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# Deployment and Flight Operations of a Large Scale UAS Combat Swarm: Results from DARPA Service Academies Swarm Challenge

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*Abstract*— **The DARPA Service Academies Swarm Challenge (SASC) was a unique opportunity for future military leaders to innovate in the rapidly evolving domain of unmanned aerial system (UAS) swarm combat. The United States Naval Academy (USNA), United States Military Academy (USMA), and United States Air Force Academy (USAFA) competed in head-to-head games of simulated aerial swarm combat. The competition culminated in a live fly event in Camp Roberts CA. This paper describes the participation of the USNA team who won the competition. The students were tasked with developing game strategy, combat tactics, and managing their UAS fleet. This challenge highlighted the need for large scale experiments to identify and push the limits of current technology.**

## I. INTRODUCTION

Unmanned aerial systems (UAS) have become increasingly common in commercial and military applications. During the past decade and a half, computing and sensing technologies have become less expensive, resulting in a significant reduction in the cost of small fixed-wing and multi-rotor UAS [1], [2], [3]. This has motivated many researchers to expand the investigation of UAS technologies into various experimental domains. The theoretical basis for multi-agent UAS swarming has been well established in the literature[4], [5]. Of particular interest more recently is coordination of large numbers of UAS as a swarm [6], [7], [8]. The implementation of a UAS swarm has required significant developments in communication architectures[9], [10], motion coordination[11] and path planning[12]. With specific application to the military, it is a high priority to understand the implications of swarming technologies on combat strategies. This requires a shift in the way UAS technologies are utilized. While currently an intelligence, surveillance, and reconnaissance (ISR) mission is conducted by a single highly valued UAS, much thought must be given to how this will be approached differently if numerous low valued UAS are sent to perform the same mission. Even more interestingly, the notion of swarm UAS operations potentially provides new opportunities and applications that have not yet been discovered. To this end it is important that the future military leaders be exposed to this technology while they are being trained, so they can help break new ground in the use of this technology.

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## II. PROBLEM STATEMENT

Defense Advanced Research Projects Agency (DARPA) approached three service academies, United States Naval Academy (USNA), United States Military Academy (USMA), and United States Air Force Academy (USAFA), with a swarm challenge to test the ability of future military officers to learn how to deploy, operate, and develop combat tactics for autonomous UAS swarms. Each of the three teams was provided with a fleet of 20 fixed wing and 20 quadrotor UAS platforms. The teams were required to field a mixed fleet of 25 UAS to compete in a game of simulated aerial combat. The motivation of the project was to determine if future junior officers at the service academies can learn how to effectively design strategies for and operate a UAS swarm in less than eight months. There were two main areas in which the teams were tasked to innovate swarm technology. The first area, was in swarm offensive and defense strategies and tactics. The second area was in determining effective ways for managing the logistics required to operate a UAS swarm.

This paper presents competition overview, approach, outcomes and results from lessons learned from the challenge from the perspective of the USNA team that won the event.

### A. Competition

The USNA team was composed of 18 Systems Engineering and Computer Science majors. This competition was a capstone project for the students who were seniors and independent research for the underclassmen. Leading up to the live-fly competition there was a series of proficiency challenges and cloud based virtual scrimmages that were used to seed a round-robin tournament. Our team received the most points during these virtual scrimmages and earned the top seed in the competition;the top seed earned our team the first choice on what days to compete.

The competition took place at Camp Roberts, CA, an Army National Guard base. The five day live-fly event consisted of a round-robin tournament between each of the three academies. Prior to the start of the tournament, there was one day reserved for a practice round where the teams had an opportunity to familiarize themselves with the provided hardware and the event operations. This was especially important since leading up to the competition teams had little opportunity to perform full-scale multi-UAS experiments. Prior to arriving at Camp Roberts each team had flown at most two platforms simultaneously. On a competition day, the teams arrived at the airfield at 0700 and the start of the battle round was near 1300 giving them

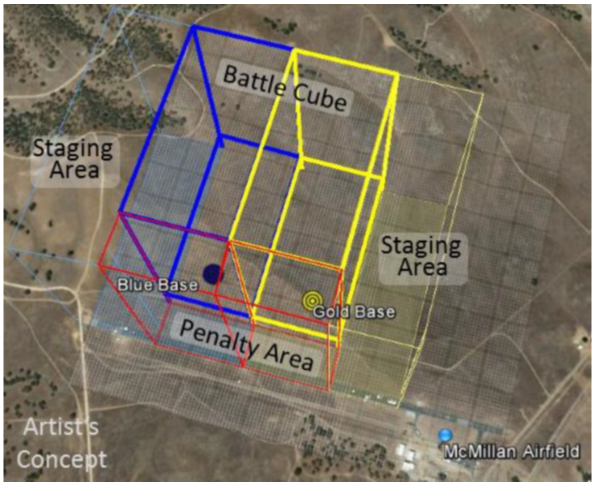


Fig. 1. Artist Concept of Battle Cube [1]

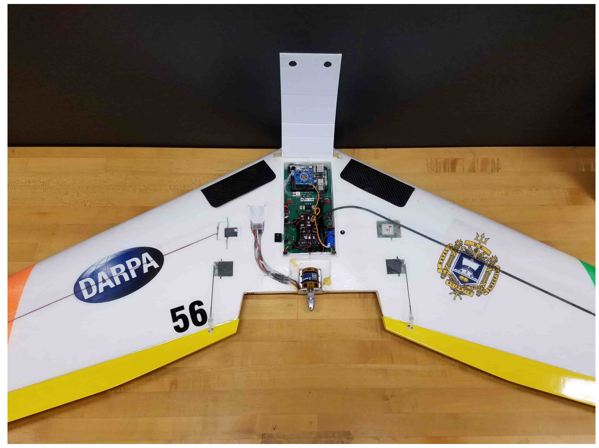


Fig. 2. Rite Wing Zephyr II Fixed Wing UAV

about 6 hours to prepare their fleets for the match. Preparing 40 aircraft for the match in 6 hours was a non-trivial task.

### B. Game Play

The game play consisted of a 25 vs 25 game of UAS "tag". One team's UAS could tag the opposing team's UAS within a certain firing range, or tag an opposing ground base by landing on it. There was a game cube which was 500m × 500m × 500m in dimension, fig. 1 shows the layout of the competition arena. On each end of the game cube was a staging area. Teams were allowed to have more than 25 aircraft in the air but would be assessed a penalty for each aircraft over 25 that entered the game cube. Additional penalties were assessed for active vehicles leaving the field of play after entering the game cube.

The competition round was 30 minutes long. 10 minutes prior to the start of the match a launch window opened wherein teams could begin launching their UAS.

In order to manage tags, the game was scored by a central computer referee (arbiter) monitoring the pose information of both swarms. Tags were simulated by a platform issuing a fire command when an opponent was within its firing range. The simulated weapons had a range of 100 $m$ and targeting angle of 15 $\deg$. If the arbiter determined the opponent was in the range at the time the fire command was issued it would tag the opponent, and it would be required to exit the game cube. The arbiter was also responsible for relaying opponent swarm pose information to the team. During the event the altitudes of the UAS were separated to minimize the chance of a collision. All of the game play occurred in a two-dimensional plane.

Points were awarded for air-to-air tags, air-to-ground tags, and swarm endurance. During the 30-minute round each team could accumulate points from these three categories. The team with the highest score at the end of the round would be declared the winner. The scoring algorithm used in the competition was defined as,

$$s = \alpha A_a + A_g + \chi \sum_{n=1}^{n_{max}} \frac{\tau_n}{T}, \qquad (1)$$

where the first term is the total air-to-air tag score, the second term is the air-to-ground tag score and the last term in the endurance score. $\tau_n$ is the duration the n-th aircraft is active in the game normalized by the total match duration $T$. The coefficients $\alpha$ and $\chi$ were 3.2 and 3.8 respectively. The weights in the scoring algorithm were determined from a series of simulations and virtual scrimmages conducted by DARPA and between the service academies. The final algorithm incentivized air-to-air tags so there would be an emphasis on tactical development and action for the duration of the match.

## III. Hardware

In order to ensure a level playing field, all hardware and basic hardware configurations were standardized by DARPA. The two vehicle platforms utilized in the competition were the Rite Wing Zephyr II (fixed-wing) shown in Fig. 2 and the DJI Flamewheel 450 (quadrotor) shown in Fig. 3. The Zephyr has a 1.5$m$ wingspan and the Flamewheel is about 0.5$m$ from rotor to rotor. Each vehicle had the same payload hardware. A Pixhawk flight controller running the APM flight stack managed low level control for the vehicles, and an Odroid XU4 handled high level planning and communication between vehicles and the ground stations. The fixed-wings had a cruise speed of 20 m/s and a nominal flight time of 45 minutes. The quadrotors had software capped cruise speed of 10 m/s and a nominal flight time of 25 minutes.

## IV. Software

### A. System Architecture

All data exchanged between vehicles or between a vehicle and ground station were sent on an ad-hoc wifi network. For further details regarding the system architecture the reader is referred to [9]. All messages were sent via UDP over the ad-hoc network. The primary benefit of this design was modularity as any entity could communicate with any other

[1]Image taken from DARPA SASC competition rule book

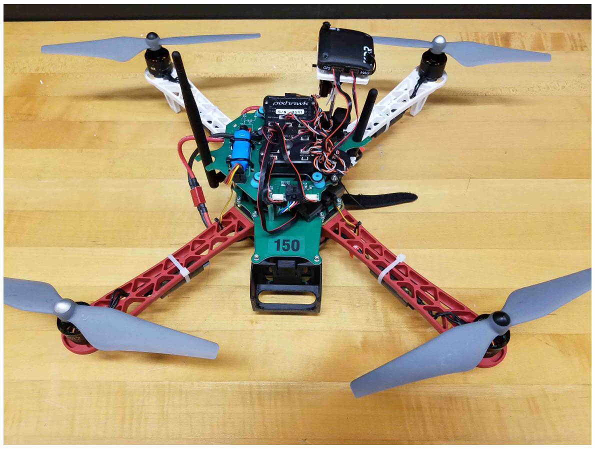

Fig. 3. DJI Flamewheel 450 Quadrotor UAV

entity on the network. During the competition this made it possible for various members of the ground crew to update the software on-board the vehicles simultaneously. To keep the communication between the two swarms deconflicted they were on two different channels and sub-nets of the network. The arbiter was connected to both networks and able to monitor the positions of both swarms and issue tags from one team to the other.

Each vehicle broadcasted its pose over the network at nominal rate of 10Hz. The nature of the network was such that many pose messages could be dropped, or not received by each entity. Particularly as the quantity of vehicles increased the reliability of the communication decreased.

### *B. Interfaces*

Since the focus on the competition was for the Midshipmen and Cadets to develop the behaviors and tactics for the game, the teams were provided several software interfaces that facilitated operations and maintenance of the aircraft. These interfaces were developed by the DARPA team for the competition.

- **Flight Tech Interface (FTI)** - FTI was the primary software interface for basic operations of the aircraft. It allowed the user to perform pre-flight checks for the aircraft as well as set the mode of the aircraft. This software was used by the maintenance crews and the launch operator.
- **Flight Logistics Operations Center (FLOC)** - The FLOC software provided a web based interface for executing the pre-flight checklist as well as recording maintenance tickets for aircraft. The web interface allowed it to be run on a tablet, which simplified the logistics of preparing the aircraft for the match.
- **Swarm Commander** - The Swarm Commander interface allowed the user to set behaviors to the swarm. The user could select individual vehicles or sub-groups of vehicles to change their behavior. This was the interface used by the *swarm commanders* (game players).
- **SwarmViz** - SwarmViz was a 3D interface used for tracking showing the locations of the vehicles in real-time. Its primary function was to provide DARPA personnel and spectators with a visual reference for the game status, which was important since the vehicles were very difficult to see and distinguish with the naked eye.
- **Game Director** - A web-based real-time scoreboard that kept track of the current game score, remaining time, as well as the status of all vehicles in the arena.

## V. Strategy, Behaviors and Tactics

A primary goal of this competition was for the Cadets and Midshipmen to develop and deploy autonomous combat tactics that would help them execute their game strategy. The individual tactics were single agent behaviors based on the estimated pose information from the friendly swarm and the enemy swarm. All of the algorithms utilized were necessarily implemented in a decentralized fashion. The control of the vehicles was way-point based, and the selection of the navigation way-point was the final output of each tactic. In order to achieve the desired trajectory for the vehicle the desired position way-point was moved dynamically by the tactic running aboard the payload computer. This implementation allowed the low-level control on the Pixhawk to be unchanged.

One of the fundamental challenges to be addressed by the tactic development was how to most effectively utilize the strengths of the fixed-wings and quadrotors. While the fixed-wings had more endurance and a higher cruise speed, they cannot hover and spin in place like the quadrotors. The quadrotors however have the constraint of being inefficient aircraft with limited flight time.

To determine our team's overall strategy for the competition we made three observations about the scoring algorithm.

1) Since a ground tag required landing on the opponent's base, an airframe that performed a ground attack would be out for the remainder of the competition. Therefore we determined to save ground attacks for the end of the match.
2) Eq. 1 indicates the points earned for each air-to-air tag was 3.2, the maximum points earned by an air-to-ground tag was 1. Therefore, sending a platform that could otherwise make an air-to-air tag to perform a air-to-ground tag, causes a net loss of 2.2 points.
3) The endurance score per airframe is effectively based on how long a particular airframe can stay in the game as a ratio of the entire game. So, if an airframe was in the game cube for the entire 30 minute match this would result in a total score of 3.8 points for that airframe.

### *A. Basic Behaviors*

The software was implemented in Python, with an object oriented structure that allowed development of tactics without requiring a full knowledge of all the implementation details. This greatly simplified tactic development for the students. The teams were provided with some baseline swarm behaviors and tactics to provide some basic functionality and to serve as a starting point for more complex tactic development. Some of the fundamental behaviors provided were as follows

- **Independent Transit** - A sub-swarm of vehicles travel to a specific way-point.
- **Simple Ground Attack** - A vehicle is sent to land on the opponents base.
- **Patrol Box** - A vehicle performs a random walk patrol within a specified box.

### B. Baseline Tactics

In addition to the fundamental behaviors provided, the teams were also provided with a few offensive tactics to serve as the genesis for more advanced tactics. The two fundamental problems in tactic design that must be addressed are target tracking and target selection. Higher complexity variants of these tactics use more sophisticated methods to achieve these two tasks. Some of the provided tactics are summarized here:

- **Greedy Shooter** - A vehicle would select the closest enemy as a target and set that location as a way-point. If the target were in range, it would fire. This tactic would not consider if a teammate was targeting the same enemy vehicle.
- **Smart Shooter** - An improvement on Greedy Shooter that selected targets using a global strategy. Each enemy aircraft was assigned to be targeted by the closest unassigned aircraft. The target tracking remained the same and vehicles flew directly at the enemy aircraft's position. This tactic also required a centralized list of the targeted vehicles to be kept on the ground station.
- **Vortex** - This tactic was designed to take advantage of the maneuvering abilities of the quadrotors. With this tactic, the quadrotor would move sideways with the motion of a fixed wing, and then rotate to track the incoming target.

These three basic tactics served as the gauge against which our custom tactics were measured during the development phases of the competition. A software-in-the-loop simulation environment was used to compare the performance of various combat tactics. Custom tactics were written to beat the fundamental tactics in simulation. In addition to the live-fly competition there were three virtual scrimmages in which teams went head to head with their tactics in a cloud based simulation. This process led the custom tactic development.

### C. Custom Tactics

When testing the baseline tactics in simulation a few observations were made that helped drive tactic development. While Smart Shooter was marginally better in selecting targets, avoiding the situation where all aircraft selected the same target, Vortex was extremely effective against fixed wing aircraft running either Greedy Shooter or Smart Shooter, with a win rate close to 100%. Due to the high success rate of Vortex against the fixed-wing aircraft, the initial strategy was to use the superior speed of the fixed wing to keep them away from the quadrotors, and focus on fixed-wing to fixed wing combat.

Two execute the strategy of avoiding quadrotors, we developed a method for identifying an enemy agent as a quadrotor or a fixed-wing. To do this we tracked the velocity of the enemy aircraft by numerically differentiating their position over time. With an understanding that the minimum speed for a fixed-wing was about 15 $m/s$ and the cruise speed of the quadrotor was about 10 $m/s$ we could use the speed to determine if a vehicle was a quadrotor. If a vehicle was determined to be a quadrotor we would avoid a confrontation and use the speed of the fixed-wing to drain their battery.

Another approach to neutralizing the perceived strength of the quadrotors was to improve the tracking strategy used. With that in mind, we focused on improving smart shooter for those situations. This led to the development of our most effective custom tactic.

- **Reverse Shooter** - This tactic emulated the distributed target selection properties of smart shooter, but required no communication. Instead, each agent ran the complete global selection algorithm individually, so each agent was aware of all the target assignments for the entire swarm. While the algorithm itself was somewhat slower than the centralized smart shooter assignment algorithm, this was offset by the reduction in communication overhead.
  Reverse shooter also improved the target tracking element of smart and greedy shooter. Instead of setting a way-point at the current location of the target, reverse shooter estimated the velocity of the target by looking at past locations, and computed an intercept way-point ahead of the enemy vehicle.

We found that in simulated fixed-wing on fixed-wing battles, reverse shooter slightly out-performed greedy shooter, with a one-on-one win rate of roughly 60%. An unanticipated effect was that these simple improvements completely neutralized the advantages of vortex. By improving tracking of the quadrotor and with a range of 100m, the fixed wing could shoot the quad before it came close enough that the maneuverability of the quad could come into play. In one-on-one match ups, reverse shooter had a near 100% win rate against vortex. This outcome led to a fundamental change to our strategy. Instead of needing to protect the fixed-wings from the enemy quadrotors, they could be the cornerstone of the approach, using their longer battery life to maximize logistic points, while maintaining an advantage in one on one or small group encounters of either fixed-wings or quadrotors.

Another key strategy that was determined during tactic development was that the most important factor determining the outcome of a match was to have a numbers advantage during individual swarm and sub-swarm engagements. In our simulations, we found that when two unstructured swarms attacked each other directly, the group with the most aircraft had an advantage larger than just the arithmetic difference between the size of the two groups. This result was robust across all pairs we tested, and led us to two strategies. The first was to keep the entire swarm together in the initial encounter. The second observation led to another tactic used.

- **Divide and Conquer** - This tactic detected if the enemy had attempted to split its swarm into sub-swarms. A k-means clustering algorithm was used to identify a split of the enemy swarm. If so, the tactic would focus our entire swarm attack on each of the sub-swarms in turn to maximize the swarm numbers advantage. The assignment strategy used in Divide and Conquer was the same as Reverse Shooter. Divide and Conquer was not used in the actual competition because we never observed any sub-swarms breaking off in any of our opponents tests or actual matches.

These two tactics made up the cornerstone of our attack.

### D. Remarks Regarding Tactics

Prior to the competition, our team thought that there would be significant use of sophisticated tactics that went beyond target selection and aiming to the use of sub-swarms, flanking maneuvers, feints, and the like. In the end, these behaviors saw little use in competition for three reasons, the reduced benefits of ground attacks, the lack of terrain effects, and the importance of quantity in swarm on swarm encounters.

One potential motivation for complex tactics would be to slip an attacker past defenses in order to initiate a ground attack. Indeed, historically, air power was developed not for it's own sake, but in order to affect events on the ground. The scoring rules only awarded one point for a successful ground attack, after which the aircraft could no longer accrue logistics points. This meant the best strategy regarding ground attack was to wait until the end of the competition, or until the battery was running out. Because this was a rare and low-scoring event, there was no incentive to create defenses against this tactic, and thus no incentive to create complex maneuvers.

Ground combat takes place on a two dimensional manifold in three dimensional space, creating terrain. The constraints created by this terrain often induce tactical maneuvers to avoid difficulties or enhance advantages. In the competition, even though it took place in a logical two dimensional space, each aircraft operated at it's own unique altitude in 3 space. There was no terrain to introduce constraints, and any aircraft could move "through" any other aircraft without adverse effects. This eliminates many of the motivations for tactical maneuvers seen on the ground.

Additionally launch logistics played an important role in the organization of a coherent swarm. While in simulation having a full swarm to execute a tactic was trivial, in the competition due to launch delays, communication errors, and environmental factors it was rare for a team to amass a group of more than 3 vehicles behaving as a swarm.

## VI. Operations

The overall team operations were conducted by a combination of DARPA personnel and Midshipmen. The DARPA team primarily manned competition logistics and safety critical roles, and the Midshipmen manned roles related to the match. The team organizational chart for the roles executed by Midshipmen are shown in Fig. 4. During the launch and flight operations the *Mission Commander* and *Swarm Commanders* were in a the tactical operations center (TOC) trailer roughly 30 meters away from the launch site. Everyone on the launch team was at the launch site and communicated with the flight team via radio.

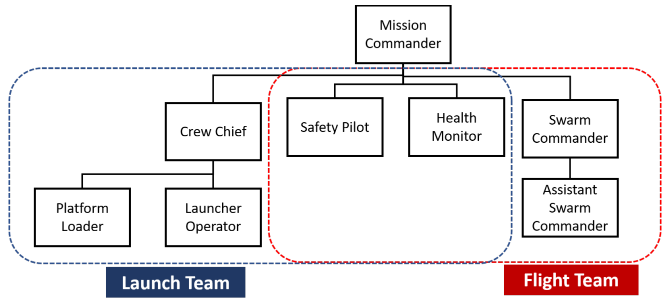


Fig. 4. Team organizational chart for Midshipmen occupied roles

### A. Pre-flight

The logistics of managing and operating a fleet of 40 UAS with commercial-of-the-shelf hardware was not a trivial task. There were two phases to the ground logistics. There was a checklist to be conducted as the start of the day to determine the number of available aircraft. These basic checks were making sure the aircraft were airworthy, that they had propellers, all the hardware was operational, and the latest software was loaded. Prior to the launch an addition set of pre-flight checks was conducted to prepare the plane for the mission. This set of checks consisted of installing flight batteries, calibrating the platforms, and moving them to the staging area. The pre-flight checks would typically be conducted in the final hour prior to the start of the launch window.

Our team's approach was to organize the ground crew into teams of two doing the actual start of the day and pre-flight checks. Another person monitored the status of the checks using FLOC and FTI. Additionally, we had a battery operations officer who was responsible for charging and allocating shop and flight batteries. A written log was kept of the vehicle status on a white board in the command center as well.

One of the issues that hindered our performance during the first match with USMA was that during our final pre-flight checks we discovered many errors without any time remaining to re-mediate before the start of the round. As a result we had about five fewer airframes actually ready than we thought. In our second match against USAFA, we corrected this by performing start-of-day and preflight checks at the start of day. We then conducted another round of pre-flight checks one hour prior to the start of the match. After the last set of pre-flight checks were completed the fixed-wings were remained powered on with shop batteries until 15 minutes before the launch window opened at which point the flight batteries were hot-swapped. This pre-flighting

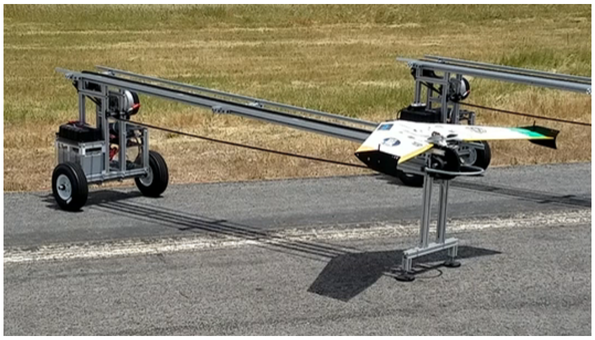

Fig. 5. Fixed-Wing mechanical launcher provided for the competition

methodology resulted in our team having 30 total vehicles in the air during the second match.

### B. Launch

While the quadrotors could launch from the ground, the fixed-wing aircraft required a mechanical launch. The fixed-wing launcher shown in Fig. 5 was used to give the aircraft enough initial velocity to take-off. Since our overall competition strategy centered around the fixed-wings, our launch emphasis was to get as many fixed-wings airborne in the 10 minute launch window as possible. After repetitions we were able to reduce our average time between launches below 30 seconds. This meant that we could get our maximum number of fixed-wings in the air before the start of the round. Since the fixed-wing launch was a serial process, our team spent a lot of time practicing the launch procedures to increase the launch rate. The launch crew consisted of 5 people. The *Crew Chief* supervised the entire launch operation and maintained communication with the *Mission Commander*, and *Health Monitor*. The *Platform Loader* performed final flight readiness checks and loaded the plane on the launcher. The *Health Monitor* ensured the vehicle was armed and in the proper flight mode. The *Launcher Operator* was responsible for firing the launcher and ensuring it was reset to the appropriate position for the next launch. Lastly, the *Safety Pilot* was standing by in case manual control of the vehicle needed to be re-established.

As our team was preparing our launch process, one thing that became immediately apparent is that communication for the launch crew was going to be a major factor. To this end, the team determined to minimize the number of people utilizing the radio. The *Crew Chief* and *Health Monitor* were the only two communicating the status of the next aircraft to be launched.

In some instances, the success rate of launching either platform was determined by factors not actually related to the launch process. For example while observing the USAFA launch operation in their match versus USMA, there were multiple instances when a quadrotor had to return to launch because of a battery failsafe. The low battery could have been caught during the pre-flight checks prior to launch.

### C. Flight

One of the more interesting developments from the competition was the distribution of flight operations tasks, since it is too difficult for one person to track and command 30 aircraft effectively. While the swarm was airborne the flight operations were conducted by four primary people. The *Launch Operator* was responsible for ensuring the newly launched vehicles went to the correct flight stack and altitude bin. The *Health Monitor* was responsible for monitoring the trajectories of the vehicles and their battery status. The *Swarm Commander* and *Assistant Swarm Commander* were responsible for setting the tactics and assigning behaviors during the match. The swarm was controlled from the Tactical Operations Center (TOC), by assigning ”behaviors” to subsets of UASs by the Swarm Commander. The autonomous behaviors (described previously) would decide which individual actions a UAS would take at each moment, freeing the swarm commander to monitor the entire swarm.

## VII. Results and Discussion

One of the largest challenges our team faced during the actual game round was having situational awareness. Due to the nature of the competition and the reality of communication limitations, coupled with the interfaces provided for game play, it was challenging for our swarm operators to determine what was happening. One common example was a vehicle being officially tagged out of the game but not leaving the game cube and appearing to still be in play. Another related challenge was being able to, in real time, determine the difference between our vehicles and the opponent's vehicles. Our swarm operators used a combination of SwarmViz, Swarm Commander, and Game Director to determine the game status, but combining information from all three of these interfaces while trying to make tactical decisions was a difficult task.

This section of the report highlights our team's observations from each of the three live-fly matches. As the top qualifying seed, our team had the first choice of the days on which we competed. We chose to compete on days two and three so we could observe our opponents prior to competing ourselves.

### A. Match 1: USMA vs. USAFA

The match between USMA and USAFA was very informative for our approach to our two matches. During this match the most apparent fact was that fleet preparation would be at a premium. In this match USMA had 15 fixed-wings and 5 quadrotors (20 total aircraft) and USAFA had 10 fixed-wings and 10 quadrotors (20 total aircraft). Being on the same side of the airfield as USAFA, we were able to observe their launch operation up close. One issue they had was two of their quadrotors had to almost immediately return to launch because of a low battery warning. Additionally they had a couple of fixed-wings for which the motor did not properly engage after being launched. Due to USAFA's launching issues, USMA was able to get a numbers advantage early. USMA's vehicles, although airborne, appeared to not be responding to commands for the tactics. Reportedly, during the last moments before the start of the launch window, some software updates were pushed to the aircraft which potentially caused this problem. As a result USAFA, despite having their own early issues, was able to continue to build their force and begin scoring several air tags. From our perspective it appeared as though USAFA had the superior tactics. The final score of the match was USAFA 58 USMA 30.

### *B. Match 2: USMA vs. USNA*

In the match versus USMA we had a disadvantage; this was our first flight operation since the practice round and only the second time our team had ever flown more than two aircraft simultaneously. Our strategy prior into the match was to get the fixed-wings airborne first. The quadrotors would be launched 10 minutes into the match so nominally they could spend their whole flight time in the game cube and then score a ground tag at the end of their battery life. Over the course of the match our team had 11 fixed-wing and nine quadrotors in the match (20 total aircraft) and USMA had 17 fixed-wings and eight quadrotors (25 total aircraft).

There were two primary causes for us having fewer aircraft aloft than USMA. First, we had several fleet issues leading up to opening of the launch window which limited how many fixed-wings we were able to launch during the round. Most notably the airspeed sensors were not responding for several of the fixed-wings and they were deemed out of commission with no time to re-mediate. The second major issue we had was one of our vehicles flying to the wrong stack (staging area) after take-off. Each vehicle had to enter the staging area in order to be cleared to enter the battle cube. We were able to reconfigure the setting mid-flight, but correcting the configuration error used 2-3 minutes of valuable launch window time.

After observing the match between USAFA and USMA, and from the scrimmage results, we believed our low level tactics would be effective in an offensive attack. After the start of the round we immediately went on the offensive. Our strategy was effective, as we jumped up to an early lead by scoring a few air tags. Additionally, it seemed as though USMA was having quite a few communications issues, as some of their vehicles were behaving erratically. Once we attained a big lead, we only needed to keep our platforms from getting tagged out in order to maintain it as all things being equal our respective endurance scores and ground tags would not be able to make up the difference. Despite our large lead and the real risk of damaging airframes that would be needed for the following match, at the end of this match we sent as many vehicles as available in for a ground attack to ensure our victory. We were successful in scoring several ground attacks with both fixed-wings and quadrotors, but did lose one fixed-wing to damage caused by the ground attack.

By the end of the match our team had scored 16 air-to-air tags and 5 air-to-ground tags, while USMA scored 8 air-to-air tags and 3 air-to-ground tags. The final score of the match was USNA 70 USMA 37.

### *C. Match 3: USAFA vs. USNA*

During our match against USAFA, we were able to correct some of the errors we had during the first match. Also, having the benefit of observing USAFA's ground operation pretty closely during their match against USMA we felt we could gain an advantage by ensuring our fleet was more well prepared than theirs. We were able to accomplish this goal by starting the preflight process earlier in the day and completing it more quickly. During this match our team had 20 fixed-wings and 10 quadrotors airborne and USAFA had 18 fixed-wings and 12 quadrotors. We each had 25 aircraft in the game cube with 5 aircraft on reserve in the staging area. This had a major implication of the outcome of the match because the match ended up being very close and any fewer than 25 aircraft in the game may have changed the result.

When specifying the flight stack for our staging area, we had several platforms not respond to the commands to change to the appropriate stack. Our *Health Monitor* scrambled to correct the error but the aircraft simply did not respond. This highlights the potential difficulties in having defaults which are established. A similar issue was experienced by USAFA force in the match, where their aircraft were not receiving altitude bin commands, and they all defaulted to the same altitude, resulting in several collisions, obviously impacting the readiness of their fleet.

Due to the flight stack error we had 3 fixed-wings loitering in the opponent's staging area that wouldn't return to our staging area. This resulted in our team being at a numbers disadvantage in the game, and missing out on the endurance points from those vehicles. Midway through the round, we received permission from DARPA ground operations to push those vehicles into the game cube. Additionally, our launch crew was able to debug two fixed-wings which failed to launch during the launch window and get them launched later in the round. The reinforcements allowed us to score additional points which turned out to be the difference in the match.

The score of the match was extremely close and the lead changed several times. Both teams were scoring points in all three ways. At the end of the match we had an unofficial win with the score 86-81 pending adjustments made by the competition judges. During this match we had 30 aircraft in the air, and our biggest concern was whether or not we had too many vehicles in the game cube during the match. Per the rules, each team would be assessed at 10 point penalty for each unauthorized aircraft in the game cube. Our team was unsure of the result because with the confusion on what aircraft were in play and on standby it was hard to be sure the limit was not exceeded. Fortunately, we had entered only 25 aircraft into the cube, and after the judge's ruling were still ahead.

### *D. General Discussion*

One adjustment to the game format that would enhance the overall strategy would be to increase the value of the ground target. There are two primary motivations that we see for increasing the value of the ground target. In the context of the game it still gives a team that is trailing by a large margin a chance of wining the match. During our team's match against USMA, when they were down by 30 points, they could have mounted a desperation ground attack to try to score big points to get the match close again. This strategy would have been very interesting to try to defend against. This also more closely matches how an actual adversary might use a swarm of drones, as a kamikaze style attack. It becomes more of a challenge to stop the opponent when their only goal is to attack the base. In the future this would motivate the development of interesting defensive tactics. This could however decentivize air-to-air tactics as the teams might only go for the high valued asset.

The execution of this event lead to some quite interesting discoveries about the nature of an experiment of this size and scope. One of big challenges in the match against USAFA was that our vehicles flying to the wrong staging area after launch. This was a result of the aircraft defaulting to that staging area and not receiving the commands to change. A potential solution would be to have the vehicle default to the stack closest to its current GPS location. USAFA had a similar situation happen with their aircraft defaulting to the same altitude bin. In both of these example cases, an unintended consequence of the default behavior resulted in a larger problem. Even though in theory and in simulation the default behaviors seemed perfectly reasonable, in practice there were unforeseen issues that occurred. This highlights one of the bigger picture realities about testing these technologies in large scale experiments. Until the technology is faced with real-world factors, such as communication failures in this case, these important unintended consequences cannot be determined.

## VIII. Conclusion and Future Work

This project was a success, especially given the scope, and complexity of the task at hand. Undergraduate students from the three service academies were able to learn how to operate and develop tactics for a heterogeneous UAS swarm [2]. For future military officers these sorts of experiences are invaluable.

There were many interesting aspects from the project that we are continuing in future work. One of the observations from the competition is that the team that was upwind won each of the three battles. With such a small sample size it is difficult to say definitively whether that is a major factor. An interesting study could characterize the effect wind has on the match outcome. Another aspect that we are currently investigating is developing models for ground operations to account for the observation that ground operations plays a large role in the outcome of the event. The work performed for the competition has set the stage for additional investigation into swarm tactics and strategy.

[2] A video of the competition results can be found at https://youtu.be/RZ-CKA4fUhg

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