DESIGN SPACE ANALYSIS OF AN AUTONOMOUS AERIAL CRANE VTOL CONCEPT WITH A DETACHABLE AIRSHIP ENVELOPE

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Abstract

This paper will argue the concept of a logistics autonomous aerial crane type VTOL aircraft capable of being able to optionally attach an airship envelope so that it will contribute to the reduction of the total weight of the aircraft and requires less energy consumption for flight. In order to overcome the disadvantages or airships those are; first the difficulty of operation in gusty condition, and second its massive size of envelope when to rely fully the weight to be afloat solely by the floating gas, this concept is to attach a medium size flotation envelope to save the energy required for the craft to be airborne which will be only used when the weather is mild, and make the powertrain flyable either with or without the airship component. In order to pursuit the reality of this idea, this study will focus on three major issues: the design on the lifting and propulsion system, method to keep the shape of the envelope in health regardless of traveling in speed or under side winds while on ground, and discussion on the weather condition to become the boundary of the usability of the auxiliary airship.

1. INTRODUCTION

In the wake of series of concepts of large-sized autonomous electrical VTOL aircraft (eVTOL) capable of carrying around or over 100kg of payload including the idea of aerial taxis, one of the applicable configuration of such craft of size for cargo transport will be a used as an urban autonomous aerial crane: a craft capable of grabbing and releasing a container by its own that is capable of helping various logistical practice, e.g. multimodal transshipment, express parcel delivery, offshore supply, as a partially evolutional replacement of current cranes and/or trucks by realizing more speed and seamlessness than the current means.

For the realization of such self-container-handling aerial crane (SCHAC) concept regarding the sever demand from the civilian logistics industries, making the energy required for this new kind of aircraft small enough to make the gross cost for running the total fleet profitable will be another major issue to make this concept real, alongside with the design on make the craft capable of self-handling the container by adjusting its final position at the same time matching the surfaces for docking. Since the concept of the SCHAC aircraft is conceived as an alternative of the existing ground transport means whose energy consumption is wholly for horizontal travel, its energy cost required for lifting the gross weight of the aircraft should be minimal.

Though the issue on making the total running cost of the SCHAC system small enough to be feasible for civilian logistics use could be also possibly achieved by cutting down the running cost of the total service fleet with operational techniques (e.g. fleet optimization, increasing service frequency by rapid refueling/recharging), this study will focus on a radical idea to directly decrease the energy consumption of the SCHAC service with a classical idea of attaching a lighter-than-air (LTA) gas envelope to reduce the energy consumption will be examined. At the same time, regarding the history of failure making airships a sustainable mass transport, contemporary technical options and ideas to overcome such weakness will be discussed.

2. METHOD

The purpose of this challenge is initially to conduct a thought experiment on possibility of the realization of a small-sized hybrid airship for urban logistics; however, the second is to expand the design space of the SCHAC system and earn a practical findings from the assumption of a constraint other than rotorcraft discussion that might be possible to apply to the operational design of the system, even if it won't use the LTA option.

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The main idea of this study is to design an auxiliary device to help the economic feasibility of the SCHAC service. Despite the fact that the idea to use an airship to sustain the weight of the airship (fully or partially) is not new at all, it hasn't become a stable solution in reality due to its poor weather capability, and need for a vast and designated land for landing and ground handling. Additionally, difficulty on price and logistics of helium exists in the consideration of airship. In order to overcome this weakness of the airship and fully utilize the expected merit, a series of decision on what function to add and to abandon will take place

For this discussion, elements related to the mission (e.g. endurance, location/size/function of the landing sites, weather capabilities) that are required from the assumed operation will be firstly discussed. Then, these elements will be each examined in relation with each other and stated in both aerodynamic functions and structure design matrix (SDM). After the configuration and design are set, technical discussion that includes both on mechanics and operational software will be held.

3. OVERVIEW OF THE ORIGINAL VTOL SCHAC CONCEPT

In this section, the concept of the basic (that means without the supplemental LTA device) SCHAC system is described in order to examine its conceived operational model and service environment. Based on this illustration, the LTA mechanism to support this mission will be designed in the sections following the next.

3.1. Assumed use scenario

The innovative meaning of the SCHAC is that it is designed to change the thought on mass transport from the use of point-to-point consolidated heavy vehicles to constant and distributed service with optimized swarm of light vehicles.

The major assumed use case of the SCHAC is as a field assistant flying delivery van for urban parcel logistics. Delivery vans currently used for package delivery services tend not to stop just in front of each consignee's in crowded urban area; they rather stop the car at designated spots in the neighbor in a milk-run, as the driver gets off and deliver and/or collect several parcels to/from nearby offices, shops, and houses. If a mid-sized aircraft can connect each of those stop and the facility and carry, drop, and make recovery of a container loaded with parcels just for that neighbor autonomously, while the deliverer (no longer a driver) delivers and collects parcels on the field, service can be provided in much shorter lead time and with lesser human powers (Figure 1).

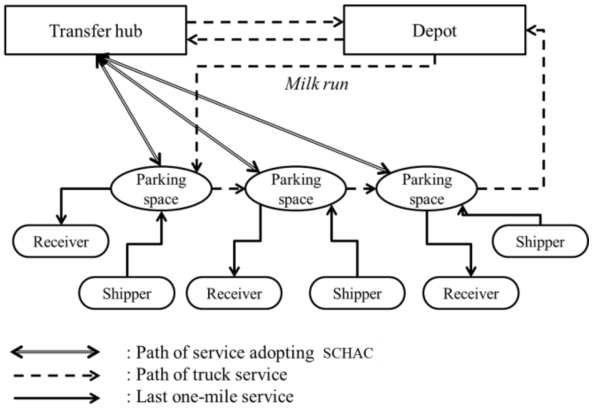

Figure 1 Service overview of SCHAC to be used in parcel delivery practice

Based on the assumption that the fixed cost for the craft will be much higher compared to the container it carries, the SCHAC aircraft has to be somehow designed to be able to dock and release the container without human handling (as discussed further in the next section) in order to obtain economical advantage against the existing transport means. By doing so, the system can now separate the operation of the aircraft and the ground staff, and make maximum efficiency of each other free from the restriction of synchronism for loading/unloading cargo (Figure 2). Regarding the idea to use human power for the very last mile delivery, the assumed payload of one container would be arround 100kg.

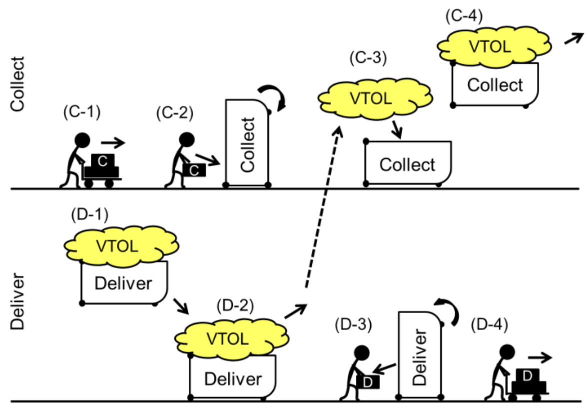

Figure 2 Service flow image of ground practice of the delivery SCHAC concept

The use of such aircraft shall also rationalize internal business as well as providing more value to its customer. Many parcel delivery enterprises bring collected parcel into their transport hubs (THs) where they are sorted and aggregated for rationalizing its service. The combined cargo is then transported to the designated THs in each region, where it will be sorted again for their final destination. Today's use of trucks that are relatively

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slow in service but have excellence of carrying heavy weight, compared to vertical flights, rationally result in stopping the parcels at THs and loading them onto the truck at once at each point. This causes the slowing down of the parcel's trip door to door, and also the facility of TH being gigantic. By using intermittent SCHAC flights that has the superiority on speed since they can fly straightly and avoid traffic jams, logistics providers will be able to run THs and transfer cargo all through the day.

The assumed mission of the SCHAC described above provides a sheer merit on using electricity for lift and propulsion. Using electricity will make it possible to make the service endurance cycle of the aircraft long by putting battery cells in each container and feeding the power system in assistance of the main power supply. These container-mounted cells can be charged eventually while grounded for loading/unloading the cargo that will be free from the problem of the needs for super-high-voltage recharging points. In addition, the assumed low maintenance cost of electric propulsion will be suitable for the mission of SCHAC that is designed to keep flying very constantly with minimum time to wait on ground.

3.2. Aeromechanical concept

In order to realize a VTOL aircraft that is capable of attaching and releasing an external container, special configuration that doesn't exist for conventional helicopter and multicopter designs have to be considered in order to easily match the surface and position at the same time for meeting the container with its latching surface for docking. If not to apply robotic arms, controlled sling, or powered taxi for container docking method, the SCHAC aircraft have to be able to accelerate itself towards any horizontal direction while keeping its belly parallel with the container surface, while most of the practically existing rotorcrafts cannot accelerate itself towards the horizontal direction without pitching and rolling (classical helicopters and the majority of multicopters), or at least rolling (powered-lift aircrafts and compound helicopters).

Possible design for such flight characteristics should include; vectored thrust, compound rotor configuration, gimbal-mounted rotors, tilt rotor, and combination among above [1]. Even though Ref [2] suggests a rotorcraft equipped with side skids that guide the craft towards the proper latching position with the container held between those skids as an operationally efficient solution (see Figure 3 for image), any form of lift thrusts can still be applicable, including the assumable special devices mentioned above.

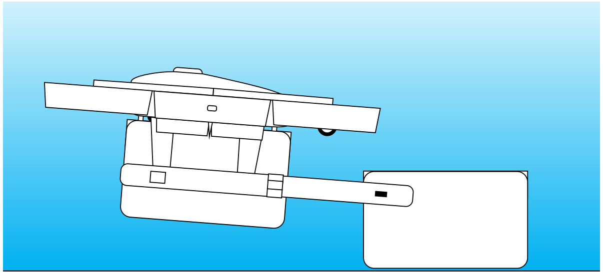

Figure 3 Concept image of a SCHAC aircraft equipped with side skids for meeting the container, carrying another for replacement

In addition, the use of electrical powering will provide ease on increasing the number of propulsion with small weight, including those for horizontal direction, with small additional weight of the system and broader available design space [3]. Regarding these flight characteristics of the SHCAC, it is highly likely that these aircrafts be equipped with some kind of propulsion mechanism to make it possible for the aircraft to accelerate itself without tilting the airframe forward like the classical helicopters do.

3.3. Infrastructures

In this section, discussion on infrastructures to sustain the operation of SCHAC will be held.

Regarding the hub-and-spokes service design to replace the current milk-run ground transport, the aircraft is assumed to land onto the TH it serves at a high rate. On the other hand, distribution density of field landing points neighboring the shippers and receivers will be desirable as high as possible in order to increase ease of the deliverers on the ground to access the site for pick-up/loading the parcels from/to the aircraft, and the and make the lead time of the service short. This means that the flight assistance function (i.e. recharging, refueling, maintenance, health monitoring, stand-by points) have to be concentrated and provided at THs, while field landing points are required to be provided with small or zero modification to the existing form.

Regarding the massive size of existing THs that should contain a package sorting system inside, its rooftop will be a suitable location to place such dedicated landing ports and support facilities (Figure 4). There also exists a merit on making TH a base for SCHAC operation so that the aircraft itself can be transported by trucks with ease on the purpose of overhaul maintenance or re-organizing the fleet among different metropolises to match the density of real-time demands. Additionally, these facilities should become emergency logistics centers in occasion of a disaster that can immediately supply necessary goods with the SCHAC fleet they operate every normal day.

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Figure 4 An example of a TH: Yamato Holdings Haneda Chronogate (Tokyo, Japan)

On the other hand, open-air parking spaces and helipads are suitable as the field landing points that are required to be as less expensive as possible. Since the center of economy that demand for logistics service is most plentiful can easily shift in urban area by re-development, opening, and closure of factories, office buildings, and shopping malls, the field landing points must be easily acquired to follow the diversion of the service. For suburban area where tall buildings are rare, parking lots will be a desirable location: designed to be able to land onto one or several adjacent parking spaces, SCHAC will be able to operate very near the end customer. On the other hand, in urban area, emergency helipads on rooftop of high buildings will be a great solution; not only these skyscraper provides an open landing space, they contain many offices and shops that require the logistics service itself.

4. ADDING MOBILITY TO LTA

In this section, discussion on the LTA option to help save the flight cost of the SCHAC system will be argued regarding its conceived mission as described before.

4.1. Existing issues on adapting LTA to SCHAC

Though LTA has long been known as a cheap and easy method of making an object airborne since long ago, there are some issues left to be solved to be applicable to the SCHAC concept, as follows.

4.1.1 Size

First, despite multiple concepts of using airship as a crane for transporting cargo have been discussed recently, these practices and concepts have mainly focused on heavy load using a gigantic airship. This trend is due to the square-cube law that makes the efficiency on buoyancy larger as the size becomes bigger [4]. These massive airships will not suitable for landing onto rooftop of urban buildings or neighbor of residential area.

4.1.2 Landing sites

Also, vast land and specialized equipment for handling the aircraft on ground will be required for operating a conventional airship. For conventional giant airships, mooring masts are required on each landing field in order to avoid an even-more complicated use of landing crews for catching and acting as anchoring weights by themselves [5]. While moored by its bow, the airship will circle around the mast in accordance with the wind like a streamer. Thus, a circle-shaped land, or surface without any obstacle higher, with its diameter larger than the length of the airship will be needed for hardstand [6] (Figure 5). To make matters worse, it has been historically founded through the evaluation on the use of the mooring mast on top of the Empire State Building that mooring an airship afloat high above the urban environment is not practical or safe [7] [1].

Figure 5 Image of a mooring mast circle (USS Macon at Moffet Airfield)

4.1.3 Gust tolerance

Another issue on the operation of airships is that they are vulnerable to bad weather conditions. According to Ref. [8], the gust requirements for airships is 25ft/sec (=14.8kn) while cruising at maximum speed on sea level. This wind velocity corresponds to the scale 4 of Beaufort wind scale, described as “moderate breeze”. Though it is hard to compare this ability apple-to-apple, Ref. [9] suggests fixed-winged aircrafts to be able to land against a 25kn side wind, if the runway is dry.

[1] Despite its failure, this attempt can be regarded as the very first plan to introduce mass aerial transport into the center of urban area, which relates to today’s urban air mobility discussion, including that on SCHAC.

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4.2. Solution

In this section, the solution to overcome the stated issues of conventional airships and apply LTA to SCAHC will be discussed. Since the SCHAC is regarded as a light and small aircraft, further discussion on airships will assume helium using non-rigid, if not mentioned otherwise.

Historically, airships have been "built on the basis of trial and error; more art, than science [10]," that concluded to a common understandings that the cigar-shaped envelope should be the solution for a high-speed airship. In fact, this configuration has the strength of making the bow, which sustains the greatest air resistance while at forward cruise [11].

Such elongate vessel is known vulnerable from bending moment caused by aerodynamic stress from the transverse direction [Ibid.]. Thus, conventional airship cannot moored at its landing gear on the belly of its control car due to the large bending moment, and therefore it should be grabbed with multiple landing staffs or moored by its bow. Recent design on airship has come to overcome this problem by making the envelope a catamaran configuration and the weight of the aircraft heavier than air to contact the ground by a face, not with a single landing gear: with these configurations, the HAV Airlander 10 has become able to be temporary available to land without mooring mast temporary [12], however it still requires a mooring mast for a long stay on the ground at its base [13]. This on the one hand shows the possibility that the operation free from mooring mast can be made possible by changing configuration and weight of the vessel. Nevertheless on the other hand, a more certain method to keep the airship on the ground without mooring mast will be required for the SCHAC's urban mission, regarding the accident of the Airlander 10 while being attached to the mooring mast [Ibid.].

As the size of the airship grows, a strong fabric for the envelope will be required. Reference [14] suggests that increasing the volume of the airship is allowed in proportion of the strength of fabric to the power of 2.4. In reverse, sizing down the aircraft will allow more choices of fabrics that can be lighter or more inexpensive.

However, smaller size doesn't mean higher tolerance to gust: in accordance to a formula shown in Ref. [8] indicates that the maximum bending moment applied to the envelope caused by side winds will increase proportionally of the airship's volume to the power of 1/4. Since this power number is smaller than 2.4 for the fabric strength that sustain the whole bending moment as for non-rigid airship, it is denied that making the airship bigger results in making harder to consume the bending moment caused by gust: as the size is realized with an enough strong fabric that can be airborne, it already has enough strength to sustain gust. Though these formula assume the classical cigar-shape airship, it is likely that weather tolerance is hard to dramatically improve by the change on size and shape for the application for SCHAC. In other words, issue on weather tolerance have to be solved with operational measure.

4.2.1 Multirotor disc envelope

As conventional airship, regardless whether rigid, semi-rigid, or non-rigid, mounted heavy power plant under the envelope, it was only possible to place propellers and/or lift rotors onto a limited area.

However, by applying the idea of electric multirotor that uses light brush-less motors for power, the design space will be dramatically improved. The configuration will to place multiple lift rotors on the horizontal edge of the envelope. This should make it easier to design an airship that will fit the required small landing zone with a moderate buoyancy.

The multirotor enables a dynamic control on the envelope inclination. This means that pitch and roll can be controlled without ballonets, which will lead to more buoyancy within the same volume of envelope. Regarding that urban mobility eVTOL including SCHAC is thought to be flown in a low altitude, a ballonet-less configuration is available.

In addition, making the powered control will make the position of the envelope stable on ground regardless of wind or gust. Although multirotor drones are usually applied with positive lift, making each rotor available to earn both positive and negative lift, the airship will be able to resist blowing wind while grounded as long as power longs. With this, SCHAC aircrafts applied with LTA envelope can stay on the rooftop helipad temporary with great safe.

Another merits of this configuration studied in Ref. [15] are that making the envelope a flat disc shape, it can create lift while cruising forward as its angle of attack is adjusted by the rotors, and also solar cells can be placed on top of the upper surface. Both of these aspect will also help the concept of helping an economical mission of the SHCAC.

As regarding only the urban mission of SCHAC to land on helipads for field landing, the size of the envelope can reach about 10 meters in length. Figure 6 shows a simulation of that size of a multirotor mast-less disc envelope compared to a conventional airship (Goodyear GZ-20) scaled

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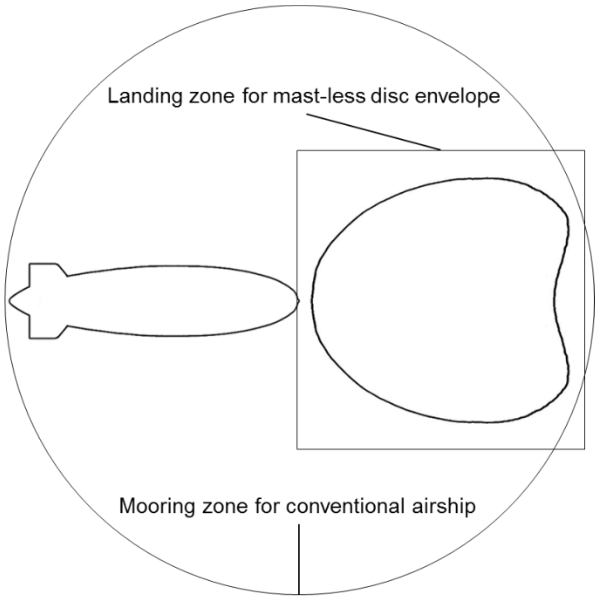
down to the same length. Smaller required landing zone indicates its suitability for the SCHAC concept, while the volume suggests some buoyancy to sustain more than 100kg, the estimated whole payload of the SCHAC itself. Though this will not be enough to sustain the entire mass of the aircraft, it will become a hybrid airship safe to be operated in urban areas.



	Conventional airship	Mast-less disc envelope
Model	Goodyear GZ-20	Based on Ref. [15]
Length	10 m	
Hardstand area	346 m^2 (circle with radius of 10.5m)	144 m^2 (square with 12m each)
Volume	29.6 m^3	168.1 m^3 [2]

Figure 6 Comparison of required hardstand area and volume of conventional airship and mast-less disc envelope scaled in the same longtitudal length

4.2.2 Mobility

Regarding the limit of weather capability of the airships, SCHAC applied with LTA option has to be kept in hangar while windy conditions. However, the mission need for constant flight will be controversial to this requirement. A cost-effective solution to possess a fleet highly available even in windy conditions, at the same time make those aircrafts save operational costs are required.

The solution to this controversial problem will to make the aircraft flyable whether with or without the LTA envelope; in other words, it is to make an axillary LTA envelope attachable to a pure eVTOL-type SCHAC aircraft.

For calm whether, the aircraft will fly attached with axillary envelope in order to save energy consumption. The electric propulsion of the SCHAC aircraft will make it possible to reduce the energy consumption while the load is kept light thanks to the LTA unit.

In accordance to weather forecast that it could change to windy conditions dangerous for airships, the SCHAC aircraft will take the envelope back to the hangar for sheltering. In order to make the LTA unit most effective, it should be made much lighter than air itself, but this will make it impossible for the envelope to return to its hangar by itself, despite it has multiple lift rotors, as these are for tilt control. Therefore, counter weight and navigation will be provided from the SCHAC aircraft. For this operation, a minute urban weather forecast system will be required, however, this should be a common infrastructure for urban eVTOL systems not only limited to the use of this LTA unit.

This detachable configuration of the LTA unit goes well with the idea of SCHAC since it can be applied to vast kinds of SCHAC aircraft. Since the concept of SCHAC is to carry a container, multiple aircraft models and configurations should appear to carry a same standardized container if its market grows. In such circumstance, it will be better for the operation to be able to use the same axillary unit to multiple aircraft models.

Two configuration of attaching the SCHAC aircraft and the LTA envelope can be conceived (Figure 7). The first will be called axillary LTA envelope (ALTAE), as the envelope will be attached to the aircraft with a solid pylon. This idea should work since the SCHAC aircraft already has the ability to propel itself forward without changing its pitch angle.

The other is to connect the aircraft and the LTA unit by a sling, which in here named as a “Ballonpack” as it resembles a rubber balloon. Though the ballonpack configuration has the advantage of being lighter than ALTAE, and also applicable to a broader configuration of SCHAC aircrafts (e.g. tail sitter), it requires a dynamic higher position control as its freedom is larger, and if failed, it has the danger of contacting the ground and the SCHAC aircraft, especially with the rotor blades.

[2] Since only the buoyancy but not volume of this model was described in Ref. [15], the volume was calculated by dividing the buoyancy by the estimated rate 1.06kg/m^3.

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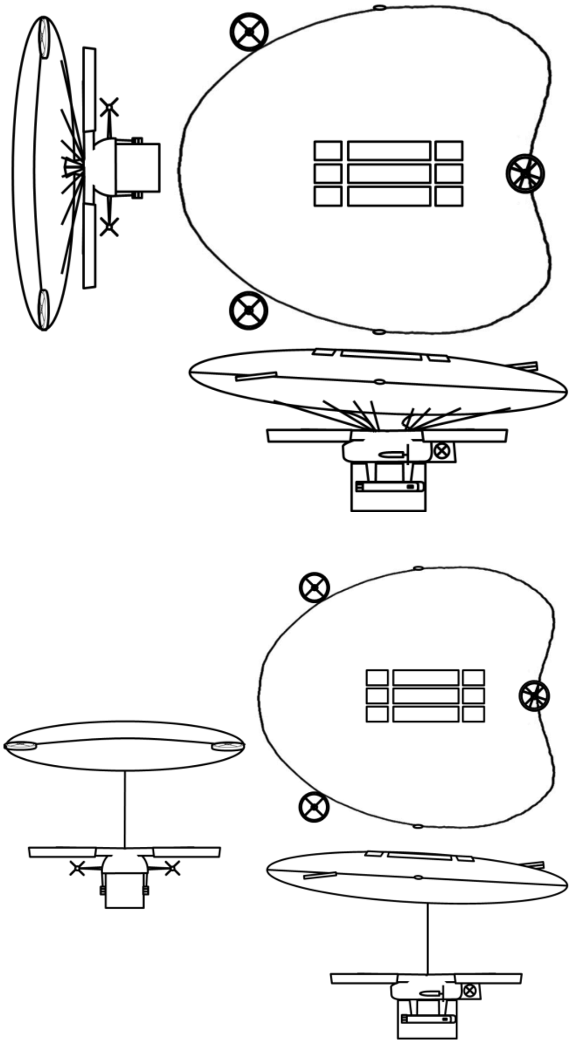

Figure 7 Image of multirotor-type SCHAC aircraft shouldering a ALTAE (above) and slung under a Baloonpack (below)

5. CONCLUSION

This study has discussed the possibility to apply a LTA operation onto a mid-size urban logistics eVTOL aircraft. By applying multirotor technologies, this study has found a possibility to realize a feasible LTA unit to support the conceived mission of the SCHAC aircraft. In parallel to the needs for detailed trials on these ripe ideas, the requirements for using rooftop helipads for urban mission, and minute urban weather forecast was founded for general eVTOL use, as a byproduct.

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7. BIOGRAPHY

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