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Autonomous Airborne Multi-Rotor UAS Delivery System

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Abstract— **Within current combat environments, there is a demand for rapid and extremely precise re-supply missions. Typical combat airdrops require long periods of planning and can produce a large signature in an operating environment which relies on stealth for various mission sets. Team Hermes, made up of four members from the West Point graduating class of 2019, offers a new re-supply method to answer this demand. The design will allow for the delivery of a quadcopter carrying 1.5 pounds of cargo within a 5-meter radius of an impact point on the ground. Each quadcopter is first transported via a wooden dispenser which is linked to the Air Force's Joint Precision Airdrop System (JPADS). JPADS is executed with a C-130. The dispenser payload is loaded into the back of the aircraft, and upon command, is dropped to route toward the impact point. JPADS descends and the dispenser releases the drones once it reaches a target altitude and proximity. The team worked through an extensive design process and developed a system capable of achieving the mission with autonomy. Through calculated testing procedures, Team Hermes achieved success and proved the capability to autonomously deliver the microlight payload to within 5 meters of a waypoint on the ground.**

I. INTRODUCTION

The Army currently has no means of delivering small, high-value payloads to Soldiers on the ground with pinpoint accuracy, especially when those Soldiers are involved in combat and have an urgent need for critical items. In spite of the many advances in robotic air and ground vehicles in recent years, autonomous resupply of troops engaged in combat remains a capability gap for US Forces. Especially in unfolding tactical scenarios, troops in contact might urgently need an item that is transportable via drone such as medical supplies, electro-optics, radio components or even ammunition.

The Autonomous Drone Delivery via Airdrop Systems (ADDAS) program is a recent initiative which offers a new capability to resupply missions within combat environments. The goal of the ADDAS program is to develop and design an improved airborne multi-rotor drone delivery system of microlight cargo by leveraging the capabilities of the Joint Precision Airdrop System (JPADS). JPADS is an Air Force system which functions as a guided canopy using GPS to deliver its payload to within 100 meters in favorable weather and wind conditions. The Aerial Delivery Directorate of the Combat Capabilities Development Command Soldier Center (CCDC-SC) sponsored a team of four cadets and two faculty advisors from the Department of Civil and Mechanical Engineering at West Point to investigate this effort as part of a senior design capstone project. The concept combines the long range and large cargo capacity of Air Force cargo aircraft with the high-altitude deployment and navigation capabilities of the JPADS with the high control authority and precision-navigation capability of multi-rotors to meet a very real need on the battlefield today.

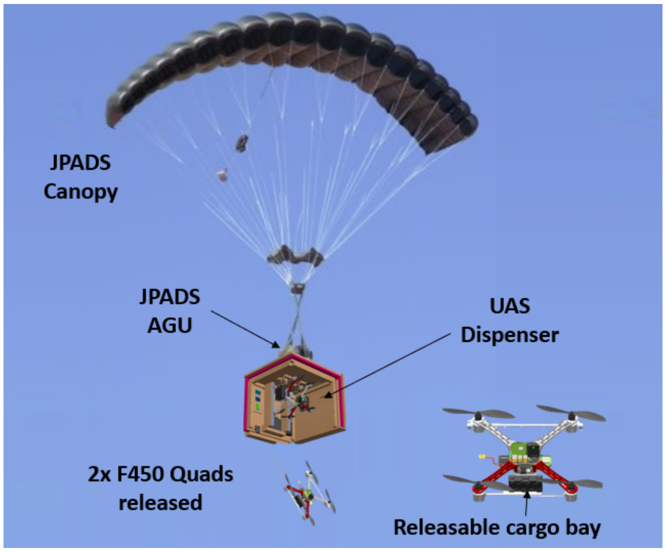

Fig. 1: West Point ADDAS Design Overview

Quadcopters equipped with releasable cargo bays are placed in the dispenser, which is then rigged to Joint Precision Airdrop System (JPADS) and dropped from a high-altitude aircraft. The JPADS self-navigates its parafoil to a landing zone near the area of interest. Once the dispenser is within a predetermined radius of the final target location, it launches drones carrying small payloads. These drones stabilize their flight and then fly to their target and drop their payload carriers within 5m of the target location. Key features of the design include dynamic retasking of small payloads, autonomous release of UAS from the JPADS at desired locations, and fully autonomous UAS with a releasable payload bay 1. A 40% scaled down prototype of

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the system was integrated with a JPADS, deployed at 10,000 ft from a cargo aircraft, and demonstrated the functionality of this concept.

The remainder of this paper is organized as follows. Section II provides background information on the technology and past endeavors related to the system presented in this paper. The system architecture, hardware, and software developed over the course of this project are detailed in Sec. III. A summary of flight tests conducted with this system is provided in Sec. IV.

II. BACKGROUND

Soldiers require supplies on the battlefield to sustain themselves in military operations. Combat operations call for a great supply of resources and consume them very quickly. As a result, it is necessary for armed forces to develop and implement effective resupply operations in order to meet this soldier-demand on the ground. For the past two decades, the U.S. Army has had the inherent benefit of centralizing operations around large Forward Operating Bases (FOBs) within its area of conflict. Current resupply operations incorporate land, sea, and air domains. However, the most common missions into today's operating environment are both ground operations via a vehicle convoy, or aerial resupply missions which drop payloads from large aircraft such as a C-130. Generally, these resupply missions require multiple days to plan the mission and execute the delivery. Consequently, commanders are forced to anticipate what supplies they will require days or even weeks before they use them in the field. Therefore deliberate resupply missions are more amenable to classes of supply that exhibit stable consumption rates, but they are not amenable to responding to unfolding tactical scenarios.

Resupply operations are also dangerous. In conflicts in Iraq and Afghanistan, where there is no distinction between the forward edge of the battle area and rear support areas, resupply convoys are often explicitly targeted by enemy forces. In response to this threat, the US military relies heavily on aerial resupply via both helicopter and conventional fixed wing aircraft. In fact, operations in Afghanistan generated a demand for airlift resupply operations that exceeded 20 millions pounds a year [1]. In response to this, the US military developed several innovative methods of aerial resupply. One successful system is the Joint Precision Airdrop System (JPADS), which utilizes an autonomously flown, GPS-guided parafoil canopy to a relatively precise location of ±100 meters of its intended landing point [2]. This system, which is capable of delivering up to 10,000 pounds of cargo, enabled significant amounts of resupply efforts to occur to isolated bases in Afghanistan.

However, the future of war is uncertain and there are expectations of a dynamic battlefield with few, if any, stable points for resupply operations. The future of combat resupply demands flexible response with high accuracy for several reasons. First, the likelihood of small units operating for long periods of time in remote areas away from conventional sources of supply, such as has occurred recently in Syria [3], will only continue to increase. Second, as the world becomes more urbanized, conflict is expected to shift to a greater extent within cities, with its highly restrictive terrain that it not amenable to either large ground convoys or large airdrops [4].

The changing security environment is taking place in conjunction with a series of innovations and revolutions in small Unmanned Aerial Systems (SUAS) technology, led primarily by a host of commercially available quadcopters. These quadcopters possess vertical takeoff and landing capabilities as well as significant control authority. Combined with Global Positioning System and sophisticated, yet cheap autopilots, they are able to accurately navigate and take off and land without a runway or arresting device. As such, they have become ubiquitous among hobbyists, photographers and videographers, and they are even being considered for commercial use by Amazon among others [5]. That said, quadcopters suffer from several well-known drawbacks. They have limited range and endurance compared to their fixed wing counterparts [6]. They are only able to fly in relatively light winds, and their performance degrades rapidly with altitude [7]. Furthermore, any significant increase in their payloads decreases their range and endurance.

In spite of these known limitations, there have been several attempts to incorporate autonomous aerial resupply in recent operations. A particularly notable case involves using an unmanned Kaman K-max helicopter for deliberate resupply operations for three years in Afghanistan [8]. Furthermore, different agencies including DARPA [9] have explored using VTOL UAS to conduct resupply or package delivery missions. Recently, there have been calls from within Army units themselves to investigate the potential to provide autonomous aerial resupply to units. Members of operational sustainment units have called for the development of a fielded capability of autonomous resupply drones [10], [11]. Indeed, the newly created Army Futures Command wasted no time and initiated a new capability development document termed the Joint Tactical Autonomous Aerial Resupply System (JTAARS) which "will enable tactical support units to provide a multiple times a day resupply capability regardless of terrain, weather or other operational limiting factors" [12].

Previous work in this effort demonstrated an initial method of deploying quadcopters with fixed payloads out of the JPADS [13]. The current project improves on this work by developing a dispenser resilient to cold temperatures experienced at high altitudes, full autonomy of the system, and a retaskable and releasable payload bay on the UAS.

III. SYSTEM DESIGN

A. Design Overview

The problem statement developed by the cadet team for this effort is to "design, implement, and test an aerial delivery system deployable from JPADS capable of transporting 1.5lbs within 5m of the target area from an altitude of 24,000ft". The sponsor determined the design requirements for the system listed in Table I as a benchmark.

TABLE I: Design Specification List
T=Threshold, O=Objective

Delivery of UAS	2 Drones (T=O)
Payload Weight	1lb (T), 1.5 lb (O)
Accuracy	5m at 80% (T), 5m at 95% (O)
Time on Impact Point	<60 sec (T), <10 sec (O)
JPADS Deployment Altitude	10,000 ft (T), 24,000 ft (O)
Drone Range	>1 km (T), >3 km (O)

The prototype developed as part of this effort includes two high-level integrated systems: the UAS dispenser and the UAS (Fig. 1). The dispenser is rigged to the JPADS to enable it to release UAS. It is designed to be environmentally hardened using insulation and heaters to withstand the low temperatures encountered at high altitudes. The dispenser is fully autonomous, and is equipped with a micro-controller to receive GPS location data, and actuate latches to release its cover door and each UAS. The UAS consist of F-450 size quadrotors equipped with a Pixhawk flight controller and Raspberry Pi (RPi) onboard computer. The RPi is directly interfaced with the Pixhawk and manages guidance of the UAS based on its mission phase. The UAS is equipped with a detachable and releasable payload bay commanded by the RPi. This allows for dynamic retasking of the delivery, a concept in which a load-master on the cargo airplane can remove and replace the small payload on the UAS to meet hasty resupply requirements. It also allows the UAS to drop the payload at low altitude while in flight before proceeding to a predetermined recovery location. An ultrasonic proximity sensor is installed on the vehicle and read into the RPi to perform the release at a configurable height above ground. Figure 2 represents the system architecture developed.

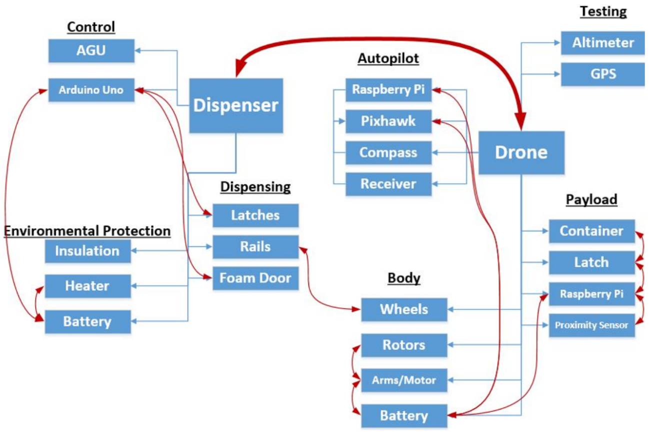

Fig. 2: System Architecture

B. *Environmentally Hardened Dispenser*

The drone dispenser was designed to be deployed at 24,000ft which is the maximum release altitude of C-130 transport aircraft. At this altitude, the ambient temperature is approximately -32.5°C which degrades the performance of lithium polymer batteries and may impact the contents of the small delivery payload. As such, environmental hardening was built into the dispenser to shelter the UAS and payloads from the external environment and maintain it at 5°C until release. Insulation, heaters, and a detachable foam door onboard the dispenser were incorporated to accomplish this.

A thermal analysis was conducted to determine the amount of insulation, heat power, and corresponding electrical energy was needed to maintain an interior of 5°C. A model of the dispenser was created in Solidworks$^{\text{TM}}$, in which parts were assigned appropriate material and thermal properties. This consists of an exterior layer of plywood, and intermediate layer of insulation, an interior layer of plywood for the dispenser, and simplified ABS model of the UAS. The analysis was also conducted in Solidworks$^{\text{TM}}$, using a worst case scenario external temperature of -32.5°C and accounting for the increased convection coefficient of the relative wind applied to the dispenser during flight under canopy (Fig. 3).

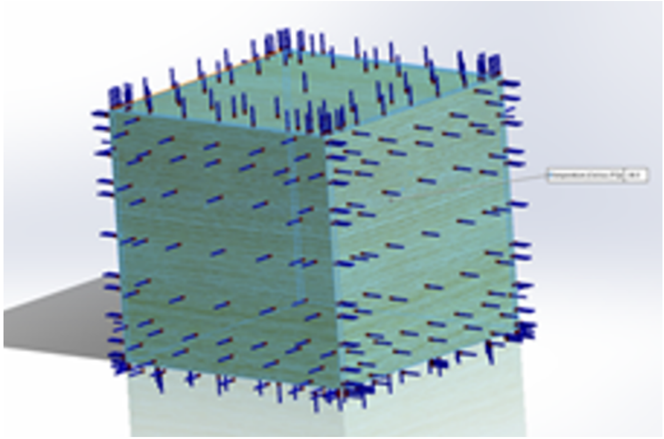

Fig. 3: Thermal Loading Conditions

The results of the analysis helped select the insulation, selection of an insulated door for the dispenser, and set a requirement for 50W of heat power to maintain the dispenser interior at the desired temperature. It also drove the selection of a 12V 20AH lead acid battery to power the dispenser. The need for insulation drove the dispenser outer mold dimensions to 32" x 32" x 29", including a 1" layer Insulfoam sheet in between two 0.5" thick plywood. The design includes a detachable foam door using the same insulation material. The door is held in place using an electro-mechanical latch which grips an aluminum rod threaded into the foam door. The dispenser design and its internal components are shown in Fig. 4.

To validate the thermal design, an experiment was conducted by turning on the heaters, closing the dispenser door, and measuring the interal temperature with a digital thermometer over time. The insulation was sufficient to retain the heat produced from the heaters.

C. *Dispenser Autonomy*

The dispenser uses electro-mechanical latches to lock and release the drones. Figure 4 shows the system orientation during deployment and the drone-dispenser attachment. Quadrotor rollers attach to the dispenser rails while the

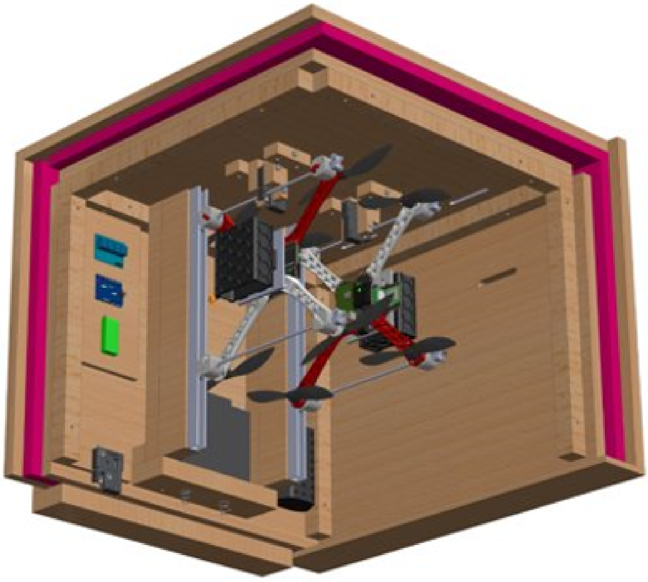

Fig. 4: Dispenser Deployed Orientation with Drones (sides hidden)

electro-mechanical latches secure UAS link rods into place. An Arduino micro-controller onboard the dispenser controls all dispenser commands, to include door and quadcopter release. Once latches are actuated open, the foam door and quadrotors fall out and away from the dispenser under gravity assistance.

The release of the foam door and UAS is autonomous and based on altitude and distance to the target thresholds preprogrammed into the micro-controller. A GPS module feeds serial data to the Arduino so that it can determine its three-dimensional location and distance to target. A remote control (RC) receiver is also integrated into the dispenser to all an operator with an RC transmitter to (1) arm the dispenser, and (2) override release each UAS if desired. The remote manual arming function was built into the dispenser to ensure safety during test so that UAS would not unintentionally be released outside the approved operating area. Once armed, the dispenser functions without operator input, and manual override is available if ever needed.

D. UAS Design

The UAS selected for this effort was the F450 quadrotor based on selection criteria described in [13]. The UAS is equipped with 3DR PixHawk flight controller and compass, a Spektrum DSMX receiver, a 5450 mAh LiPo battery and 10" diameter propellers. In addition, the UAS has 3D printed link blocks and payload carriers mounted as part of the design. A payload latch and carrier are installed underneath each UAS (Fig. 5).

To achieve autonomy, the drones are fitted with a Raspberry Pi 3B+ onboard computer that is connected to the Pixhawk via USB to the Micro-USB port on the Pixhawk. The RPi has an APSync operating image, Python, and the Dronekit library which provides several built-in functions to connect the RPi to the Pixhawk and feed it commands to execute [14]. Once connected to the Pixhawk, the RPi monitors GPS position as well as the current flight mode of the UAS. It uses this information in a script running a state machine of the drone to decide which actions to command the UAS over the course of the mission. The following are the mission states:

1) The drone is outside the prescribed operating area, and set to *STABILIZE* mode with throttle cutoff. This ensures the UAS does not fly outside the approved area if unintentionally released or later drifts outside of it.
2) Once inside the allowed area, the RPi switches the Pixhawk to *THOW* mode and arms the motors. *THOW* mode is configured to detect a downward acceleration consistent with a drop, and then initialize the motors so that the UAS stabilizes in flight.
3) The UAS transitions to *AUTO* mode to autonomously navigate to a selected GPS coordinate provided by the RPi.
4) Upon arrival at GPS coordinate, the UAS starts a vertical descent sequence using *LAND* mode after which the UAS releases the payload upon reaching its desired low altitude.
5) Finally the UAS transitions back to autonomous flight to and landing at a *recovery* waypoint. In the future, this is envisioned to be the same location where the JPADS ultimately lands.

In mission state four, during its descent, the RPi reads the distance to the ground from an ultrasonic distance sensor. Once the sensor determines it is 2 meters from the ground, the RPi activates the electro-mechanical latch which releases the payload. The sensor and latch are interfaced with the RPi through its General Purpose In/Out (GPIO) pins. Payload release relies on an electro-mechanical latch that is mounted on an ABS plate and a custom 3D printed payload carrier with 4.5" x 8" x 3.5" inner dimensions as shown in Fig. 6. The payload carrier is designed to fit a bag of blood and utilized a honeycomb structure to minimize weight while maintaining structural strength. The latch has a mechanical override to allow a load-master to dynamically retask supplies.

Fig. 5: ADDAS F-450 Quadcopter Design

Modelling the quadrotor range was important to evaluate the design compliance with design specifications (Table I).

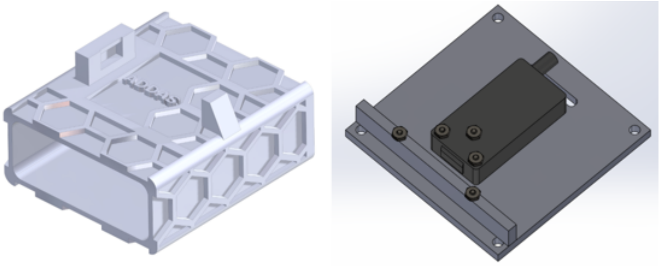

Fig. 6: Payload Assembly

A MATLAB script was developed to estimate power consumption using Momentum Theory and Blade Element Momentum Theory (BEMT) under varied payload weights at hover. BEMT accounts for both profile power and induced power unlike Momentum Theory which only accounts for induced effects and is therefore only used as a baseline for the model [15]. The BEMT model incorporates a script available from [16] and accounts for fixed blade pitch angle, rotor speed, blade characteristics, and airfoil selection [17]. By setting thrust equal to weight and using an initial rotor speed guess based on motor KV rating, trim rotor speed is calculated using a Newton Raphson iteration method. This value symbolizes the trim rotor speed for the quadcopter in hover flight which is fed into the BEMT calculation.

The resulting total power required for hover flight estimates are used to estimate flight endurance. The electrical power needed to generate the required mechanical lift power is evaluated by accounting for efficiency losses due to the propellers, motors, and electronics speed controllers [18]. The battery capacity is then divided by this number to obtain available flight time. Finally, assuming the power required at hover approximates the power required at max range speed [15], the range of the UAS is determined using a nominal flight speed of 30 mph. Based on Fig. 7, the quadcopter can achieve a maximum range of approximately 3.4 km with maximum payload.

IV. FLIGHT TESTING

The culminating event for this effort was a full system demonstration conducted during a CCDC-SC sponsored JPADS flight test campaign in Eloy AZ in May 2019. Multiple buildup tests were conducted locally at West Point and in Eloy AZ to assess subsystem functionality prior to full integration and execution of the final event. These tests often revealed improvements needed in the design, and fed into the overall student led *fly-fix-fly* iterative design and implementation process.

A. Dispenser Buildup Testing

Multiple ground tests were conducted to ensure full functionality of the UAS dispenser. Stationary tests of the equipment were conducted in a lab to verify that (1) the latches release upon manual command from the RC transmitter, (2) the foam door and UAS can adequately be loaded into the dispenser and secured, and (3) release of all latches leads to successful release and separation of the door and UAS. The dispenser autonomous release logic was tested by loading the device into a car, and moving it in and out of a range of a test target point to observe proper function based on sensed location.

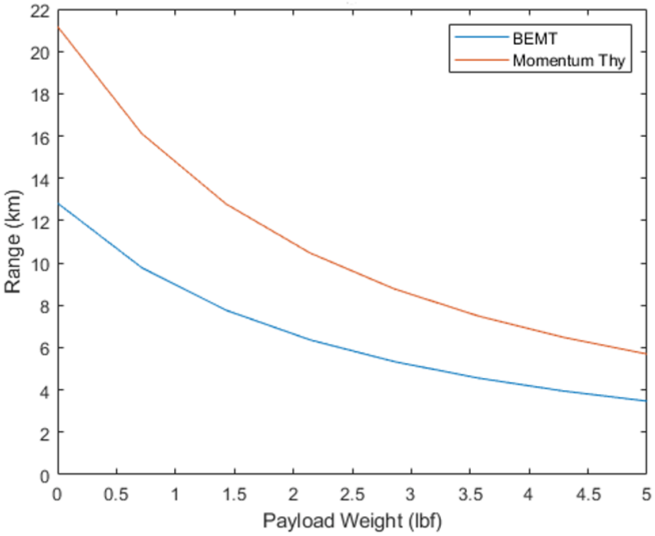

Fig. 7: Range with Varied Payload Mass

The team was then invited to take part in a first JPADS test campaign in Eloy AZ in March 2019 to specifically demonstrate the functionality of the dispenser without releasing live UAS. The dispenser was rigged to a JPADS canopy and released from a cargo aircraft over a remote part of the Arizona desert. Two tests releases were conducted with a JPADS. During each the dispenser was loaded with two form factor representative *dummy* UAS to verify release without transition to UAS flight. In the first test run, the dispenser was commanded manually using an RC transmitter to observe proper release of the foam door and dummy UAS articles. In the second trial, the dispenser operated autonomously under supervision from the test team. This "dispenser only" test campaign was successful in demonstrating proper functionality of the autonomous sequence. This built confidence in the system which was critical to ensure UAS would only be released in safe approved operating areas. It also highlighted some clearance issues which prevented some of the dummy UAS from cleanly separating, as well as wiring harness modifications needed in the dispenser electronics. Lessons learned were incorporated into the design in the month following this event.

Separately the functionality of the heating system was also verified to ensure heaters could provide enough heat to keep the dispenser interior warm during flight. The dispenser was sealed using the foam door and power was applied to the heaters. A thermocouple recorded a 30 degree Fahrenheit increase in temperature inside the dispenser. Ultimately, the heating subsystem was disabled during the final demonstration described later to minimize safety concerns during flight on the cargo aircraft.

B. UAS Buildup Flight Testing

Ground based UAS testing was conducted verify the ability to (1) maintain airworthiness during captive carry travel on the cargo UAS, (2) initialize the drone after release, (3) navigate to prescribed waypoints, and (4) sense proximity to the ground and release its small cargo bay. First, basic functionality of the UAS was verified through familiarization flights. This enabled the cadets to build experience assembling and configuring UAS to deliver basic navigation and failsafe functionalities provided by the Pixhawk flight controller. Next the team validated the *THOW* mode of the Pixhawk which initializes and stabilizes a rotary wing UAS after sensing a vertical acceleration (up or down). Finally, additional electronic components such as the RPi, ultrasonic sensor, and latch that feed into the autonomy behavior of the UAS were incrementally added and tested. This led to numerous *fly-fix-fly* iterations and lessons learned, from which the importance of the state machine logic was highlighted.

In addition to flight testing, multiple tests were also conducted to ensure proper functionality of the Pixhawk based failsafe system. A challenge associated with the final test is that the UAS and dispensers are loaded onto the JPADS at an airfield that is miles away from the approved operating area. The cargo aircraft then flies to that location and releases its JPADS in sequence. It is critical to ensure that the UAS are not be permitted to fly outside of the test area if inadvertently released early. However it is also important to make sure the UAS are then not prohibited from flying after a proper release. The state machine on the RPi helps manage which mode is enabled on the Pixhawk, and in turn helps activate loss of link and geofence failsafe protocols as appropriate for the mission.

In the days prior to executing the culminating flight test from the JPADS in AZ in May 2019, the team conducted a fully integrated UAS ground-based checkout test at the test location. The UAS were powered on away from the target release area, and subsequently driven onsite, thrown up in the air, and conducted a fully autonomous mission with payload delivery. This helped confirm proper functionality of the state machine for flight test.

C. Final Test

The culminating test event took place in Eloy AZ over two days. On each day, the team was provided one JPADS flight with the dispenser carrying two live UAS. The test procedure consisted of powering on the dispenser and its two UAS at the Eloy Municipal Airport. After completing final mission configuration checkouts, the UAS were loaded in the dispenser, and the dispenser sealed with the foam door and loaded onto a Skyvan cargo aircraft operated by Skydive Arizona (Fig. 8). The test team then traveled to the dropzone located miles away from the airport in an open patch of desert. The USMA test team consisted of a dispenser operator and two drone safety pilots, all three equipped with a RC controller to be able to issue backup commands. Approximately 60-90min elapsed from when the UAS were powered on, until they were released for flight from the JPADS.

Fig. 8: Loading Dispenser and UAS onto JPADS

The following was the flow for each JPADS sortie. The Skyvan released the JPADS 10,000ft above the dropzone, after which it navigated autonomously to a landing point while being monitored by a CCDC sponsored test team. At an altitude of 2,000ft above ground level (AGL) and within clear visual range, the dispenser operator sent a command to *arm* the autonomous dispenser. At 1,000ft AGL the dispenser automatically released the foam door. Then at 400ft AGL and within 800m of the JPADS target point, the dispenser released the first drone, and then the second one three seconds later. This would lead to two UAS expected to be simultaneously airborne. From there the results of each of the releases varied.

On JPADS flight 1, the autonomous functionality of the dispenser functioned as expected. However, the first drone failed to release from the dispenser, and the second one was successfully released but failed to initialize and fell to the ground. Post mission analysis revealed a mechanical interference between the guiding rail of the dispenser and the roller interface on UAS 1 that jammed it during release. This issue was fixed. For UAS 2, it was assessed that an unreliable reading from the ultrasonic proximity sensor, likely caused by exposure to desert dust, caused an error in the state machine and prevented the drone from entering *THROW* mode and initializing after release. As a result, the proximity sensors were disabled, and the UAS were reprogrammed to rely on GPS altitude only in its descent to lower altitudes for its cargo release.

On JPADS flight 2, the dispenser also functioned flawlessly. UAS 1 was successfully released, initialized, and stabilized (Fig. 9). However a loss of link failsafe triggered which prevented the drone from completing the rest of its mission. UAS 2 was also successfully release, initialized, and stabilized. From there the drone pilot issued an RC command to force it to switch to *AUTO* mode after which it successfully completed the rest of its payload delivery mission as planned.

Fig. 9: ADDAS UAS Released from JPADS

V. CONCLUSION

Over the course of one academic year, a team of four West Point mechanical engineering cadets and two faculty advisors developed and tested a design to effectively respond to the ADDAS initiative. Autonomy and accuracy proved to be the most important features of the design. With respect to both design requirements, the team found success. During testing in March of 2019, the dispenser achieved successful autonomous deployment of the foam door and drones within the prescribed altitude and proximity to the impact point. Furthermore, the testing in May of 2019 built upon this success by achieving an autonomous deployment and delivery of the payload via the quadrotor. Additionally, the team was able to extend this system's application by environmentally hardening the dispenser. Finally, the team developed the new method of dynamic retasking which effectively creates a hasty aerial resupply mission which currently does not exist on the battlefield.

While the project was successful, the team recognizes the design can be improved. The current design relies on GPS in order to successfully deliver the payload. However, the future battlefield anticipates multiple forms of jamming which will effectively deny GPS and make the system ineffective. Further research may enable alternate means of navigation not reliant on GPS. Additionally, future models of this design can be used for sensor emplacement rather than resupply operations. Sensors would effectively scan the battlefield for biological, chemical, and nuclear threats prior to soldiers entering the area. Future technologies operating within the team's system have the capability of aiding soldiers in a rapidly changing and tumultuous combat environment.

VI. ACKNOWLEDGMENTS

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