Development of a Cargo Airdrop Modeling Method for a Tactical Blended-Wing-Body UAV

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Abstract. In this paper, the development of a cargo airdrop modeling method is presented for a fixed-wing tactical UAV. The UAV, which is being developed in the framework of the DELAER UAS project, is based on the Blended-Wing-Body layout, and its mission is to deliver cargo and lifesaving supplies via airdrop, to remote and isolated Greek territories as well as over isolated islands in the Aegean Sea. At first, a simplified kinematic model is developed, to describe the trajectory of the cargo. Then, the critical airdrop parameters, such as the aerodynamic drag and the effect of wind gusts, are identified and incorporated to the model. Based on this model, an analysis methodology is proposed, conducted in several simulation loops. In each simulation loop, the cargo mass, release height, drop velocity and wind gust speed are the main variables. The results are given in a form of scatter plots, depicting the simulated cargo airdrop positions on the ground (or sea), around an actual target location, with respect to the drop height, drop velocity and wing magnitude. A solid conclusion is that, by releasing the cargo box with tailwind, the accuracy of the airdrop can be improved as much as 67% compared to any other wind direction.

1. Introduction

Airdrops have become a well-established alternative to the standard supply and equipment delivery methods, due to the significant advances in the fields of aeronautics, electronics and communication systems in the 20th and 21st century. Airdrops are used to deliver vital cargo, equipment and supplies, to support operations related to military and civilian needs such as ground troops support, humanitarian aid operations and civil protection missions [1].

In general, airlift operations offer several advantages over other delivery methods. More notably, they can be used when no other means for transporting equipment or supplies are available, whereas they can also greatly reduce shipping times. However, current airlift methods have some significant disadvantages as well. Most airdrop operations utilize manned aerial vehicles. That way, highly skilled pilots and personnel can potentially be exposed to danger during adverse conditions (high winds, rugged terrains or due to military activities). Moreover, most aerial vehicles are large aircraft or helicopters, which have very high operational and maintenance costs. This can greatly reduce the efficiency of the
mission, especially in the case of smaller-scale, tactical, civilian and rescue support operations, where a small payload, with mass of several kilograms, is required. These drawbacks can potentially be eliminated, though, by considering the option of fixed-wing Unmanned Aerial Vehicles (UAVs). More specifically, due to the absence of crew on board, fixed-wing UAVs have some key advantages compared to manned aircraft, including lower operational costs and the ability to operate under adverse or hazardous conditions without risking human lives [2].

The current study is conducted in the framework of the DELAER UAS research project. The project involves the design, development and flight-testing of a tactical UAV experimental prototype, marked as RX-3, to provide direct support to Greek isolated territories and islands. To that end, the RX-3 is capable of carrying a useful payload (cargo of lifesaving supplies) of up to 50kg, and delivering it via airdrop. The RX-3 configuration (Figure 1) is based on the Blended-Wing-Body (BWB) layout, which offers a considerable increase in aerodynamic efficiency and performance, compared to conventional layouts [3,4]. Moreover, the BWB layout has a unique combination of large available internal volume and low wetted area to volume ratio, which is ideal for the cargo delivery-related mission of the DELAER RX-3. Its typical mission profile is to take off from the base of operations, cruise to the point of interest, deliver the cargo via airdrop, and cruise back to the base, or to a predefined location. Concerning the airdrop procedure, it is arguably one of the most important phases of the RX-3 mission, when it comes to successfully fulfilling the requirements it was designed for. The number of available studies in the literature is relatively limited, both for manned and for unmanned aircraft. Furthermore, the approach of those studies is either too simplistic [5], based on statistical methods, or too complex, based on time- and resources-demanding high-fidelity Computational Fluid Dynamics (CFD) modeling. A typical example of the latter is the study presented in [6,7], where the authors tried to reach detailed results about the trajectory dynamics of the cargo. An interesting approach is that of [8], where a statistical analysis is employed to predict the landing location of a broken-down UAV. Although in this case the body under investigation is an entire UAV configuration that falls from the sky (instead of a falling cargo box), there are comparable aspects between the two cases, mainly concerning the treatment of the wind gust effect.

In the present paper, a method is proposed to investigate the cargo airdrop of the RX-3. The proposed method is more simplified than CFD-aided methodologies, but requires considerably less computational resources and time. At the same time, it does not depend on generic statistical methods. The aim is to estimate the possible landing locations of the cargo after airdrop, in relation to a specific target point. A critical parameter that introduces a possible deviation (Euclidian distance in meters) between the target point and the estimated landing locations is the presence of wind gusts, which impede and alter the cargo trajectory (as a horizontal projectile motion). The RX-3 is designed to withstand adverse weather
condition and winds up to 8B (approximately 70 km/h) [9]. Another critical parameter is the shape of the actual cargo being dropped, as a non-streamlined rectangular box, easily affected by aerodynamic loads, present during its descent. It should be noted at this point that a free fall life raft airdrop is being investigated, as an indicative RX-3 mission. That is, no parachutes or other deceleration systems are considered, in contrast to some other, well-established cargo delivery examples (supplies and equipment) mainly encountered at military operations that would otherwise be destroyed upon impact. Dropping a life raft still requires considerable airdrop precision to ensure that the person in need can actually reach it. “Ready to deploy” life vests are usually cased in rectangular boxes, such as the one modeled throughout this analysis. Summing up, the proposed methodology does not precisely calculate the complete cargo box trajectory, after it is released from the RX-3, but rather allows for a rapid investigation, in rough terms, of the effect of the UAV airspeed (as a vector), wind gusts and box shape to the overall precision of the airdrop.

2. Tools and Methods
In this chapter the basic philosophy and principles of the algorithm, investigating the accuracy of cargo airdrops are presented and analyzed. The core of these simulations is a basic kinematic model that includes the differential equations of motion of the cargo during an airdrop. Supplementary to these equations, a wind magnitude is chosen by the algorithm, based on statistical data, while solving the simulating loop. After the complete kinematic model (drag forces and wind forces included) is set up, the algorithm solves the physical model and calculates drop trajectories, using the drop height and velocity as input parameters (boundary conditions). Due to the short duration of the airdrop procedure, the velocity and the direction of the wind is assumed to be constant throughout each airdrop simulation loop. Each simulation loop defines an impact point which is at a specific radius from the actual target point. The sum of these impact points composes contours around the actual desired target (Fig 2).

2.1. Model Philosophy and Critical Assumptions
The overall physical model of the airdrop procedure includes a kinematic model, based on horizontal projectile motion equations through air, and a wind magnitude/direction model. However, since presenting the methodology in its final form is rather confusing, a step-by-step presentation is made in following paragraphs, starting with a simplified approach and assumptions and adding more details towards the of the current section.

In its most simplified version, the RX-3 cargo airdrop procedure is treated as a 2D horizontal projectile motion problem. It is assumed that atmospheric conditions (both aerodynamic drag and wind gusts) are neglected so that the problem can be easier expressed analytically, using two linear differential equations of motion. These analytical expressions are presented in eq. (1) and (2).

\[ \sum F_x = 0 \Rightarrow \ddot{x} = 0 \]  
\[ \sum F_y = m \cdot \ddot{y} \Rightarrow \ddot{y} = -g \]

Note that g is the acceleration of gravity. Integrating equations (1) and (2) with respect to time produces a rather simplified and well-known center of gravity trajectory plot for a projectile motion problem (Figure 3), considering that the initial horizontal velocity and drop height are given [10].
The next step is to include the effect of the atmospheric conditions, namely air resistance and wind gusts. On one hand, the air resistance (aerodynamic drag) has to be included to the previously stated equations of motion. Equations (1) and (2) transform into a non-linear system, due to the loads being proportional to velocity squared (eq. 3). As a general observation, adding the effect of the aerodynamic drag into the problem has a considerable effect to the trajectory of the cargo by limiting its horizontal range. Note that calculating the air resistance is considerably easier for axisymmetric bodies, such as spheres, because the rotation of the body is predictable. As far as any other shape is concerned, the air resistance prediction becomes significantly more complex. On the other hand, the effect of wind gusts must also be included. The gusts are highly affecting the actual landing position, during an airdrop [5]. The integration of the wind related phenomena is achieved by treating the wind loads as aerodynamic drag loads parallel to the ground or sea surface.

For the current research the rotational motion of the cargo box during airdrop is not taken into account for three reasons. Firstly, it is assumed that the cargo release is taking place at a very low altitude thus the rotational motion cannot play a significant role to the airdrop precision. Secondly, the wind gusts, drifting away the airdropped cargo, are the main parameter being examined in this paper. And lastly, the preliminary level of this analysis implies the use of a simpler kinematic model than adopting a much more complex one.

2.2. Model Description and Equations of Motion

The airdropped cargo is treated as a cubic body (cargo box) with a side area of 0.25m² and a mass of 20kg, typical for RX-3 designed payload during search and rescue missions [9]. The 3D kinematic model consists of three non-linear differential equations for the translation motion of the cargo center of gravity. Each of the three is expressed parallelly to the main axes of the solution space. The main loads acting on the cargo during drop are the weight and the drag force (analyzed into two vector components, one for the horizontal and one for the vertical direction). Moreover, the effect of the wind gusts is taken into account in the form of an additional force. The latter is treated as an extra aerodynamic load, caused by the relative velocity component between the cargo direction of motion and the wind velocity vector (Figure 4). It is assumed that the wind aerodynamic load can be acting on any given direction around the cargo (from 0 to 359 degrees around the vertical y-axis). The drag forces acting on the cargo box are calculated analytically using:

\[ D = \frac{1}{2} \rho V^2 S c_D \]  

(3)

where \( c_D \) is the drag coefficient of a cube, \( S \) is the side area of the cargo box and \( V \) is the velocity of the cargo box, parallel to the axis of interest. Note that this equation can applied consecutively to all three main axes of the cargo box. Concerning the drag coefficient, a value of 1.05 is selected based on fundamental fluid mechanics literature [11] and is identical for every direction.

Furthermore, the set of the three non-linear differential equations, can be written as follows:

\[ m \cdot \ddot{x} = D_x (\dot{x}^2) + F_{w,x}(\dot{x}_{rel}^2) \]  

(4)

\[ m \cdot \ddot{y} = D_y (\dot{y}^2) + F_{w,y}(\dot{y}_{rel}^2) \]  

(5)

\[ m \cdot \ddot{z} = F_{w,z}(\dot{z}_{rel}^2) \]  

(6)

where \( m \) is the mass of the payload being dropped, \( F_w \) is the wind forces acting on it and, lastly, \( D \) is the drag forces during its descent. Note that equations (4), (5) and (6) include the effect of non-linear factors.
such as drag forces (defined by the velocity squared) and wind forces (defined by the relative velocity squared).

2.3. Wind Modelling

The wind is modeled as a vector parallel to the ground, thus creating a corresponding aerodynamic force to the airdropped cargo, similar to drag force due to air resistance. Its direction is considered completely random due to the obvious uncertainty about the relative angle of the UAV airspeed and the wind velocity (both seen from an observer on the ground), the moment of the airdrop. However, unlike the wind direction, the wind magnitude has a specific behavior over the Aegean Sea, which is useful for the current research providing the limits of the wind simulation along with a certain statistical distribution of wind velocities. Statistical data [12] show that through the duration of the year, winds velocity span from 4m/s to 25m/s with a mean value of around 7m/s. Due to operational limits of the DELAER RX-3, the wind velocity is limited to 19m/s (8B) [9]. For each simulation loop, with given drop velocity and drop height, the wind is chosen based on literature statistic distribution of magnitude and a randomly chosen direction.

2.4. Model Facilitation and Simulation Code Development

To facilitate the model calculations and conduct the simulation loops, a dedicated algorithm and a corresponding simulation code is developed. The code is written on the Python programming language and a time-dependent model is set-up and solved, with a time step equal to 0.01s. This time step is selected following a corresponding study based on trials with three different time steps (0.1, 0.01 and 0.001s) on a simplified model with no wind and no forward velocity of the cargo box. This study verified that the value of 0.01s is adequate for providing time step–independent results, without causing an extensive increase in computational demands. As mentioned above, the only initial conditions used as simulation parameters are the drop height and velocity. Referring to these parameters, the tested height range is set to span from 50 to 125m from the ground, based on the RX-3 mission profile and drop velocity is set to vary between 25 and 32m/s. All forces are assumed to act on the cargo box center of gravity while moments, around it, are neglected, as they will be incorporated in a higher fidelity tool in the future. After calculating the forces in each time step, total acceleration is calculated and through double Euler integration position (in x,y,z axes) is subsequently acquired. Finally, the ground impact position, for each loop (over 40000 loops in total), is extracted and noted in data spreadsheets where the deviation from the desired point of impact is calculated in meters.

3. Results

For the current study, all airdrop simulation loops have been conducted with a reference cargo weight of 20kg for search and rescue missions. Cargo mass was chosen to be 20kg, as a nominal value, aiming to verify the presented simulation tool as a robust methodology and to be more easily compared with experimental data, in the future. Results, extracted for 20kg cargo weight, can be easily extrapolated to lower or higher values, as the fundamental physics of the phenomenon remain unchanged. The results are presented in the form of scatter plots indicating simulated impact points around a given target. For comparing the airdrops precision, featuring different drop velocity and drop height, scatter plots are created, depicting the pattern of a thousand (1000) loops of simulation for each parameters pair. These plots (Figures 5 to 8) are divided into three zones, the first one (green zone) corresponds to “good” weather conditions (wind magnitude under 3B), the second one (yellow zone) to “moderate” wind conditions (3-6B) and last is the orange zone with winds up to 8B. A first, and rather obvious outcome is that higher winds drift the point of impact further away from the actual target, which is expected. Wind drift can cause a deviation from the target point of impact for several meters. In general, this deviation radius is comparable, as a value, with the drop height. Indicatively, as shown in Fig. 6, airdrops from 75 meters altitude can deviate 63 meters away from the target.

Airdrop velocity is also affecting the simulated impact point pattern. More specifically, as the drop velocity rises, the pattern of impact points alternates from a circular shaped region to a more ellipsoid
one. This observation indicates that as higher is the velocity of the UAV at the moment of the cargo release, the wind has lesser influence in this direction (coaxial with the UAV). This phenomenon could be explained due to the relative velocity of the descending cargo against the wind gusts. From this point of view, the portion of wind velocity seen by the cargo box is minimized when the drop velocity increases and the wind direction is 0 or 180 degrees relative to drop direction, i.e. the wind is coming head-on or from behind the dropping cargo box. That way, the accuracy of the airdrop can be increased as much as 67%, compared to the other directions. That can be attributed to the fact that, when the relative velocity portion hits its minimum, the depended drag force is less significant for the overall dynamics of the physical system.

Drop height seems to have a minor impact when the airdrop takes place in calm weather, rising from a 14.2m radius of deviation to 25.6m, for airdrops happening from 50 to 125m altitude range. This observation indicates that drop height has no significant effect on the airdrop accuracy. By noticing that no rotational motion was taken into account in this research, its absence in the kinematic model could be a strong factor in changing the final airdrop precision. At this point, it is safe to assume that drop height should be kept to a minimum in order to execute a successful airdrop, close to the actual target. This cannot be a concrete conclusion and more research should be made towards this direction. Seemingly, for a predictable and thus successful airdrop to be achieved, the UAV has to fly as low as possible, and the airdrop should be performed with tailwind. Nevertheless, a rather clear observation is that a sophisticated targeting system (taking into account the wind gusts) is needed for the RX-3 airdrop missions to be dependably accurate.

![Figure 5](image1.png)

**Figure 5.** Scatter plot for airdrops from 50m drop height at 90 and 110km/h

![Figure 6](image2.png)

**Figure 6.** Scatter plot for airdrops from 75m drop height at 90 and 110km/h
4. Conclusions

An investigation of the airdrop procedure for a fixed-wing, tactical BWB UAV configuration is conducted in this work. A dedicated, rapid and low-fidelity methodology is proposed, emphasizing on the effect that the wind gusts have on the trajectory of the cargo. The goal is to come up with a rough estimation for the deviation of the impact point for the airdrop aiming point, without the need for time- and resources-consuming computational modeling or the dependency from generic statistical models.

For the simplified preliminary airdrop precision study, a kinematic simulation methodology is adopted. This simulation is based on a kinematic model of the physical system, including the forces acting on the cargo during its descent. The wind aerodynamic loads are treated as drag force components acting on the cargo box from the direction of the wind relative to it. Moreover, concerning the wind gusts, the wind magnitude is calculated using statistical data for the weather conditions encountered over the Aegean Sea throughout the year.

The given parameters for each simulation are the drop velocity and the drop height. For each pair of the selected parameters the 1000 simulation loops are executed, yielding 1000 impact points around a designated target. The results are given in form of scatter plots with points teamed up in three groups, in respect to the wind magnitude. One group corresponds to winds bellow 3B, one to 3 to 6B and one to
6 to 8B. For each group, a maximum radius of deviation from the target is given, as an indication of how precise, or not, the simulated airdrop is. A key conclusion concerning the airdrop procedure accuracy is that, by releasing the cargo box with the wind blowing from behind, the deviation from the target location can be improved as much as 67% compared to any other direction.

Concerning suggestions for future work, many simplifications have been made to the kinematic model, so that the differential equations of motion can be rapidly integrated, for the airdropped cargo box. A more precise kinematic model should include the rotational aspects of the physical system’s motion as well as the affection of this rotation to the final trajectory and precision of the airdrop. Moreover, real scale testing must be employed to calibrate the model and evaluate the validity of the assumptions. Most importantly, though, the predictions of the current model can be employed to define the exact position of the UAV, the moment of release, in order to fine-tune the accuracy of the airdrop.

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