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Precision Guided Airdrop for Vertical Replenishment of Naval Vessels

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This paper addresses the investigation into the feasibility of the use of precision guided airdrop as a means to deliver cargo to naval vessels at sea. In this context, precision guided airdrop means delivering unmanned cargo packages that, once dropped from an aircraft at high altitude, have the capability to guide themselves to a precise landing point by controlling an aerodynamic decelerator (parafoil or parachute) to which the cargo package is attached. The paper describes the problem of replenishment of naval vessels at sea and describes the benefits that the application of precision airdrop might provide. Improved accuracy of aerial delivery systems is the major focus of analysis, and how the application of model predictive control has potential to achieve the necessary improvements in accuracy that would make shipboard landings possible. A simple example is developed of a model predictive control algorithm adapted to track a target landing area that is moving with constant velocity. Additional techniques are also surveyed, as well as other potential applications of precision airdrop to maritime operations.

Nomenclature

ADS	Aerial Delivery System
AGM	Air-to-Ground Missile
ASW	Anti-Submarine Warfare
CEP	Circular Error Probable
CLF	Combat Logistics Force
DDG	Destroyer, Guided Missile
DOF	Degree of Freedom
GN&C	Guidance, Navigation, and Control
GSM	Global System for Mobile Communications
LTP	Local Tangent Plane
MPA	Maritime Patrol Aircraft
MPC	Model Predictive Control
NAVAIR	Naval Air Systems Command
NSRDEC	Natick Soldier Research, Development, and Engineering Center
PATCAD	Precision Airdrop Technology Conference and Demonstration
SBIR	Small Business Innovation Research
SLAS	Shipboard Landing Assist System
UAV	Unmanned Aerial Vehicle
UNREP	Underway Replenishment
VERTREP	Vertical Replenishment

I. Introduction

MAINTAINING supplies for naval vessels at sea is an age-old challenge. The U.S. Navy currently operates Combat Logistics Force (CLF) ships that shuttle between supply ports and other ships at sea, delivering

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fuel and stores to each patrolling ship at least once every two weeks. This process is known as "Underway Replenishment", or "UNREP." UNREP operations are expensive to plan and execute, and can be executed on the order of days, not hours, for an unforeseen need. Precision guided airdrop delivery capability can potentially make available a rapid and inexpensive means to get items out to a ship underway. This capability would be especially useful for high-value items that are needed quickly before the next scheduled CLF visit, such as aviation parts to repair helicopters and unmanned aerial vehicles (UAVs). Precision guided airdrop capability might also provide means to have mail delivered more frequently to ships underway.

Time-critical and unplanned deliveries to ships today are often conducted using "Vertical Replenishment," or "VERTREP," a subset of UNREP that is a method of delivering cargo to ships using rotary winged aircraft, including landing slung loads on the ship's flight deck. The VERTREP is a well-understood and often-practiced technique in the U.S. Navy today; therefore, this paper will apply some of the fundamentals of rotary-winged flight operations in the VERTREP process to the idea of using precision airdrop.

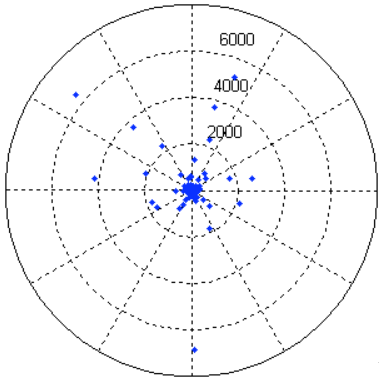
Critical performance factors of precision airdrop that will determine its suitability for shipboard deliveries include landing accuracy, and the landing descent rate onto the ship's flight deck. U.S. Navy ships conduct flight operations while steaming on a fairly constant heading during the landing phase; therefore, a key component of landing accuracy will be the capability of the aerial delivery system to track and reach a moving landing area. Also, whereas some aerial delivery systems achieve improved accuracy by using a higher descent rate, and shock-absorbing material to protect the cargo, the descent rate upon landing on a ship's flight deck should be quite limited. For these reasons, and, adopting the terminology introduced in Ref. 1, systems of the "low-glide" type, such as round parachutes, were rejected in favor of "mid-glide" types, such as parafoils, with a better glide ratio for moving target tracking. Also, for controlled rate of descent for shipboard landing, a guided parafoil was chosen over other classes of aerial delivery systems for this investigation. In fact, previous research has been done in the use of parafoils for shipboard landing. One previous experiment detailed in Ref. 2 studied the use of a parafoil to aid the landing of a UAV under power onto a representative helicopter flight deck area.

Continued improvements in the accuracy of precision airdrop systems has been both the motivation for, and an objective of this investigation. Until now, the prospect of delivering cargo to ships at sea using precision airdrop might not have deserved serious consideration due to the achievable accuracy that has been demonstrated. Recently, it is due to the continuing efforts of the U.S. Army Natick Soldier Research, Development, and Engineering Center (NSRDEC) that the accuracy of payload delivery has been improving drastically.[3,4] Numerous systems in different weight categories, such as those below 150 lbs, 500 lbs, 2000 lbs, 5,000 lbs, 10,000 lbs, and up to 30,000 lbs, have been developed and demonstrated at a series four biennial Precision Airdrop Technology Conferences and Demonstrations (PATCADs) at the U.S. Army Yuma Proving Ground, Yuma, Arizona, since 2001. A similar series of events has been held in Europe near Toulouse, France since 2001.

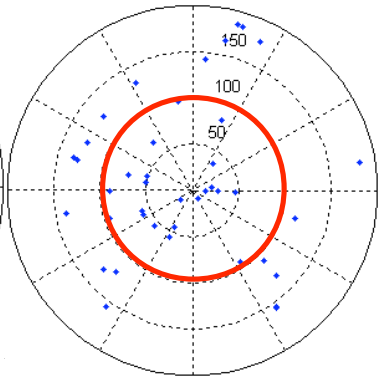
The most recent PATCAD was conducted in October 2007. During that event, 19 state-of-the-art cargo delivery systems were demonstrated. In figure 1, a very general comparison is made between the aggregate results of PATCAD 2007, and some recent flight test results of a system called "Snowflake" being developed jointly between the Naval Postgraduate School in Monterey, California, and the University of Alabama, Huntsville. The composite plots of the PATCAD 2007 results are shown in figures 1a and 1b.[5] Specifically, the distance in meters and bearing in degrees to the actual point of impact relative to the desired target impact point for 103 drops of all the cargo delivery systems across the spectrum of weight classes is presented in figure 1a. The desired target location is at the origin of each polar plot, with range rings representing miss distances in meters, and red circles showing approximate circular error probable (CEP).

Many of the demonstrated systems were still in the development process at the time of this event; consequently, there were some drops during which the given aerial delivery system (ADS) did not perform as expected. The impact locations outside the 2,000 m ring in figure 1a illustrate this point. In order to get a better understanding of the accuracy of current systems, the best 40% of the 103 drops conducted during PATCAD 2007 were chosen and plotted in figure 1b. The 50% CEP is plotted for this set as a red ring that contains half of the data set inside, and the other half outside. From this plot, it was estimated that the average accuracy of current systems is approximately 100 m CEP.

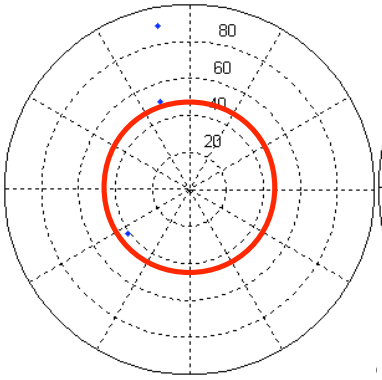
Recent developments in miniature payload delivery systems with increasingly sophisticated control algorithms show even more promise. For instance, figures 1c, 1d, and 1e show the performance of the Snowflake ADS. The first flight tests of this system were conducted in May 2008, at Camp Roberts, California, and demonstrated an accuracy of 55 m CEP as shown in figure 1c.[6] Upon analyzing the results of this test, it was



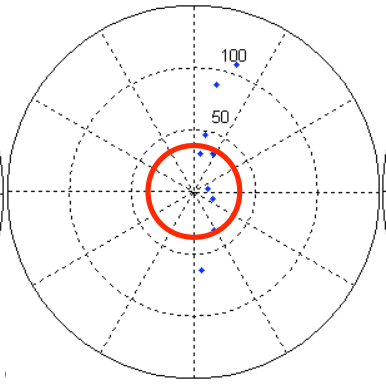
(a) PATCAD 2007, all drops



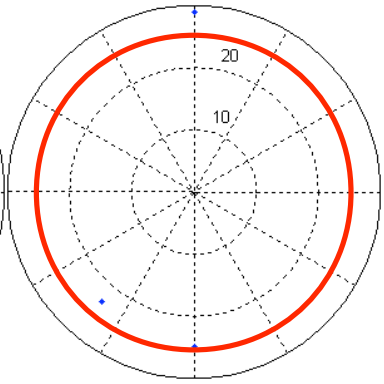
(b) PATCAD 2007, best 40% of drops



(c) Snowflake ADS, TNT 08-3, May 2008, Camp Roberts, CA



(d) Snowflake ADS, October 2008, Yuma Proving Grounds, AZ



(e) Snowflake ADS, TNT 09-2, February 2009, Camp Roberts, CA

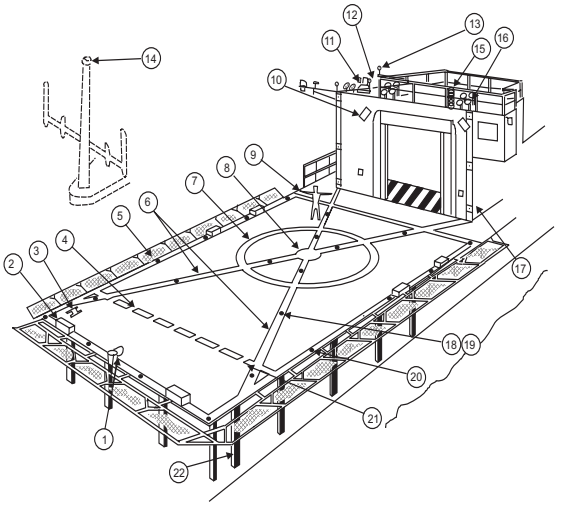
Figure 1: Comparison of PATCAD 2007 results with recent Snowflake flight test results

discovered that there was a bias error in the control algorithm. This error was eliminated for the next flight tests in October 2008; the observed accuracy then improved to 35 m CEP as shown in figure 1d.[7] The most recent results for the network-capable modification, Snowflake-N, showed 25 m CEP as shown in figure 1e.[8] The ultimate goal of the Snowflake-N research program is to improve terminal accuracy to 10 to 15 m CEP. This level of accuracy puts the use of precision airdrop for underway replenishment of naval vessels within the realm of possibility.

In this paper, the modeling of the ADS and the target ship will be explained in Section II, and the results of simulations with these models will be given in Section III. Section IV will explore additional enhancements that have the potential to improve the terminal accuracy of precision airdrop systems in the maritime environment, and Section V will briefly mention some other possible applications of precision airdrop for maritime operations.

II. Model

For the purposes of these simulations, a guided missile destroyer, or DDG, was chosen as the target ship, since this type of vessel is the most numerous of the combatant ships of the U.S. Navy. Furthermore, this type of ship does not have the capability, as aircraft carriers and larger amphibious vessels do, to recover longer-range fixed-wing aircraft; thus, the potential benefit of precision airdrop may be greater with this type. The DDG is capable of helicopter operations with a flight deck aft of the superstructure of the ship. An approach view to the landing area of a typical destroyer is shown in figure 2.



1. MAINTENANCE FLOODLIGHT
2. DECK SURFACE FLOODLIGHTS
3. HIFR AREA MARKING
4. VERTREP LINEUP LINE
5. LANDING AREA PERIPHERY LINE
6. LANDING LINEUP LINES
7. TOUCHDOWN CIRCLE
8. LANDING SPOT
9. LSE AIDS
10. FORWARD STRUCTURE FLOODLIGHTS (DECK SURFACE FLOODLIGHT TYPE)
11. WAVE-OFF LIGHTS
12. STABILIZED GLIDESLOPE INDICATOR
13. HIFR HEADING LIGHTS
14. HOMING BEACON
15. DECK STATUS LIGHTS
16. OVERHEAD FLOODLIGHTS
17. EXTENDED LINEUP LIGHTS
18. LANDING LINEUP LIGHTS
19. SEQUENTIALLY FLASHED LINEUP LIGHTS
20. EDGE LIGHTS
21. VERTREP LINEUP LIGHTS
22. VERTREP DROPLINE LIGHTS

Figure 2: Approach view to flight deck of a typical destroyer

The aft flight deck landing area of a "Flight II" ARLEIGH BURKE-class guided missile destroyer is approximately 16 m in length by 12.5 m in width, so the effective landing area for this investigation was set to 15 m in length by 10 m in width. A plan view of the landing area of a ship of this class, USS OSCAR AUSTIN (DDG 79), is shown in figure 3.

In addition to the challenge posed by the small landing area, a ship underway also exhibits dynamic translational and rotational motion, each in three axes. For the rotational motion, the familiar terms roll, pitch, and yaw are used, and for translational motion, the terms surge, sway, and heave are used to describe

USS OSCAR AUSTIN DDG 79 (MAIN DECK AFT) (USA)

Avg Cl Helo Dk Ht Abv WL: 14 ft 10 in (10.82 m) Avg Cl Mast Ht: 149 ft 7 in (45.60 m)

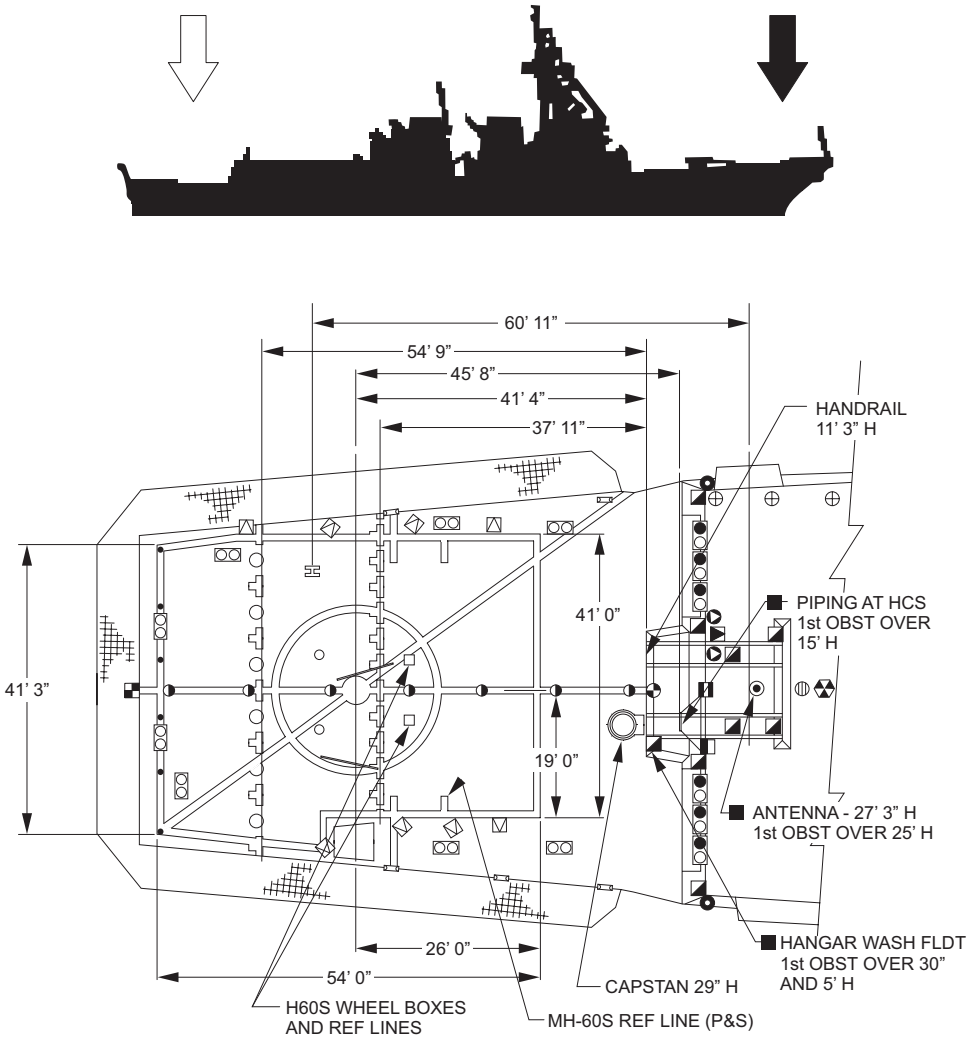
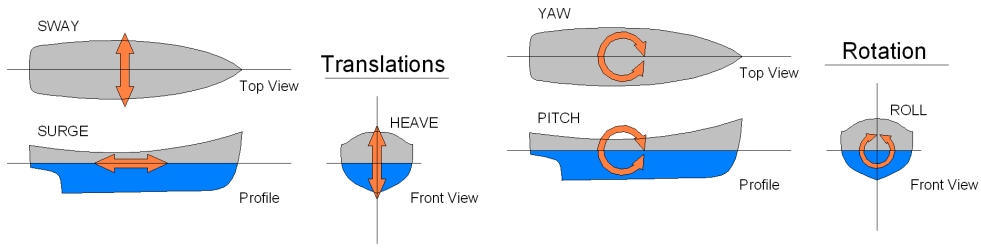


Figure 3: Landing area of USS OSCAR AUSTIN (DDG 79)

motion along three orthogonal axes. These translational and rotational motions with respect to the body axes of a ship are depicted in figure 4.



(a) Translations (b) Rotations

Figure 4: Definition of terms for ship three-axis translational and rotational motion

For the very simple model of the motion of the landing platform, it was assumed that the target ship was underway in relatively calm seas. The condition chosen is known as sea state 3, and is characterized by waves less than 1 m in height. It was assumed that the translational motion of the landing area platform would affect the ADS landing the most; therefore, the motion of the landing platform was modeled in sway and yaw only. Both of these motions were modeled as sinusoidal and having a 15 s period, with the amplitude of sway chosen to be 0.3 m, and the amplitude of yaw chosen to be 0.15°, as shown in equations 1 and 2.[a] Note that, in addition to these motions, the height of the landing platform above the sea surface was chosen to be 10.8 m in accordance with the information presented in figure 3. In order to complete the simple model of the target ship, it was assumed that the ship was steaming directly into the prevailing winds at a speed of 8 kts.

$$\text{sway} = 0.3 \text{ m} \times \sin\left(\frac{2\pi}{15 \text{ s}} t\right) \tag{1}$$

$$\text{yaw} = 0.15^\circ \times \sin\left(\frac{2\pi}{15 \text{ s}} t\right) \tag{2}$$

For the model of the ADS, a 6 degree-of-freedom (DOF) MATLAB representation of the Snowflake was used. Snowflake is a much smaller ADS than would actually be used for this situation; the purpose of choosing this model was to use it as a simple platform on which the model predictive control (MPC) algorithm could be modified to seek a trajectory to a moving target, and some initial results evaluated. The size and speed parameters of the Snowflake ADS are shown in table 1, and an image of this system is shown in figure 5.

Table 1: Snowflake ADS size and speed characteristics.

Parameter	Value
mass	1.95 kg
forward speed	7.2 m/s [14 kts]
descent rate	3.66 m/s
glide ratio	2

The approach of this ADS to a moving target, using the MPC algorithm described in Ref. 9, was simulated using MATLAB. Since the forward speed of the Snowflake as listed in table 1 is only 14 kts, and the target ship was modeled as having a constant speed of 8 kts, the simulations were run with zero wind relative to a local tangent plane (LTP) coordinate system. The MPC algorithm was modified so that the MPC calculations were made to produce an optimal trajectory to a landing point with a constant velocity of 8 kts relative to the LTP coordinate system.

[a]simple formulae obtained via email from Naval Surface Warfare Center, Carderock Division, Seakeeping Division

(a) (b)

Figure 5: Snowflake Aerial Delivery System

The MPC algorithm causes the ADS to follow a repeatable, predictable trajectory relative to the target during the final approach phase. A predictable trajectory in this phase is advantageous for the application of shipboard landing because it allows the approach of the ADS to the ship to be designed to fit well with current shipboard flight operations procedures.[10] Figure 6 shows a comparison between the trajectories of the Snowflake ADS during a recent flight test in February, 2009, and the trajectory of the Sherpa 1200 ADS during one of the drops during PATCAD 2007. The Snowflake trajectory shown in figure 6a shows the first part of the trajectory, denoted by a blue line, from the drop location to a holding pattern (delimited by red "x" markers). Then, Snowflake executes one half-turn in holding (yellow line), followed by the set-up to approach (green line), the approach turn (cyan line), and the final approach to landing (red line). In contrast, the trajectory flown by the Sherpa ADS shown in figure 6b is much less predictable.

A complete description of the MPC algorithm that Snowflake uses to compute the setup and final approach turn is given in Ref. 9; however, in general terms, the algorithm includes the following steps:

1. The desired amount of time that Snowflake will spend on the final, straight approach to landing must be set by the user. This quantity is labeled T_{app}.

2. The algorithm then calculates the altitude, z_f, and the coordinate x_f at which the final, straight approach must begin, based on an assumed constant steady-state descent rate that is known before flight.

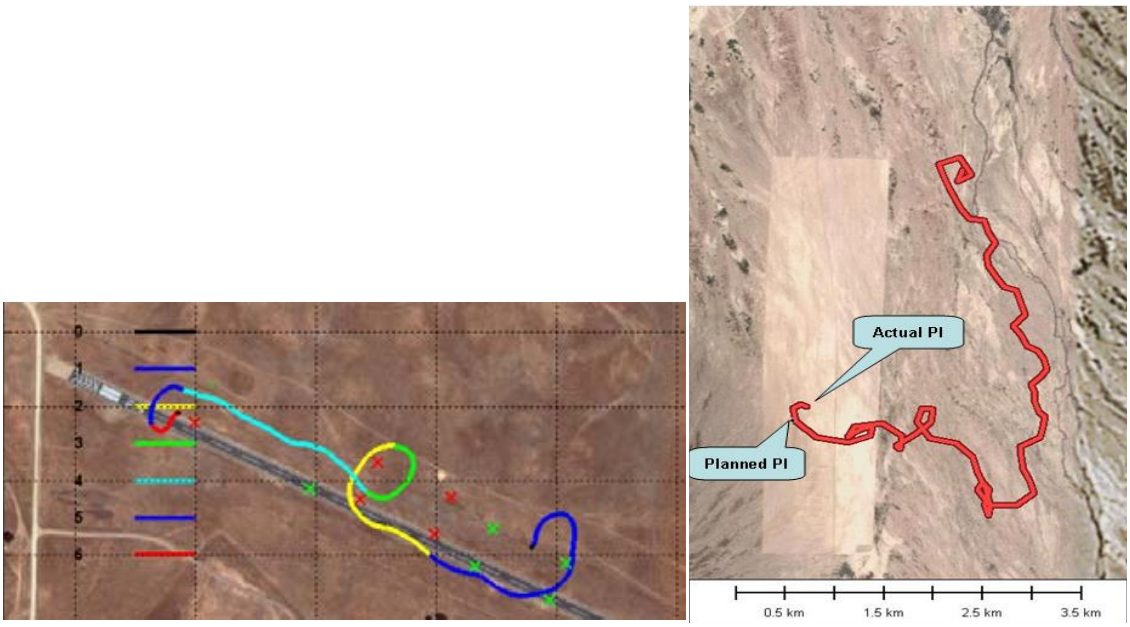
3. The radius R of the final approach turn must also be set by the user.

4. The algorithm then calculates the amount of time T_{turn} that will be spent in the turn, and also the altitude z_0 at which the approach turn must begin.

5. Based on the assumed constant speed of the target ship, the algorithm calculates the distance D_{switch} past the position directly abeam the target ship.

6. In flight, once the Snowflake has reached the position that is D_{switch} past the abeam position, it calculates an optimal approach turn that executes a change in heading of 180°, and terminates at the final coordinates x_f and z_f, where the straight approach to landing will be executed. The computed trajectory is optimal in the sense that it minimizes a cost function that includes deviation from the prescribed time in the turn T_{turn}, and use of excessive yaw rate. In Ref. 9, the optimization routine was designed to overcome the effect of wind on the final approach turn; but for this simulation, wind was set to zero, and the routine was instead tuned to track a target point moving with constant velocity.

In summary, the controller for this model has perfect knowledge of the moving target's location, and the target's constant velocity. The controller also has perfect knowledge of the current position, velocity,



(a) Snowflake trajectory, February, 2009, Camp Roberts, CA

(b) Sherpa 1200 trajectory, October, 2007, Yuma, CA

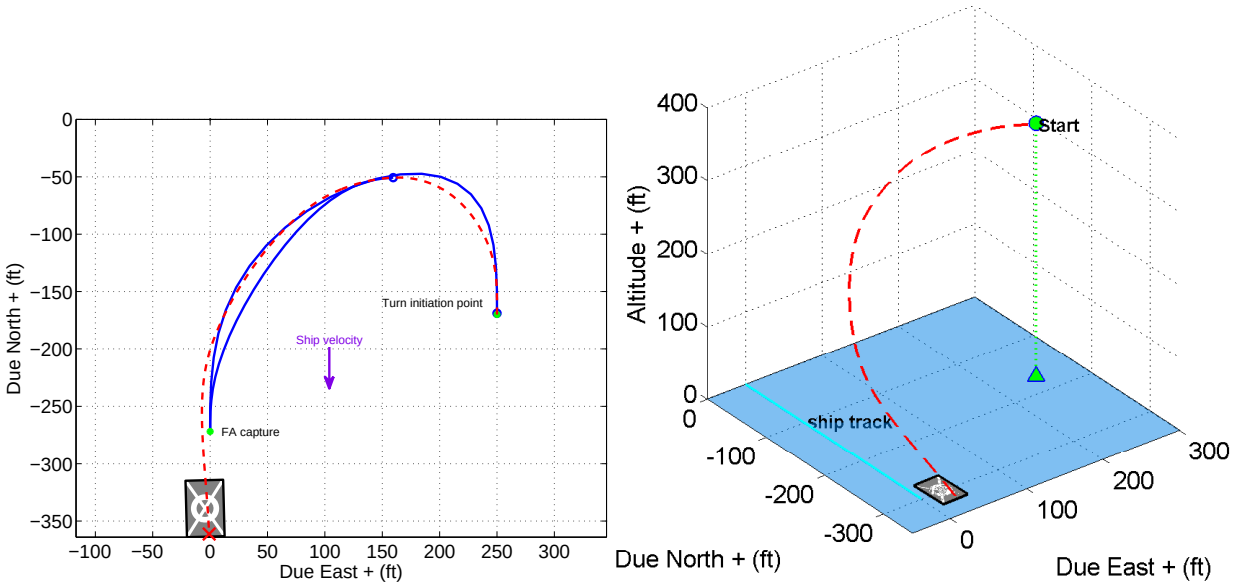
Figure 6: Comparison of trajectories of Snowflake and Sherpa aerial delivery systems

and orientation of the parafoil. Also, the controller is given values for steady state horizontal and vertical velocities of the parafoil. The controller does not have information on the sway and yaw motion of the target landing area.

III. Results

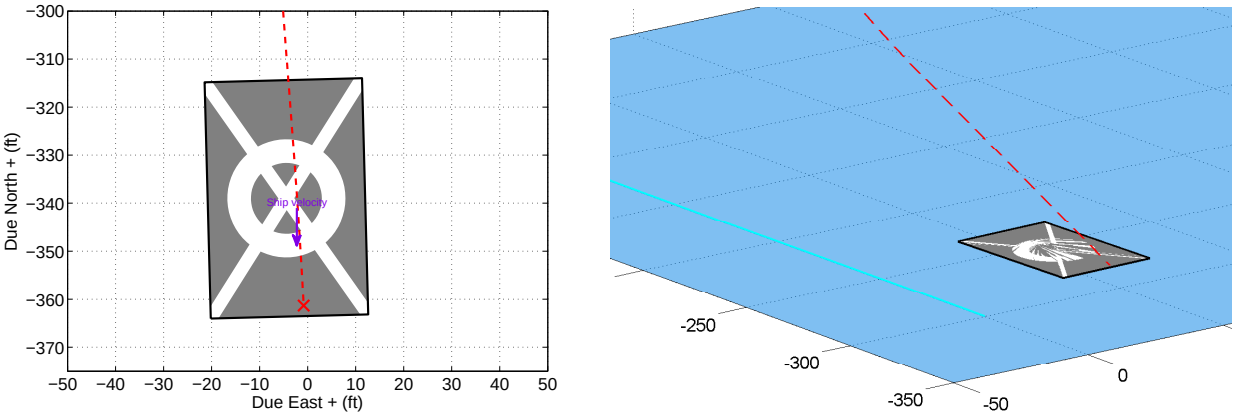
Using the MATLAB model of the control algorithm and the dynamics of the Snowflake ADS, it was found that the control algorithm could indeed be modified to execute an approach turn and final straight approach to landing to a target moving with constant velocity. As stated in Section II, the model used was very simple in that it did not contain random disturbances such as wind. Since each run of the simulation was identical, the results presented here show only one trial. Figure 7a shows the plan view of the approach turn and final straight approach to the landing area. Figure 7b shows a three-dimensional view of this trajectory. The final location of the ship's landing area is depicted in each plot, with the ship's displacement in sway and yaw incorporated into the drawing of the platform.

Figure 7a shows that in the simulation, the Snowflake ADS landed on the far forward edge of the landing area. One possible reason for this overshoot is that the actual time taken for the approach turn may have been less that that originally estimated by the controller when the optimal trajectory was calculated. Overshoot of this sort could be corrected easily with the incorporation of a control method to use both parafoil trailing edge control surfaces as flaps for a flared landing. In this current model, only differential, or aileron control input is used. Figure 8a shows a close-up view of the landing area, and figure 8b shows a close-up three-dimensional view of the landing area, with the location of the parafoil touchdown indicated.



(a) Plan view of Snowflake approach trajectory (b) Three dimensional view of Snowflake approach trajectory

Figure 7: Snowflake approach trajectory to a moving target



(a) Plan view of Snowflake approach trajectory (b) Three dimensional view of Snowflake approach trajectory

Figure 8: Expanded view of Snowflake approach trajectory

IV. Enhancement to Precision Airdrop for VERTREP

In order to achieve further improvements in the accuracy of precision airdrop systems so that consistent shipboard landings may be accomplished, additional communications links or sensors may need to be integrated into the guidance, navigation, and control (GN&C) packages that will be used. One such technique that is already in use to assist shipboard landing of rotary-wing aircraft is automatic data communication. The target ship's current position and current observed winds across the flight deck would be two streams of information that would be very useful to the algorithms in the GN&C package. In fact, this idea is the focus of current research involving the Snowflake-N ADS.[8] In these experiments, the Snowflake-N ADS receives in-flight updates of target position and ground winds using a mobile telephone communications link on the Global System for Mobile Communications (GSM) network.

Another technique that could assist in the final approach to landing phase is optical tracking of the landing area using visible light or infrared sensors. Previous investigation conducted at the Naval Postgraduate School into the use of infrared sensors for autonomous UAV shipboard landing showed that a UAV could determine its orientation with respect to the ship using three reference points in an infrared image of the target ship.[11] Furthermore, video image tracking techniques that have been proven in weapon systems such as AGM-62 Walleye and AGM-65 Maverick could be employed to maintain a precise tracking lock on the center of the flight deck landing area.

One recent additional technique that has been tested to aid autonomous recovery of manned rotary-wing aircraft is the incorporation of a laser rangefinder mounted near the flight deck landing area. As part of the development of the new SH-60K patrol helicopter for the Japanese Maritime Self-Defense Force, an autonomous landing of a manned SH-60K aboard ship was demonstrated through the use of the Ship Landing Assist System (SLAS). The automatic control algorithms in SLAS incorporated information from a laser rangefinder aboard the ship that tracked a reflective marker on the helicopter in range and azimuth as shown in figure 9.[12] This technique could also be applied to aid in the landing of a precision airdrop system.

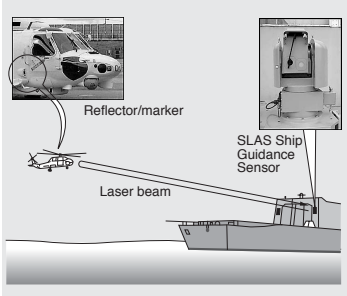


Figure 9: Use of a laser rangefinder

The preceding discussion has yet to address one of the most fundamental questions of employing precision airdrop at sea: "what if the cargo misses the target?" For further development of this concept, detailed consideration should be given to algorithms in the GN&C package that try to determine in flight whether an on-deck landing is either impossible or unsafe, perhaps due to high risk of collision with the ship's superstructure. In the case that the ADS and cargo do not land on the flight deck, and hit the sea surface instead, it might prove worth the extra weight and complexity to incorporate a flotation system into the ADS.

V. Other Maritime Applications of Precision Airdrop

Cargo delivery is only one of many potential application of precision airdrop technology to the maritime environment. Whereas the discussion above has centered on landing cargo on a cooperative target ship underway, this idea could also be extended to landing a small payload aboard a non-cooperative target ship. Potential applications of this concept include landing small sensor and tracker payloads on commercial shipping in order to detect certain types of material aboard a vessel, or to enable constant tracking of a particular vessel. Miniature, high-accuracy aerial delivery systems have the potential to land their payloads aboard ships undetected to accomplish these functions.

The next two maritime applications of precision airdrop are related to anti-submarine warfare (ASW), and are being investigated in conjunction with the development of the U.S. Navy's next-generation maritime patrol aircraft (MPA), the P-8 Poseidon. Unlike its predecessor, the P-3 Orion, the P-8 is designed to conduct its search, localize, track, and attack mission from high altitude. Because MPA rely on sensors and weapons dropped from the aircraft into the sea, i.e. sonobuoys and torpedoes, the higher operating altitude of the P-8 necessitates a greater need for accuracy in these airdrops. All current sonobuoy and torpedo systems now include aerodynamic decelerator systems in order limit the velocity of the sonobuoy or torpedo

before it hits the sea surface; in the future, these aerodynamic decelerators may have the additional function of providing a high level of accuracy to the airdrop.

The Naval Air Systems Command (NAVAIR) is the agency in the U.S. Navy responsible for development and procurement of aircraft-deployed sensor and weapon systems. A previous NAVAIR study on improving the accuracy of sonobuoys launched from high altitude had listed two improvements that could improve the accuracy of high-altitude sonobuoy drops: improved wind prediction using rawinsondes, and delayed deployment of the sonobuoy's aerodynamic decelerator.[13] In December 2007, the Program Manager, Air (PMA) 264 Air Anti-Submarine Warfare Program management office issued a research solicitation through the U.S. Government's Small Business Innovation Research (SBIR) program to study techniques for increasing the accuracy of landing for sonobuoys dropped from high altitude.[14] The name given to this solicitation was Precision High Altitude Sonobuoy Employment (PHASE); a general illustration of the concept is shown in figure 10. The requirements imposed upon the techniques included:

- Deployment altitude: 20,000 to 30,000 feet above ground level
- Spash Point Accuracy: 500 m required / 100 m desired
- Maximum Descent Time: 300 seconds from 30,000 feet
- Guidance: GPS cannot be utilized

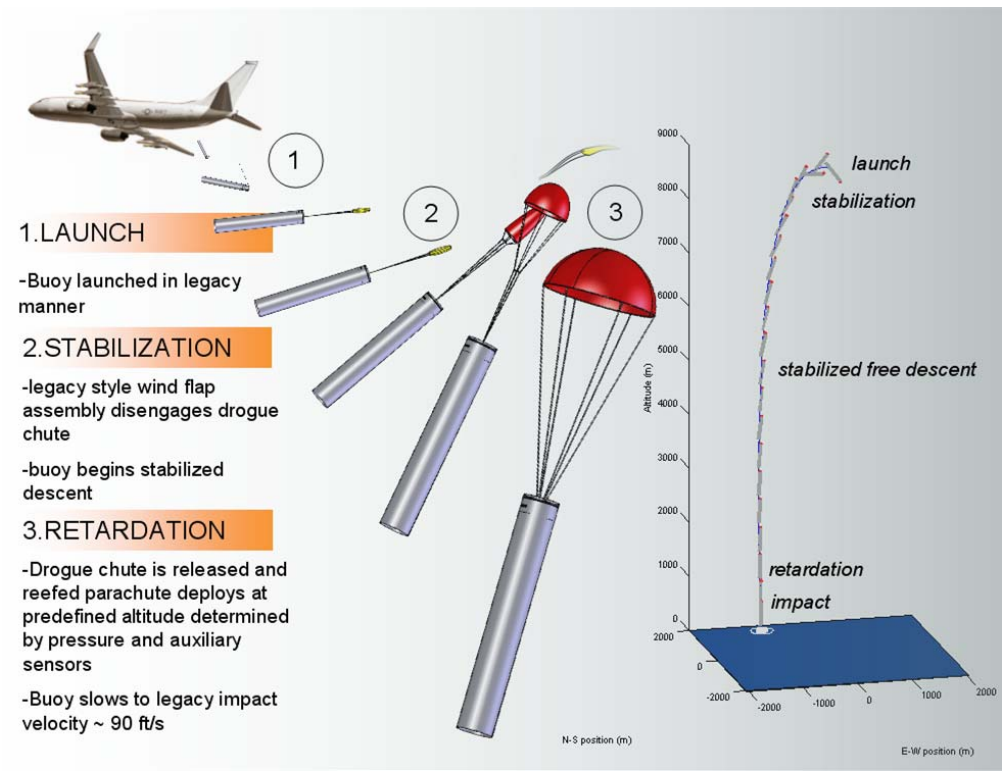


Figure 10: Precision High Altitude Sonobuoy Employment (PHASE) concept

At first glance, a high-velocity, two-stage decelerator might be best suited to this task, since a key performance parameter for a sonobuoy is speed of deployment. Of the technical reports that were submitted to NAVAIR in October, 2008, two reports reviewed did indeed focus on high-velocity, multiple-stage decelerator systems, where an initial drogue parachute or reefed main parachute stabilized the sonobuoy during the majority of the descent, and a second-stage parachute system was used at low altitude to slow the sonobuoy to the required impact velocity.[15,16] Most likely due to the requirement stated in the SBIR solicitation that the Global Positioning System (GPS) satellite navigation system could not be used to perform guidance on the sonobuoys, precision guidance to a desired splash point was not one of the functions of the aerodynamic

decelerator system detailed in these reports. The exclusion of GPS was likely due to concerns about compatibility with the current generation of sonobuoys, which do not have an integral GPS receiver. Nevertheless, future generations of sonobuoys will almost certainly incorporate GPS, and a low or mid-glide parachute or parafoil system might be suitable for the tasks of terminal deceleration and guidance to a precise splash point, using navigation information received by the sonobuoy.

For the application of precision airdrop to the employment of torpedoes, NAVAIR's PMA-264 Air Anti-Submarine Warfare Program management office awarded a contract to Lockheed Martin in June 2006 under the name High Altitude Anti-Submarine Warfare Weapons Concept (HAAWC). The contact was for demonstration of a system that allowed a torpedo to be dropped from an aircraft at high altitude, while being able to achieve high accuracy to a desired splash point. In May, 2007, Lockheed Martin successfully demonstrated a drop of a Mk-54 lightweight ASW torpedo (about 800 lbs) from a P-3 Orion MPA.[17] The torpedo was released at an altitude above 8,000 ft, and flew to the desired water entry point using a set of foldable fixed wings attached to the torpedo body. It is logical that speed of employment of a torpedo is even more important than glide-ratio for a high-altitude drop, because it is assumed that the MPA can, at high altitude, fly over or near the location of the submarine. Therefore, a high-velocity, two-stage system might be better suited for the task of providing precision guidance to high-altitude torpedo drops. Like the case of the sonobuoy, the tasks of terminal deceleration and guidance to a precise splash point might be accomplished using a guided parafoil as the second stage of a two-stage system.

VI. Conclusion

From this investigation, it was concluded that precision airdrop systems do have the potential to be used for vertical replenishment of naval vessels, provided further improvements in accuracy can be made. Along with improvements that can be made to precision airdrop systems for maritime vertical replenishment, and additional applications for other maritime missions, there is certainly ample ground for further research.

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