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Airborne Delivery of Unmanned Aerial Vehicles via Joint Precision Airdrop Systems

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The purpose of this project is to provide a technology demonstration of the aerial delivery of cargo-carrying UAVs. This capability will allow small, high-value payloads to be delivered over the same long distances as the traditional airlift and Joint Precision Airdrop System (JPADS) combination with previously unattainable accuracy. A team of undergraduate students at the United States Military Academy accomplished this goal by designing, building, testing, and demonstrating a scale model of a UAV aerial delivery system. The customer for this product is the Aerial Delivery Directorate at Natick Soldier Research Development and Engineering Center, which will expand the scale model prototype into an operational system. The system leverages the existing technologies of JPADS and GPS-enabled multi-rotors and combines them to create the airdrop method of the future. The operational system will have the capability to deliver a 5-15 lb. payload to within 5 meters of the target location. This will enable effective resupply of individuals or troops in contact, who could pick up an airdrop without having to leave cover.

I. Introduction

Aerial resupply of troops has been a key enabler of military operations for approximately 100 years. Since 1916[1], logisticians have looked to the sky to receive needed supplies and ensure the sustainment of their operations. Whether by vertical take-off and landing (VTOL) assets such as helicopters, or via airdrop systems, aerial resupply is now endemic to military operations. Indeed operations in Afghanistan saw the demand for airdrop resupply increase from 1.2 million pounds to exceeding 20 million pounds a year[2] by the end of 2009. Airdrop technologies have expanded significantly in recent years. Work sponsored by the US Army's Natick Soldier Research Development and Engineering Center (NSRDEC), has culminated in the development and deployment of the Joint Precision Airdrop System (JPADS)[3]. JPADS is an autonomous airborne payload delivery system that consists of a steerable canopy, an Airborne Guidance Unit (AGU), and a payload. This capability allows airdrop payloads to be autonomously navigated to within 100 m of a target coordinate, significantly enhancing the reliability and efficiency of airdrop operations. Because the JPADS system uses parafoil technology, its ability to operate in restricted or urban terrain is limited. Additionally, although multiple control methods have been developed[4–7], it is difficult to improve on the accuracy of the system, primarily because it is unpowered.

In an effort to provide a higher level of precision, unmanned powered resupply solutions have also been proposed[8]. Several Unmanned Aerial Vehicle (UAV) concepts are in development[9,10]. However, all of these VTOL-based technologies suffer from well-known limitations of range and efficiency due to the nature of VTOL flight.

Other work has been done on deploying UAVs from larger aircraft or from ground mobile stations. For instance, a series of flight tests between 2014 and 2016 demonstrated the mid-air deployment of the Perdix micro-UAS from F-16 and F/A-18 fighter aircraft. In this case the UAS were 290g tandem fixed wing pusher propeller aircraft with the

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ability to operate as an autonomous swarm of over 100 units[11]. Another example is the Coyote, a larger fixed wing pusher UAS, which is designed to deploy from tubes built into military aircraft such as the P-3 Orion and H-60 Blackhawk. This system enables manned aircraft to deploy sensors from a safe standoff distance, and have them travel to more hazardous locations[12]. Further aerial deployment of drones has been accomplished by Insitu with its Flying Launch and Recovery System (FLARES)[13]. However, this system uses a quad copter to launch the ScanEagle fixed wing drone from mid-air. Additionally, Workhorse has developed an mobile ground-launch autonomous drone delivery system for United Parcel Service (UPS) that can launch and recover drone vertically from a truck[14].

The purpose of this effort is to address a capability gap in the field of aerial resupply. Specifically, the goal of the Autonomous Drone Delivery from Airdrop Systems (ADDAS) project is to develop a system to combine the range and efficiency of the JPADS system with the precision navigation capability of powered UAVs. This system enables cargo-carrying VTOL UAVs to be carried and dispensed by a JPADS system, once it is near the final target location. The cargo carrying drones then power on and fly a relatively short distance to the final destination to drop its cargo. A concept sketch of the ADDAS capability is shown in Fig. 1. The system must therefore carry, dispense, and initialize multiple Unmanned Aerial Vehicles (UAVs) capable of carrying a 5 lbs load, and launch the UAVs in flight without damage.

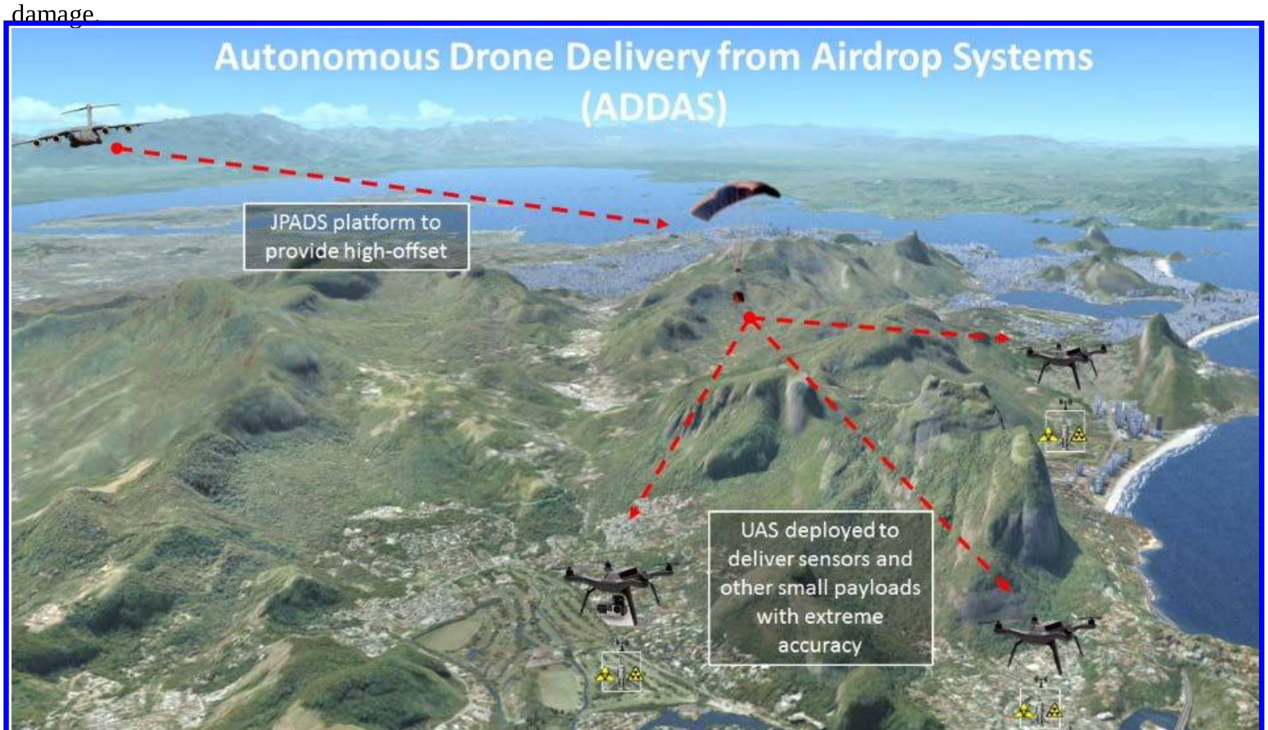

Fig. 1 Automated Drone Delivery from Airdrop Systems (ADDAS) concept sketch.

The effort was conducted as part of an undergraduate senior level capstone design engineering course, with a team of four Mechanical Engineering cadets from the United States Military Academy (USMA), and two faculty advisors. The final product is shown in Fig. 2 during flight test. The system is designed to be a technology demonstrator that will guide future development in this area. At 40% scale, each drone carries a load of one pound and flies autonomously to a target grid. The dispenser holds two drones to demonstrate the capability to drop multiple UAVs without interference.

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Fig. 2 Automated Drone Delivery from Airdrop Systems (ADDAS) prototype during flight test.

II. Models and Methods

In order to systematically address the problem of how to design, develop, build and test a system, a series of design, modeling, analysis, and design of experiments were conducted. The design of the system requires that careful consideration be given to both the requirements of the drone and the requirements of the dispenser, since the problem is coupled.

A. Market Research

1. Multi-Rotor

Multirotor drones were chosen over fixed-wing platforms for their versatility and maneuverability and VTOL capability. A four rotor (quadrotor) solution was then down selected based on space efficiency considerations for the dispenser. Despite this selection, future work may investigate use of other configurations.

Table 1 compares four drones of varying sizes and present several important data for each. The project had a limited budget of $5,000 to acquire multiple drones and build a drone dispenser. An acceptable price range of less than $1,000 for the drone was therefore established. Most commercial cargo drones are too expensive, however, many camera drones fit within that price point. Most available drones, having cameras, therefore use gimbal attachment points and would require modification to accept another payload. Almost no manufacturers provide information on maximum acceptable G-loading and very few specify acceptable operating temperatures.

Table 1. Drone cost, size, and weight comparison

Drone Nomenclature	MSRP	Prop Diam. (in)	# of Props	Area (in^2)	Payload (lbs)	Gross Weight (lbs)
Quanum Nova PRO	$ 330	8	4	201	1.9	10.8
Walkera AiBao AR Gaming FPV	$ 470	7.3	4	167	0	1.3
DYS D800 X4 Professional	$ 1200	15	4	706.9	14.3	8.6
DJI Matrice 600	$ 3500	21	6	2078.2	13.2	20

2. Dispenser Considerations and Technology

The drone dispenser must safely store the drones in the aircraft and under the JPADS. Market research was conducted to focus on three main components: supports, dampeners, and releases. This facilitates understanding of how to support UAVs while they are in the dispenser, protect them from impact and G-forces, and release them from the dispenser into their final, individual flight.

The ability to support the load and shape of the drones in the dispenser can be achieved through a combination of support beams, fasteners, and other hardware. The system must translate the weight distribution of the payloads and drones to the dispenser, and from there to the JPADS rigging. There are many types of release mechanisms, none of which are used currently to release drones from a dispenser. However, a similar concept can be seen in bomb racks used on military aircraft. Several applications use a pneumatic and/or pyrotechnic release assist, which would be impractical and risky for the UAV dispenser design. There are bomb racks that primarily use electro-mechanical and/or gravity-assisted ejectors. The BRU-15 Electro-Mechanical Ejector Rack from Marvin Engineering Co. uses a reliable “electro-mechanical spring-loaded actuator”[15], which ultimately served as inspiration for the latch used in the final design. The Gravity Bomb Rack Unit from Cobham uses a similar electro-mechanical system but also has a gravity assisted release[16]. Such ideas are useful to any bottom-oriented dispenser mechanism. This design concept is less complex as it is not subject to the same large weights or high velocities experienced by these bomb systems.

B. Prototype Scale Decision – 40%

The scaling decision is primarily driven by cost analysis. A full scale COTS drone capable of carrying a 10-15 lbs payload costs at least $3,000[17]. Based on market analysis, there is a nonlinear relationship between drone size and cost. At around 40% scale, there is a substantial drop off in price. A drone of this scale with 8 inch propellers (the full scale would have 20 inch propellers based on the sizing analysis and market survey) costs $300-500. Fig. 6 in Section II.F shows that a 40% scale still allows for a payload of 1-2 lbs, which allows for a proof of concept or mockup payload to be attached and carried in order to demonstrate how the final product would carry and release its payload.

Another concern was how the scaling decision would affect the actual drone dispensing system. At small scales, it becomes difficult to acquire and build the actuators and release mechanisms that would interact with the scaled down drone and dispensary system. 40% scaling is large enough that interfacing components are simple to acquire and work with. Because of the reduction in cost by using 40% scaling, it will be possible to build four drones (in order to have two backups) to use with the system for testing, technology demonstrations, and similar exercises. The estimated total cost to buy 4 drones at 40% scale is $1,200-$2,000, well within our budget of $5,000.

C. Conceptual Design

The conceptual design begins with a concise statement of the problem to be solved: Develop a system that carries, dispenses, and initializes multiple UAVs capable of carrying a 1-pound payload. The system must be carried by the Joint Precision Airdrop System (JPADS) and launch UAVs in flight without damage.

The system design was abstracted to two inherently interconnected design aspects: the drones and the dispenser. These two systems interact via the drone storage method and the drone release method. The selection of the design path required the drones and the dispenser to be designed in tandem, rather than separately. The drones can be attached to the dispenser either by using electromagnets, mechanical latches, or a friction-based mechanism. Drones can be released in one of three identified options: vertical drawers, a vertical stack, or a horizontal stack. The drawer method would consist of multiple drawers on the dispenser that would open via actuation, providing individual platforms for each drone to take-off from. The vertical “stack” would consist of multiple drones stacked on top of one another inside of the dispenser, so that they would drop out of the dispenser bottom via gravity one at a time.

The final decision for both methods are mechanical release latches and a horizontal stack configuration. Mechanical release latches use little power, are secure and reliable, and do not introduce electromagnetic interference. The horizontal stack configuration drives the drones to be stored in the dispenser perpendicular to their flight orientation. This method simplifies loading the drones into the dispenser. It also allows any drone in the dispenser to be released independently at any point, preventing total system failure in the event of a single drone hang-up. The time and distance it takes for the drones to stabilize after they are gravity-released allows them to clear the dispenser and JPADS rapidly, significantly reducing the risk of collision.

There are specific features in this project that are particularly innovative and contribute to the overall design. First, the system itself is innovative in that is holds and releases multirotor UAVs from the air. Systems exist to complete this task, but all are ground-based[14]. Aerial delivery of UAVs adds the challenge of initializing flight from unusual attitudes, since there is no stable platform to take off from. The fact that this has not been done before induces substantial technical risk, which is mitigated through a robust and comprehensive testing plan of the initialization process from unusual attitudes.

D. Embodiment Design

The major components of the UAV Aerial Delivery system are the UAV itself and the dispenser. These components and their functions are intrinsically linked, and many components of each are specifically selected based on aspects of the other, such as the link bars on the drone, which must fit into the clasp of the mechanical latch in the

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dispenser. The dispenser must also interface with the JPADS through rigging straps, which can not interfere with the inner mechanisms of the dispenser when attached.

1. Drone Components

The major components of the drone are the frame, the avionics, and the power system. The frame contains the Hobbypower F450 Quadcopter Kit and the custom-built cargo bay and attachment points where the frame interfaces with the dispenser. The propulsion system, consisting of four sets of motor, propeller, and electronic speed controllers (ESCs), is also included in the frame kit. The avionics are what control the drone in flight, consisting of the flight controller (3DR Pixhawk Mini), a 2.4GHz Spektrum DSMX receiver, and a Pixhawk GPS sensor. The power system is made up of the drone battery, which is a three-cell lithium polymer (LiPo) battery (MaxAmps 5450mAh 3s LiPo) and the power distribution board.

2. Dispenser Components

The dispenser is a plywood box that is a 40% scale model of the four-foot cube standard JPADS payload. The subsystems within the dispenser are the storage and release mechanism, the control architecture, and the power system, which are depicted in Fig. 3. The power system consists of a LiPo battery with a larger capacity than the flight battery that provides power to the microcontroller, mechanical latches, and whisker sensors. The ability to charge the drones via the dispenser battery was considered and deemed unnecessary due to the slow rate of power loss while the drones are at idle. The control architecture consists of an Arduino Uno R3 microcontroller linked to a radio receiver (Spektrum DSMX), which enables a human operator to signal to the microcontroller when the dispenser reaches the drone release point. The microcontroller is able to actuate the release of the mechanical latch (SouthCo Light Duty Electronic Rotary Latch), and contains data-logging capabilities for troubleshooting. This latch and the slider system make up the storage and release mechanism. The drone is supported at all four corners by the sliders and held in place by a mechanical latch. The slider systems precluded the need for any divider between the drones in the dispenser, as they already prevented the drones from interfering with each other.

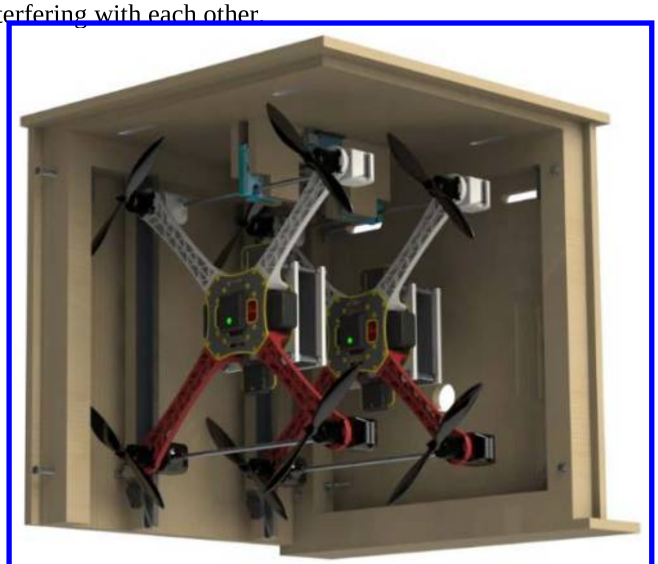

Fig. 3 Embodiment Design Rendering (two sides removed).

3. Sequence of Events

When a drone is inserted into the dispenser, the mechanical latch grasps the drone with an audible click. Sliders are calibrated to the individual drones and lubricated if necessary. The JPADS is dropped and flies to the drone release point, where the human operator signals to the dispenser microcontroller to release the drones. The microcontroller triggers the mechanical latch to release the drone. When the latch releases the drone, it slides down the slider system out the bottom of the dispenser, upon which the motors spin up and the drone stabilizes after a programmed delay to allow the drone to completely clear the dispenser. Once the drone is stabilized, it switches to Mission Mode and continues to a preloaded GPS coordinate. The detailed sequence of events is provided below.

- Loading dispenser and drones onto cargo aircraft
    - Complete visual preflight for each drone
    - Load payloads onto drones
    - Turn drone power on

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- Slide drones into dispenser
- Rig dispenser to JPADS
- Load mission plan onto Pixhawk
- Dispenser controller (Arduino) powered on
- Test radio link for manual control
- Load JPADS into aircraft

- In flight
  - JPADS Autonomous Guidance Unit (AUG) powered on and check complete
  - AGU programmed
- Release.
  - JPADS is deployed and flies to release point
  - Manual command to Arduino to release
  - Arduino selects drone to be released
  - Dispenser releases selected drone
  - JPADS flies to next release point; repeat release with next drone
- Flight and Landing
  - Drones begin flight to target area
  - Pixhawk navigates to landing area
  - Pixhawk executes an autonomous landing

E. Detailed Design

All screws, bolts, and hex nuts are corrosion-resistant. Maple and birch plywood is used primarily due to its higher quality and ability to maintain its shape. This was necessary for building dispensers with more accurate dimensions. Lower quality oak plywood was used for the dispenser skids, on which the system would have direct contact with the ground. Several extra skids were built in case some were damaged from ground impact. Additionally, the 2” x 2” pine lumber spars reinforce the plywood box and give it structure. Acrylic plastic is used for the cargo bay because it is less prone than wood to crack under incidental contact. 6000-series aluminum is used for the sliding mechanisms due to its high strength-to-weight ratio, low cost, and ability to be machined easily.

The aluminum parts and acrylic parts were machined with a mill to enable simple precise machining in three dimensions. These parts were finished with a power sander, files, and sandpaper. The bulk of the wood was cut with a table saw capable of precise and straight cuts to ensure consistency across all dispenser parts. The more technical wood components (the latch boards and whisker sensor slots) were cut with a mill or bandsaw. Rigging slots and dispenser touch-ups were cut with a combination of a power drill, jigsaw, and handsaw. The dispenser required hardware (screws, bolts, nuts, washers, and brackets) to hold the system together. Application of the hardware required power drills, a wrench and socket kit, and several clamps. Also, a small amount of epoxy was used to bond wood pieces to the dispenser top, as well as application of the aluminum sliders to the wood slider supports. One part, the link block, was 3D-printed in ABS plastic (Fig. 4, below).

Fig. 4 Link block fitted with slider and link rod. The diagonal slot fits onto the drone frame.

This platform was chosen due to the precision required by the part, and the quantity that needed to be produced. The slider system tolerances are tight, so 3D printed parts enable consistency across each drone without an otherwise

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intensive and repetitive labor process. A total of 24 link blocks are used in the project, and the drone-based aluminum sliders are fixed to the blocks with epoxy and a press-fit. A complete system schematic can be found in Fig. 5.

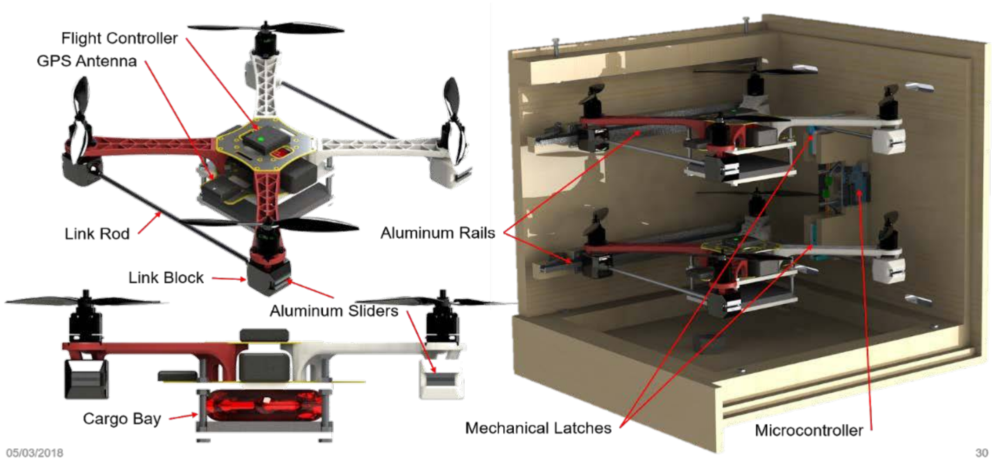

Fig. 5 System Layout.

In total, the team constructed three working prototype dispensers and four working drones. Two dummy dispensers were also built, one intended for rigging analysis and the other for dispenser flight test validation. Two dummy drones were built to validate the latch release mechanisms during flight. Dispenser units were given double-letter identifiers: Models BB, CC, and SS, with the second dummy dispenser being DD. The live drones were denoted as D1, D2, D3, and D4.

The first dummy dispenser was built before the other systems, and sent in advance to Wamore, Inc., the company responsible for rigging systems during the cumulative test event in Arizona, for rigging evaluation. The feedback from Wamore was invaluable, and enabled the team to construct the remaining dispensers to be compatible with the JPADS and be more robust. This was done by adding skids, weight plates, and a second layer of plywood to the outside of the dispensers.

F. Analysis

A computational model was created to plot the relationship between propeller diameter and payload capacity, based on Blade Element Momentum Theory. Propeller diameter is used as an index of size because it is directly linked to the thrust of the system, and the overall size can be varied depending on the spacing between rotors. The propeller proportions used were a chord/radius ratio of 0.175, a root pitch angle of 30º, and a twist of 15 º over the radius. The propeller rotational velocity was set at 4200 RPM, which was determined by setting the diameter and payload equal to that of a DJI Phantom 4 and solving for rotor RPM using the same blade element code. Uniform inflow is assumed.

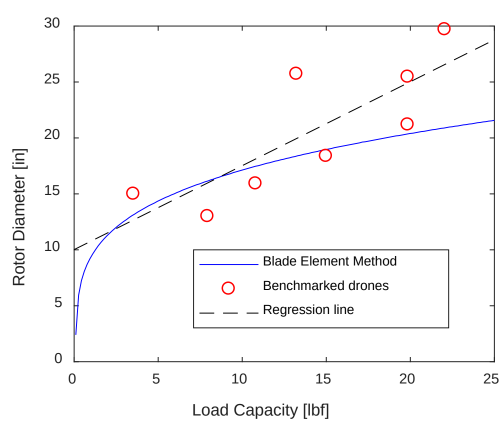

Fig. 6 Quadrotor Payload vs. Propeller Diameter.

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The result of the numerical analysis is a curve with a noticeable inflection point right around 3 lbs of payload (Fig. 6). Above this point, increases in load capacity cause much smaller increases in propeller diameter. Tripling the useful load from the threshold value of 5 lbs to the objective value of 15 lbs results in only a 4.6 in increase in propeller diameter, from 14.4 in to 19 in.

In order to validate this analysis, the published payload values and propeller diameters for eight consumer multi-rotors[17] are compared to the theoretical results. Where necessary, the propeller diameters are adjusted to keep the number of rotors constant in the analysis. This is done by finding the total disk area, dividing by four, and finding the diameter of that circle. The data are plotted in Fig. 6 as red circles.

A linear regression was performed on the validation data. The trendline is plotted as a black dashed line in Fig. 6, and its R^2 value is 0.66. The large spread in the data is likely due to the wide variety of propellers and motors that are available. Different propeller geometry and motors perform best at widely varying rotational velocities, which makes it difficult to directly relate propeller diameter to payload. In reality, many factors other than size affect how much weight a multi-rotor can carry. However, the trendline is fairly close to the theoretical data, at least in the 5-15 lbs payload range where this project will be operating. This analysis is useful in sizing the final design, though actual testing of motor/propeller combinations is necessary to accurately determine payload capacity.

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III. Results and Discussion

The results and discussion extend directly from the testing. The test schedule is designed to logically follow the build process. There are 19 total tests that were conducted, which are divided into seven test events of related tests, which are listed in Table 2. Test events are labeled A through G, and the tests within them are numbered. Some tests also have preliminary checks associated with them that will be conducted during the assembly process to ensure components have been correctly installed, programmed, and calibrated (labeled as A-1.1, F-4.2, etc.). Tests were conducted on each component of the system to ensure that it meets the relevant design specification(s) and is capable of completing the required tasks. The test objective tree is a numbered outline with four main categories that draws from both the functional decomposition and planned sequence of events. Resources for all tests include the specific test apparatus, the drone and required components to fly, at least two personnel and a safety observer. Risk of injury is mitigated by operating the drones on a tether when possible and positioning personnel opposite the intended flight direction. All personnel participating in or observing the test wore personal protective equipment (PPE), to include eye protection and a hard hat. Risk of drone flyaway was mitigated by programming a GPS boundary and failsafe behavior of return to home and land, as well as having the possibility of reverting to manual control.

Table 2. Complete Test Plan.

Cat	Test ID	Name	Description
A	**DRONE INITIALIZATION TEST**		
	A-1	Drone initialization	Test drone's capability to initialize from multiple orientations and with different initial velocities.
		A-1.1	Static level initialization.
		A-1.2	Static angled initialization.
		A-1.3	Dynamic angled initialization.
C	**CARGO BAY TEST**		
	C-1	Load cargo bay	Load cargo bay, ensure payload is secure in all orientations and with reasonable accelerations
	C-2	Flight with payload	Take off, perform full deflection maneuvers with 1 lb. payload, observe flight characteristics/performance
	C-3	Safe landing	Manual control of drone, land with payload, check for damage.
D	**AUTONOMOUS FLIGHT TEST**		
	D-1	GPS test	PixHawk receives GPS position.
	D-2	Autonomous flight	Drone navigates to GPS waypoint.
	D-3	Autonomous landing	Drone lands at GPS waypoint autonomously.
E	**LOAD VALIDATION TEST**		

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	E-1	Latch test	Power latches, push dowel into latch, ensure closure, ensure retainment force = drone weight * 3Gs (progressive force test).
	E-2	Attachment point strength test	Hang dispenser by rigging attachment points, load to system weight * 3Gs (progressive force test).
Cat	Test ID	Name	Description
F	**DISPENSER RELEASE TEST**		
	F-1	Remote controller test	Give Arduino drop command via manual remote control. Monitor Arduino recognition. Varied distances.
	F-2	Arduino latch activation test	Hook up Arduino to mechanical latches. Receive drop command via manual remote control. Arduino commands latches to actuate.
		F-2.1	Manually update latch position variable in code. Ensure latches actuate.
		F-2.2	Send full "drop command" data packet. Ensure latches actuate.
	F-3	Guide rail test	Latch drones in box. Disengage in vertical orientation via Arduino command. Ensure drones fall clear.
		F-3.1	Slide drone through unmounted guide rail(s). Ensure smooth travel.
		F-3.2	Manually slide drone through mounted guide rails. Ensure smooth travel with no interference.
	F-5	Timed release	Release 2 drones in rapid succession. Time from initial release command to 1st drone clear. Time between 1st drone clear and 2nd drone clear. F-5 is "dry drop" with props (not powered).
	F-6	Timed release	Release 2 drones in rapid succession. Time from initial release command to 1st drone clear. Time between 1st drone clear and 2nd drone clear. F-6 is "live drop" without props (powered).
G	**ARIZONA TEST**		
	G-1	Load test	Run through entire pre-flight checklist. Timed event.
	G-2	Rigging test	Rig dispenser to JPADS. Timed event.
	G-3	AZ testing	Determine # of successful drops, divide by total drones released.

A. Stabilization Testing

The first test event is the drone initialization test, which addresses the drone's capability to initialize and enter a stable flight regime from all orientations as well as in freefall. The test event is progressive and builds up to initializing in freefall from an orientation 90° away from level. These tests were conducted indoors. The final drop test was done by hand since the dispenser had not yet be constructed. The dropping cadet wore gloves and oriented the flight direction away from themselves to mitigate the risk of injury from the propellers. The cargo bay was also attached to the drone to allow a handhold further from the rotors. This leads into the outdoor freefall initialization test.

The first phase of this test consisted of taking off from angled platforms. First, drone flights were conducted from a flat platform to a hover, and basic maneuvers were performed to ensure functionality. Then, flight was initiated from platforms at increasing angles, up to 45°. The limiting factor was the initial sideways velocity gained by taking off at an angle, and the size of the room precluded increasing the angle further. The next phase took place in the gymnastics center, a much larger indoor space. This testing consisted of hand-dropping the drones in the 90° orientation from 15 ft and throttling up the motors manually immediately after release. This testing was also successful, and the drones were able to stabilize and recover into level flight before hitting the ground. This test achieved the chief purpose of the stabilization testing: it verified the drones could stabilize from a 90° orientation without losing significant altitude.

The next phase of testing took place in an open field, with plenty of space to maneuver the drone. The drone was flown to heights of about 100 ft. The drone was maneuvered suddenly and volatilely to test the drone's flight dynamics. Then, the drone's motors were cut. Once the drone had started falling freely about 30 ft, and achieve perpendicular to level flight attitude, the motors were turned back on, and the drone was able to stabilize itself before hitting the ground.

This test was conducted four times to ensure repeatability. This phase of testing differed from indoor testing in that the drone's ability to initialize from freefall was tested. This test confirmed that the drones could initialize and stabilize from nearly the exact orientation and attitude they would face while being dropped from the dispenser.

B. UAV Release Testing

The final test prior to the ultimate test in Arizona was the dispenser release test event. This consisted of mounting the dispenser with adequate ground clearance and testing the release mechanism. The first rounds of testing involved manually triggering the release of a single dummy drone. Drone hang-ups occurred about half of the time, which resulted in modifying the slider system to be easily adjustable via tightening/loosening a series of nuts. This modification increased the system reliability and also enabled each slider track to be "tuned" specifically to an individual drone. Testing then progressed to releasing live drones using the remote controller. No hang-ups were observed, and the latches were able to hold and release drones loaded to three times their gross weight in order to assure survival of opening shock,

C. Flight Testing

The cargo bay test was conducted indoors and ensured that the cargo bay holds a payload securely and prevents it from being damaged on landing. This test consisted of a short indoor flight to ensure that the drone was controllable with a payload and could hover out of ground effect under load. No differences in stability were observed from the no-payload configuration, and hover was achieved at ten feet above the floor, well out of ground effect. Outdoor flight testing was conducted to ensure GPS functionality. Selection of the target GPS coordinate was done using QGroundControl software, which leverages the Google Maps API to make target selection intuitive. A point was selected fifty meters from the takeoff point, and the drone was manually flown to a high hover at about 30 ft before being switched to GPS guidance. The drones were able to successfully navigate to the point and land autonomously within five meters of the target coordinates. The next level of progression was to link a GPS navigation to an unusual attitude initialization. The drones were flown to about 100 ft, and the motors were cut in a repeat of the stabilization testing. After the drone stabilized from freefall, it was immediately switched to GPS guidance and allowed to fly to and land at the target autonomously. Initializing from freefall did not change the results of the first GPS tests, verifying that the GPS and magnetometer continue to function after tumbling and accelerating rapidly.

D. Additional Testing

The Pixhawk has a data logging function that was utilized on every flight test. This data can be used to determine parameters such as attitude of the drone and battery life throughout the flight. It was used to verify the behavior of the flight controller, particularly in the early stages of stabilization testing. Spikes in control response could be seen (as in Fig. 7, below) when the drones were in unusual attitudes, indicating that the flight controller was attempting to correct the instability. It was also used to verify battery consumption at idle and in flight; a sample plot can be found below in Fig. 8. Drones in flight draw 60 times more power than those at idle, meaning for every hour at idle inside the dispenser, the drones lose one minute of flight time. This allowed the elimination of umbilical power from the design.

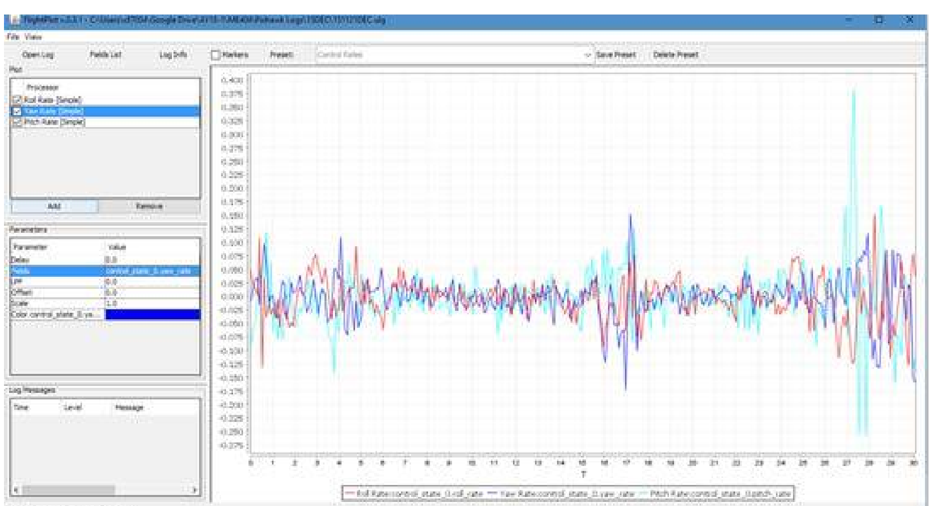

Fig. 7 Control Response Plot; the three curves represent the pitch, roll, and yaw axes.

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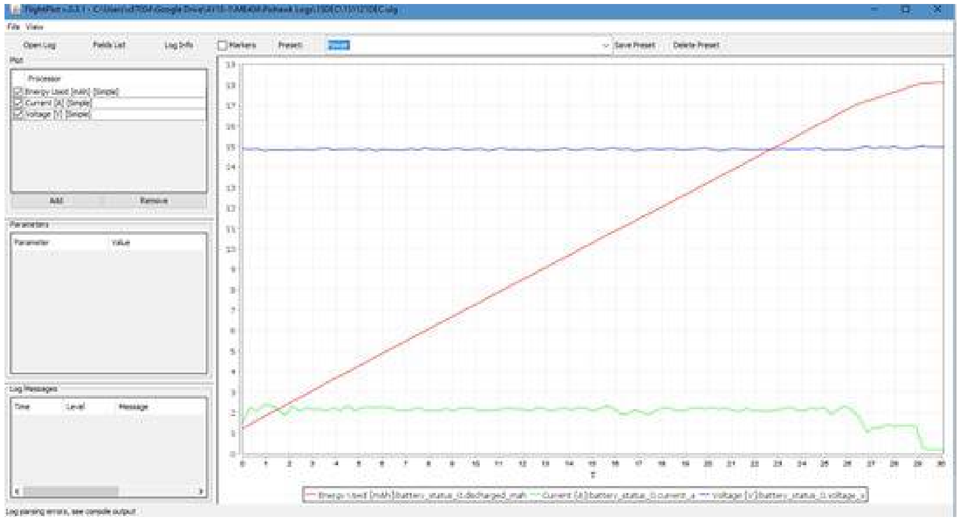

Fig. 8 Battery Usage Plot; the red line represents amp-hours of consumption over time.

Testing was also conducted to ensure that the drones were stable in their standby configuration. To test this behavior, the drones were turned on as they would be prior to loading in the dispenser. They were then placed in a metal cabinet, simulating the RF environment inside the aircraft. After two hours, the drones were removed and initialized. No difference in behavior was observed between drones that initialized immediately after powering on and drones that initialized after two hours at standby other than the slight decrease in battery life. This confirmed that the drones would not be adversely affected by long intervals between loading the dispenser and releasing the drones.

E. Cumulative Test Event

The cumulative test for the project occurred in March 2018 at the Skydive Arizona facility in Eloy, Arizona. The week-long event coincided with NSRDEC's testing of the next-generation JPADS. Wamore, Inc. provided the rigging capabilities throughout the testing. Each day allowed enough time for three airlifts, with about ten loads each. The team participated in two of those lifts each day and the dispenser units were the first to be dropped from each lift, except for very first lift, in which it was the second drop. Due to safety and land constraints, a human was in the loop for all of the testing, and the drones had to be within visual range of the pilot at all times, limiting the drone release height. Human operators were needed to initiate dispenser latch release and drone initialization. The remainder of drone flight was automated by the Mission Mode setting, with the human operator maintaining the ability to input drone controls at any moment if necessary. The load plan is provided in Fig. 9.

			Dispenser	Track 1	Track 2	System Weight
27MAR18 TUESDAY	LIFT 2	DROP 2	DD (Dummy)			210 lb
	LIFT 3	DROP 1	CC	D1 (Dummy)	D2 (Dummy)	228 lb
28MAR18 WEDNESDAY	LIFT 2	DROP 1	BB	Donatello	D3 (Dummy)	
	LIFT 3	DROP 1	SS	Donatello	Leonardo	
29MAR18 THURSDAY	LIFT 1	DROP 1	BB	Leonardo	Raphael	222 lb
	LIFT 3	DROP 1	BB		Raphael	

Fig. 9 Load plan for flight tests.

A typical test iteration was as follows: before being loaded into the dispenser, the drones were initialized and loaded with GPS coordinates. The entire system was then rigged, loaded with the drones, and turned on. Once loaded into the aircraft via a forklift, the system sat idle for up to one hour before being deployed. At the designated time, the loadmasters pushed the system out of the back of the aircraft, with the JPADS parafoil immediately opening and then being navigated by the AGU to the designated drop zone point. Once the system descended to below 1000 ft AGL, the drone-drop sequence would begin. One RF controller was used to initiate dispenser latch releases, and a second RF controller was used to initiate drone flight after release, or to manually fly the drones if necessary.

Testing took place over four days. Day One encompassed the system preparation, maintenance, and set up, and it provided an opportunity to view the rigging operation that was necessary. Day Two was focused on validating the dispenser system. The dummy dispenser (Model DD) was dropped from Lift 2, demonstrating that the system construction was robust enough to survive opening and landing shock. Dispenser Model CC was then dropped later that day from Lift 3, loaded with two dummy drones. This test validated the latch-release control mechanism and slider systems. Dummy 1 and Dummy 2 were released when the system was around 600 and 500 feet AGL respectively. Both dummies demonstrated a natural stability in pitch and roll, as both righted themselves and landed upright on their cargo bays.

The entire system completed a full successful test on Day Three. Lift 2 contained Model BB, loaded with D1 and Dummy 3 on tracks 1 and 2. On command, D1 was given the command to release. The dispenser successfully released D1, which was then given the command to stabilize and carry out Mission Mode, which included flight to a GPS-designated target and auto descent. All tasks were executed successfully. Shortly after, Dummy 3 was released, performing the same as the previous dummy drones. Next, on Lift 3, Dispenser SS was loaded with two live drones, D1 and D2. D1 was released successfully, followed by D2 22 seconds later. The large time interval was necessary to allow the safety pilot to ensure that the first drone was operating nominally before switching control to the second drone.

Day Four was the final day of testing. Lift 1 in the morning had Model BB, loaded with D2 and D3. This was intended to be a repeat of the previous successful test. With the system in the air, D2 was released, followed by D3 20 seconds later. Both drones stabilized and switched to Mission Mode successfully. However, D2 experienced a fatal crash when a zip tie rubbed through and severed the GPS sensor wires. The drones are programmed to cut motors when GPS signal is lost as a safety measure. D2 was a total loss upon impact with the ground.

Lift 3 that day contained Dispenser BB again, but with D4 and D3. The dispenser Arduino code was modified for this drop in order to increase the automation of the system by triggering the second drone release a specified time after the first. The second latch was placed on a time delay from the first latch so that the human in the loop did not have to issue that second latch command. However, a bug in the code caused the second latch to open repeatedly. With time constrained, D4 was pulled out before the system was loaded into the aircraft. Once the system was in the air, D3 was successfully released and completed all tasks and landed safely on the ground, and it was then used to complete a follow-on delivery mission with a human operator, validating that capability.

In total, six lifts were conducted in Arizona, four of which contained live drones. A total of six live drones were released from the airborne dispensers, all of which completed the main project objective to initialize, achieve steady-level flight, and begin Mission Mode. Three of the six drone drops were able to land successfully at a preloaded GPS target, with a fourth drone on course to do this but manually overridden. Additional capabilities that were validated include a distance of delivery up to one half-mile, and use of the drones for follow-on missions after landing on target.

IV. Conclusion

The test results demonstrate that this technology is feasible and worth pursuing. Being able to dispense multirotor UAVs from tactical airlifters with the significant lateral offset provided by the JPADS is a capability that would allow the centralization every small UAV operation at the theater level, freeing the soldiers on the ground from having to carry UAVs with them while placing the wide range of capabilities provided by small UAVs within easy reach of the smallest units.

The following capabilities were successfully demonstrated:

- Delivered payload to within 5 meters of target coordinates.
- Drones stabilized within 2 seconds of release.
- Dispensed drones with 100% reliability.
- Delivered payloads of various sizes and shapes.
- Drones capable of flying over 1/2 mile from release point.
- Drones held in dispenser inside aircraft for over 1 hour.
- Survived 3 G's opening shock and landing.
- Dispenser and drones prepared and loaded in <5 minutes.

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- Recovered/reused dispensers with no maintenance required.

Possible missions that could be facilitated by aerial delivery of UAVs include ISR, sensor emplacement, weapons delivery, and cargo delivery. The system is modular and can be easily adapted to a wide range of UAVs that are being developed for those various mission sets. This project has demonstrated that this technology is technologically feasible.

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