Towards a General-Purpose, Replicable, Swarm-Capable Unmanned Aircraft System

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***Abstract*— This paper describes an effort to create a general-purpose Unmanned Aircraft System (UAS) swarm using entirely Commercial Off-the-Shelf (COTS) parts and a reusable swarming software architecture. The software architecture used in this research was originally designed for a UAS warfare competition in 2017 called the Service Academies Swarm Challenge (SASC), hosted by the Defense Advanced Research Projects Agency (DARPA). The SASC software is a multipurpose swarm-control software architecture that allows a swarm to be tailored to many different purposes by third-parties. However, the UASs used in the original SASC competition contain custom parts which have begun to deteriorate over years of use. A COTS UAS solution using the SASC swarm architecture is the next step towards expanding the usefulness of the swarm so that it can be deployed, replicated, modified, and generalized to suit many different needs in a variety of sectors to include homeland security and defense.**

I. INTRODUCTION

As UAS and robotics technology has improved over the last decade, UASs have seen increased use in a variety of situations such as defense, reconnaissance, surveillance, mapping, post-disaster assessment, and search and rescue [1]. An ability to automate UAS flight using modern flight controller technology has led to the development of autonomous UAS capability, which in turn has led to the use of UASs in swarms. However, despite these advances, widespread use of swarm technology has not yet become the norm, partially because of the challenges inherent in designing robust swarming software architecture that can be replicated on commercially available Unmanned Aircraft Systems (UAS).

The Service Academies Swarm Challenge (SASC) software infrastructure designed by the Naval Post-Graduate School (NPS) and Georgia Technical Research Institute (GTRI), and sponsored by DARPA, offers a potential solution to this gap by providing high-level autonomy to aerial vehicles, removing the need to program infrastructure or consider low-level tasking [2]–[4]. Using the SASC architecture, a user can define specific behaviors for UAS, including swarming behaviors, by writing relatively simple software modules. Detailed knowledge of the SASC architecture, flight control systems, low-level control of UAS sensors and software, and messaging protocols are not required in order to use UAS equipped with this architecture. For this reason, SASC offers a potential avenue for more widespread, generalized use of swarm robotics.

This paper provides a description of an effort to design and build new hardware platforms upon which to host the SASC architecture. Although the original SASC fixed wing and quadcopter platforms fulfilled their roles successfully, they suffered from several drawbacks likely resulting from a variety of factors such as time and budget constraints. Also, drone technology had advanced rapidly since their design. This rapid advancement has made it difficult to find replacement parts for legacy UAS platforms, while opening up the possibility to design newer, more capable systems.

Three new platforms were designed as part of this effort. All three were based upon designs originally produced by United States Naval Information Warfare Center (NIWC) Atlantic (LANT) and GTRI, and then evolved by the United States Military Academy (USMA) Robotics Research Center (RRC). These platforms represent a significant advancement in homeland security and national defense by providing easily-replicable, swarm-capable UAS that can be used in a large variety of mission contexts.

II. RELATED WORK

Swarms and other cooperative, multi-agent systems showcase the concept of emergent behavior; that is, the emergence of complex behaviors from simpler, interconnected parts [5] [6]. Although this phenomenon is leveraged across many fields [7], Brooks was an early exploiter of this concept in the robotics field, using it to create behavior-based artificial intelligence in robot control [8].

One of the earliest descriptions of swarm intelligence is attributed to Beni and Wang [9] in the context of cellular systems. It was further elaborated upon by Kennedy and Eberhart [10], who described swarm intelligence as the resultant intelligent behavior of groups of independent heterogeneous entities behaving as a single system, such as

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a flock of birds, swarm of ants, or a hive of bees. Through the behaviors of many individual entities, intelligence emerges as the swarm works together to accomplish a single goal [10].

Swarm algorithms for controlling groups of UAS have been under exploration for homeland security and defense purposes for some time now [11]. However, there appears to be a general absence of swarm UAS systems outside of the research context. This is likely due to a combination of factors including regulations, laws, and technical difficulties which we begin to address in this paper. However, one example of a reusable swarm sofware architecture was used in a 50-UAS swarm flown by the Navy in 2015 [12]. This software was matured into a swarm control framework called the Service Academies Swarm Challenge (SASC) architecture [4]. The SASC architecture is used to control swarms of heterogeneous robots using the C++ and Python programming languages. SASC has undergone successful field tests deployed on swarms of fixed-wing and quadrotor UASs. It was used in the Service Academy Swarm Challenge in 2017 in a live-fly swarm vs. swarm warfare competition [4], and then again by West Point in a radiation heat-mapping effort sponsored by the Defense Threat Reduction Agency (DTRA) [13].

Humans will be unable to keep pace with the rapid decision-making required by a swarm, such as maintaining formation and performing detection and sensing tasks [14]. Therefore, the continued development and application of swarms in robotics is critical. Swarming UAS provide many improvements over non-swarming systems, such as robustness, low manpower requirements, parallel processing, and an ability to cover more area and perform more tasks in shorter time than the use of single UAS.

The swarm software used in this research was used previously in multiple government-funded efforts including a USMA radiation heat-mapping effort [13], [15], in research to develop on-board object classification capability [16], and described in other swarm-related research [17]. The UASs to be replaced are a customized version of the Flamewheel F-450 quadrotors used in those efforts. Over time, their hardware has begun to age, deteriorate and break. Attrition has caused parts to wear, snap, and fail. Rather than rebuilding these UAS with custom components, it will be more cost-effective for the Army to acquire and integrate one or multiple vehicles with strictly Commercial-Off-the-Shelf (COTS) elements. By replacing these aircraft with COTS solutions, the swarm will become more easily maintainable, deployable, and tailorable, opening up the possibility for use on a variety of additional homeland security, defense, and civil applications.

III. BASELINE ARCHITECTURE

The original SASC swarm system architecture was built upon the Aerial Combat Swarms work performed at the Naval Postgraduate School (NPS) [2] [3]. The Aerial Combat Swarms work culminated in the autonomous launch of 50 UAS [18] flying together as a swarm. DARPA then sponsored further development of that system to host the Service Academies Swarm Challenge.

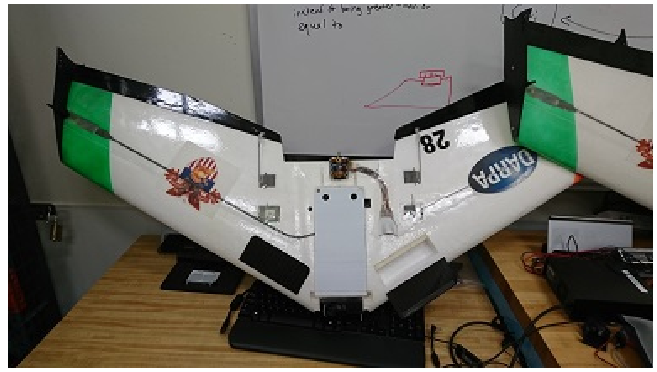

Fig. 1. Zephyr fixed-wing aircraft used in SASC swarm

Fig. 2. Flamewheel F-450 quadrotor aircraft used in SASC swarm

DARPA provided two types of Small Unmanned Aerial Systems (sUAS) for the SASC effort. The first type is a fixed-wing aircraft called the Zephyr II developed by NPS (Fig. 1). It's specifications are shown in Table I.

TABLE I
ZEPHYR II SPECIFICATIONS

Type	Fixed Wing
Wingspan	56 inches
Weight	7 lbs
Flight time	45 minutes
Flight controller	Pixhawk 1
Carrier board	ODroid XU4
Extras	Custom payload circuit board

The second sUAS is a quadrotor called the Flamewheel F-450 (Fig. 2). The F-450 was originally built by GTRI. Its specifications are listed in Table II.

In both types of sUAS, flight control is provided by the Pixhawk while the Odroid companion computer runs the high-level SASC autonomy software. The custom circuit

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TABLE II
FLAMEWHEEL F-450 SPECIFICATIONS

Type	Quadcopter
Weight	3.3 lbs
Flight time	10-15 minutes
Flight controller	Pixhawk 1
Carrier board	ODroid XU4
Motors	DJI 2312 960KV
Battery	3S 5450 mAh LiPo
Propellors	9” DJI 9450
GPS	3DR GPS
WiFi module	Alfa AWUS036NEH
Extras	Custom PCB

board is used to integrate and mount electronics [2].

The SASC infrastructure is used by the multi-agent sUAS swarm to execute autonomous control [2]. Communications are enabled via an ad-hoc WiFi network. Using the network, positions and control messages are exchanged between all sUAS, Ground Control Stations (GCS), and a computer equipped with the Arbiter software which arbitrates the game. Swarm behaviors are built on a Robot Operating System (ROS) architecture [19], running on an Odroid Linux companion computer mounted on each sUAS. Through this architecture, inputs from on-board sensors are collected, intra-team network messages are exchanged, and situational awareness of the entire swarm is maintained. The software on the Odroid processes position and behavior messages, computes waypoints, and sends waypoint commands to the Pixhawk flight controller. The Pixhawk receives these commands and flies the UAS to the specified waypoint [2]. The benefit of this architecture is that it allows individuals to develop specific UAS behaviors in Python or C++ without full knowledge of the software or system architecture. In this way, the swarm can be tailored for many different uses or scenarios without a full ramp-up or core engineers required.

In our research, we decided to focus on quadcopter upgrades as this platform is more maneuverable, easier to launch, and more versatile in a wider variety of environments. The quadcopter vehicle was modified from its original SASC form by West Point cadets by adding 0.91 lbs of payload weight to enable the radiation heat-mapping mission [13]. The payload consisted of a Thermo Scientific Radeye radiation detector, a SF-11 laser-range finder, cables to interface these sensors with the on-board Odroid computer, 3D-printed mounts for sensor integration, and 3D-printed stilts to provide additional ground clearance for the sensors. Despite measuring the maximum payload capacity to be 2.8 pounds via flight test, the effects of adding the relatively lighter West Point payload had a significant detrimental effect on the observed performance of the vehicle. Over the course of several outdoor flight tests, the average endurance was measured to be approximately 6.5 minutes using a 3S 5450 mAh battery. This was nearly insufficient to support timelines to launch multiple vehicles, execute an interesting swarm behavior, and recover them before end of life. The West Point team was able to recover some of the lost endurance by switching to a higher voltage 4S 4000 mAh battery which enabled 10.5 minute flights. However, due to limitations from power train components, further battery upgrades were not possible without revisions to the original air vehicle design. The desire to carry more payload, operate for longer periods of time, and replace the aging fleet added motivation to investigate of the design alternatives listed in the next section.

IV. APPROACH

We designed three new swarm-capable UAS quadcopter platforms as potential upgrades to the legacy SASC Flamewheel F-450 quadcopters. All three designs were based on work originally performed by the United States Naval Information Warfare Center-Atlantic (NIWC-LANT) based in Goose Creek, South Carolina, USA. For the purposes of this paper, we refer to the first design as Variant 1 (V1), the second design as Variant 2 (V2) and the third as Variant 3 (V3). The variants increase in capability and cost as their ”variant numbers” rise, with Variant 1 representing the lowest-cost, least-capable platform, while Variant 3 is the highest-cost and most-capable platform.

A. *Variant 1 - Cost-Effective*

Variant 1 is intended to be the simplest and lowest-cost replacement to the original, legacy F-450 platform. Variant 1 replaces the custom components of the legacy F-450 with Commercial Off the Shelf (COTS) components and mounting plates fabricated with water-jet cutting. This approach saves significant time and cost as opposed to the former method which required the fabrication of Printed Circuit Boards (PCBs) at a manufacturing facility. The use of PCBs significantly increases the barrier to entry to the acquisition of swarm-capable hardware, and their elimination in our design represents a significant step forward.

Although Variant 1 is, by design, as close to the original F-450 as possible, it actually uses many different components as a significant number of the original F-450 parts are obsolete and no longer available. The custom PCB is replaced with a combination of COTS components and aluminum mounting plates (Fig. 3). The mounting plates were designed by modeling the physical size, shape, measurements, and fastener locations of the two custom PCBs. We have made both plate designs available as DXF files. The plates may be cut from any appropriate material or using any machine capable of handling such DXF files (e.g. water-jet, laser, CNC, etc.). In our research, we chose to use 1/8” aluminum plates as they are light, strong, and well-suited to many different applications of the UAS.

In order to support the SASC software, we selected the legacy flight controller (Pixhawk 1), carrier board (ODroid XU4), and WIFI module (Alfa). These items are not obsolete and are sufficient for a low-cost replacement design.

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Based on present availability, the DJI E305 2312E motors were selected as a direct replacement for the legacy E300 motors, which are an earlier variation of the same model. The legacy GPS module had become obsolete, so we selected the most popular and cost-effective GPS module to fit with the current version of the Pixhawk 1 flight controller. Specifications for Variant 1 are shown in Table III.

TABLE III
VARIANT 1 SPECIFICATIONS

Type	Quadcopter
Cost estimate	$650
Weight	3.1 lbs
Flight time	18-20 minutes
Flight controller	Pixhawk 1 (V2)
Carrier board	ODroid XU4
Motors	DJI E305 2312E 960KV
Propellors	9” DJI 9450
GPS	ReadyToSky GPS
WiFi module	Alfa AWUS036NEH
Extras	Aluminum mounting plates (DXF)

B. Variant 2 - Balance

Variant 2 is built upon the same DJI F-450 frame as Variant 1, but uses an upgraded power train and flight controller. The flight controller was upgraded to the Pixhawk 2 Cube to leverage more up-to-date hardware and a newer SASC compatible software build provided by NPS. To reduce the number of required software changes, we continued to use the ODroid XU4 carrier computer and the Alfa WIFI module. However, the upgraded flight controller coupled well with the Here2 GNSS module, which provides significantly more GPS capability over the ReadyToSky GPS used on Variant 1. Therefore, we decided also to upgrade to the Here2 GPS module.

As opposed to the DJI E305 2312E 960KV motors used in Variant 1, we moved to the more powerful DJI E600 3508 415KV motors for Variant 2. Although these motors require an upgraded battery, their carry capacity is significantly higher and allows for a more versatile platform with greater payload capacity and endurance. To accommodate the size of the new 22.2V battery, 3D-printed spacers were added between the power distribution board and the quadcopter’s arms. The design and 3D-print file for these spacers was provided by U.S. Navy NIWC-LANT. Specifications for Variant 2 are shown in Table IV.

C. Variant 3 - Most Capable

Unlike Variants 1 and 2, which were built and tested in swarm configuration as part of this research effort, Variant 3 is still in the design phase. Variant 3 uses an entirely new carbon fiber frame, while maintaining a similar but upgraded payload architecture to that used by the Variant 2. V3 uses the Tarot Iron Man 650 Folding Carbon Fiber Quadcopter Frame

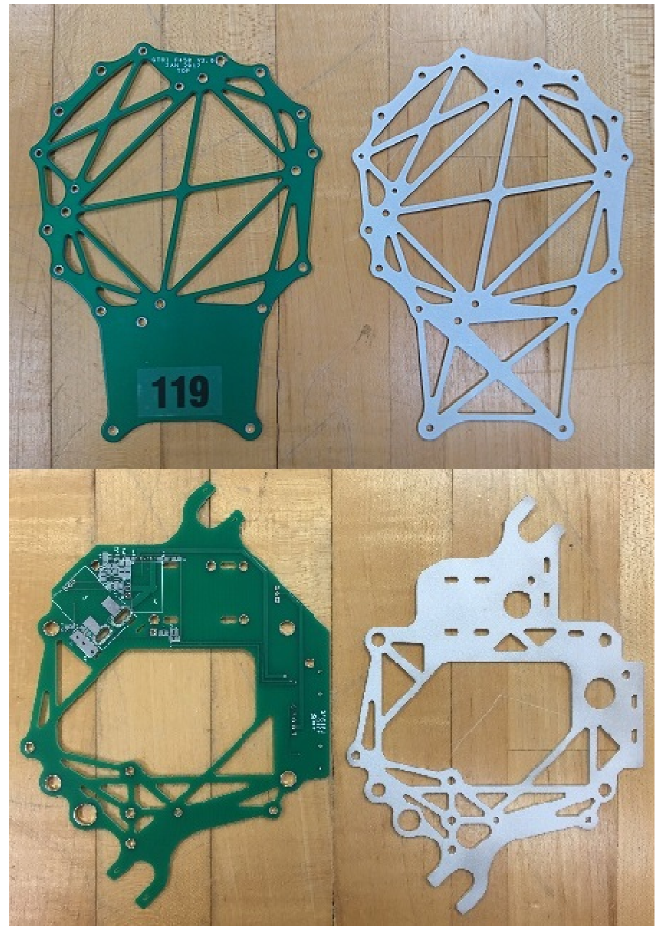

Fig. 3. On the left side are the original top and bottom mounting plates for the legacy system. Both are printed circuit boards. On the right side are our new aluminum replacements used in Variants 1 and 2. They are lighter, more cost-effective, and easier to replicate.

(Fig. 4) in lieu of the DJI F-450 frame used by the Variants 1 and 2. The Tarot 650 frame was selected due to its durability, light weight, and ability to easily accommodate the SASC carrier board and associated hardware. Additionally, this frame can support larger propellers, a larger battery, and more powerful motors, increasing its lift capacity and usefulness in many different scenarios. The platform is both quieter and more capable than the Variant 2, though these capabilities come at a higher price point.

The Tarot Iron Man 650 frame is equipped with a fully folding design suitable for users with high portability requirements. The full frame with rack weighs 476 grams, and allows the user to adjust the center of gravity according to the weight of the payload and any additional sensors or equipment.

The frame uses Toray 3K carbon fiber cloth woven carbon fiber board with 3K hollow twill pure carbon fiber with Computer Numerical Control (CNC) machining. As stated by the manufacturer, the frame is particularly suited to do surveillance, remote sensing, mapping, aerial reconnaissance, fire observed explore life cable line patrol, farm monitoring, and other tasks.

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TABLE IV
VARIANT 2 SPECIFICATIONS

Type	Quadcopter
Cost estimate	$850
Weight	3.8 lbs
Flight time	24-26 minutes
Flight controller	Pixhawk 2 Cube
Carrier board	ODroid Xu4
Motors	DJI E600 3508 415KV
Battery	22.2V 6S 6000 mAh LiPo
Propellors	12” DJI
GPS	Here2 GPS
WiFi module	Alfa AWUS036NEH
Extras	Aluminum mounting plates (DXF) 3D-printed nylon spacers (STL)

TABLE V
VARIANT 3 SPECIFICATIONS

Type	Quadcopter
Cost estimate	$1250
Weight estimate	5 lbs
Flight time	26+ minutes
Flight controller	Pixhawk 2 Cube
Carrier board	ODroid Xu4
Motors	DJI E800 350KV
Battery	22.2V 6S 6000 mAh LiPo
Propellors	13.5” DJI
GPS	Here2 GPS
WiFi module	Alfa AWUS036NEHa
Extras	3D-printed mount 3D-printed battery cage

Fig. 4. Tarot Iron Man 650 frame used in our Variant 3 UAS design.

In addition to the carbon fiber frame, Variant 3 is equipped with upgraded motors as compared to both V1 and V2. V3 uses DJI E800 motors and their associated ESCs, along with a 13.5” propeller that provides significantly more lift than even V2. The result is a quieter, smoother platform with greater battery life and a greater payload capacity.

Due to the size of the battery, a specialized 3D-printed undercarriage was designed. Also, as the frame is very different from the F-450, a 3D-printed mounting solution was designed as a replacement for the aluminum mounting plates used in V1 and V2. Specifications for Variant 3 are shown in Table V.

V. RESULTS

A. Successes

Variants 1 (Fig. 5) and 2 were successfully developed and flown in test flights in the Aerial Robotics Lab at West Point. A swarm of six Variant 1 platforms was also built and tested at Picatinny Arsenal, New Jersey, in swarm configuration in a laboratory environment using the SASC software. Variant 2 was verified as swarm-capable using a near-real flight scenario: the UAS platform was tested live with motors spinning, but with propellers removed and using simulated GPS. Both variants 1 and 2 can be assembled from scratch in approximately 3 hours if all parts and fasteners are available.

One core success was the removal of the legacy printed circuit board in the new UAS designs. As an alternative, the top and bottom mounting plates were made from water-jet-cut aluminum plates, and the electronic components for the circuit board were replaced with a USB-to-UART (Universal Serial Bus to Universal Asynchronous Receiver-Transmitter) module, a voltage regulator, a USB connector, a 5.2mm power connector for the Odroid, and several commercially available power cable connectors and wires. The resulting UAS platform completely eliminates the need for a custom PCB, and all components are available from standard online retail stores with the exception of the mounting plates. The mounting plates may be fabricated quickly and cheaply from aluminum by any suitable machining process that accepts DXF (Drawing Interchange Format) files. DXF is a common, free standard which is supported by many manufacturing processes.

Variant 1 is lighter, cheaper, and more robust than the legacy F-450. Variants 2 and 3 both allow significantly greater carry capacities and battery life. All three variants are swarm-capable when loaded with SASC software. All three are also built using COTS parts; as they become damaged or break after repeated use, they can easily be replaced through widely available, commercial sources. The GPS systems have been universally upgraded, the batteries have been upgraded, the software and firmware and improved, and the platforms are less vulnerable to rain and other environmental factors.

B. Challenges

As the UAS electronics community advances at a rapid pace, many parts from the legacy F-450 design have become obsolete and are no longer available. New replacement parts were required to be sourced and purchased as part of our effort. In some cases, these parts forced redesigns of UAS components, such as the placement of various holes, cuts,

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Fig. 5. Variant 1 of the three swarm-capable UAS platforms developed at the Robotics Research Center, USMA

and features in the mounting plate assemblies. This trend is likely to continue in the future as parts become obsolete. As a case-in-point, the motors for Variant 2 already become commercially rare during the design of Variant 3. Although our original plan was to reuse the V2 motors on our V3 platforms, we were forced to move to a new, upgraded motor type. As the UAS community moves rapidly forward, a plan for continuous evaluation and update of all three variants and their descendants is highly desirable.

C. Future Research

The next step in our research is to finalize the design for the Variant 3 carbon-fiber UAS platform, then build and test the result in swarm configuration alongside Variants 1 and/or 2. A live test including all three variants flying as a swarm using evolved SASC software is the ultimate goal.

Potential future efforts could include several key initiatives. The first is to design a platform that does not require any custom-designed parts, including custom-cut or 3D-printed parts, and can be purchased entirely from commercially available sources.

The second initiative is to standardize the swarm-capable hardware and software assembly so that the same assembly can be mounted on many different platforms. This strategy likely requires custom 3D-printed mounting designs that can accommodate different types of air frames. With this method, a simple 15-minute adjustment to a 3D-print file, such as a Solidworks STL file, may be all that is needed to accommodate a brand new air frame. In this way, the SASC swarm software can be continually upgraded and easily ported to a large variety of new hardware platforms, enabling a wide number of swarm use cases across many different fields.

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