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A VTOL SMALL UNMANNED AIRCRAFT SYSTEM TO EXPAND PAYLOAD CAPABILITIES

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Abstract

One of the goals of Unmanned Aerial Systems (UAS) is to increase the capabilities of flight vehicles while maintaining small airframes that are also lightweight. Private package delivery companies and government agencies have an interest in vehicles that have large payload to weight ratios; thus allowing to deliver heavy payloads. Currently, UAS configurations suffer from propulsive and aerodynamic limitations that decrease the payload weight and/or mission range. In order to decrease these limitations, the Kinetic and Potential Energy Alternation for Greater Lift Enhancement (KP EAGLE) concept provides a novel way to transport payloads that may be too heavy for vehicles in a similar weight class. The concept vehicle takes off vertically without the payload. It then performs a dive maneuver that transfers the gained potential energy into kinetic energy to pick up the payload. This concept does not require special equipment during takeoff or landing and provides a better payload to weight ratio than other conventional vehicles in the same weight class.

1 Introduction

In the emerging market of Urban Air Mobility (UAM)[1], package delivery through the air has become appealing for easier and quicker access. However, there are limitations in the package weight and distances that can be covered by current Unmanned Aerial Systems (UAS). Most UAS vehicles fall into two categories: fixed-wing airplanes that takeoff and land horizontally or with assistance, and vertical takeoff and landing (VTOL) vehicles.

Fixed-wing vehicles use wings as the main component to generate lift. Ultimately, the aerodynamic and propulsive components have a large effect on the payload capabilities. Fixed-wing vehicles tend to have larger payload to weight ratios than other configurations. The main disadvantage of this type of vehicle is the large takeoff distances required. This is often addressed by using special takeoff equipment such as catapults.

Inside the category of VTOL vehicles, there are multirotors and vehicles that transition from VTOL to horizontal fixed-wing flight (forward flight). The design of multirotor configurations, due to the lack of wings, focuses on propellers and motor selection in order to generate lift; thus, the payload capabilities are determined by the amount of thrust that can be generated by the motors. Finally, a VTOL vehicle that can transition to forward flight has the potential of having better range due to the aerodynamic benefit of having wings. In order to increase payload capabilities, multiple propulsors are often used.

This paper presents a novel vehicle configuration inspired by nature that has payload to weight ratios typical of fixed-wing vehicles but can take-off and land vertically. This vehicle is called the Kinetic and Potential Energy Alternation for Greater Lift Enhancement (KP EAGLE) configuration. This unique concept allows the vehicle to takeoff like a VTOL vehicle, transition to forward flight, and use the vehicle momentum and aerodynamics to snatch a payload at high speeds and angle of attack. The maneuver to pick up the payload enables heavier payloads that can currently only be delivered by drones that require catapults.

2 Background

2.1 Motivation

For companies like Google and Amazon or government agencies like the Department of Defense (DOD) and NASA there has been an interest in the capability of heavy lift for a specified range. In order to do this, the traditional way is to add more power to the aircraft, which in turn adds to the overall weight and often size of the vehicle. There is a unique gap in development of non-complex vehicles that are capable of providing substantial lift with a reasonable range. A vehicle able to takeoff and land with minimum equipment and deliver heavy payloads while being able to cover large distances can increase the capabilities of UAS delivery.

2.2 Market

Package delivery companies such as Amazon are focusing on using drones to deliver payloads that weigh 5 lbs or less. This is because approximately 86% of packages delivered by Amazon are in that weight range.[1] This means that 14% of packages will not be able to be delivered by a drone. Although the number of large payloads (greater than 5 lbs) represent a smaller percentage of deliveries, a drone with those capabilities could more effectively cover the available package delivery market or increase the range of packages delivered at 5 lbs or less. In addition, in order to deliver to a large portion of the US population (greater than 50%) through Amazon, DHL, Walmart, and Target an approximate range of 180 nautical miles is desired [2].

Another important market is humanitarian relief. A vehicle that requires simple takeoff and landing equipment can be used to deliver payloads to and from rural areas since it does not need special equipment such as a catapult or paved runways. Companies such as Zipline[2] have proposed and implemented concepts that deliver medical supplies to rural areas by using a fixed wing UAS. This type of concept is revolutionizing humanitarian relief by using ideas being developed in the package delivery arena.

Another potential market alternative is science missions proposed by NASA. Payloads can be taken from one location to another with relative ease. This type of approach would benefit science missions where multiple samples from a variety of locations are desired.

2.3 Prior Examples

There are different vehicles and ideas that explore the delivery of heavy payloads (large payload to weight ratios). Some of the vehicles that have been explored for heavy lift aircraft including the Boeing LIFT vehicle [3], which is large in size and must have tethered power for a long endurance (greater than 18 minutes). The design showcases a modular quadcopter to accomplish a higher payload capability by increasing the size and power options. Another company, Flytrex,[3] utilizes a family of multicoptors that are rated at different capabilities in order to overcome the needs of the consumer. Flytrex's largest vehicle maxes out on payload at 6.6 lbs with a range of 5.4 nautical miles. Although Flytrex has surpassed the payload capability, the range of the vehicle is low. Finally, Zipline has successfully implemented package delivery using an automated catapult launched fixed wing vehicle capable of 3.3 lbs of payload with a range of 80 nautical miles. [4] Some of the potential improvements for the Zipline concept include handling heavier payloads and eliminating the need for a base to assist in takeoff and landings.

[1] https://www.theverge.com/2013/12/1/5164340/delivery-drones-are-coming-jeff-bezos-previews-half-hour-shipping

[2] http://www.flyzipline.com

[3] http://www.flytrex.com/

[4] https://www.technologyreview.com/s/608034/blood-from-the-sky-ziplines-ambitious-medical-drone-delivery-in-africa

Nature has also provided a plausible solution to delivering 'heavy' payloads. Birds of prey have weight carrying capabilities that exceed their body weight [4]. Table 1 shows the weight carrying capabilities for some selected birds of prey. These birds of prey can carry more than their own body weight. This is in part, possibly, because they can acquire the payload during flight, avoiding a power intensive takeoff. Thus, an UAS that is able to replicate some of this behavior could potentially provide payload to weight ratios similar to the ones obtained by birds of prey.

Table 1 Weight carrying capabilities of selected birds.

	Approx. Body Weight (lb)	Approx. Weight of Item (lb)
Pallas's fish eagle	8	13
Bald eagle	14	15
Steller's sea eagle	19	20

There are previous vehicles that have been designed to behave like birds of prey by capturing a payload during flight. In particular, the GRASP Lab at University of Pennsylvania has proposed a concept that can grab a payload at slow speeds [5]. This vehicle is a quadcopter and is able to capture the payload while flying at 4.5 and 6.7 miles per hour. This speed is slow but provides a point of reference of the current state of the art in grabbing payloads mid-flight.

Vehicles that can perform maneuvers at high speeds to capture payload have the potential of providing large payload to weight ratios as seen in Table 1. This type of vehicle differs from the concept proposed by the GRASP Lab at University of Pennsylvania because of the large speeds at which the vehicle should be able to operate in order to use the lift provided by the wings to carry heavy payloads.

A comparison of the capabilities of different vehicles is shown in Table 2. This table shows that a vehicle that can mimic bird-like maneuvers to pick up payloads mid-flight has the potential of having a high payload to weight fraction, a medium range, and it would not need complex equipment for takeoff and landing. This is in part due to the fact that lift generated is a function of velocity, so the faster a vehicle flies, the greater lift force is generated. The bird-like vehicle would take the beneficial aspects of each of the other types of vehicles and combine them into a single vehicle by utilizing the maneuver.

Table 2 Vehicle comparison.

	Payload Weight Fraction	Range	Ground Ops Complexity
Multicopter	Medium	Low	Low
Fixed-Wing	High	High	High
VTOL	Low	High	Low
Bird-like	High	Medium	Low

3 Vehicle & Mission Requirements

The main requirement of the proposed vehicle is to ensure that it can be used practically anywhere while providing a payload to weight ratio that exceeds what other vehicles in the same weight class can achieve. In order to operate nearly anywhere, the proposed vehicle must be able to takeoff and land with minimal assistance. A fixed-wing VTOL configuration would satisfy the criteria of operating nearly everywhere but would not be able to deliver higher payload to weight ratios than multicopters because VTOL vehicles rely solely on the propulsion system to generate lift during takeoff. In addition VTOL vehicles are typically complex in nature and the majority of the weight capability is consumed by actuation (tilt wing/rotor). To work around this limitation, the payload will be picked up while the vehicle is already in horizontal flight similar to the behavior seen by birds of prey. All other beneficial aspects of VTOL including the low ground ops complexity and higher range will be utilized. However, there will be a slight degradation of range capability due to the mission profile of the vehicle utilizing a lot of power as well as the wing to generate lift and the need for two climbing maneuvers. Figure 1 shows the planned mission.

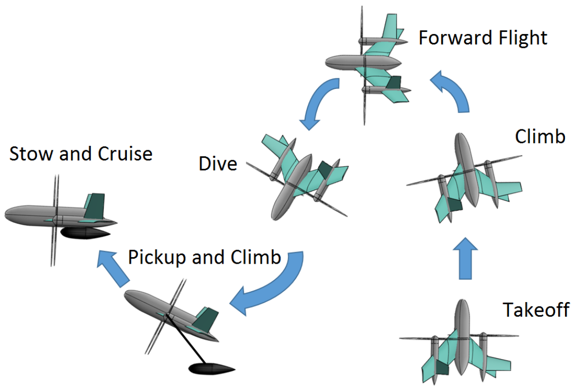

Fig. 1 KP EAGLE mission profile.

In the first iteration of the design cycle the focus is on establishing a proof of concept rather than designing an optimized vehicle. Another specific requirements for the mission is to be able to pick up the payload on the move without any adverse dynamic effects. For an initial assessment and prototype, 8 lbs will be used as maximum vehicle weight, while being able to carry an additional 8 lbs of payload.

There are some secondary requirements that must also be included. The vehicle must have a high angle of attack point in order to use a pick up and drop off maneuver to reduce the dynamic loads on the vehicle. In addition, the vehicle should be able to maintain a high speed and withstand the loading on the vehicle while picking up the payload.

4 Analysis Methodology and Design Challenges

The KP EAGLE concept provides an alternate means to pick up payloads that may be too heavy for the rating of the current vehicles. The goal is to maintain a small takeoff weight, while still being able to carry a relatively heavy payload. The highest amount of energy required is during takeoff and landing, therefore taking off without the payload saves a large amount of energy that can be used to extend the endurance or increase the maximum payload rating for the vehicle. The concept is modeled after an eagle and the large weight to payload capability that the animal has, which is approximately 1:1 (as seen in Table 1). The project includes the design of an aircraft that can take off at a very low power, climb to a certain altitude to gather potential energy, which will transfer into kinetic energy to provide the extra energy that is needed to pick up a heavy payload. The vehicle will be able to locate the payload, initiate a dive towards the package, grab the payload during flight, gain altitude again, and have enough power and energy remaining to have a useful endurance.

There are different mechanisms to capture payloads when the vehicle is already in the air. One of these mechanisms consists of a gripper installed at the bottom of a UAV to hold the payload. A second mechanism consists of suspending the payload with cables [6]. A third possible option is based on work performed in the GRASP Lab at University of Pennsylvania [5]. In this configuration a robotic arm is attached to a quadcopter and is able to mimic a bird's grasp. The main observation of this configuration is the low speed at which the vehicle operates.

One of the main design challenges includes the unwanted dynamic loads and possible swing loads after connection with the payload. This inherently comes from the Center of Gravity (CG) shift in the total aircraft system. Having the CG shift from the designated stable location to a different location potentially further back and below the aircraft could adversely affect the stability of pitch and yaw of the aircraft during its most critical moment. The aircraft should be designed accordingly to be robust against any shifts in CG.

Snatching a payload at high speeds is equivalent to having a controlled collision. Depending on the mechanism used, different approaches to model this collision can be used to provide information to size the vehicle. Ultimately, this shift in momentum provides stresses in the vehicle airframe and can greatly affect the aerodynamic forces, causing an unstable system.

A key bird-like maneuver that can benefit the design of the KP-EAGLE concept is perching.

The perching maneuver will allow the vehicle to land and deliver the payload without the need of parachutes. The KP-EAGLE concept will need to optimize its trajectory to ensure that such maneuver will provide the desired behavior [7].

In order to achieve the maneuvers that are required to capture and carry a payload that is equal to the vehicle weight, the vehicle needs to have special considerations during the design. The vehicle first and foremost must be able to handle the loads that it will see upon impact. The structural limits at certain places along the wing and/or fuselage will need to be extra rigid, which will also add weight to the vehicle. Material considerations should be taken into account during the prototyping phase. The next aspect to tackle is the vehicle being able to achieve high angles of attack without stall or minimal stall effects. Finally, to reduce the take-off and landing requirements, the preferred vehicle should have VTOL capabilities. VTOL vehicles that can transition to forward wing-borne flight have challenges with complexity, stability and safety depending on the chosen configuration. With all of the design challenges, the vehicle should use simplicity in order to keep the weight down allowing for a higher payload capability.

5 Vehicle Design and Analysis

5.1 Vehicle Geometry and Performance

The idea of simplicity for a VTOL vehicle leads to a design with minimal moving parts and robust take off and landing considerations. A vehicle that can takeoff and land on any surface brings many benefits to the mission operations. In order to accomplish this, as well as being able to maintain fast forward flight, the vehicle will need either separate lift-thrust or a tilting mechanism . The chosen method of operations for a prototype will include vectored thrust with single axis gimbaling motors. The motors will have enough available movement to lay on it's belly or at an angle provided by the grasping mechanism and take off. Figure 2 shows the preliminary prototype design of the KP EAGLE. The vehicle is a bi-rotor flying wing with additional slanted tails attached to the wing for natural stability. The vehicle employs a multi-reference frame controller to transition into a forward flight configuration. The motors will be used for both the hovering and the forward flight portion of the mission. With the motors being able to gimbal and using differential revolutions per minute (RPM), there will be full control authority for operations without the need for any additional control surfaces.

Figure 3 shows the top view of the KP EAGLE vehicle with the half span, root chord and tip chord dimensions. An approximately 5 foot wingspan vehicle with a reference wing area of 2.4 ft^2 is similar to other vehicles in the weight class and mission scenarios. For a more robust design, the vehicle contains sweep in order to open up the CG allowable range. During the pick up of the payload, there may be moments that the CG will shift aft and therefore the vehicle should be designed to have a range of CG locations that are acceptably reliable. Sweep assists in the ability to maintain stability, specifically pitch, throughout the picking up maneuver. Ideally the vehicle would have variable sweep capabilities for optimal flight during each phase, similarly to how birds fly. However, for a first iteration prototype and initial analysis the sweep will be static. For simplicity in the vehicle design, an aircraft without a tail was desired. Traditionally a tailless vehicle comes with it's own complications, but in this mission scenario, complications are actually removed and saves weight. Without tails, the vehicle does not have to worry about tail strike during a pullout near the ground.

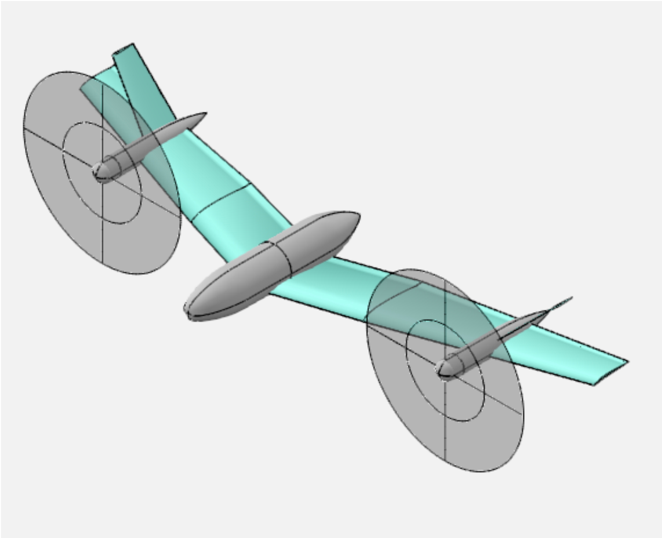

Fig. 2 KP EAGLE vehicle.

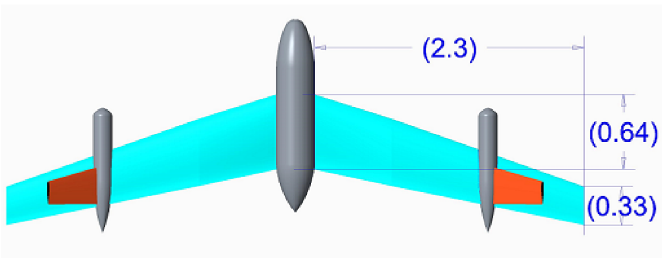

Fig. 3 KP EAGLE vehicle top view (ft).

In order to prevent significant stall effects, an airfoil and wing will be uniquely designed that will be consistent with the requirements of having natural stability and flight performance. Similar to designing an UAS for a unique mission on Mars, a family of airfoils from the University of Illinois Urbana-Champaign airfoil database[5] was investigated and altered until desired performance was achieved [8]. In Fig. 4, an airfoil was designed based upon the NACA 5206 for both the ability to maintain simplicity by providing reflex to handle the pitching moment instead of a tail and for performance pushing the stall point to a higher angle of attack. The airfoil is relatively thin and must be reinforced to maintain the stiffness in the wing with spars and composites. There is a significant trade off between having the additional weight from materials for stiffening the airframe and having thicker airfoils, which degrade the performance of the overall vehicle.

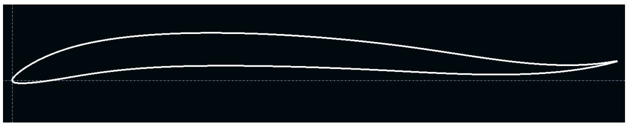

Fig. 4 NACA 5206 reflexed.

Finally an estimate of the performance of the vehicle in Fig. 2 can be seen in Fig. 5. The analysis was performed using a mix of tools including OpenVSP[6] and XFLR5[7]. OpenVSP is an open source parametric geometry tool that also has the ability to predict parasitic drag directly from the geometry using Hoerner Form Factor equations and Blasius laminar and turbulent skin friction coefficient equations. XFLR5 is an analysis tool for airfoils, wings, and planes designed for low Reynolds numbers, which provided the initial uncorrected performance of the vehicle.

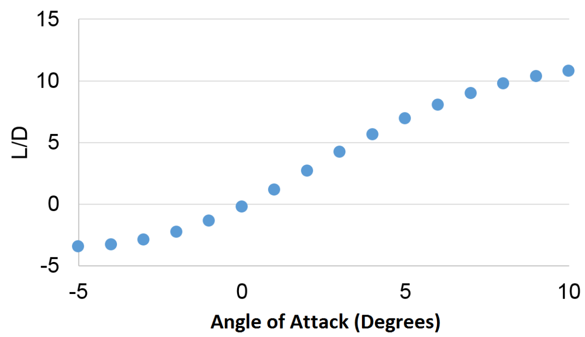

Fig. 5 L/D vs α for the KP EAGLE concept.

The lift generated by the vehicle is computed by

$$L = \frac{1}{2}\rho V^2 S_{\text{ref}} C_L \qquad (1)$$

where ρ represents the air density, V the free-stream velocity, S_{ref} the reference area, and C_L the lift coefficient. From Eq. 1 it can be observed that lift is sensitive to the vehicle's velocity. Therefore, higher velocities during the pickup maneuver would provide higher payload

[5] http://m-selig.ae.illinois.edu/ads/coord_database.html

[6] http://openvsp.org/

[7] http://www.xflr5.com/xflr5.htm

capabilities. The vehicle's velocity is restricted by dynamic and structural considerations.

5.2 Grasping Mechanism

Two grasping mechanisms were considered. The first option consisted of using a robotic arm with a passive system to capture the payload as seen in Figs. 6 and 7. Preliminary analysis suggested that such a configuration introduced large moments that the vehicle is not able to handle. These moments are the result of the large speeds at which the maneuver must take place in order to successfully pick up the payload. These moments can be reduced by flying at a slower speed but this leads to a decrease in lift capabilities which translates to a decrease in payload. The second option involved using ideas previously employed in banner towing, where an advertising banner is towed by an aircraft. In banner towing, the aircraft takes off without the banner and then picks up the banner by using a hooking mechanism that uses a tow rope attached to the aircraft. The option investigated uses a string similar to a fishing line and a passive hooking mechanism (similar to Figs. 6 and 7) that would allow the payload to be picked without the addition of extra moments. The string is retracted once the payload has been picked. This allows the payload to be closer to the vehicle; thus, minimizing drag and adverse swinging motion dynamics.

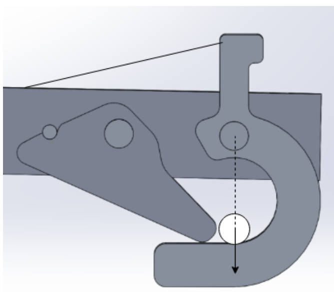

Fig. 6 Grasping mechanism.

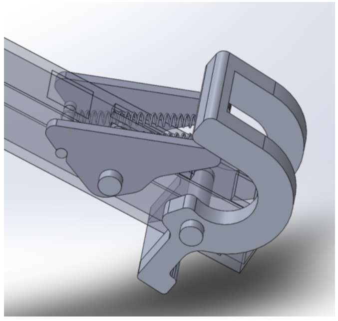

Fig. 7 Grasping mechanism.

5.3 Dynamics of Pickup Maneuver

Most of the complexities in designing the vehicle are derived from the payload pickup maneuver. Preliminary analysis assisted in selecting the grasping mechanism that would work best. A rotating arm of fixed length was initially considered, but it was determined to be infeasible for the specific configuration being studied due to the large moments the vehicle experienced. In contrast, the selected mechanism discussed in Section 5.2 decreases the moment experienced by the vehicle and changes it to a force applied at the center of gravity. A simplified free body diagram of the vehicle is shown in Fig. 8.

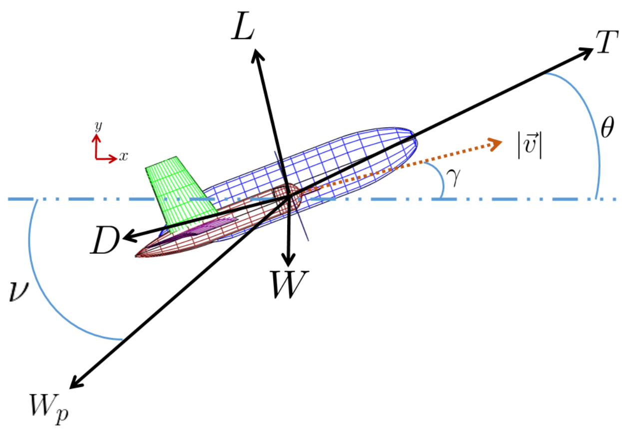

Fig. 8 Free body diagram.

In order to pick up the payload, the thrust and lift forces must counteract the drag force, vehicle weight, and tension due to the payload. The resulting propulsion, aerodynamic, and weight forces experienced by the vehicle are given by Eqs. 2 to 4

$$\vec{F_T} = \begin{bmatrix} F_{T_x} \\ F_{T_y} \end{bmatrix} = \begin{bmatrix} T\cos(\theta) \\ T\sin(\theta) \end{bmatrix} \quad (2)$$

$$\vec{F_a} = \begin{bmatrix} F_{a_x} \\ F_{a_y} \end{bmatrix} = \begin{bmatrix} -(L\sin(\gamma) + D\cos(\gamma)) \\ L\cos(\gamma) - D\sin(\gamma) \end{bmatrix} \quad (3)$$

$$\vec{F_W} = \begin{bmatrix} F_{W_x} \\ F_{W_y} \end{bmatrix} = \begin{bmatrix} -W_p\cos(\nu) \\ -W_p\sin(\nu) - W \end{bmatrix} \quad (4)$$

where T, L, D, W, W_p represent the thrust magnitude, lift, drag, vehicle weight, and payload weight respectively. The angle γ represents the flight path angle, θ measures the angle between the thrust and the horizon, and ν is the angle between the horizon and the cable used to pick up the payload. The angle of attack can be computed by

$$\alpha = \theta - \gamma \quad (5)$$

The acceleration of the vehicle must be greater than zero for the pick-up maneuver to be feasible. This can be easily computed by

$$\vec{a} = \frac{1}{m}(\vec{F_T} + \vec{F_a} + \vec{F_W}) \quad (6)$$

where m is the mass of the vehicle.

A preliminary weight estimate suggests that the vehicle will weigh approximately 7.5 lbs From previously designed and prototyped vehicles, the air frame of a similar sized vehicle will be approximately 7 lbs. The remaining 0.5 lbs will allow for the complexity of a retractable grasping mechanism or additional structure reinforcement. The thrust obtained from each propeller is adjusted to 5 lbf (10 lbf total). Also, the payload is assumed to weigh 7.5 lbs to ensure that a 1:1 payload to weight ratio. By using Eq. 6 and assuming that the angle of attack obtained during the pickup maneuver is 10 degrees, it is possible to obtain a net acceleration in the y axis. Further analysis is required with a prototype to better understand aerodynamic penalties and the effects of a temporary swinging payload.

6 Concluding Remarks and Future Work

The KP EAGLE concept has the potential of improving the current delivery capabilities of UASs by using a novel approach to handle payloads. Preliminary analysis indicates that the KP EAGLE concept is feasible to handle a 1:1 payload to weight ratio. Future work will include the development and building of a prototype to further confirm the preliminary analysis and provide the information needed for more detailed analysis. Further work in identifying GPS technology and high data rate sensors needed to locate the payload and perform the pick up and perching maneuvers at precise locations. Advanced battery and motor technology can increase the payload capability while avoiding battery weight penalties. Testing to investigate the g-forces expected during the pickup maneuver will be performed to ensure structural integrity.

Other potential modifications of this concept include acquiring the payload on a moving surface (e.g., truck or train). This modification would allow the KP EAGLE concept to decrease structural and dynamic constraints while allowing for an even higher payload to weight ratio.

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