Flight Experimentation Towards Enhanced UAV Capabilities – The Multi-rotor Air-Crane

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Abstract

This paper discusses the development and successful flight testing of a multirotor sky-crane system used for launching aircraft from altitude. Research and testing has been conducted on the configuration of the multi-rotor, the length of the cable to reduce the influence of the downwash on the load, the launch cradle design which holds the load in the correct position until release and the launch procedures to ensure safe operation of both the multi-rotor and the test airframe. Flight testing with an instrumented test aircraft allowed the determination of the optimum launch attitude and the general operating procedures, including a fast and safe method for the sky-crane to rapidly descent from altitude after the launch.

Keywords: Flight testing, Multi-rotor, Sky-crane, Blended Wing Body Aircraft, Air Launch

Introduction

The rise of unmanned aerial systems has renewed interest in developing novel airframes capable of increasing range and endurance over traditional-configuration aircraft. While the cruise characteristics of these airframes may be highly desirable, designs such as blended wing bodies can have poor ground-handling properties, highly thrust-dependant flight characteristics and poor low-speed handling. This can lead to difficulties launching and operating the aircraft, especially from un-sealed airfields [1].

To overcome these problems, launching systems, such as catapults, are typically used to accelerate the aircraft to flying speed. Catapult-style systems however put large stresses on the airframe and, especially with new aircraft, give very little time for the pilot to learn how the aircraft handles before a potential crash. Car-based launches mostly solve these problems; however a large space is required and can be very expensive solution. Hand-launches can be very successful, though there is a limit to the weight and wing loading of the aircraft, how fast it can be thrown, and how awkwardly the vehicle is shaped. Hand launching can also be dangerous if the pilot turns the motor on too early, especially for pusher propeller configurations.

Launching an aircraft from altitude with a 'sky-crane,' however, removes the previously mentioned problems. It allows for more time for the pilot to learn how the aircraft handles, does not put excessive loads onto the airframe and the weight and size of the test aircraft are limited only by the lifting capacity of the sky-crane. This approach has been utilised by NASA for flight research of scaled models [2] and recently for a glide test of the Dreamchaser orbital vehicle [3]. This type of launch system is also utilised by Insitu in the Flying Launch and Recovery System (FLARES) [4], but it is a highly tailored solution that mounts the UAV directly to the sky-crane, as compared to the more versatile cable suspension method discussed in this paper and in the other references.

The Dreamchaser launch gave the idea to use a multirotor UAV instead of a helicopter as multirotors are now far more accessible and easier to pilot than a traditional helicopter. The question immediately arose, however, as to whether the standard, commercially available flight stabilisers, which are vital for multirotor control, would be able to handle the disturbances of a slung load of considerable size and weight. As will be discussed later, these flight controllers can indeed handle loads that equal or exceed the weight of the sky-crane itself, if certain guidelines are followed. Other issues were the performance of the two connected vehicles in the presence of wind, the launch attitude of the test aircraft for a smooth separation and the method of returning the sky-crane back to the ground safely after the drop from considerable altitude before the batteries are expended.

This paper presents the design, development and operation of such a sky-crane system for launching experimental aircraft. Flight testing showed very positive results with many successful launches conducted of otherwise difficult aircraft. Optimisation of factors such as tether-cable length, launch angle and speed and flight path/mission design were used to improve the reliability and safety of the operation which are also outlined in this paper.

System Description

The Sky-crane

Several multirotors of different size were built during development of the method. The first was a small quadrotor for initial testing (lifting capacity of approximately 700 g), before the configuration was changed to a hexacopter for better stability and redundancy. The initial hexacopter had a lifting capacity of approximately 2 kg, which was just too small for most of the intended test aircraft. A slightly larger version (Figure 1a) was subsequently designed and was used for the tests discussed in this paper. It is constructed from square aluminium sections and uses pool noodles for landing gear and orientation determination.

(a) The Hexacopter Sky-Crane

(b) The Sky-Crane Lifting the UAV Milan

Fig 1: The Hexacopter Sky-Crane

The hexacopter has six NTM Propdrive 35-30 1100kV brushless outrunners spinning 10x4.5 propellers, six MultiStar 40A Opto ESCs and is powered by two MultiStar 4.0Ah 4S LiPo batteries in parallel to provide the required peak current of 120A when fully loaded. The flight controller used is a PixHawk running APM:Copter [5] and the system weight is 2.49 kg with a diagonal motor distance of 0.66 m. A mount point close to the centre of gravity (to be discussed later on) is used to attach the tow cable to the hexacopter.

Aircraft Support Frame

Originally the attachment to the aircraft was a single point approximately at the centre of gravity. A servo controlled release mechanism was attached to and controlled from the test aircraft. This set-up did not hold the aircraft in a stable attitude and the vehicle had a tendency to oscillate randomly in roll, pitch and yaw with little damping.

(a) Photo of the Aircraft Support Frame

(b) Aircraft Sitting from the Support Frame

Fig 2: The Support Frame Used to Drop the Aircraft

To solve this, a frame was designed (Figure 2) to hold the aircraft at a defined attitude which could be adjusted in steps, similarly to the cradle used for the Dreamchaser [3]. To simplify operation and to enable its use with various aircraft types, the release servo mechanism was moved to the frame. The servo lead is then connected to a connector embedded into the top of the test aircraft which is pulled out when the aircraft is dropped. The total weight of the frame is 193 g and has a 9.6 m tether cable with a weight of 74 g.

Test Aircraft

The primary drop-test vehicle is a composite, custom-designed blended wing body (the UAS Milan) depicted in Figure 3a. Initial flight testing showed poor ground handling characteristics, with takeoff being particularly difficult to achieve due to the low longitudinal stability and short coupling of the elevator [1]. As such, it suited the aerial launch application as there was no other launching method available. The UAS Milan has a takeoff weight of 1.88 kg, a wingspan of 1.5 m and a PixFalcon running APM:Plane [5] is used as the data acquisition platform. As no airspeed sensor was installed, the ground speed estimates from the GPS were used for analysis.

(a) The UAS Milan

(b) The AXN FloaterJet

(c) The MantaRay and Test Pilot

Fig 3: The Test Aircraft

An AXN FloaterJet with custom-designed wings and a wingspan of 1.3 m (Figure 3b), was used as a second aircraft to do the initial development. The foam construction makes it more resilient to crashes than the UAS Milan and the lighter weight of 0.72 kg gives more flight time and excess thrust for control to the sky-crane. Being a conventional fixed-wing aircraft configuration, the FloaterJet is a very stable platform and was ideal for the initial tests.

A third, heavier vehicle, the custom designed experimental MantaRay (Figure 3c), was used to test the lifting capabilities of the sky-crane. The MantaRay is another blended wing body with a small inverted V-tail and has a weight of 2.55 kg with a wingspan of 1.8 m. It is powered by an electric ducted fan (EDF), giving it jet-like performance in a highly efficient airframe.

Mission Profile

Launch Profile

The sky-crane was launched in manual mode and switched to position hold a few metres above the ground. It was flown over the test aircraft and the slack in the cable was slowly taken up. The tether was held by an observer to ensure it didn't catch under the wing of the plane and the remaining slack length was called out to help the sky-crane pilot judge ascent speed. Once the aircraft was fully held by the sky-crane, a landing gear and motor check were performed before conducting a fast climb and position to an altitude of about 100 m. Any oscillation in the suspended test aircraft was allowed to die out as much as possible before the aircraft was released. Two launch situations were tested: one with the sky-crane holding position and zero airspeed, the other with the sky-crane translating into the wind to build up some speed before the release. In the cases of the moving launches, translational motion was slowly applied and the aircraft was released once the sky-crane speed had stabilised.

After release, the pilot of the test aircraft was instructed to allow the aircraft to roll freely. The elevator was used to control the dive and pull out when the test pilot felt it was safe and was comfortable to do so. Throttle was applied as the pilot felt necessary. The pilot's inputs were checked from the logs to ensure the control inputs were similar between flights.

Sky-Crane Descent Profile

The fully loaded sky-crane requires substantial amounts of power which, if there is a longer-than-expected drop sequence, can leave the batteries very depleted and requires a fast descent and landing. Fast vertical descents risk the development vortex-ring state, a dangerous condition that can lead to loss of attitude control and a subsequent crash. A zig-zag type descent was experimented with that, while more difficult to perform, allowed higher descent rates by manoeuvring the sky-crane away from its wake.

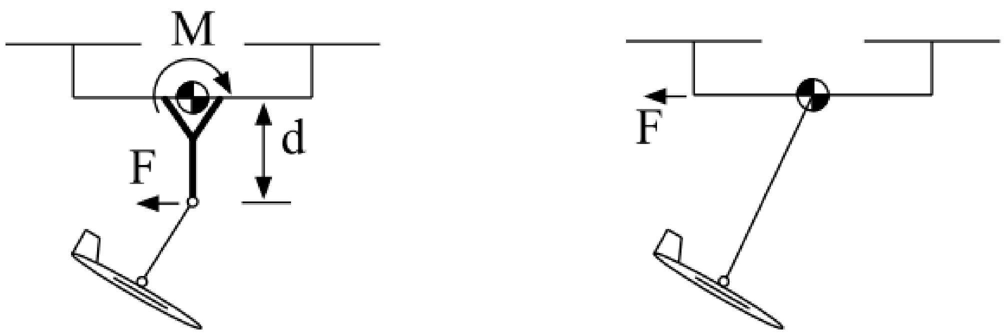
Results

Early Development

Early development of the sky-crane system provided many valuable lessons on the basic set-up required to successfully lift a load. Initially, the tether cable was very short (in the order of 3 m) and was connected a reasonable distance vertically below the centre of gravity of the first generation quadrotor sky-crane, as shown in Figure 4a. The attachment point far from the centre of gravity meant that any swinging of the load produced a moment on the sky-crane, as depicted in Figure 4a. When the sky-crane controller attempted to correct for this moment, the resulting rotating motion of the sky-crane and the load attachment point fed more energy into the swing of the load, resulting in a fully divergent oscillation similar to pilot induced oscillation (PIO). This was not recoverable and eventually caused the sky-crane to crash. Hence, all subsequent sky-crane designs have the load attachment point right on the CG to avoid these issues.

The short tether cable also contributed instabilities in the system. As the sky-crane attempts to hold position, any swinging motion of the load will pull it away from the target position as shown in Figure 4b. As the sky-crane attempts to correct this error, it imparts a force back onto the load, effectively swinging it in the opposite direction. The frequency of this motion is dependent upon the length of the cable, and, as the position holding system response is relatively slow, the swinging frequency of a shortly tethered load becomes too fast for the sky-crane to deal with, causing an unstable growth in the swinging motion. The short tether also puts the load directly in the prop-wash of the sky-crane, causing unstable flow to hit and further de-stabilise the load. All full scale helicopter slung loads are carried on cables at least two rotor diameters long to avoid these issues [3], yet, in case of the small scale multirotor, a cable of about 10 times the vehicle size (and thus combined disk diameter) is required to fully alleviate the problem of load swinging due to the rotor downwash.

A weight was used as the test load as to not risk a more valuable payload, which in turn proved to be a source of problems - the steel weight with its small cross-sectional area had very little aerodynamic damping to suppress any swinging motion. A large foam box was subsequently used, however, the shape meant that the system wasn't directionally stable and was blown around in the wind. Tests with aircraft behaved much better as they tend to weather-cock into the wind and aerodynamically stabilise themselves.



(a) Attachment Below the Centre of Gravity *(b) Attachment at the Centre of Gravity*

Fig 4: Forces and Moments Generated by the Load on the Sky-Crane

Launching the Test Vehicle

Initial drop tests were with the FloaterJet and were not instrumented. Around ten tests of the final design were completed before the system was deemed reliable enough to carry the UAS Milan. A total of nine air drops of the UAS Milan were completed that produced seven usable sets of data. Overall, the turnaround times for the tests were very quick, with less than five minutes between drops being achieved on a number of occasions.

Since airspeed measurements were not directly available, the drop tests were done in as little wind as possible so that the GPS speed estimate matched the actual airspeed. The pitch angle was calculated as the average angle one second before the drop as there was some swinging of the load. The drop begins when the release channel changes to command the servo to open the hook and ends when the vehicle attains a positive climb rate. Table 1 lists some data obtained during the drops at various attitudes and airspeeds.

Table 1: Summary of Drops

speed [m/s]	step [-]	pitch angle [deg]	recovery time [s]	altitude loss [m]	final speed [m/s]
0.4	1	1.5	3.4	28.5	20.8
0.5	2	-12.5	4.0	30.2	26.7
1.4	3	-33.2	3.2	30.0	22.1
0.2	4	-43.0	3.6	25.6	22.8
4.8	0	-15.1	4.5	30.8	20.6
4.9	1	-26.3	3.0	22.5	19.8
5.0	2	-28.0	3.0	22.0	18.1

Fig 5: Overlay of Stills Captured During a Launch

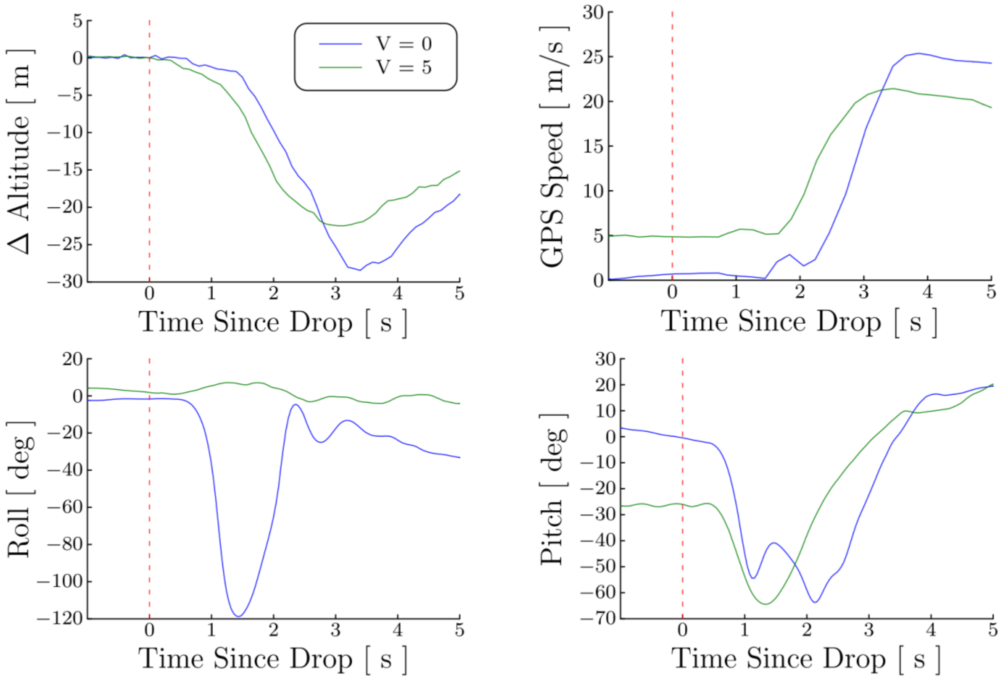


Fig 6: Comparing Two Drops from Step 1 on the Support Frame

During the near-zero speed drops, the test aircraft pitched down rapidly and did not keep wings level - highly undesirable, especially for an untested aircraft. The translating drops behaved much more sedately - there were no abrupt pitch or roll movements and the aircraft tended to stay wings level with no input. During the initial stages of the drop, this behaviour is very important as the pilot relies on the natural stability of the aircraft as there is little to no airflow over the control surfaces. The required throttle varied between flights and it was noticed that as the pilot became more comfortable flying the aircraft, the amount of throttle applied decreased. The amount of elevator applied was far higher in the stationary cases, a result of the much poorer control authority at the lower speeds.

The UAS Milan proved to be more difficult to stabilise in yaw than the FloaterJet. The cable often had some twist in it during ascent and the low directional stability of the UAS Milan meant this moment was not well damped out. In future, a swivel joint will be added to the support frame to try and prevent this problem.

Figure 6 shows two sets of data taken from the same support frame set-up - in blue, the aircraft is dropped from a stationary position; in green, the aircraft is dropped while moving at about 5 m/s. In both cases, the aircraft falls a similar distance during the manoeuvre, though during the stationary drop it gains more speed as approximately 50 % more throttle was applied by the pilot. The roll angle for the launch at speed stays nearly level the entire time, but during the stationary launch it banks heavily, passing 90 degrees. Even though the pitch setting on the frame was the same, the two data sets have very different launch angles: 1.5 degrees for the static case, -26.3 degrees for the moving case. This is because the drag on the aircraft causes the plane to be 'dragged' behind the sky-crane, changing its angle of attack (Figure 7). This 'dragging' produces a much more problematic side-effect - lift is generated from the plane downwards, effectively increasing the load the sky-crane must support. Overall, the more pitched down the aircraft was dropped while stationary the better. Conversely, while translating, the more level the aircraft was dropped at the better. A final set of two tests were carried out on the heavier Manta-Ray, with two successful launches with forward airspeed. For the second launch, the motor was spooled up on the test vehicle to approximately match the drag so it held below the sky-crane. This gave the best overall result and will be the focus of future work into improving the launching technique.

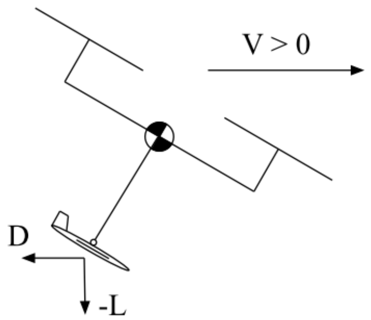


Fig 7: Forces Produced when Translating Forwards

Sky-Crane Dynamics

Power Required for Lifting

The required power for hover is shown in Table 2. As a rule of thumb, the hover throttle should range between 30 and 70 % [5] and the handling qualities of the sky-crane at these extremes mirror these recommendations. Unladen, the sky-crane is very agile and is difficult to manually stabilise altitude due to the excess power. Fully loaded, the sky-crane has just enough excess power to climb and manoeuvre, however any fast translations cause the sky-crane to drop altitude as attitude control is prioritised over altitude control. The power requirements were also affected by swinging of payload - up to an extra 10 % required when the load was swinging.

Table 2: Required Power vs. Weight for Hover

Payload	Payload Weight [kg]	Total Weight [kg]	Power [W]	Throttle [%]
None	0.00	2.49	478	31
Frame	0.27	2.68	560	36
FloaterJet	0.98	3.47	720	43
UAS Milan	2.15	4.63	1 090	60
MantaRay	2.81	5.30	1 297	71

Translating the sky-crane with a payload significantly increases the required power of the system, in general requiring about extra 15 % of the total throttle available. When lifting the UAS Milan, this at times spiked to 100 % of the available throttle. Any significant movement of the MantaRay generally resulted in a loss in altitude as very little excess thrust was available. The maximum power consumed by the sky-crane was 1560 W.

Descent

A study into the achievable descent rate of the sky-crane was conducted to minimise the battery capacity that needed to be carried. The maximum vertical descent rate was measured to be about 2.5 m/s before the sky-crane's ability to stabilise itself was reduced, indicating the onset of unstable ring vortex state. This was a very conservative test as fully developed unstable ring vortex state could have very dire consequences for the sky-crane, and safety was prioritised. The throttle for the descent was around 35 % and a total of 397 mAh over 40 s were used on average to descend from 100 m altitude. Using momentum theory, the induced velocity in hover produced by the sky-crane can be calculated by

$$v_i = \sqrt{\frac{T}{2\rho A}} \tag{1}$$

where v_i is the induced velocity, T is the thrust, ρ is the density of air and A is the total disk area of the propellers [6]. From [7], as the ratio of the climb rate to induced velocity in hover, V_c/v_i, drops below -0.5, the flow around the rotors becomes turbulent and starts to recirculate, causing vibrations and degraded control. For the case of the sky-crane during the tests, v_i was approximately 6.19 m/s, giving a predicted maximum vertical descent rate of 3.10 m/s - close the (very conservative) observed value of 2.5 m/s.

Aggressive translation was then used to manoeuvre the sky-crane out of its wake and a descent rate of on average 5.7 m/s, peaking at 12 m/s, was achieved without compromising stability. This descent rate was limited by the drop-cable flying precariously close to the propeller blades rather than any aerodynamic effects on the propellers. For a 100 m descent, 139 mAh were used at an average throttle of 26 % for 18 s, less than half that taken for the vertical-descent approach. The drawbacks to this method are a large amount of excess power is required to arrest the high descent rate near the ground, manual piloting is required, and there is a higher risk to the sky-crane.

Acknowledgements

The authors would like to thank Jeremy Randle for flying the test aircraft during this study.

Conclusion

This paper has detailed the development and successful flight testing of a multirotor sky-crane system used for launching experimental aircraft from altitude. Extensive experimentation has shown a long tether mounted close to the centre of gravity on the sky-crane works best, along with a frame to hold the test vehicle at a specific attitude. More flight tests need to be done to determine the optimal angle at which to launch the test vehicle, however indications are that for stationary drops, vertical drops are the best, and for moving drops, the vehicle should be dropped as level as possible. Further to this, complications involved in launching the aircraft at speed were discussed, as well as power requirements for lifting the various payloads used. Finally, optimal methods for returning the sky-crane safely to the ground were discussed.

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