CELLDRONE - A MODULAR MULTI-ROTOR AIRCRAFT

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Abstract

Electrically powered multi-rotor aircraft gain popularity among fire brigades, police and military units. The driving forces behind this trend are decreasing unit costs and increasing capabilities. Particularly the steady advances in sensor and microprocessor technologies allow the use of more sophisticated control algorithms. The current development of batteries that possess a significantly higher energy density will further accelerate this trend. The aim of this paper is to introduce a novel concept for scalable and modular multi-rotor aircraft. These aircraft are made from three or more identical hexagonal cells. Each cell contains two ducted, directly driven counter-rotating propellers as well as motor controllers, batteries and a control unit. Cells can be arbitrarily connected to each other to create a highly redundant, energy and cost effective aircraft for a wide range of mission requirements.

1. INTRODUCTION

The field of Unmanned Aerial Vehicles (UAV) has attracted a lot of attention in recent years. One reason for the growing interest in UAVs is the current development stage of many key technologies. The use of increasingly strong and lightweight materials, powerful engines and advanced control systems resulted in military aircraft where humans are the limiting factor during many flight manoeuvres. As a consequence, many next generation aircraft will be unmanned. Hence, the market for military UAVs in the U.S. is expected to have a volume of $62 billion between 2010 and 2015 and an annual growth rate of 10% [1].

Furthermore, there is a tendency to use, whenever possible, electric instead of fossil fuel based propulsion systems. This is not only driven by the decreasing availability of fossil fuels but also by increasing energy densities and decreasing battery prices. For example, Sikorsky presented their first electric helicopter [2] in July 2010. However, the design of this helicopter is, apart from the propulsion system identical to the fossil fuel powered production model S-300C.

The aim of this paper is to introduce a novel concept for electrically powered, scalable and modular multi-rotor aircraft. These aircraft are made from three or more identical hexagonal cells. Each cell contains two ducted, directly driven counter-rotating propellers as well as motor controllers, batteries and a control unit. Cells can be arbitrarily connected to each other to create a highly redundant, energy and cost effective aircraft for a wide range of mission requirements. It is shown that the use of a large number of ducted propellers increases the energy efficiency compared to a small number of larger free-running propellers. Hence it is believed by the authors that future manned and unmanned electric helicopters might differ from current designs insofar that they possess several directly driven propellers instead of one main rotor.

2. LITERATURE REVIEW

Breguet and Richet built the first piloted multi-rotor aircraft that left the ground under its own power in 1907. Although their quad-rotor design hovered for only a minute at an altitude of less than two meters it is widely considered to be the first helicopter [3]. However, the encountered difficulties of controlling several rotors at the same time forced subsequent helicopter designs to employ only one or two rotors.

Recent advances in sensor, microprocessor and battery technologies completely eliminated the constraints that enforced current helicopter designs. A consequence of this was a mushrooming development of multi-rotor aircraft that was mainly carried out by hobbyists [4-6], university based research groups [7-8] and small businesses [9-12]. However, the focus of most of these development efforts is on the dynamics, control and electronics. This paper continues the work by Pagitz and Mirats-Tur [13] that investigated alternative structural concepts for multi-rotor aircraft. Similar work in this area can be found, for example, in [14].

The outline of this paper is as follows. Section 3 introduces a novel structural concept for scalable and modular multi-rotor aircraft that is referred to as CellDrone. Section 4 presents the airframe design of a small-scale CellDrone with a duct diameter of 0.3m. Section 5 outlines the considered electronic and propulsion systems and Section 6 compares the expected efficiency of this novel concept with existing designs. Finally, Section 7 concludes the paper.

3. CELLDRONE CONCEPT

A CellDrone is made from three or more identical, hexagonal cells as shown in Figure 1 and Figure 2. Each cell contains two ducted propellers, two brushless motors, motor controllers, batteries, a control unit and payload compartments. Since cells can be arbitrarily connected there exists a large number of possible combinations. A few combinations where at least two cell sides are connected to neighbouring cells are shown in Figure 3.

FIG 1. CellDrone made from three cells

FIG 2. CellDrone made from seven cells

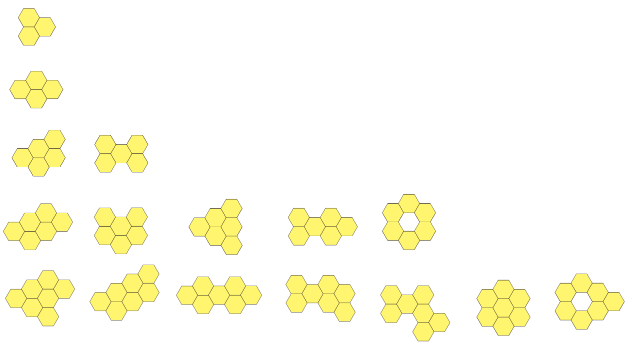

FIG 3. A few possible cell combinations

Furthermore, it is possible to connect propulsion cells with payload cells. For example, the cell in the middle of the seven-cell-version could be replaced by a payload cell. Hence, this topology might be of interest for a manned aircraft where the passenger sits in the middle.

Batteries, electronic boards and payloads are clipped into holders that can be connected to inserts at the outer surface of each cell, Figure 4. Due to the hexagonal cell shape, up to six holders can be mounted to a single cell. For example, additional batteries can be added to increase flight time. Furthermore, the load carrying capacity can be increased by adding additional cells. Hence, the CellDrone concept is simple, inexpensive and highly adaptive to a wide range of mission requirements.

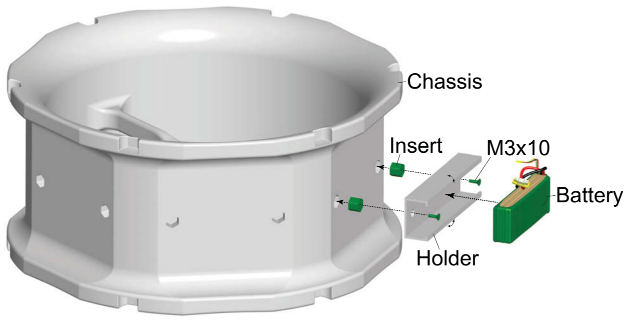

FIG 4. Connection between battery and airframe

Modular cover shells that surround each CellDrone protect batteries, electronics and payload from rain and dirt and increase performance in crosswinds. Each cell has attachment points for the cover shells so that, under all possible combinations, only two different cover shells are required, Figure 5.

FIG 5. Two types of CellDrone cover shells

4. AIRFRAME

The chassis is the central part of each cell to which motors, electronics, batteries and payloads as well as neighbouring cells are connected, Figure 6. A chassis is made from a foam core and a thin carbon fibre reinforced plastic (CFRP) shell at the outside, Figure 7. The shape of the chassis is a compromise that is driven by the conflicting requirements of a low self-weight, an efficient duct geometry and large payload compartments. To reduce the design complexity we have optimized the geometry of a symmetric duct with a diameter of 0.3m for a maximum self-weight of 300g.

FIG 6. Chassis

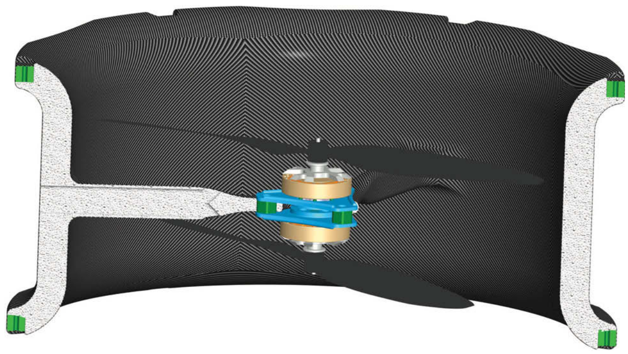

FIG 7. Cross-section of sandwich structure

To reduce material costs and to simplify production we made the foam core from several identical parts. Hence, all foam parts are glued together afterwards and reinforced by the outer CFRP shell.

Plastic inserts are used to connect cells as well as motors, electronics, batteries and payloads to the chassis. Since inserts are glued into the foam core, their load carrying capacity increases with the bonded area. Hence, inserts have to be quite large. To reduce their weight we have designed them in a cellular fashion as shown in Figure 8.

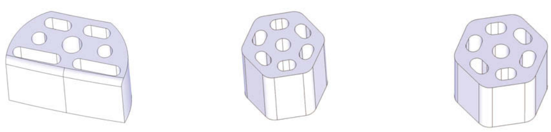

FIG 8. Three different CellDrone inserts

The multilayer CFRP shell around the foam core is made from three parts as shown in Figure 9.

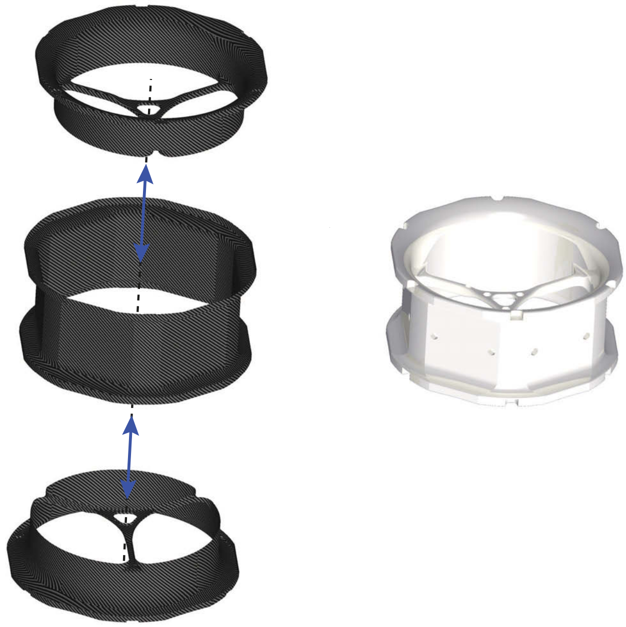

FIG 9. CFRP shell around foam core

The cover shells that surround each CellDrone are made from a single layer of CFRP. To increase their stiffness they possess a doubly curved surface where the curvature increases towards the top and bottom edge. Furthermore, ribs are added at the other two edges to provide a load path towards the attachment points. Plastic inserts are integrated into the ribs for connecting them to the chassis, Figure 10.

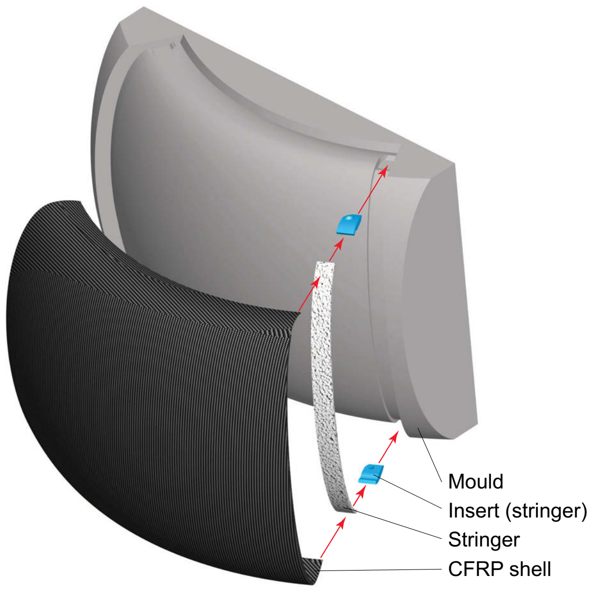

FIG 10. Assembly of the cover shells

Both motors are connected to the chassis via mounting plates. The motor cables are placed in a cable channel inside the foam core of the chassis.

The connectors between two and three cells are shown in Figure 11 and Figure 12. Aluminium plates that are screwed to inserts at the top and bottom hold the cells together. On top of each plate is a pyramid-shaped facing that separates the in- and outflow. These parts are made from plastic and clipped and glued to the aluminium plates.

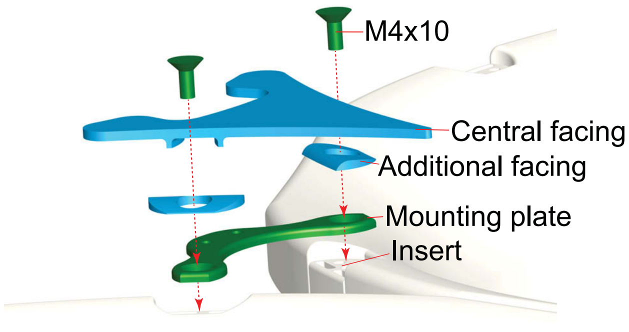

FIG 11. Cell connector between two cells

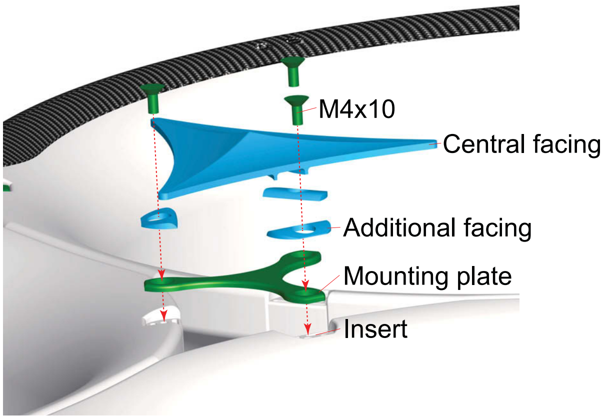

FIG 12. Cell connector between three cells

A cross-section of the whole assembly of one cell is shown in Figure 13.

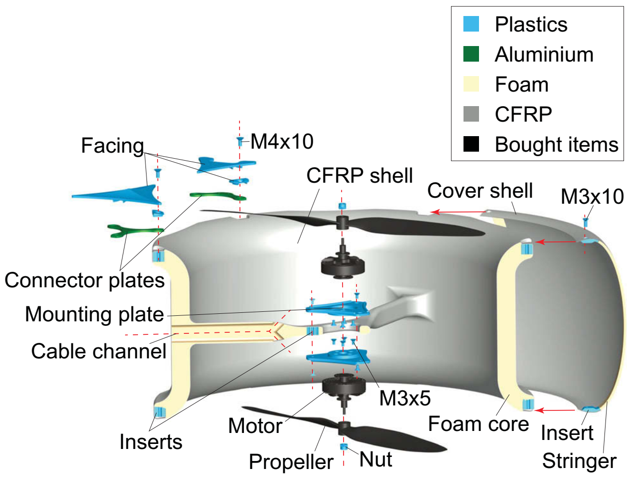

FIG 13. Cross-section of one cell

5. ELECTRONICS AND PROPULSION

Each cell contains two directly driven, counter-rotating propellers that minimize torque and maximize thrust for a given cell volume. Although we currently use commercial brushless motors and propellers we plan to increase performance by optimizing motors and propellers as a unit.

The current state of a brushless motor is measured by three Hall sensors and send to a Brushless Control (BlCtrl) unit. Based on the desired motor speed or acceleration, the Hall sensor data, the battery voltage and the mass distribution of both, motors and propellers, the BlCtrl computes and delivers the required pulse width modulation to the motor coils.

Each cell possesses two kinds of batteries. The first kind of batteries supplies energy to the electronics and the second kind to the motors. This increases the reliability in two ways. Separating the power supply for the electronics from the propulsion considerably reduces the noise to which the electronics is exposed to. Using a complete set of batteries in each cell increases the redundancy since the failure of any battery can be compensated by neighbouring cells.

Figure 14 shows the electronic schematic of a CellDrone that is made from three cells. Each cell possesses its own flight control that comprises a set of sensors and a processing unit. Flight controls are communicating via a CAN bus to share their sensor data with each other. If one flight control fails, the others can send the required commands to the BlCtrls of that cell. If the whole cell fails, the remaining cells can take over.

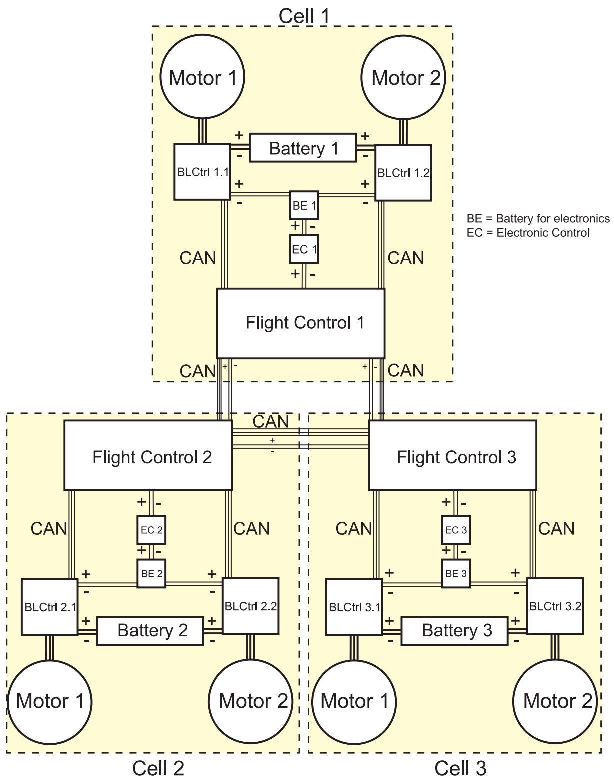

FIG 14. Electronic schematic of a CellDrone (three cells)

6. PERFORMANCE COMPARISON

In the following we compare the expected propulsion efficiency of a CellDrone with existing designs. Table 1 lists all parts that are needed to build the structure of a single cell with a duct diameter of 0.3m together with their respective masses. The total mass of a CellDrone that is made from three cells is summarized in Table 2.

The use of ducted propellers does not only increase the structural mass, it also increases the thrust for a given power by up to 26% [15]. Therefore, a ducted design is more efficient if its total mass increases by less than 26% compared to designs that use free running propellers. For example, a CellDrone that consists of three cells and a payload of 500g weights about 3.5kg. Hence, it is advantageously to use ducts instead of free running propellers if the additional structural weight is less than 722g. Since the structural mass of a CellDrone is 912g, the mass of a design that uses free running propellers would need to be less than 190g which is hard to achieve.

TAB 1. Mass table of one cell

Parts	Material	Mass [g]
Foam core	Depron	80
Inserts	PA 6	38
Cell shell	CFRP	109
Cover shells	CFRP	30
Mounting plate for motor	PA 6	13
Cell connectors and screws	PA6, Alu	24
Miscellaneous (e.g. glue)		10
	Total mass:	304

Table 3 compares the expected propulsion efficiency of the CellDrone concept with that of the electrical helicopter Firefly from Sikorsky [2], the md4-1000 from Microdrones [10] and the theoretical values for ideal free running and ducted propellers. Note that the ideal values are calculated according to [15] and based on a propeller diameter of 0,3m and an air density of ρ=1,225kg/m³.

Although the propulsion efficiency of the electrical helicopter Firefly is about three times higher than that of conventional helicopters [2], it is worse than the efficiency of, for example, the multi-rotor drone md4-1000 from Microdrones [10]. The estimated CellDrone efficiency is about 110 W/kg and thus approximately 15 % better than the efficiency of the md4-1000. In addition, the CellDrone concept has advantages due to its redundancy and modularity.

TAB 2. Total mass of CellDrone with 3 cells

	Mass [g]
Structure	304
Battery (14.8V, 4Ah)	452
Motors	130
Rotors	18
Electronics	100
Single cell	1,004
CellDrone (3 cells)	3,012

Hence it can be concluded that electrically powered multi-rotor aircraft might be an interesting alternative to currently used electric helicopter designs.

TAB 3. Efficiency comparison

	Efficiency [W/kg]
Firefly (Sikorsky)	~ 200
md4-1000 (Microdrones)	~ 130
CellDrone	~ 110
Perfect free running propeller	74
Perfect ducted propeller	52

7. CONCLUSIONS AND FUTURE WORK

This paper introduced a novel concept for electrically powered, scalable and modular multi-rotor aerial vehicles. These aerial vehicles are made from three or more identical hexagonal cells where each cell contains two ducted, directly driven counter-rotating propellers. It was shown that the use of a large number of ducted propellers increases the energy efficiency compared to a small number of larger free-running propellers. Hence it is believed by the authors that this concept might be of interest for future manned and unmanned helicopter designs as we move from a fossil to an electric age.

A major advantage of this concept is its high redundancy since each cell possesses its own motor controllers, battery and control unit. Hence, an aircraft that is based on this concept could survive the loss of several cells as long as the remaining cells produce sufficient thrust and torque around all axes. Furthermore, the construction of a staged aircraft is possible by unlocking some cells after their batteries are drained.

To get a first data point we designed a hexagonal cell with a duct diameter of 0.3m. The cell is made in a carbon fibre sandwich construction that incorporates several inserts for the attachment of various mounting parts. The calculated mass of an aircraft that consists of three cells and the expected propulsion efficiency indicates that such a design is potentially superior to existing electrically powered vertical take-off and landing aircraft. Future work will focus on the construction of a small scale UAV with a duct diameter of 0.3m. Furthermore, we will investigate the dependency of the structural mass and propulsion efficiency on a wide range of duct diameters.

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