASP Lab at the University of Pennsylvania also developed two fixed-wing UAVs for coordination research.[5] They used the Piper Cub J3 model aircraft, with high-level control handled by a Dell laptop on the ground, with low-level control managed by a Piccolo autopilot equipped with an avionics board.

Researchers at the Georgia Institute of Technology developed a UAV testbed primarily for undergraduate educational objectives aligned with advanced research efforts.[6] A Goldberg Decathalon ARF model aircraft was used, and like many of the previous efforts, the high-level control was managed on the ground.

The Australian Centre for Field Robotics (ACFR) at the University of Sydney has a long history of aerial field robotics, including development of their own airframes called the Brumby Mk III.[7] The testbed was created for developing control algorithms and decentralized information gathering, and various research initiatives include terrestrial mapping, target tracking, surveillance systems, and platform design.

The Apollo project is an interdisciplinary UAV project at the University of Porto.[8] Their two primary aircraft include one that is based on a commercially available RC airframe and a second platform developed in house. Focus of this research was on a software architecture, which allows abstraction to enable different kinds of autonomous vehicles (UUVs, UAVs, UGVs) to cooperate using this common architecture.

The Rapid Flight Test Prototyping System is another parallel research effort at the Naval Postgraduate School, which primarily uses Sig Rascal 110 RC model, gas-powered hobby aircraft.[9] Various experiments and research efforts with two or three UAVs include aerial image processing, autonomous path following, and time-critical coordination between the UAVs. This research leverages unique access to restricted airspace (also used in live-fly capabilities presented in this paper) to conduct field experiments, and represents the ability to rapidly explore new payload, autonomy, or configuration modifications in the field.

Efforts by the Center for Collaborative Control of Unmanned Vehicles (C3UV) at Berkeley include various aircraft, including their fixed-wing Sig Rascal 110 (identical to the ones described above).[10] Relevant interests include cooperative search and rescue, multi-UAV path planning, and target localization and tracking using aerial vehicles.

The University of Colorado at Boulder also has several UAV projects and airframes built for the Research and Engineering Center for Unmanned Vehicles (RECUV).[11,12] Their two main aircraft are the CU Micro Air Vehicle and the ARES, where the former is a flying wing with a minimal sensor payload similar to SMAVNET (described below) and the ARES is an in-house design. In addition to multi-tiered network research, other efforts include environmental and disaster response applications of cooperative UAVs.

The Unmanned Systems Research Group at KAIST (Korea Advanced Institute of Science and Technology) has numerous UAV platforms and research interests, including flight controls for aggressive flight, swarm control for distributed UAVs, and platform design and validation studies.[13] Relevant to the presented initiative, field experiments on vision-based landing techniques use a foam, blended wing body electric powered airframe.

The Swarming Micro Air Vehicle NETwork (SMAVNET) project at École Polytechnique Federale de Lausanne investigated how to establish network infrastructure using swarms of micro air vehicles[14]. The SMAVNET project developed a much simpler control mechanism (largely based on potential fields), which reduced cost and enabled them to demonstrate simultaneous flight of ten aircraft with minimal intervention from the ground control station. Multi-UAV flocking tests with these fixed wing platforms were recently demonstrated, and reflect the latest advancements in operations of increasingly larger number of outdoor UAVs.[15]

Robotics Competitions: Additionally, robotics competitions have been extremely successful in facilitating innovations and leaps in advanced capabilities, although limited in their design to explore adversarial robotic opponents or large numbers of interacting robotic agents. Numerous challenges from DARPA, including UAVForge[16], ASW Continuous Trail Unmanned Vessel (ACTUV)[17], Grand and Urban Challenges[18], and the Robotics Challenge[19], represent archived and active programs to capture multi-institutional efforts in a variety of fundamental challenges for integrated autonomous systems. Further, competitions such as RoboCup[20] for soccer-playing robots and Google's AI Challenge[21] for ant colony behaviors touch at the boundary of adversarial robotic teams, but are limited in size of the teams (and thus, their relevance to saturation attack scenarios) or too simplistic simulated environments, respectively.

Active live-fly competitions dedicated to aerial robotic systems with a mission-oriented focus (e.g., such as search and surveillance, payload delivery, airspace operations) include the Outback

Challenge[22], the AUVSI International Aerial Robotics Competition[23], the AUVSI Student Unmanned Air Systems (SUAS) Competition[24], and NASA's UAS Airspace Operations Challenge[25], whereas more informal competitions for the hobby and consumer-driven UAS communities include "Trust Time Trial" (T3) contests facilitated by the community at DIYDrones.com[26], which challenges individual users to demonstrate interesting open-source controlled UAS capabilities.

Similar to these examples, the Swarm vs. Swarm UAV Challenge is designed to drive innovation through friendly competition environments. However, unique to the ambitious competition events presented in this paper is the emphasis on revolutionary innovations necessary to specifically enable swarm UAV operations in the face of a dynamic adversarial swarm, requiring disruptive approaches for, e.g., scalable infrastructure, human-swarm interactions, and swarm tactics generation. Such advances could directly impact a variety of civilian and defense applications.

Main Contributions

The main contributions of this paper are to outline the vision and design of the Swarm vs. Swarm UAV Challenge Competition, including a summary of nominal guidelines to aid in swarm UAV developments ranging from allowable classes of UAV platforms to nominal interaction rules for overseeing conduct of game play. In addition, we present highlights of recent preliminary efforts at the Naval Postgraduate School to instantiate this testbed for exploring swarm UAV capabilities, including results from field experiments that help identify key lessons learned in such live-fly endeavors. From these experiences, we further derive and outline both the near-term and forward-looking challenges where innovations may significantly and potentially profoundly alter the future of swarm autonomous systems in research and operational contexts.

Organization of the Paper

The remainder of the paper first details the competition design concept, providing general details on the scale and scope of the Swarm vs. Swarm UAV Challenge, as well as the guidelines that serve as the basis for competition rules. To demonstrate advances – both technological and logistical – that are prerequisite for swarm UAV operations, we describe preliminary efforts and present results that highlight current research thrusts conducted at the Naval Postgraduate School. Finally, we identify some of the key challenges to be faced throughout the evolution of both the state-of-the art as well as the competition itself, with closing remarks discussing a roadmap for the way ahead.

COMPETITION DESIGN CONCEPT

Scenario Overview

The scenario provides operational relevance by abstracting a naval context of a surface action group engaging an enemy surface action group (SAG). By construction, the Swarm vs. Swarm UAV Challenge identifies opposing end zones or "flags" as the high value units to be defended/attacked by the respective UAV swarms, as illustrated in Figure 1. As an aerial version of the "capture the flag" game, each side seeks to "attack" (i.e., land sufficiently close to) the opponent's flag with its UAV swarm elements, whilst simultaneously "defending" its own flag by intercepting the opponent's inbound UAVs. Further, the time and spatial spans of the scenario are designed to mimic the previously mentioned naval engagement, such that sufficient standoff detection of the adversary is appropriately modeled and scaled.

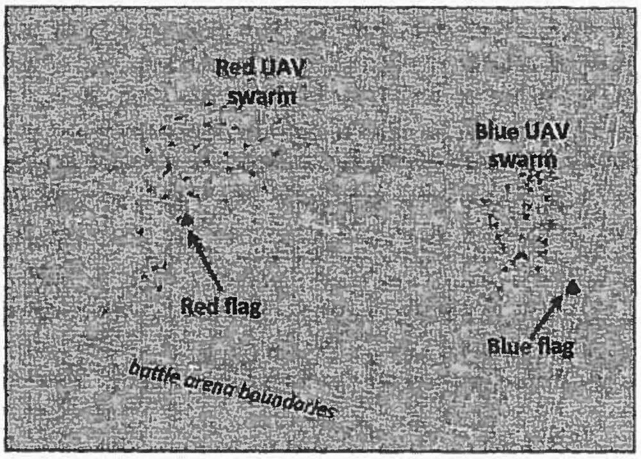

Figure 1: Scenario: Aerial "Capture the Flag" Setup with Opposing Flags and UAV Swarms with the Battle Arena

Arena Description

Given the scenario-driven context, the venue of the competition events is designed to reside wholly and safely within restricted airspace at the selected range. The bounding box representing the (proposed) battle arena is no more than one kilometer in width and two kilometers in length. These dimensions provided a notional scaled replication of a possible naval engagement scenario. For example, consider such an engagement between SAGs occurs at distances that they can detect each other (e.g., with radar or airborne sensors). Using distances appropriate for visual detection, we define the separation between flags to be approximately two kilometers.

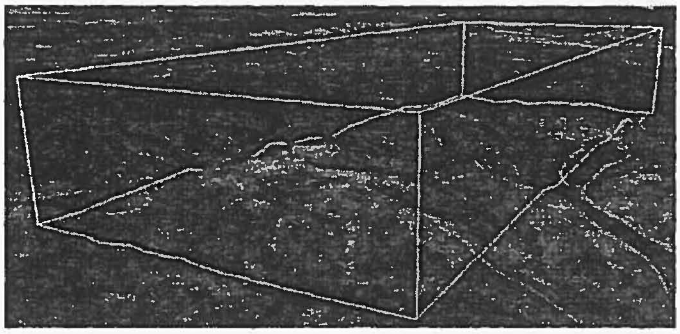

Figure 2: Swarm vs. Swarm UAV Challenge Battle Arena (notional)

Similarly, a geo-fence defining the permitted airspace altitude floor and ceiling provides a contained arena that still enables both teams to fully leverage the three-dimensional space to conduct their swarm maneuvering and attack/defense.

Another consideration is the possibility of creating a virtualized arena; that is, one that exists in non-physical dimensions. This would allow a team of UAVs flying in one physical space to compete in a virtual arena along with another team in a separate physical space as well as completely virtual UAVs flying in a simulated space. Teams with no physical UAVs would then be able to compete with flying teams. Two teams could also compete in the same airspace but at different altitudes, allowing for safer gameplay with reduced risk of in-air collision.

As the basis of the inaugural competition event, the locations of both teams' flags will be known to both teams and assumed to remain stationary throughout the game. As outlined in the Roadmap section, future instances of the competition are designed to include unknown and/or mobile flag locations to enhance both the level of complexity and operational relevance of the challenge.

Game Flow

The timeline of the individual games between the two participating teams is nominally designed to span a three-hour window, inclusive of setup, launch of UAVs, the battle itself, and recovery. The sequence of events are sketched below:

Time	Description
STARTEX	Start of the game: - Teams deploy to assigned bases of operations
+2:00	Dedicated time for base station and swarm setup
+0:15	Deployment of UAVs - Teams must deploy within launch window
+0:10	First half of live-fly battle
+0:05	Intermission - Teams switch sides to equalize environmental or geographic advantages
+0:10	Second half of live-fly battle
+1:20	Recovery of UAVs and shutdown
ENDEX	End of the game

At the start of the game, the two teams are each randomly assigned their respective base station locations corresponding to one side of the battle arena. To mitigate any advantages due to environmental (e.g., wind), geographic (e.g., terrain), or operational (e.g., RF interference) effects, teams will switch sides between halves, i.e., the assigned flag locations and re-start volumes will be swapped at intermission.

Both teams must launch their respective UAVs within the allotted launch window to ensure maximal duration of the battle itself as well as to challenge teams to develop innovative approaches to rapidly launching large numbers of UAVs. Both UAV swarms are assumed to remain in safe holding patterns within designated starting volumes near their respective sides until the battle commences.

Upon completion of the battle, remaining aloft UAVs are recovered in a controlled and safe manner, and "downed" UAVs are retrieved from specific locations designated for landing of "killed" UAVs during the course of the battle.

UAV Swarm Specifications

In order to highlight innovation opportunities in swarm UAV designs, ranging from payload and platform trade offs to networking and autonomy approaches, the range of specifications for permitted UAVs within the competition are intentionally broad. However, in consideration of safety, the general class of UAVs is nominally constrained by total kinetic energy, that is, dependent on mass and velocity, of the individual UAV.

The UAVs must demonstrate core capabilities, including safe and controllable operations, frequency and data management, reliable failsafe behaviors, and transparent interfaces with the competition infrastructure, e.g., telemetry broadcasts. General guidelines and interface specification documents are to be provided to direct these integration efforts, including networking protocols (e.g., standard telemetry packet formats), necessary emergency protocols, and test environments for development and demonstration of compliance. However, specific implementation is delegated to the participants.

In the first year of the competition, to encourage focus on foundational competencies in swarm UAV design, development, and operations, individual elements of the UAV swarms will leverage simulated sensing and simulated kills provided by the game construct. As described further in the sections below, development of methods for onboard perception (e.g., detection and classification of opponent UAVs) is not explicitly required, nor should the ability to inflict or register damage be included in submitted designs. Note, however, that future instances of the competition are envisioned to encourage innovations in these areas to transfer such determinations (e.g., presence of opponents or registration of successful kills) to onboard capabilities (such as by use of computer vision or integration of "laser tag"-like emitters and detectors, respectively).

These simulated "kills" are registered according to the relative configurations, that is, positions and orientations, of the attacking and the defending UAVs. The nominal model for weapons engagements is air-to-air guns, which allows for added emphasis on research and development in flight control for aggressive maneuvering to obtain targeting advantages. Relevant parameters governing weapon effectiveness, such as maximum weapons range or probability of kill, are predefined and provided to participants in advance, so as to guide in the development of associated targeting tactics and the hardware and algorithmic implementations thereof.

Further, in order to both referee gameplay and monitor flight safety, an "Arbiter" entity is employed. It resides on the ground and communicates with team UAVs and ground stations via a communications network. Each UAV must regularly communicate its position and flight status to the Arbiter, which uses that information in determining the game status and is able to "penalize" UAVs based on rule violations and force UAVs to land based on gameplay and flight safety issues. The telemetry messages UAVs use to report this information will contain (at a minimum) a UAV-unique identifier (assigned prior to the game), the current game time, its current position in LTP or similar coordinates, and its attitude (i.e., roll, pitch, and yaw).

Initially, UAVs may not have the ability to detect other UAVs using cameras or other proximity sensors. Hence the Arbiter will also issue "sensing" messages based upon the telemetry it receives from each UAV. Sensing messages would contain telemetry from other UAVs as well as some status information. For instance, since other UAVs would not observe smoke and flames from a UAV that was already shot down but would need to know its position to avoid collision, a status flag would indicate whether each sensed UAV is "shootable." The Arbiter may constrain which other UAVs it reports back to each UAV based on relative position (e.g., reporting only those within a sphere of fixed radius from the last-reported position of the concerned UAV). This would simulate a rudimentary RADAR.

Likewise, UAVs will not be equipped with actual weapons, kinetic or otherwise. Instead, UAVs will be able to virtually "fire" on one another using messages sent to the Arbiter. These messages would be similar to telemetry messages, except that they would indicate the position and attitude of the firing UAV at the time of firing. The Arbiter would then project a line from the firing UAV outward to a fixed distance and determine if that line intersects any other UAV (or other game target). Since the GPS positions of both firer and firee will contain some error and telemetry is reported only at discrete times, it is necessary to interpolate positions at the time of firing. An initial proposal is to create "hit regions" described by spheres (or more generally, elliptical solids) where each pair of adjacent reported positions is affixed to opposite ends of a great circle diameter of that sphere. A 2-D approximation of this technique is shown in Figure 3. If a UAV reports its position less frequently, the distance between the telemetry points increases and so does the hit region. This incentivizes sending telemetry frequently. So as to de-incentivize over-reporting, the Arbiter could ignore telemetry messages within a yet-to-be-determined grace period following the last message.

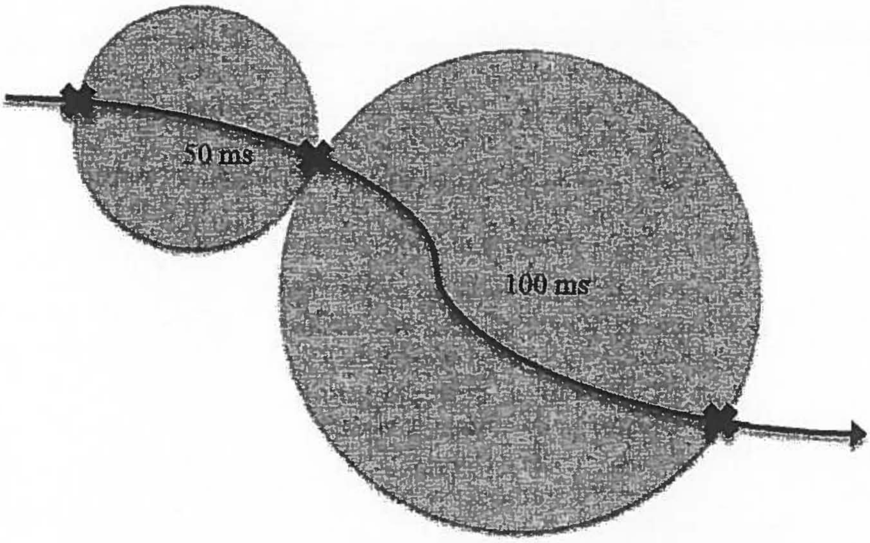

Figure 3: Hit Regions between reported UAV positions

The messages sent from the Arbiter to each UAV can be roughly categorized as hits, penalties, and game status and control. Hits are sent by the Arbiter when it is determined that another UAV fired at and successfully hit the concerned UAV. The action is determined by the competition rules below but in general it would be to land immediately. Penalties are sent when a game play rule is violated and may have various associated actions and repercussions. Game status and control range from announcing when the game starts and ends to issuing emergency all-land messages, indicating that all aircraft must land immediately.

Competition Execution

In keeping with the rapid pace of advancements in swarm UAV capabilities, the competition design described herein proposes the following rules as a basis for the finalized rules, and are subject to evolving with development of new technologies or identification of additional emerging operational needs.

Individual Battles: As with all adversarial contexts, both offensive and defensive actions are critically important to the game. As such, there are two ways to score points within the construct of the game. Specifically, the offensive capability represented by landing one's UAV sufficiently close to the opponent's flag (at a predetermined and measurable distance) is awarded one point. The defensive capability of intercepting and negating the opponent's UAV with one's own UAV, that is, conducting air-to-air combat, is notionally awarded fifty points for each successful UAV kill. The relatively low value of the former reflects the current technological maturity of automatic landing for UAVs, already available in many commercial and open-source mission planning software. In contrast, autonomous aerial interdictions of adversarial contacts are still an open, if not incredibly difficult, technological challenge, likely requiring substantial resources to develop the requisite capabilities to accomplish such a task. As such, the point value of this defensive capability is (again, notionally) assessed to be fifty times greater.

With such a point system construct, teams are able to develop strategies for both game plan and UAV swarm design that maximize their expected number of points obtained in each battle. Not only is the relative importance of defense versus offense captured by this point scoring system, it also provides a measure of the technological disparity at present, which can be used as a guide for future investment in core or enabling technologies. Further, with each iteration of the competition, one can potentially observe the impact of new innovations revealed at each event,. For example, the following competition's respective valuations for offense versus defense might be 1:25, representing a two-fold improvement in defensive capabilities (i.e., instead of 50) but still reflecting a disparity measure of 25 times (i.e., defense is "25 times harder" than offense).

At the conclusion of each game, comprising the two battle halves described earlier, the team that has accrued more points will be designated the victor and will advance within the competition.

Tournament play: The Swarm vs. Swarm UAV Challenge competition is envisioned to draw participation from multiple university and research institutes, enabling a tournament-style, single elimination construct. In particular, the inaugural year will provide for **eight** participating teams, to engage in quarter-, semi-, and final rounds of competition resulting in a single winner of the overall competition.

PRELIMINARY RESULTS IN SWARM UAV FIELD EXPERIMENTS

Ongoing development and demonstration of enabling capabilities at the Naval Postgraduate School have continued to push towards realization of the Swarm vs. Swarm UAV Challenge. Specifically, over the past year, the academic, research, and engineering team in NPS' Advanced Robotic Systems Engineering Laboratory (ARSENL) has made significant and accelerated progress towards fielding an autonomous UAV swarm as a candidate participant in the Swarm vs. Swarm UAV Challenge. We focus the discussion on several key areas and results, highlighting the holistic systems approach spanning swarm concepts through field experiments.

Agile Development of Swarm UAV Capabilities

As the rapid pace of technological development in robotic and unmanned systems continues to accelerate, so must the processes and operational constructs also advance in tandem to fully utilize and achieve their potential. In this context, ARSENL engages in an aggressive spiral development approach to rapidly innovate, integrate, and instantiate new concepts and capabilities. The confluence of lower costs for autonomous systems, easier access to experimentation sites, faster identification of issues through crowd-sourced testing, and increasing operational relevance of swarm technologies creates an ideal opportunity for accelerated iterative development. Rather than conventional, more sequential approaches used for development and testing of new technologies, a tight spiral process model often implemented for software development is better suited to ARSENL's needs for "agile innovation" in robotics capabilities. Even a moderately paced, quarterly experimentation schedule (Aug-12, Oct-12, and Jan-13) was too slow to match the pace of development within the ARSENL group. Rather, these experiences led to adoption of a much faster operational tempo of frequent experimentation every four to six weeks (Feb-13, Mar-13, May-13, Jun-13), enabling substantial progress in both refining processes and identifying lessons learned, to be incorporated into subsequent experiment events.

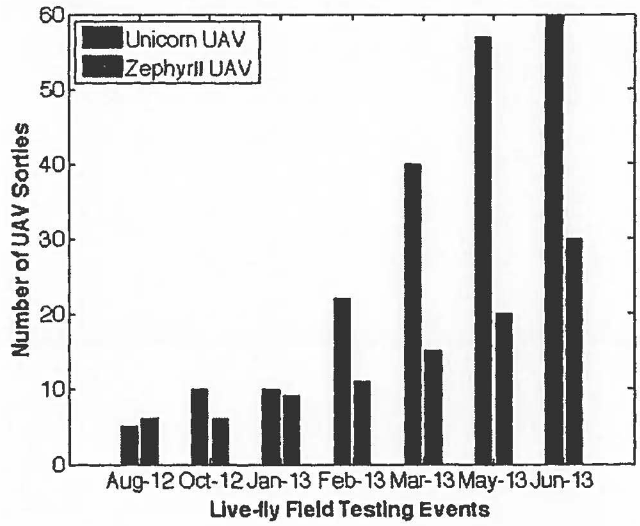

Figure 4: Cumulative Number of Sorties Since Start of Field Experimentation Activities

The benefit of this accelerated pace is evident in Figure 4, which showcases the number of sorties for two UAV platforms used in live-fly field tests as a function of experimentation event annotated by month. Notably, from the time the ARSENL was established at the Naval Postgraduate School in June 2012 until the team's ability to conduct its first live-fly field experiments in August 2012 (that is, only 2.5 months) readily demonstrates the enabling technologies available through advances in commercial and open-source robotics communities. As a highlight, in the past thirteen months since becoming operational last year, NPS ARSENL has conducted seven experimentation events comprising 90 UAV sorties between two different fixed-wing UAV platforms.

Access to field experimentation sites continues to be a critical enabler for facilitating these rapid advancements in UAV swarm capabilities, such as NPS partnerships with Camp Roberts or Fort Hunter Liggett in California and their restricted airspace and test ranges. The importance of such experimentation locales highlights one of the objectives of the Swarm vs. Swarm UAV Challenge, that is, to *provide a venue* where innovation can be fostered and demonstrated. Though selection of the competition venue has yet to be concluded, the above experiences highlight that such partnerships can be both readily viable and incredibly beneficial to the robotics communities.

Leveraging Both Commercial and Open Source Resources for Swarm UAV Innovation

As evidenced by the rapid explosion of aerial robotics technologies, new capabilities afford new opportunities to innovate, whether in the academic, commercial, or personal domains. Recent efforts at NPS described above highlight the advantages of leveraging commercial-off-the-shelf UAV capabilities as a baseline system on which to gain experience and identify limitations in platform, command and control, and other relevant systems for swarm UAV operations. However, parallel development efforts increasingly focus on leveraging open source resources for flight control, platform, and autonomous capabilities that provide not only significant cost savings but take advantage of an accelerated development timeline due to their crowd-sourced nature.

In order to benchmark current capabilities in multi-UAV research, ARSENL uses its fleet of 60" *Unicorn* UAVs (see Figure 5), made by Procerus Technologies (a Lockheed Martin company).[27] These flying wing airframes are manufactured out of EPP foam, are nominally catapult launched, and are powered by lithium polymer batteries with an average endurance of about 45 minutes. Flight speeds can vary with nominal cruise around 20 meters per second (40 knots). Associated with the *Unicorn* UAVs are the *Kestral*™ autopilot for avionics and autonomous flights and *Virtual Cockpit*™ ground control station (GCS) software for real-time flight management. Communication between UAV and the GCS is across 900MHz radio communications, which provides exchange of telemetry and commands.

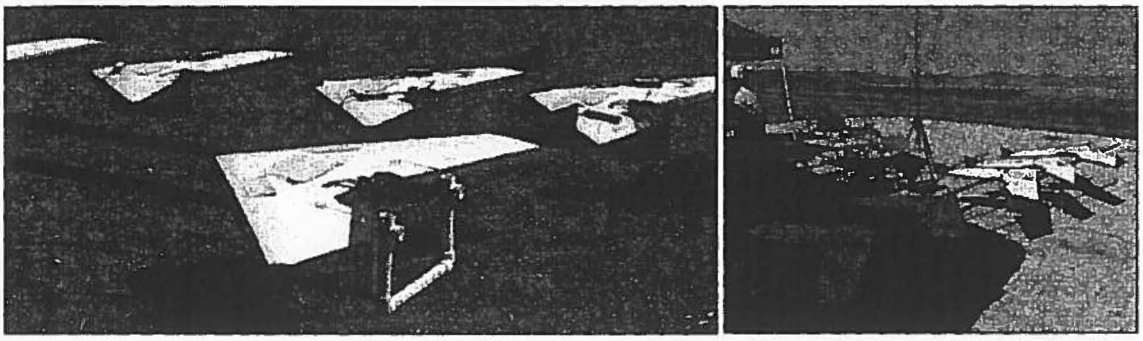

Figure 5: NPS ARSENL fleet of 60" *Unicorn* UAVs

The COTS ability to fly several UAVs simultaneously through *Virtual Cockpit*™ enabled extensive early testing and characterization of such multi-UAV operations, including identification of shortcomings in equipment, operator software, flight preparation processes, and infrastructure. These insights remain invaluable in the design of NPS' swarm UAV capabilities.

To realize these advanced capabilities, the requirements for customizable and modular components, cost effectiveness for large numbers of UAVs, and rapid development and testing are more so critically important, and as such, we look to leverage open-source resources and low-cost solutions to commercial alternatives. Examples of such resources include open-source hardware and software designs for flight control, autonomy, and management, like the APM or PX4 autopilots, community-developed APM:Plane firmware, and *Mission Planner* or *QGroundControl* ground control station software.[28,29] Coupled with a rapidly increasing hobby and consumer marketplace for (semi-) autonomous small UAVs (e.g., RC/model aircraft), the open-source community offers substantial benefits in virtually all elements of the systems development process.

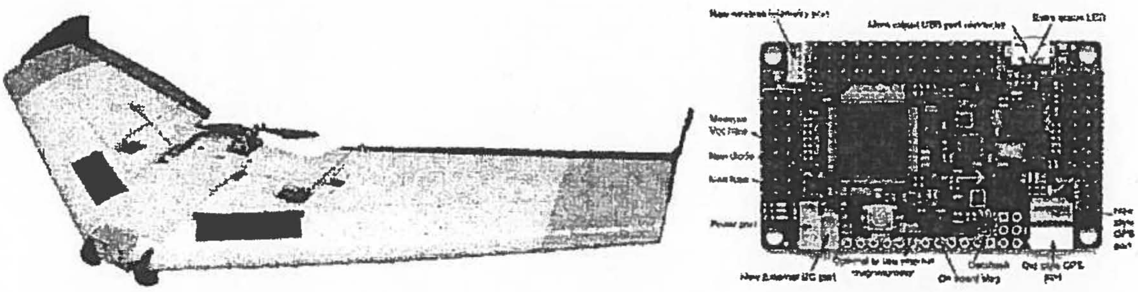

Figure 6: Prototype NPS ARSENL UAV designs integrating low-cost Ritewing *ZephyrII* RC aircraft platform (left) and the open-source APM autopilot (right, from Reference 29)

As a prototype and baseline system, the NPS ARSENL team constructed several initial iterations using the Ritewing *ZephyrII*[30] flying wing, which is nominally an RC model aircraft, and integrated the open-source APM autopilot, as illustrated in Figure 6. The *ZephyrII* has a 56" wingspan (770 sq. inches wing area), with elevons and throttle as its control inputs in the flying wing configuration. The APM autopilot provides a variety of interfaces, including outputs for motor, servos, and additional telemetry as well as inputs from sensors, e.g., GPS, barometer, airspeed, magnetometer, inertial measurements, and also command messages from the ground control station.

Flightline Optimization

As the number of planes per mission increases, the efficiency of the flight line becomes more and more important. Since planes have a limited endurance, takeoffs and landings need to take place as quickly as possible.

One of the means we used to speed up preflight checks was to parallelize tasks. Initially we had a single preflight checklist, but we found that some things could be done at the same time. While the flight technician is checking the plane for physical defects, the GCS operator checks to ensure that the radios are functional, that software settings are correct, etc. During final preparations before launch, flight techs can perform the motor run-up check and prep the plane on the launcher while the GCS operator confirms waypoint placement, geofence placement, GPS connectivity, and obtains permission to takeoff from the tower.

Another means to decrease preflight check time was to identify tasks that only need to be performed once per day or once per trip and remove them from the checklist used for every flight. Radio channel settings and center of gravity are verified before the first flight of an entire event and do not need to be checked again until the next event unless the plane suffers a hard landing. Emergency beacon tests and range checks only need be performed at the start of every day of an event.

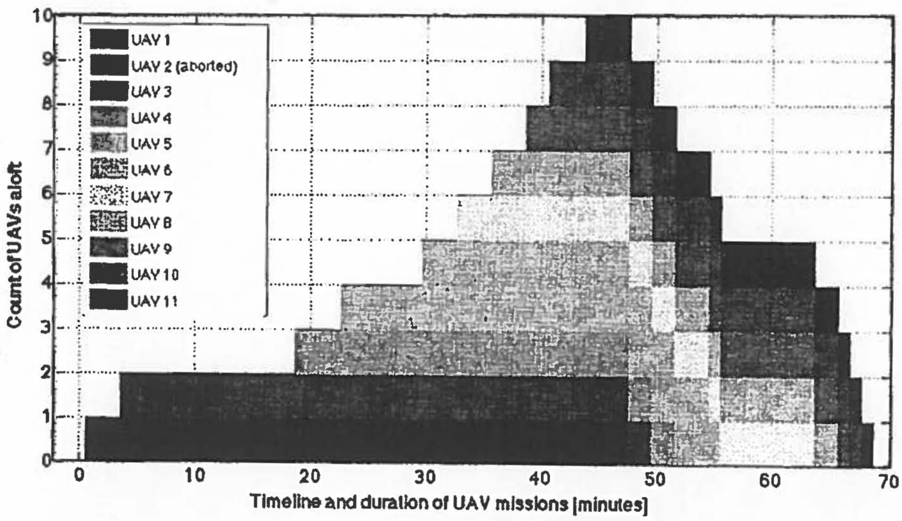

Figure 7: Ten-UAV Mission Timeline, including time between launches and recovery

The resulting capabilities afforded by these enhancements to flightline operations include the successful deployment and operation of ten UAVs during recent field experiments. The objectives of these experiments included demonstration of the impact of improved logistics processes and determination of the workload levels for flight technicians and ground operators (rather than on cooperative multi-UAV behaviors). The timeline and visualization of the launch, flight, and recovery of the UAV fleet are illustrated in Figure 7 and Figure 8. One can observe the challenges faced when attempting to deploy larger numbers of UAVs, including the required time for a launch window for current approaches using a manual catapult launching system. Further research in automated and/or parallel launch capabilities is clearly merited to address this challenge.

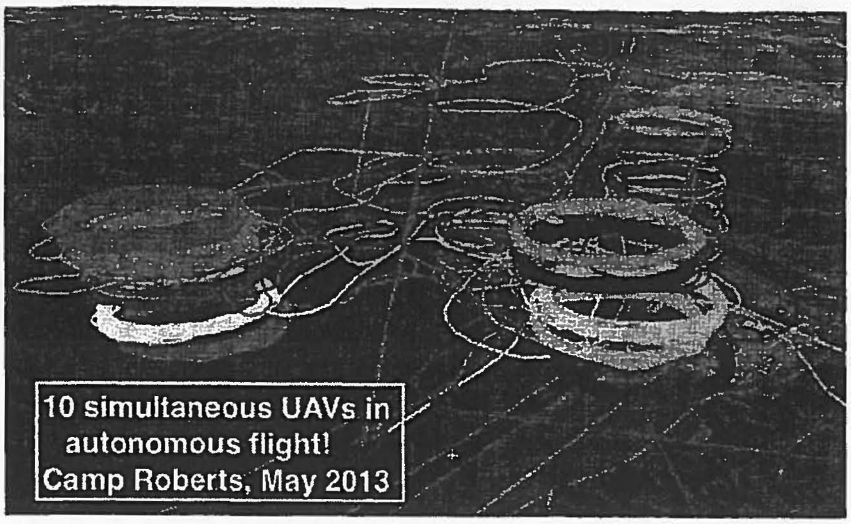

Figure 8: Trajectories of the Ten-UAV Mission (Camp Roberts, Calif., May 2013)

Algorithms for UAV Swarm

Studies have been done on the coordination of teams of UAVs sharing a common goal, but typically team sizes are small, numbering from two to ten.[31,32,33]. Other relevant studies do employ larger swarms, but their models are based on cellular automata and individual agents in a swarm are not as complex as an individual UAS.[34,35,36]

Once swarms have been formed around common goals using some assignment methodology, it is often desirable that they maintain spatial cohesion (e.g., fly in formation). One method to achieve cohesion is Boids flocking[37], though numerous other methods may be used, such as collective potentials[38] a variation of Boids flocking that incorporates inertia[39], or various other flocking methodologies.[40] We have verified Boids flocking is feasible for UAVs in simulation and have also completed some encouraging fieldwork that indicates this should be possible in operational scenarios as well.

Operational test flights of swarms of size three were done in which planes flew in formation using a leader-follower model. These initial tests employed altitude separation as an additional safety, though in future flights we will enforce separation between swarming planes via the Boids algorithm itself. Planes will also need independent collision avoidance methods independent of Boids to avoid crashing with planes of their own team, which are flying in a different swarm. Two methods were tested to allow followers to stay with lead planes: `Mimic_Waypoint` and `Pure_Follow`.

The `Mimic_Waypoint` implementation allows for followers to receive updates whenever their leader began flight towards a new waypoint (see Figure 9). No attempt is made to ensure that speed is matched, that is, a follower might arrive at a waypoint before the leader. In that case, then the follower would loiter until the leader starts towards its next waypoint. In the case of air-to-air combat, if a swarm is transiting towards a target, then all planes should fly at their maximum velocity and not be tied too much to the velocity of the "lead" plane if that plane is slightly slower than other planes in the swarm. The plane that arrives at the target first should engage without having to wait for the leader to arrive. However, we still wish to enforce some sort of spatial cohesion in a swarm, that is, swarm mates should not get too far from one another.

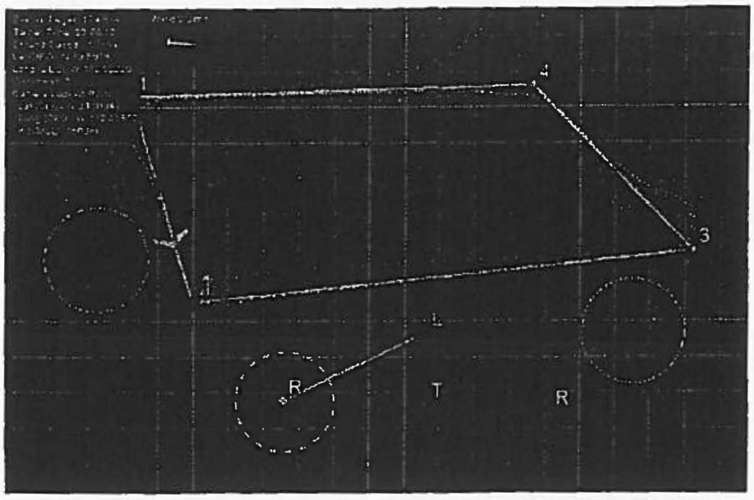

Figure 9: Screenshot of *Virtual Cockpit*™-based simulation of three UAVs employing `Mimic_Waypoint`, where follower UAVs use same waypoint and speed as lead plane

The `Pure_Follow` method (illustrated in Figure 10) removes the requirement for the leader to communicate its intended destination waypoint to followers. Followers instead employ dead reckoning to determine the direction and velocity of the lead plane using telemetry received from the leader plane. This approach requires periodic updates about the lead plane's position to be sent to all followers. Since following planes know the lead plane's velocity, followers are able to adjust their speed to maintain swarm cohesion without getting too far ahead of the lead plane.

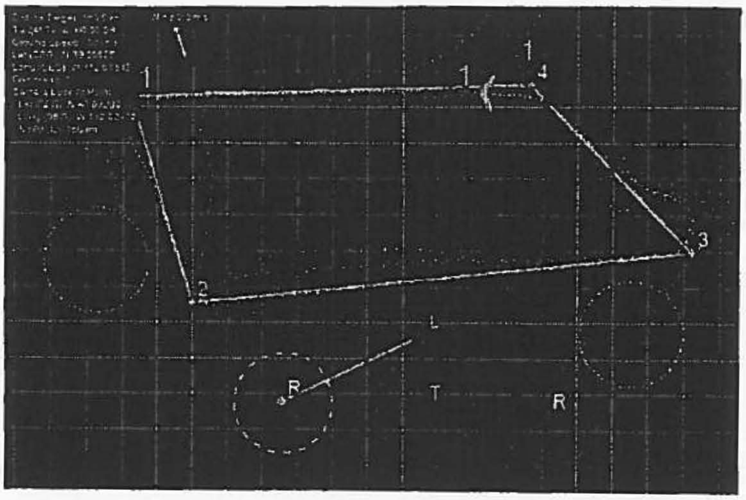

Figure 10: Screenshot of *Virtual Cockpit*™-based simulation of three UAVs employing `Pure_Follow`, with Blue following Orange, and Red following Blue.

In both `Mimic_Waypoint` and `Pure_Follow`, a centralized controller is employed to pass data between planes through the ground control station software. In recent field experiments, both methods functioned nominally for several waypoints, but the system began suffering communication lag about midway through a mission, that is, following planes gradually received data about the lead plane that were increasingly out of date. This lag was slower to affect the `Mimic_Waypoint` method than the `Pure_Follow` method. Since the `Pure_Follow` method requires more messages to pass through the system, we attribute the lag to queuing delay. As *Virtual Cockpit*™ is a closed source system, we could not control its approach to queuing of messages and commands. We verified that queuing delay was a factor in the problem by waiting until lag was sufficiently severe and then commanding followers to stop following the leader and to choose their own waypoints. The waypoint change commands did not make it to the followers before the end of flight due to the backlog of waypoint commands already in the message queue.

Ongoing development and integration efforts to mitigate the lag include:

- Not sending waypoint updates through a centralized GCS, but rather determine the updates onboard the plane. This will reduce the overall traffic flowing through the network and is one means of dealing with queuing delay.
- Use an open source system for the GCS (e.g., *QGroundControl*[41]). If it should be the case that queuing delay causes lag again, then an algorithm such as leaky bucket[42] could be employed to empty over-full queues.

In order to form a team into swarms, each swarm must decide upon a common goal. Selecting a common target is one means of arriving at a common goal. For example, previous works examine methods for assigning individual members of a team to given tasks, such as with multi-agent simulations used to investigate different methods for assigning blue agents to red targets in a typical red/blue combat scenario.[43]

Efficient closed form solutions for assignment using linear programming are possible when employing a centralized method. However, a centralized assignment strategy requires a hub-and-spoke communication architecture, the disadvantages of which are discussed in the Swarm Networking Architecture section. Furthermore, a centralized solution introduces a single point of failure in the swarm design and removes some of the autonomy from individual agents.

To address some of the problems introduced by centralized assignment we explored decentralized methods. The first approach assumes implicit coordination, in which each agent implements a centralized solution based on current world state. No communication is required between agents; each agent chooses its optimized solution and executes it. Second, a market-based approach is developed, in which blue agents bid for targets they can sense based on a cost criteria (e.g., distance to red target). This market solution is more decentralized than the linear programming method, but does require a centralized broker. To achieve a more distributed solution, a third method, termed implicit market-based, allows each agent to act as their own broker and carry out auctions independent of other agents.

Additional research within the ARSENL considered significant factors for a UAV swarm defending against an aggressor swarm in air-to-air engagements.[44] This study found individual agent speed, team size, armoring, and endurance to be significant factors in predicting a successful engagement. Surprisingly, the blast range of a weapon was found to be a less significant factor. Though not initially intuitive, this conclusion becomes clearer when considering that the effectiveness of a weapon is mitigated if (a) a UAV is slower than its target to such a degree that it cannot lock on its weapon, (b) a single UAV is engaged by so many adversaries at once that its weapon is rendered ineffective, or (c) if the weapon cannot pierce the armor of a target it is useless. This study also was conducted entirely in simulation and results will be verified as part of ongoing efforts to develop swarm tactics and design swarm UAVs.

Swarm Networking Architecture

Design of the communications network that allows UAVs to communicate among themselves and with the aforementioned Arbiter is crucial to the quality of game play, and has thus been a focus of research and development within ARSENL. Network latency and therefore loss must be minimized. Unlike typical Internet traffic where some increased latency is acceptable in exchange for the opportunity to resend messages lost in transit, decisions here must be made in near-real time. Hence for many messages, it is better to accept loss than to wait while they are resent. At the same time, the ordering of certain messages, such as virtual fires, must be preserved. Suppose two opposing UAVs, *A* and *B*. *A* fires at *B* a fraction of a second before *B* (not knowing yet that it has been hit) fires at *A*. However, due to the nature of the network, the message from *B* arrives at the Arbiter first. Both the network and the messaging protocol must be designed to ensure, within some reasonable margin, that *A* is judged to have fired first.

There are numerous network models that might be used to address communications in this setting. One of the simplest and most intuitive is the hub-and-spoke model. For instance, each UAV has its own dedicated communications channel (e.g., wireless frequency) between itself and the Arbiter. Each could then send and receive messages with the Arbiter at will. Supposing that operating 100 different channels is impractical, all UAVs could operate on a common channel using an access protocol such as Time Division Multiple Access (TDMA). In this case, each UAV would get an equal fraction of time on a single channel, in which it can communicate with the Arbiter.

However, this model suffers from a few deficiencies. First, how do UAVs communicate among themselves? A separate mechanism may be used, but the issue remains. Second, what happens when one UAV is out of communications range of the Arbiter? The current approach taken by ARSENL is to leverage wireless mesh technology, which allows each UAV to route its messages through other UAVs to the Arbiter (or to the destination UAV). This allows communication between any two endpoints, and individual UAVs need not operate within communications range of the Arbiter so long as the *collection* of UAVs is within range of the Arbiter. However, this model too comes at a cost, namely in terms of capacity and latency. Each time a message is routed through another UAV, the communication channel is further consumed (reducing capacity). This routing also requires added processing time in addition to added transmissions (increasing latency). At this point, the wireless mesh network configuration still appears to be the most favorable communication model in this setting.

It is assumed that each team develops its own intra-swarm communications protocol. The focus here is on the communications necessary for game play, between UAVs and the Arbiter. There is much work in network gaming protocols that inspires this approach.[45,46]

Establishing a common sense of time is essential for many of these operations. Since messages are communicated across a network with latencies ranging from 10s to 100s of milliseconds, a UAV may have moved considerably from its last reported position. The Arbiter must know the time at which positions were reported to calculate hits, and other UAVs must know how recent telemetry is to project future positions of enemy UAVs. It is currently assumed that common time is established outside the network protocol used for the game, either by GPS time or by the Network Time Protocol (NTP) or similar methods. In practice, a custom protocol for synchronizing clocks will not be more effective than these methods.

WAY AHEAD

Competition Roadmap

The ambitious vision for the Swarm vs. Swarm UAV Challenge competition leverages the accelerating trends exhibited by the robotics and unmanned systems research communities in the areas of many-agent robotics. Forthcoming actions relevant to the competition include:

1. Generation of detailed competition rules and specifications
2. Integration of collaboration tools to create an ecology for collaborative development

3. Designation of competition site, including logistics and infrastructure support
4. Call for participation, with screening and selection of qualifying participants
5. Continued live-fly testbed development, e.g., networking and airspace management
6. Determination of qualification and main event dates and associated schedules

Ongoing engagement with academic, research, government, and industry partners and stakeholders will ensure close interactions to help shape and create this cross-cutting competition event.

Near-term Research Focus Areas

In addition to the organization and design of Swarm vs. Swarm UAV Challenge competition, the Advanced Robotic Systems Engineering Laboratory at the Naval Postgraduate School is actively engaged in furthering its advances in swarm UAV concepts, operations, and live-fly field experiments. Example areas for active and/or targeted near-term research efforts by the ARSENL research team include a number of scientific and operational endeavors through both theoretical and field experimentation avenues.

Enhanced Onboard Autonomy: Advances in low-cost, small size, and power-efficient, communication, computation, and perception hardware opens up new avenues for applying high-level autonomous capabilities directly onboard the individual UAV swarm elements.

Human-Swarm Interaction: The challenges of human factors when engaging, let alone commanding, swarms of autonomous agents is an emerging area of research, but one that highlights the role of humans in addressing the scale, dynamics, and collective decision making aspects of swarm UAVs.

Swarm Mesh Networking: New paradigms for networking of large numbers of highly dynamic autonomous systems are vitally important to enabling many of the essential capabilities that will allow for low-latency, high-bandwidth communications both intra- and inter-swarm.

CLOSING REMARKS

The breadth of the research challenges posed by exploring and developing swarm UAVs, ranging from advances in swarm tactics to integration efforts for swarm live-fly operations, ensures that many opportunities for innovation, largely through conversation and collaboration, are readily available. The Swarm vs. Swarm UAV Challenge presented in this paper, as well as the preliminary research efforts at the Naval Postgraduate School in swarm UAV concepts and capabilities, demonstrate the rapidly changing landscape of future robotics and unmanned systems, particularly in collective systems of large numbers of autonomous agents, whether cooperative or adversarial. It is the intent of this outlined effort to inspire innovation in key research areas that have the potential to initiate longstanding impact across academic, defense, and commercial robotics communities.

REFERENCES

[1] T. McLain and R. Beard, "Unmanned air vehicle testbed for cooperative control experiments," in Proc. American Control Conference, 2004, vol. 6, pp. 5327–5331.

[2] R. Beard, D. Kingston, M. Quigley, D. Snyder, R. Christiansen, W. Johnson, T. McLain, and M. Goodrich, "Autonomous vehicle technologies for small fixed wing UAVs," AIAA J. Aerospace, Comput., Information, Commun., vol. 2, no. 1, pp. 92–108, Jan. 2005.

[3] J. How, E. King, and Y. Kuwata, "Flight demonstrations of cooperative control for uav teams," in In Proc. of AIAA 3rd Unmanned Unlimited Technical Conference, Workshop and Exhibit, 2004.

[4] J. S. Jang and C. J. Tomlin, "Design and Implementation of a Low Cost, Hierarchical and Modular Avionics Architecture for the DragonFly UAVs," in Proc. of the AIAA GNC Conference, 2002.

[5] S. Bayraktar, G. Fainekos, and and G. Pappas, "Experimental cooperative control of fixed-wing unmanned aerial vehicles," in in Proceedings of the 43rd IEEE Conference on Decision and Control, 2004.

[6] D. Jung, E. J. Levy, D. Zhou, R. Fink, J. Moshe, A. Earl, and and P. Tsiotras, "Design and Development of a Low-Cost Test-Bed for Undergraduate Education in UAVs," in in Proceedings of the 44th IEEE Conference on Decision and Control, 2005, pp. 2739–2744.

[7] D. T. Cole, S. Sukkarieh, A. H. Goktogan, H. Stone, and R. Hardwick-Jones, "The development of a real-time modular architecture for the control of UAV teams," in In Proceedings of the 5th International Conference on Field and Service Robotics, 2005.

[8] P. Almeida, R. Bencatel, G. M. Gonçalves, and J. B. Sousa, "Multi-UAV Integration for Coordinated Missions," in Encontro Científico de Robótica, Guimarães, 2006.

[9] V. Dobrokhodov, O. Yakimenko, K. Jones, I. Kaminer, E. Bourakov, I. Kitsios, and M. Lizarraga, "New Generation of Rapid Flight Test Prototyping System for Small Unmanned Air Vehicles," in AIAA Modeling and Simulation Technologies Conference Proceedings, 2007.

[10] J. Tisdale, A. Ryan, M. Zennaro, X. Xiao, D. Caveney, S. Rathinam, J. K. Hedrick, and R. Sengupta, "The software architecture of the Berkeley UAV platform," in Proc. IEEE Conf. Control Applications, 2006, pp. 1420–1425.

[11] B. Argrow and A. Houston, "UAS for in situ sensing of an atmospheric airmass boundary," in In AIAA InfoTech at Aerospace Conference, 2007, vol. 1, pp. 453–460.

[12] J. Elston and E. W. Frew, "Hierarchical distributed control for search and tracking by heterogeneous aerial robot networks," in Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on, 2008, pp. 170–175.

[13] S. Huh and D. H. Shim, "A Vision-Based Automatic Landing Method for Fixed-Wing UAVs," in in Selected papers from the 2nd International Symposium on UAVs, Reno, Nevada, U.S.A. June 8–10, 2009, K. P. Valavanis, R. Beard, P. Oh, A. Ollero, L. A. Piegl, and H. Shim, Eds. Springer Netherlands, 2010, pp. 217–231.

[14] S. Leven, J.-C. Zufferey, and D. Floreano, "A minimalist control strategy for small UAVs," in In Proceedings of the 2009 IEEE/RSJ Int'l. Conf. on Intelligent Robots and Systems,, 2009.

[15] S. Hauert, S. Leven, M. Varga, F. Ruini, and A. C. et al., "Reynolds flocking in reality with fixed-wing robots: communication range vs. maximum turning rate," in IEEE/RSJ International Conference on Intelligent Robots and Systems, 2011.

[16] DARPA, "UAVForge." http://www.uavforge.net/. [Accessed: 15-Jul-2013].

[17] DARPA, "ACTUV." http://archive.darpa.mil/actuv/. [Accessed: 15-Jul-2013].

[18] DARPA, "Urban Challenge." http://archive.darpa.mil/grandchallenge/. [Accessed: 15-Jul-2013].

[19] DARPA, "Robotics Challenge." http://www.theroboticschallenge.org/. [Accessed: 15-Jul-2013].

[20] RoboCup Federation, "RoboCup." http://www.robocup.org/. [Accessed: 15-Jul-2013].

[21] Google, "Google AI Challenge." http://aichallenge.org/. [Accessed: 15-Jul-2013].

[22] "UAV Challenge - Outback Rescue." http://www.uavoutbackchallenge.com.au/. [Accessed: 15-Jul-2013].

[23] AUVSI Foundation, "International Aerial Robotics Competition." http://iarc.angel-strike.com/. [Accessed: 15-Jul-2013].

[24] AUVSI Seafarer Chapter, "Student Unmanned Air Systems (SUAS) Competition." http://www.auvsi-seafarer.org/news-events/2013-competition.aspx. [Accessed: 15-Jul-2013].

[25] NASA, "Unmanned Aircraft Systems Airspace Operations Challenge (UAS AOC)." http://www.nasa.gov/directorates/spacetech/centennial_challenges/uas/index.html. [Accessed: 15-Jul-2013].

[26] DIYDrones.com, "DIYDrones Trust Time Trial Contests." http://diydrones.com/notes/Contests. [Accessed: 15-Jul-2013].

[27] Lockheed Martin Procerus Techonologies, "Kestrel Flight Systems," http://www.lockheedmartin.com/content/dam/lockheed/data/ms2/documents/procerus/Kestrel_Flight_Systems_2012.pdf, July 2013.

[28] Swiss Federal Institute of Technology, "PX4 Autopilot." https://pixhawk.ethz.ch/px4/modules/px4fmu.

[29] DIYDrones.com, "APM:Plane." http://plane.ardupilot.com/.

[30] Ritewing RC, "ZephyrII RC Aircraft." http://www.ritewingrc.com/.

[31] J. Bellingham, M. Tillerson, A. Richards, and J. P. How, "Multi-task allocation and path planning for cooperating UAVs," in in Cooperative Control: Models, Applications and Algorithms, Springer, 2003, pp. 23–41.

[32] Y. Jin, A. A. Minai, and M. M. Polycarpou, "Cooperative Real-Time Search and Task Allocation in UAV Teams," in Proc. of 2003 IEEE Int'l. Conf. on Decision and Control, 2003, vol. 1, pp. 7–12.

[33] V. K. Shetty, M. Sudit, and R. Nagi, "Priority-based assignment and routing of a fleet of unmanned combat aerial vehicles," Computers & Operations Research, vol. 35, no. 6, pp. 1813–1828, 2008.

[34] T. Fukuda, S. Nakagawa, Y. Kawauchi, and M. Buss, "Structure decision method for self organising robots based on cell structures-CEBOT," in Robotics and Automation, 1989. Proceedings., 1989 IEEE International Conference on, 1989, pp. 695–700.

[35] H. Guo, Y. Meng, and Y. Jin, "Swarm robot pattern formation using a morphogenetic multi-cellular based self-organizing algorithm," in Robotics and Automation (ICRA), 2011 IEEE International Conference on, 2011, pp. 3205–3210.

[36] G. Prencipe and N. Santoro, "Distributed Algorithms for Autonomous Mobile Robots," in Proceedings of the Fourth IFIP International Conference on Theoretical Computer Science, 2006, pp. 47–62.

[37] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," ACM SIGGRAPH Computer Graphics, vol. 21, no. 4, pp. 25–34, Aug. 1987.

[38] R. Olfati-Saber, "Flocking for Multi-Agent Dynamic Systems: Algorithms and Theory," IEEE Transactions on Automatic Control, vol. 51, no. 3, pp. 401–420, Mar. 2006.

[39] D. Lee and M. W. Spong, "Stable Flocking of Multiple Inertial Agents on Balanced Graphs," IEEE Transactions on Automatic Control, vol. 52, no. 8, pp. 1469–1475, Aug. 2007.

[40] N. Xiong, J. He, Y. Yang, Y. He, T. Kim, and C. Lin, "A Survey on Decentralized Flocking Schemes for a Set of Autonomous Mobile Robots," Journal of Communications, vol. 5, no. 1, pp. 31–38, Jan. 2010.

[41] Swiss Federal Institute of Technology, "QGroundControl." http://qgroundcontrol.org/start. [Accessed: 15-Jul-2013].

[42] J. F. Kurose and K. W. Ross, Computer Networking. 5th ed. Boston, MA: Pearson Education, 2012.

[43] M. Day, "Multi-Agent Task Negotiation Among UAVs to Defend Against Swarm Attacks," Master's Thesis. Naval Postgraduate School, March, 2012.

[44] M. F. Muñoz, "Agent-Based Simulation and Analysis of a Defensive UAV Swarm Against an Enemy UAV Swarm," Master's Thesis. Naval Postgraduate School, June, 2011.

[45] P. Bettner and M. Terrano, "1500 archers on a 28.8: Network programming in Age of Empires and beyond," Presented at GDC2001, vol. 2, p. 30p, 2001.

[46] Valve, "Source Multiplayer Networking." https://developer.valvesoftware.com/wiki/Source_Multiplayer_Networking. [Accessed: 15-Jul-2013].

AUVSI Unmanned Systems 2013

Washington, DC, USA
12-15 August 2013

Volume 1 of 2

ISBN: 978-1-62993-324-5

Printed from e-media with permission by:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571

Some format issues inherent in the e-media version may also appear in this print version.

Printed by Curran Associates, Inc. (2013)

For permission requests, please contact the Association for Unmanned Vehicle Systems International at the address below.

Association for Unmanned Vehicle Systems International
2700 South Quincy Street
Suite 400
Arlington, VA 22206

Phone: (703) 845-9671
Fax: (703) 845-9679

info@auvsi.org

Additional copies of this publication are available from:

Curran Associates, Inc.
57 Morehouse Lane
Red Hook, NY 12571 USA
Phone: 845-758-0400
Fax: 845-758-2634
Email: curran@proceedings.com
Web: www.proceedings.com

TABLE OF CONTENTS

VOLUME 1

VOLUME 2