The TetraheDrone: A Structured Fractal HFW-VTOL UAS

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***Abstract*— We introduce the TetraheDrone, a hover-capable module in the shape of a tetrahedron that can be assembled in larger tetrahedral configurations and can transition to winged flight. Inspired by earlier designs by Alexander Graham Bell, the TetraheDrone can become a large vehicle while keeping an inherent ability for horizontal flight and efficient aerodynamic properties.**

I. Introduction

The system introduced in this work answers the need for *modular* yet sufficiently powerful airborne systems capable of carrying high payloads. The concept of modularity in air- and space-borne systems is not new. Perhaps one of the earliest modular systems was the system resulting from the historical Apollo-Soyuz rendezvous in 1975, as depicted in Fig. 1a. A much larger system, the International Space Station, has been progressively constructed from several modules as shown in Fig. 1b. In addition to permanently connected modules, the Space Shuttle and other vehicles, such as the Soyuz capsule, can also dock on the Space Station for crew rotation and commodities replenishment. At a much lower scale and lower altitude, many insects form small modular flying systems by mating. This is for example the case of bees, flies, and dragonflies as shown in Fig. 2.

(a) Artist's concept of an Apollo-Soyuz rendezvous [1].

(b) International Space Station with docked Space Shuttle [2].

Fig. 1: Modularity in space systems

The systems of interest to the present paper are modular systems made of several identical element and capable of atmospheric flight. Such systems include numerous past designs [3], [4], [6], [7], some of which are shown in Fig. 3. These modular drones offer linear or co-planar arrangements that offer both advantages in terms of storage geometry and disadvantages in terms of structural integrity. Indeed, the operation of such vehicles requires a delicate coordination; otherwise, the overall shape of the composite system may quickly be subject to oscillations reminiscent of those undergone by large solar-powered vehicles, such as NASA's Helios and Pathfinder aircraft.

Fig. 2: Composite flying system made of two mating dragonflies.

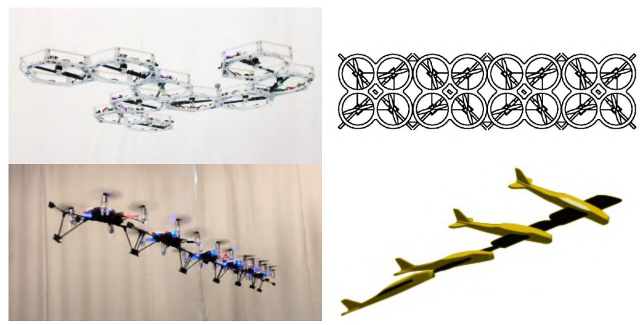

Fig. 3: Various modular drones. Clockwise from top-left: The Distributed Flight Array [3]. Boeing's Lift project [4]. Meta aircraft [5]. Modquad [6].

For that purpose, Garanger and co-authors have developed a tetrahedral module allowing the recursive construction of large drones following the same formula that defines Sierpiński's fractal tetrahedra [8]. Such a structure enjoys much improved structural semantics because of its natural three-dimensional configuration. This tetrahedral structure also enjoys interesting characteristics. For example, assuming propellers are designed so as not to touch each others' tips, the total lifting disc density as seen from above is about 0.60,

Fig. 4: Sierpiński tetrahedron-shaped modular drone. Left: single module. Middle: First-generation drone. Right, second-generation drone.

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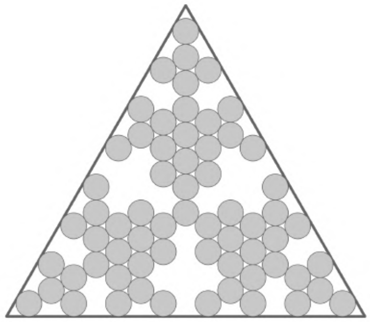


Fig. 5: Horizontal footprint of 3rd generation drone with 64 propellers.

Fig. 6: Generation 2 kite designed by Alexander Graham Bell in flight [12].

which is two thirds of the maximum packing density that corresponds to an infinite honeycomb arrangement, which is slightly more than 0.91. Perhaps more interestingly, that same arrangement is 77% the density achieved by quadrotors (0.78) connected in a planar arrangement. Thus a lot more structural rigidity can be achieved for a modest overall size increase. Experimental work presented in [9], [10] indicates that the propellers not being co-planar anymore does not influence the thrust they produce for hovering flight at equal electric power input.

Alexander Graham Bell's tetrahedral kites form the second element of inspiration for the work presented here. During the early 20th century, the communications pioneer directed the development of scientific kites made of a vast collection of smaller tetrahedral units appropriately covered by silk-made lifting surfaces. Some of Bell's kites are Sierpinski's tetrahedra as shown in Fig. 6 [11]. These kites are known as "tetrahedral kites". Initially sold as "Tetra Kites" in 1974, such kites, sometimes of astonishingly large dimensions, can be built with the help of several online resources and household supplies. For example, it is possible to build large tetrahedral kites with up to 100 tetrahedral cells from elements as simple as plastic straws for structural elements, paper or plastic sheets for aerodynamic surfaces, and string to link all elements together.

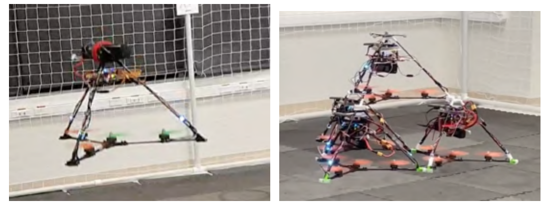


Fig. 7: Modified tetrahedral design of the *Tetracopter*. Left: Generation 1 Module in-flight. Right: Generation 2 vehicle in-flight.

In the rest of this paper, a possible arrangement allowing the designer to transform the foregoing tetrahedral rotorcraft into a modular hybrid fixed-wing vertical take-off and landing (HFW-VTOL) machine capable of winged flight is described.

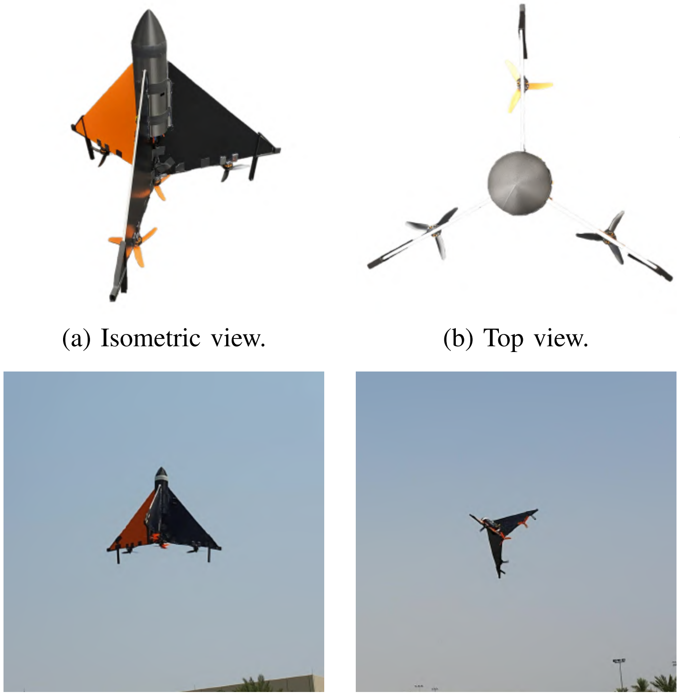
II. Module Design

The winged design presented here follows a modification to the tetrahedral concept of [8]. In essence, the basic module consisting of a 1-propeller tetrahedron is aggregated into a tetrahedral module comprising four co-planar propellers. This module is capable of flight and four copies of it may be assembled into a "Generation 2" system, as shown in Fig. 7. As such however, the module exhibits poor aerodynamic characteristics.

A. Aerodynamic module description

The foregoing module is modified by adding lifting surfaces allowing the module to enter gliding flight once the proper airspeed is reached. The aerodynamic module features three separate, yet identical, triangular wings evenly distributed around the longitudinal axis of the module so as to all have a dihedral angle of 120 degrees as shown in Fig. 8. The leading edge of these wings is parallel to and slightly ahead of the underlying tetrahedral structural rod that is visible in Fig. 7. In this first attempt, and keeping in mind a desire for maximum isotropy, the symmetric sheet airfoils are used, at the cost of somewhat reduced aerodynamic performance. For prototyping convenience, however, the winged prototype was built separately from the tetrahedral, non aerodynamic module. The winged prototype also features a different positioning of the motors, which are placed in a pusher configuration.

It is worthy to note that this tri-wing arrangement is very different from Bell's own arrangement of lifting surfaces on the tetrahedral kites, as shown in Fig. 9. It is clear why Bell's arrangement of lifting surfaces is unsuitable for a system with propellers arranged as in its powered counterpart. Indeed, the propeller wakes are approximately co-planar with the three aerodynamic surfaces of the configuration described here. For the same prop arrangement, the prop wake would be slightly less than 20 degrees off the aerodynamic surfaces according to the geometry of the regular tetrahedron where



(a) Isometric view. (b) Top view.

(c) Hover flight. (d) Fixed wing flight.

Fig. 8: An individual *TetraheDrone* module.

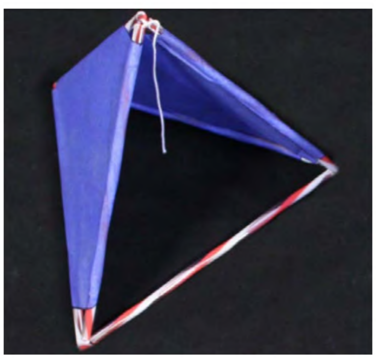


Fig. 9: Tetrahedral kite module [13].

the dihedral of two facets is approximately 70 degrees. Such an angle of 20 degrees is a lot compared with the commonly encountered angles between aircraft wing chords and their engine outflow.

B. Geometry

As illustrated in Fig. 5, the horizontal footprints of the propellers do not overlap, which minimizes wake interactions between propellers. The pusher configuration also implies that rotor outflow is unobstructed. Both these factors result in better aerodynamic performance.

Considering that the drone lacks control surfaces, it is useful to align the center of gravity (CG) with that of aerodynamic lift (CL) along the longitudinal axis. In forward flight, a CL that is ahead of the CG results in unstable flight in the longitudinal, or pitching, plane. When the CG is ahead, flight in the longitudinal plane is stable but the controls have to compensate for different deviating moments. The location of the center of gravity can be tuned by careful positioning of the vehicle's electronics, especially the relatively heavy battery.

In a fractal tetrahedral assembly (as seen in Figs. 4, 6 and 7) of n drones of equal mass m, where n is a multiple of 4, if the CG of module $i \in \{1, \ldots, n\}$ is located at $(x_{cg_i}, y_{cg_i}, z_{cg_i})$, the overall CG of the system is

$$x_{CG} = \frac{\sum m_i x_{cg_i}}{\sum m_i} = \frac{m \sum x_{cg_i}}{nm} = \frac{1}{n} \sum x_{cg_i}$$

The same follows for the y and z coordinates. The center of lift is defined as the point where the sum of the lift forces act. Thus, for the same assembly, the location of the overall CL is

$$x_{CL} = \frac{\sum L_i x_{cl\,i}}{\sum L_i} = \frac{L \sum x_{cl\,i}}{nL} = \frac{1}{n} \sum x_{cl\,i}$$

where L is the lift force magnitude acting on each module at its CL located at $(x_{cl\,i}, y_{cl\,i}, z_{cl\,i})$. It is assumed to be equal for all modules in the assembly. The y and z coordinates can be found in the same fashion. It can be concluded that the distance between the CG and CL remain constant for successive generation of fractal assemblies.

III. Prototype

With the vision of a multi-module Sierpinski patterned air system, a preliminary prototype of one TetraheDrone module shown in Fig. 8 is built. The design rationale is to produce a light, inexpensive, sufficiently aerodynamic and structurally sound, and easy and quick to manufacture module. The expectation is to facilitate the production of numerous modules that will be arranged into a larger but similar structure. The overall weight of the system is $\sim$700 g including the battery. The dimensions of the module are $\sim 60\,\mathrm{cm} \times 54\,\mathrm{cm} \times 37\,\mathrm{cm}$. A brief description of the components follows.

A. Prototype's components

1) Airframe: Most of the components and electronics are enclosed in a 3D printed fuselage as shown in Fig. 8. The concept allows some decoupling between the wings and the other components. This has advantages for design, analysis and testing. Foam board wings are the most vulnerable part of the structure and a multitude of airfoil designs are possible. In case of a crash while testing, they are likely to be damaged while the rest of the drone remains intact. In this design, the wings can be easily and inexpensively swapped to test new wings or replace damaged ones. In addition, having a 3D printed fuselage yields better aerodynamic properties and protection for otherwise exposed components. The material used for the printing is Onyx™from Markforged which is a fusion of engineering nylon and chopped carbon fiber. The propulsion system is mounted via printed parts and hot-melt adhesive to the wings and will need to be unplugged and remounted on new wings for reuse. The landing feet are also printed. Three triangular wing shapes are effortlessly cut out from foam board. This readily available lightweight material consists of a polystyrene foam board sandwiched between paper. The triangles are glued together to form a tetrahedral shape. A wooden rod is inserted at the glued joint prior to gluing for reinforcement. A single module was built and flown in both flight modes with transitions.

2) Propulsion: The prototype is propelled by four brushless Emax ECO series 2207 motors rated at $1900\,\mathrm{kV}$ per unit. Attached to each motor is a three-blade $125\,\mathrm{mm}$ diameter propeller and a $35\,\mathrm{A}$ HAKRC electronic speed controller (ESC). The propeller pitch angle is $\sim 22°$.

3) Power: The ESCs are wired into a power distribution board. This board is powered by a six cell $276\,\mathrm{g}$ Lumenier lithium-polymer battery rated at $1550\,\mathrm{mA\,h}$.

4) Communications: To enable radio command remote operation, a FrSky X8R receiver is installed.

5) Flight controller: The flight controller board is a Pixhawk 4 Mini. It communicates via cables with the ESCs, the radio receiver and any other components that may be needed in the future.

6) Thrust tests: Thrust tests were performed with the chosen motor. At a $50\,\%$ pulse-width modulation signal, the available thrust was found to be about to $2.1\,\mathrm{N}$ at an angular speed of $17\,000$ revolutions per minute.

IV. Conclusion

The TetraheDrone prototype described in the foregoing lines represents the last evolution of a sequence of modular aerial vehicles introduced by Alexander Graham Bell more than a century ago. Combining a drone-like propulsion system with lifting surfaces on a single module brings forward the possibility of building and operating large modular systems capable of transitioning from hover flight to gliding flight. A rapid aerodynamic study indicates that the TetraheDrone flying qualities are satisfactory and independent of the system's roll angle, with the exception of induced drag and related moments. The TetraheDrone's propulsion system allowing it to hover is predicted to also meet the needs of gliding flight at higher speed. Early prototypes indicate good hovering and glide characteristics for individual modules as well as more complex shapes arising from the assembly of several of these modules.

V. Proposed Work

Several areas of study intrinsically emerge. They are listed in order of priority:

1) **Multi-robot system control.** Controlling a four propeller VTOL vehicle without control surface is a challenging task addressed in several recent works listed in Table 3 in [14]. In addition to controlling a single module, it is a critical research goal to control an assembly of four, shown in Fig. 10. Extending this to control a sixteen module drone is desired.
2) **Module design.**
3) **Aerodynamics.**
4) **Energy consumption.**
5) **Structural integrity.**

Fig. 10: An assembly of four *TetraheDrone* single-modules.

6) **Safety.**
7) **Payload delivery system.**
8) **Flight formation disassembly and assembly.**

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