Mechanical aspects of mothership with sensing drones system

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Abstract

Purpose – This paper aims to describe the mechanical aspects of unmanned Mothership Plane and Sensing Drones. The presented conceptual system shows the idea and possible way of designing different sizes and objective systems based on experience gained during the SAE Aero Design Competition.

Design/methodology/approach – The UAS is based on a SAE Aero Design Competition designed and manufactured Mothership Plane converted to a high endurance platform modified to launch up to six small copters. The process of designing and converting the Mothership is described. The methodology of selecting and planning either the structure or hardware of the drones is presented.

Findings – A key finding is that the presented conception of mothership plane deploying in flight a group of small sensing multirotors is achievable. Moreover, the modular build of the system provides the possibility to adapt currently existing unmanned aircrafts to be converted to the described mothership plane.

Practical implications – To conduct flight tests and to study encountered problems. Presentation of the unmanned aerial system (UAS) concept that can be used to scan an area and create 3D maps for Search and Rescue missions as well as agriculture applications.

Originality/value – The paper describes the conceptual approach to design a UAS consisting of the mothership plane and the sensing drones. The paper highlights the potential solutions gained by using such a UAS. The focus is to present a technology and system that can perform real time observations in widespread and difficult to reach areas.

Keywords UAV, UAS, Mothership, Multirotor, Drones

Paper type Conceptual paper

Introduction

In the past few years, unmanned aerial vehicles (UAVs) have impacted a significantly increasing number of life areas. In the beginning, they were mainly used by defense organizations and tech-savvy consumers. However, thanks to technological advancements, they have started to be more accessible and common (Tahir *et al.*, 2019).

This emerging technology has enormous potential to enable new military and civilian applications and become an integrated part of society. In recent years, the UAVs have started to be more popular and, therefore, found their way to many industry branches. As they are becoming more cost-efficient and reliable, the use cases range from data collection and sensing to delivery as they gradually grow in complexity. The application of UAVs can already be noticed in areas such as agriculture, manufacturing (Maghazei and Netland, 2019), emergency response (Goetzendorf-Grabowski *et al.*, 2021), scientific activities and entertainment. Whatever missions are chosen, the potential for sensing broad inaccessible or extensive areas arises. Many of these applications require a whole unmanned aerial system (UAS) including ground station, air vehicles, associated equipment and communication between its elements to cover much larger areas.

A UAS consists of a fleet or swarm of UAVs as well as of the main platform. Smaller sensing drones have been recently studied for their advantages and leading to possible new brands of usage (Varela *et al.*, 2011). There are various approaches to designing multi-UAV systems. In Han *et al.* (2013), the authors describe using a fleet of fixed-wing UAVs, which significantly expand the range of mapping areas and reduce task completion time compared to using a single UAV. However, from a maneuvers point of view, a fleet of fixed-wing UAVs is often not adequate for the mission. This problem can be solved by using a swarm of multirotor UAVs (Preiss *et al.*, 2017), which could improve usability for collecting data. However, drawbacks of this solution include the range and endurance of flight, which are lower than using fixed-wing UAVs. Another approach described in Adcock *et al.* (2019) uses micro unmanned gliders, which could be dropped from larger UAVs and then

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autonomously collect data during gliding to a specified waypoint. An advantage of this solution is a large land coverage, but it is highly dependent on weather conditions. Analyzing these possible solutions shows that there could be enormous potential for multi-UAV systems, which combine advantages of fixed-wing and multirotor UAVs (Boon *et al.*, 2017).

The idea presented in the paper was born completely independent and was not bound by Aero Design competition rules, but the main platform was used as a starting point. Experience gathered during constructing a system of UAVs for the Society of Automobile Engineering (SAE) Aero Design Competition, where autonomous gliders were towed behind primary aircraft, inspired the team members to develop a new concept derived from the original design. The focus was on potential benefits of using successful fixed-wing UAV and converting it into a carrying platform for multiple smaller multirotor UAVs equipped with sensors. This solution is expected to have significant impact on expanding mapping areas. It would benefit from superior range of the Mothership as it would have much higher endurance. The larger capacity offered by a fixed-wing provides a greater number of sensing drones (like multirotor UAVs) which could potentially enhance the accuracy of data gathering and be used for a wider application such as 3D mapping. A similar issue using fixed-wing optimization for long endurance UAVs, used during the design of the original platform, is present by Grendysa (2019).

System overview

The proposed system consists of the main platform (mother ship) and small multirotor drones. The brief description of the whole system is presented below, including the genesis of the main platform.

Competition requirements

The system was originally designed and manufactured for SAE Aero Design WEST 2020 Advanced Class Competition. Participants of this competition needed to create a heavy lifting UAV that meets specific rules and requirements. The construction was later validated during design reports, oral presentations and flight performances. The challenge of the most unique advanced class was to perform precise "colonist" and supply payload (SP) delivery to the surface of Mars as reliably, safely and as accurately as possible. The mission involves a demonstration of delivering "colonists" to a designated landing zone in a small autonomous glider towed by the primary aircraft and released in a designated area. The mothership must also deliver "habitats" and "supplies" to the same location by dropping them from the main platform (Figure 1) (SAE -Society of Automotive Engineers, 2019).

Gathering experience from previous versions of the SAE Aero Design, the team decided to design the plane with a large cargo space in the fuselage for a Nerf Vortex AeroHowlers (Nerf) as "habitats" and water bottles as "supplies" in three gliders on towlines behind the primary aircraft to reduce interference effects. This solution caused additional challenges related to communication between elements of the system and gliders' control laws. However, the growing potential for this UAS in the field of research is growing, and it became the inspiration for further testing and development of our project for a possible new application.

Figure 1 Drop from the UAV (water bottles and Nerfs)

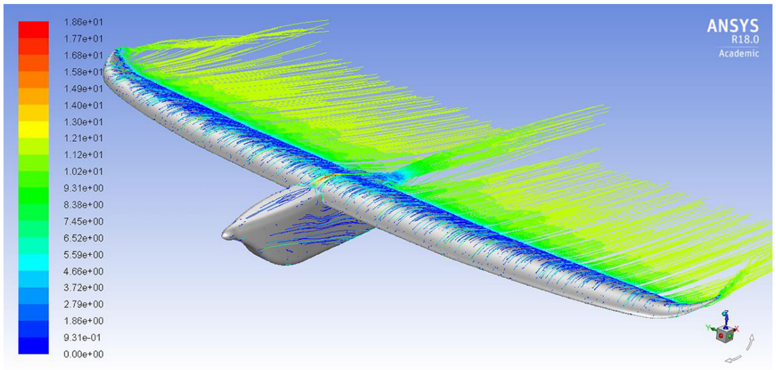
Primary aircraft

A platform that met the competition requirements and which had potential for a wider purpose defined the objectives for the research. Based on mission requirements, the research focuses on the use of a high wing configuration with all-moving horizontal stabilizer that allows for better longitudinal stability and controllability. Using a large area single vertical stabilizer allows sufficient lateral and directional stability. The configuration also features high lifting capabilities, simple construction and low empty weight. The design stands at almost maximum allowed wingspan of 131.9 in., 40 lbs maximum take-off weight (MTOW) and just 10 lbs empty weight to allow for bigger payload. The battery weight is 1 lb. According to Munk's law, elliptical load distribution gives the lowest induced drag, so the team went with half-elliptical planform with straight trailing edge to minimize 3D flow behind the wing. Due to divergence from elliptical load distribution, the necessary washout was calculated to lower local angle of incidence along the span. Both stabilizers were also made elliptical so that along the aerodynamic fuselage, the aircraft would produce least drag and guarantee its high-level performance. The aircraft's aerodynamics was designed using XFLR5 (2019) and ANSYS Fluent shown in Figure 2.

According to competition rules, the plane is electric powered with a 750-watt power limiter. The capacity of the aircraft is mainly determined by the shape of the fuselage that was originally designed for large volume of the SP. Due to its vertical arrangement, the fuselage has smaller influence on the aircraft's wing performance and allows for the installation of a propeller with larger diameter. A two-part drop bay (DB) door allows the payload to be released almost simultaneously to increase the accuracy of the drop (Pacuszka, 2019).

Most components of the aircraft were produced using vacuum bagging with lightweight yet strong materials, mostly carbon fiber. The wing of the aircraft is a typical application of stressed-skin structure with closed torsion box. The stiffness of the construction was achieved by implementing sandwich

Figure 2 Flow around the aircraft in Fluent software



structure with Rohacell foam cores. Both horizontal and vertical stabilizers are made of Computerized Numerical Control (CNC)-milled Rohacell foam core covered with Carboline fiber. The fuselage is made from carbon fiber sandwich with Rohacell foam core. Two vacuum laminated symmetrical halves are joined together with plywood frames. Over 95% of the production process was conducted with numerically controlled machines either directly or indirectly so that the parts are replaceable and the whole process repeatable. However, as there is always possible human error in the process of laminating by hand, all components were weighed so that designed mass could be achieved.

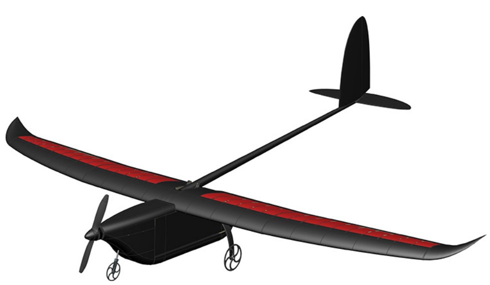
As the Advanced class has the most sophisticated mission, it requires complicated electronics. The team decided to use Pixhawk with an open source ArduPilot software system as an onboard computer to make the aircraft more stable and predictable during cruise and maneuvers.

Visualization and dimensions of the UAV from the Computer Aided Design program are shown in Figures 3 and 4. Some empirical tests proved that this designed aircraft is not only capable to perform its mission but also to become a mothership platform for a variety of applications (Figure 5).

Colonist Delivery Aircraft

The following part of the system are autonomous gliders with ping-pong balls as "colonists" on board. Due to the weight limitation of 9 oz., the team decided on delta-like configuration with just elevons as control surfaces, a long fuselage ensuring big cargo space for "colonists" and a single vertical stabilizer to limit the number of servos needed for a safe flight. Considering that the Colonist Delivery Aircraft (CDA) needs to be fully autonomous, electronics equipment and control algorithms were crucial steps in the design process. To increase landing accuracy, the glide slope is based on several concentric circuits with decreasing radii with center in the center of drop zone. The problem of trajectory tracking was solved by the nonlinear guidance logic which selects a reference point on the desired path and generates a lateral acceleration command based on that chosen point. Both the simulation and test flight results showed that this solution provided repeatable performance of the mission (Figure 5).

Figure 3 Visualization of the main platform (Pacuszka, 2019)



Development of the system concept

Due to the growing potential of systems consisting of a primary aircraft and sensing UAVs, the project was extended for mapping usage. After analyzing the available solutions, the team decided to use copters UAVs instead of towed gliders as shown in Figure 6. This option allows for increased maneuverability over the sensing area. Multirotors equipped with powered engine can be controlled in all directions independently from weather conditions. In addition, according to the initial research, they can obtain greater endurance than glider flights which results in extending operation time up to 10 min in comparison to 2 min gliders flight. Additionally, the drone has the possibility to hover in desired location.

The idea is to place the copters in the modified main aircraft's cargo bay that was previously created for carrying large volume payload. Due to space limitation and engineering experience, the team decided to design new Sensing Copters that would meet conception requirements rather than use commercial ones.

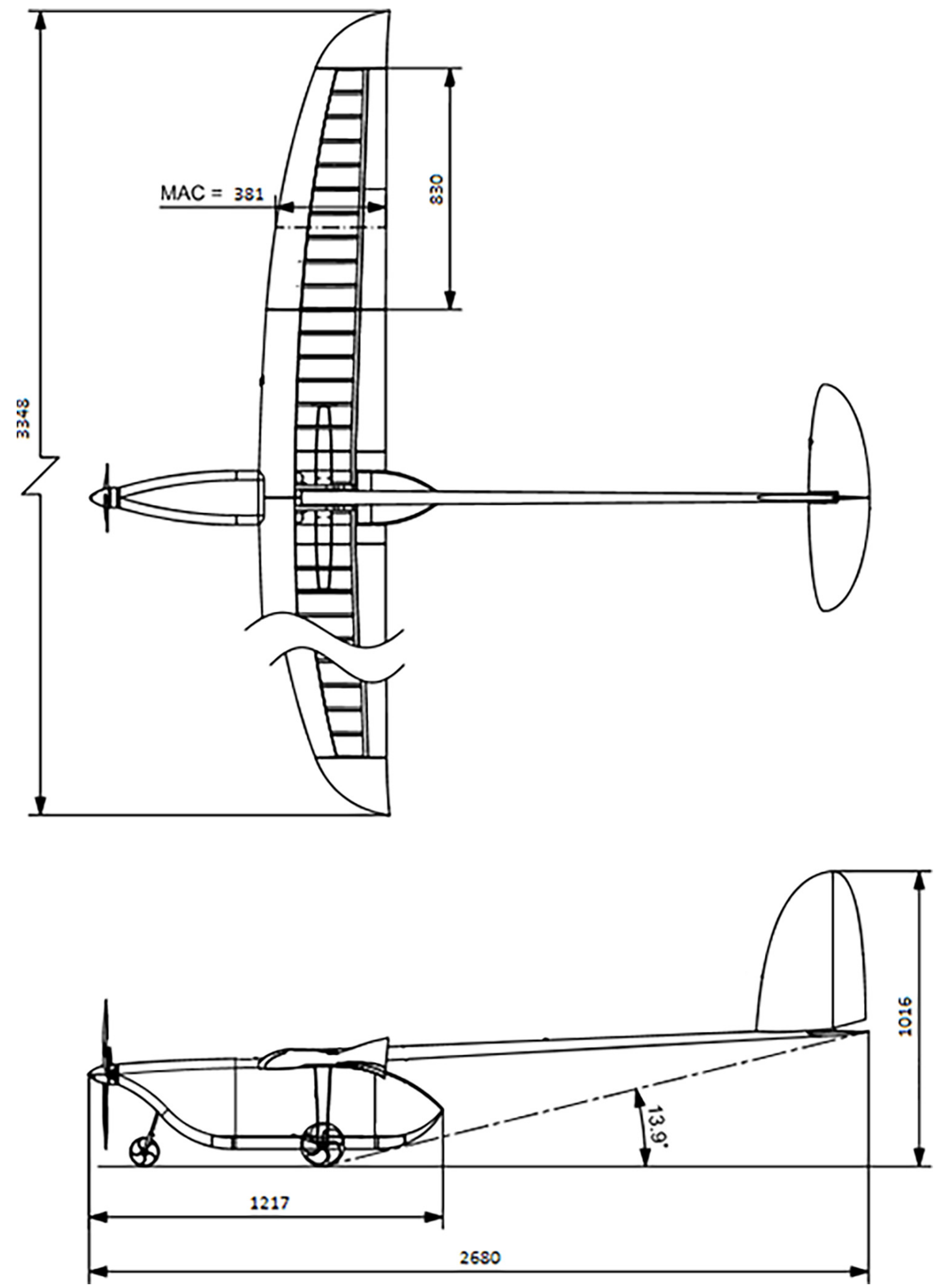
Mechanical improvements

The team designed the new copter, reconfigured the mothership's fuselage and implemented the DB door enhancement. These aspects are discussed in the present chapter.

Sensing drones

The main reasons for designing new multirotor vehicles are to accommodate the mothership's fuselage with dimension shown in Figure 7 and mass limitations. The project requirements include the ability to fit the sensing drones into the

Figure 4 Dimensions of the main platform



mothership's fuselage with a drone structure lighter than 600 g and small enough dimensions (Figure 8).

The key assumption was to arrange the drones in the cargo bay in two vertical columns that determine their overall dimensions. The sensing drone diagonal was restricted by the width of the mothership's fuselage.

The solution is to use an "X" frame configuration rather than "+" shape one. This design accommodated six UAS drones. To fulfill low mass requirements, the drones equipment should be minimalistic and durable. During market research, it has been found that there are example modules widely available.

Equipment necessary to perform the defined mission consists of telemetry module to transmit obtained data to the mothership plane and Global Positioning System receiver module to determine exact position of each drone. Additionally, drones flying equipment consists of: Power Distribution Board with flight controller comprising Inertial Navigation System, Remote Control receiver, four electronic speed controllers (ESC), power battery and four brushless engines. Listed components allow automatic flight mode. As the drones have be relatively lightweight, they would have to be manufactured using composite materials: carbon/glass fiber.

Figure 5 UAVs in the dropping and towing action

The electronic components are kept to the minimum for simplicity, mass and cost reduction. The chosen components are presented in Table 1.

The way of transporting the drones in the mothership plane fuselage allows to modify configuration and equipment of the drones, for example to use bigger drone or mothership battery.

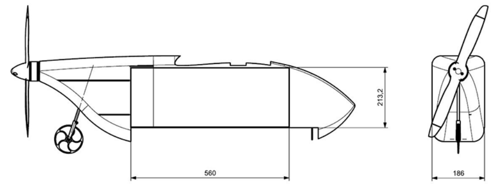
Comparing estimated drone mass (approximately 530 g) and original SP (Table 2), it turned out that the drones would not exceed static stability margin of the mothership. In SAE Aero Design configuration, the difference in position of the MTOW CG for the operating empty weight CG of the mothership plane is about of 2% of mean aerodynamic chord (Pacuszka, 2019). The drones should be designed in such a way that their parts are easily accessible and replaceable. Costs and production of the airframe and fairing should be minimal and do not require advanced technology or mechanisms.

Drop bay door enhancement

The main goal of redesigning the fuselage was to improve the DB door mechanism shown in Figure 9 and to introduce a safe storage compartment for transporting drones. Originally the assembly consisted of two doors opening sideways with the hinge aligned along the fuselage and supported and mechanized by two sets of strings connected to a servo motor. It was a very promising and simple design, but as the strings tended to fall off the motor spool, it was not reliable enough.

The current approach established using non-flexible parts to minimize possible backlash in the system. Stiff pushrods connected to the center of the DB doors and common slider, moved by a lead screw and powered by a step motor were introduced. Such a setup provides symmetric deflection of the doors and allows for quick opening and closure. Additional components required a dedicated fuselage frame with a built-in rail constraining the slider's motion. Moreover, three small stiffening frames were added to each door – one in the front and back and one aligned with the frame in the fuselage, which also provides pushrod connection point. The motion range is designed so the dropped drones do not touch any of the doors.

Figure 7 Dimensions of the mothership cargo bay



Drone release system

In original competition design, the payload consisted of water bottles and Nerfs toys, which were stored in the main payload bay. The Nerfs were put loosely in the cargo compartment, which simplified the original design. In our redesigned concept, instead of competition payload, we are transporting drones inside the cargo bay. The drones had to be stored in orderly fashion to allow for synchronized arming and drop release to account for an alignment system. During the transition to the drop zone, drones would be stored in two stacks of three, fitted in the fuselage as shown in Figure 10. The stack alignment would be guaranteed by two rails holding drones one over the other. Each drone has two sets of rollers matched to the rails, which constrain the rotation in respect to the vertical axis meanwhile allow for movement along it as shown in Figure 11. The rails are mounted on the additional frames providing alignment and support for the release mechanism.

The release mechanism consists of a single servo motor equipped with a double-sided lever and two pivots – one holding the stacked drones and the other securing next-to-release drones from unintended drop. The principle of operations is rather simple – the lowest drone in the stack is held by the extended pivot in place while the other two drones are on top of each other. In the moment of release, the lower pivot hides inside the frame, while the securing pivot extends catching the remaining stack of drones. After a successful start, the mechanism returns to its previous state, letting the stack of drones slide onto the lower pivot. Each drone has enough space for a pre-release diagnostics including motor testing. It allows for drones to be completely prepared for flight right before the drop.

In the original design, the cargo bay compartment was not particularly stiff due to the vast volume of storage area and

Figure 6 Comparison of the CDA and the sensing drone

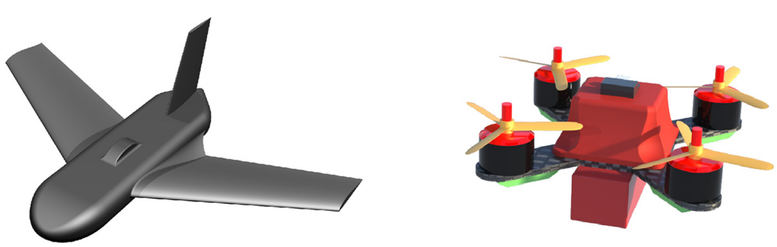


Figure 8 Sensing drone main dimensions

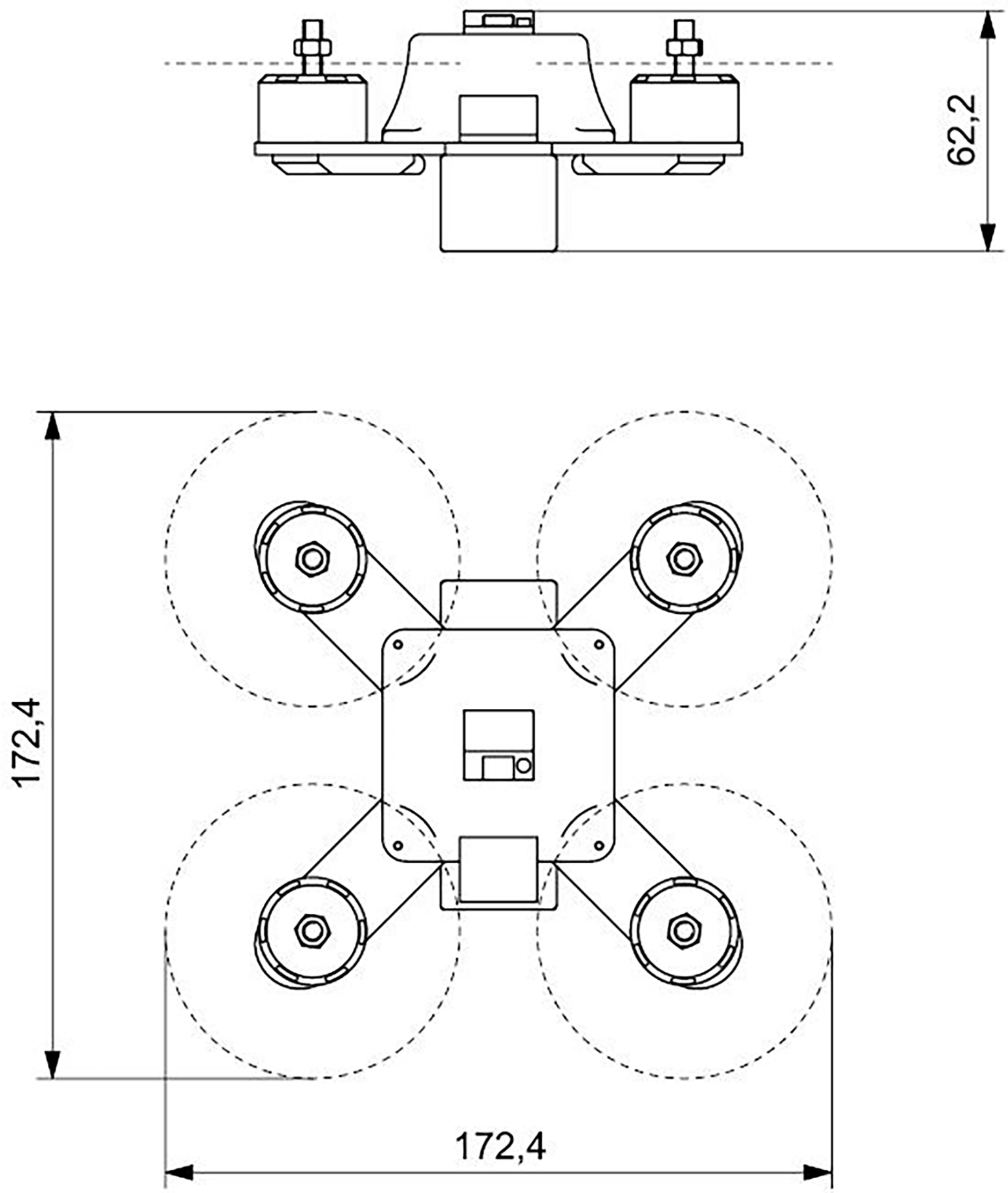


Table 1 Equipment of sensing drone

Sensing drone's equipment	
Flight controller	Mind Racer
GPS	Beitian BN-180
Receiver	FrSky XM+
Telemetry	ESP8266
ESC	30A
Engine	Racerstar BR1106
Battery	1,800 mAh

Table 2 Mass comparison

Component mass [g]	Glider	Sensing drone
Airframe	136	125
Electronics	63	190
Propulsion	–	212
Payload	78	–
Total weight	277	527

Figure 9 Drop bay doors mechanism – principle of operation

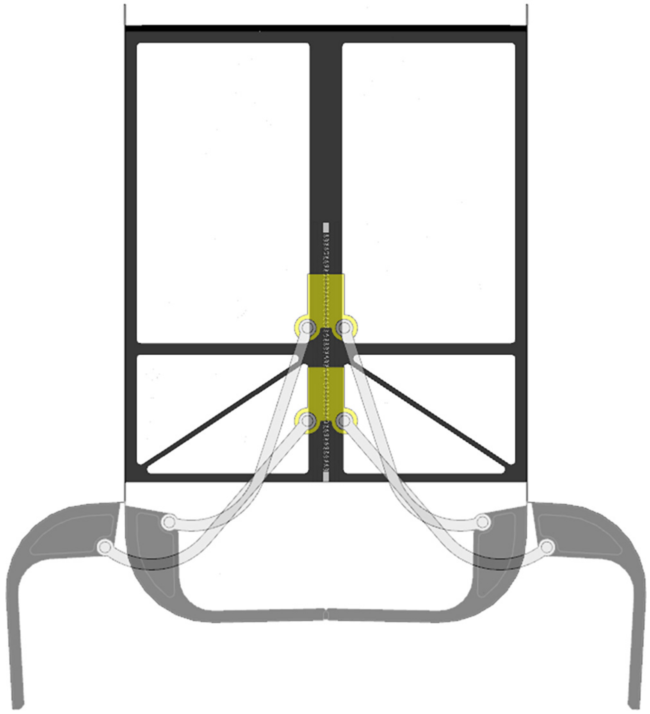
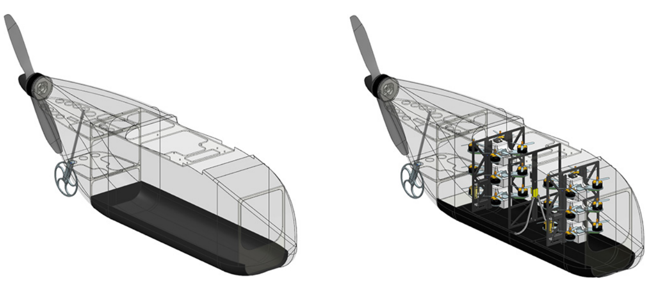
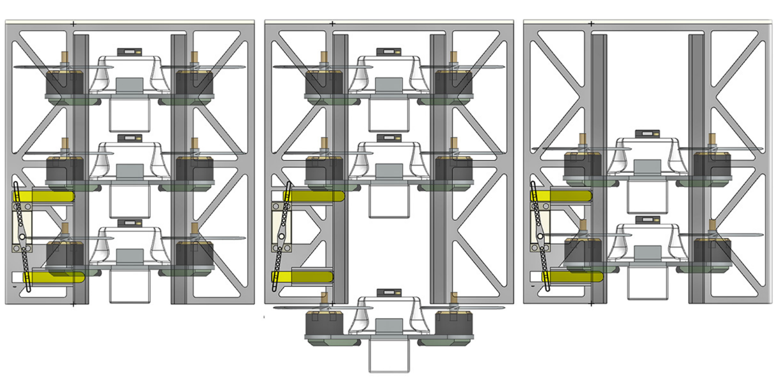


Figure 10 Fuselage internal layout: left – original, right – redesigned



monocoque structure of this airframe section. The presence of the two drone-holding frames and the opening mechanism frame for the DB doors significantly increases stiffness of the whole structure.

Figure 11 Drone release sequence



Further development

The plan regarding the system is to develop the communication solution. Initial ideas focused on connection via local wireless network that provides real-time data transmission from sensors carried by copters to the Ground Control Station. It could potentially be developed as a secondary subsystem that can be used whenever the mobile network connection is lost. The idea has initially been tested during SAE Competition where the autonomous gliders were towed behind the primary aircraft and local (mothership - glider) wireless communication for sending a release command was a necessity. The communication never was tested on a range greater than 100 meters and additional checks need to be done to determine whether or not to abandon current components and look for something more specialized. Development direction is set to use previously designed heavy lift aircraft as a mothership plane for sensing drones and create communication system based on commercially available hardware (Pixhawk, Rasp-berry Pi, RFD, etc.) and open-source software (ArduPilot, Mission Planer, Dronekit, etc.) that can be easily modified for various applications. This approach has a significant influence on decreasing the cost of the system and makes it more versatile. The second area of research is to apply Multidisciplinary Design Optimization techniques to improve the project in terms of aerodynamics and structure weight while not degrading any flying qualities (Goetzendorf-Grabowski and Mieloszyk, 2017; Mieloszyk *et al.*, 2020).

Summary

The paper presents an approach to technical issues that arose during the design of the UAS, focusing on the endurance and the concept of the payload release ability. An attempt to modify and adapt the existing proven platform was presented. The issues met within the redesign process of the mothership's fuselage and during the design of the sensing drone were discussed. The original glider used for the competition was compared to the newly designed concept and shown how the multirotor drone fits better to the modified mission of the mothership. There was shown a thought process tying up modified elements with existing competition system. Attributes presented by the use of a UAS might be advantageous for commercialization by various industries. One of them may be using drones to scan an area and create 3D maps of various parameters for data visualization. The UAS can be used to perform Search and Rescue missions. Multiple drones can cover much bigger search areas in shorter time. High rate of agriculture development demand systems providing possibility to either collect soil samples for further analysis or monitor wildlife activity.

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