

Design and Testing of a Vertical take-off and Landing UAV optimized for carrying a Hydrogen Fuel-cell with Pressure Tank.

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ABSTRACT

Flight endurance is still a bottleneck for many types of UAV applications. While battery technology improves over the years, for flights that last an entire day, batteries are still simply insufficient. Hydrogen powered fuel-cells offer an interesting alternative but pose stringent requirements on the platform. The required cruise power must be sufficiently low and flying with a pressurized tank poses new safety and shape constraints. This paper proposes a hybrid transitioning unmanned air vehicle that is optimized towards carrying a hydrogen tank and fuel cell. Hover is achieved using twelve redundant propellers connected to a dual CAN network and dual power supply. Forward flight is achieved using a tandem wing configuration. The tandem wing not only minimizes the required wing span to minimise perturbations from gusts during hover, but it also handles the very large pitch inertia of the inline pressure tank and fuel cell very well. During forward flight, eight of the twelve propellers are folded while the tip propellers counteract the tip vortices. The propulsion is tested on a force balance and the selected fuel-cell is tested in the lab. Finally a testing prototype is built and tested in-flight. Stable hover, good transitioning properties and stable forward flight were demonstrated.

1 INTRODUCTION

The advent of Unmanned Air Vehicles (UAV) offers many great new opportunities for surveying and inspection tasks. Many tasks however are requiring flight times of several hours, as well as vertical take-off and landing [1, 2, 3, 4]. To achieve very efficient forward flight, fixed wings have clearly shown to be the most efficient way of flying [5]. But the requirement for a runway or launch and recovery system limits their applicability [6].

Several hybrid concepts have been proposed to merge the advantages of hovering aircraft with efficient fixed wing air-



Figure 1: NederDrone2 with 12 propellers of which 8 are fold-able and stop during forward flight. The 4 tip propellers remain active during forward flight and have a higher pitch for efficient fast flight. The large fuselage can accommodate a 9 liter pressure tank and a fuel-cell.

craft [7, 8, 9]. The DelftaCopter [7] has proposed a conventional helicopter rotor combined with delta-wings. While good efficiency was obtained, the concept had a high center of gravity and many single points of failures, which is not ideal when more dangerous fuels are used. [10] has proposed to use coaxial rotors to simplify control and remove the need for tip propellers, but does not solve the issues of the previous concept. Several researchers have proposed tilt-wing UAV [9, 11]. These concepts are great but have difficult control properties and require a complex wing actuation mechanism.

Many tandem tailsitter concepts have been proposed for a long time already [12, 13]. [14] presents the design of a tandem tailsitter and its control. [15] also describes the design and control of tailsitter tandem wing UAV. While the tandem configuration offers good properties for the installation of all hydrogen systems, the fact that it sits upright and can fall over is seen as a problem for a fuel-cell VTOL long endurance

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aircraft, especially when operating on moving ships.

The current paper presents the NederDrone concept. It consists of an angled tandem wing with 12 propellers for the hover, 8 of which are fold-able during forward flight. The concept was named NederDrone and is shown in Figure 1.

Section 2 explains the design choices behind the concept. Section 3 investigates the required propulsion. Given the design specifications, the selected fuel-cell will be tested in Section 4. Finally Section 5 presents flight test results of the concept using battery power. Conclusions are presented in Section 6.

2 CONCEPT OPTIMIZATION

While the typical application requirements for marine operations are very long flight and vertical take-off and landing, the fuel-cell poses several extra design requirements. Safety is amongst the top requirements. The fuel-cell being fuelled by a 300 Bar carbon pressure tank, avoiding crashes is primordial. This leads to a requirement of redundancy in all flight controls. No single electronic point of failure was allowed in the design.

Hovering is achieved using 12 independent propellers. This allows the failure of at least 2 propellers without endangering the flight. If more propellers are to fail, then the concept can still fly in forward flight, given sufficient altitude at the time of failure. To overcome electrical failures in hover, every Brush-less Electronics Speed Controller (ESC) of every motor receives power from the 2 power busses and can fly with a single power bus. The command cables are also doubled. On top of that, monitoring of all ESC was required. This quickly amounted to an overwhelming amount of control cables. Therefore a dual Controller Area Network (CAN) control bus was designed through the airframe. To convert the commands to normal ESC pulses, special electronics was designed that accepts commands from any CAN bus and sends status information back for health monitoring. The PCB design is shown in Figure 2. The motor controllers are housed inside 3D printed motor mounts made from ABS plastic, which blend nicely into the wing and let the propellers fold nicely over the controller housing (See Figure 11).

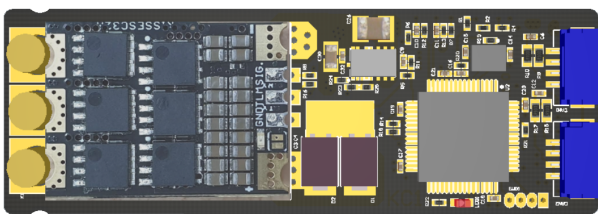


Figure 2: Dual power bus and dual CAN control network brushless electronic speed controller.

Also during forward flight, the heavy, bulky and long hydrogen pressure tank places a lot of constraints on the air-

frame. The fuel-cell itself also made the fuselage longer. The very large moment of inertia of the fuselage in the pitch direction that results from this spread of mass requires a very large horizontal stabilizer. In hover, the wings can catch turbulence and complicate the hover. To reduce this effect to the minimum, shorter wings are better and create smaller perturbing torques. Both previous constraints lead to the choice of a tandem wing configuration with equal wing span. This maximizes longitudinal stability, minimizes the grip gusts have on the airframe during hover and it yields optimal structural properties.

Finally, to allow a stable passive attitude after the landing, the tailsitter concept was discarded. The long pressure tank would make the risk of tipping over too high. Instead, after landing the fuselage sits stable and flat on the ground. To nevertheless allow autonomous take-off without the need for extra support, the wings were pitched up, hereby slightly pointing the propellers up while on the ground. This makes sure the propeller tips have sufficient clearance from the ground.

Table 1 shows the final design specifications of the NederDrone2. A schematic view is shown in the Appendix Figure 11.

Table 1: Specifications of the Nederdrone2.

	Precision	Recall
Wingspan	2.24	m
Length	1.32	m
Airspeed	17	m/s nominal
MTOM	8	kg
c.g.	32	cm from leading edge

3 PROPULSION OPTIMIZATION

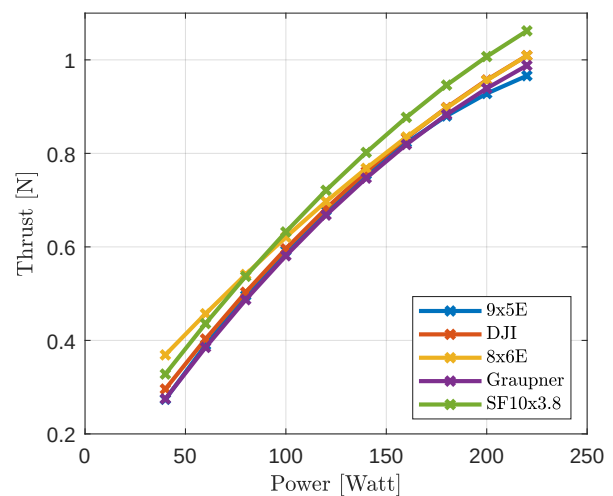


Figure 3: Thrust in function of power for a selected combination of propellers.

One important aspect of the forward flight is that 8 propellers are folded while the 4 tip propellers provide the required thrust. The tip propellers are placed such that they counteract the tip vortices. But since the choice of foldable propellers is limited, an own folding mechanism was designed. To validate that the selected propeller and motor combination was sufficient for flight, static balance testing was performed.

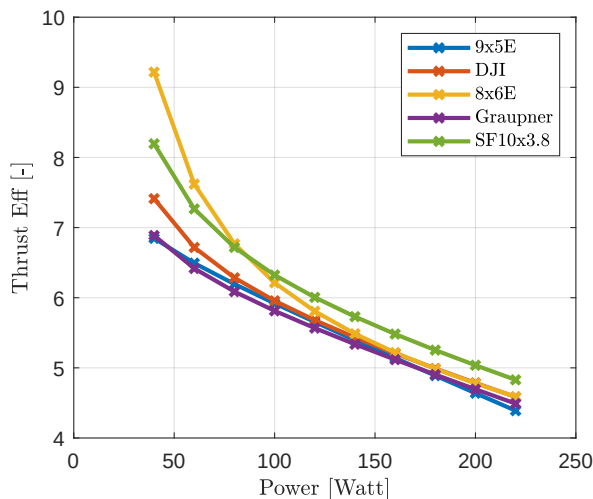


Figure 4: Thrust efficiency in function of power for a selected combination of propellers.

A Hacker A20-38L motor was designed to fit the selected propellers. Figure 3 presents the results of thrust measurements on a static test setup. Figure 4 shows the efficiency estimates associated with it. The selected propeller is the DJI propeller with a custom folding mechanism. The results show it performs almost as well as the best rigid propellers. The total available thrust with 12 motors was shown to be 12 kilograms. This leaves a factor of 50% given the design weight of 8 kg.

4 FUEL CELL TESTING

With the airframe and propulsion design figures, a suitable fuel-cell was searched. The Intelligent Energy 800 Watt cell was selected for availability, price and specification reasons. To verify the data-sheet specifications, a laboratory test setup was created in which the power output could be evaluated. Figure 6 shows the test setup with the fuel cell. Specifications of the cell are given in Table 2.

The fuel-cell was found to deliver the 800 Watt reliably. However, when more power than 1100 Watt was used, the total fuel-cell system would shut down. It is therefore crucial to limit the current drawn from the system.

While fuel cells can provide power for a very long time, they provide only little power at a time. To provide sufficient power during the power hungry take-off, landing and hover

Table 2: Specifications of the Fuel-Cell.

	Precision	Recall
Max Cont Power	800	Watt
Max Peak Power	1400	Watt
Mass	880	gram
Output voltage	19.6 to 25.2	Volt
Size	196 x 100 x 140	mm

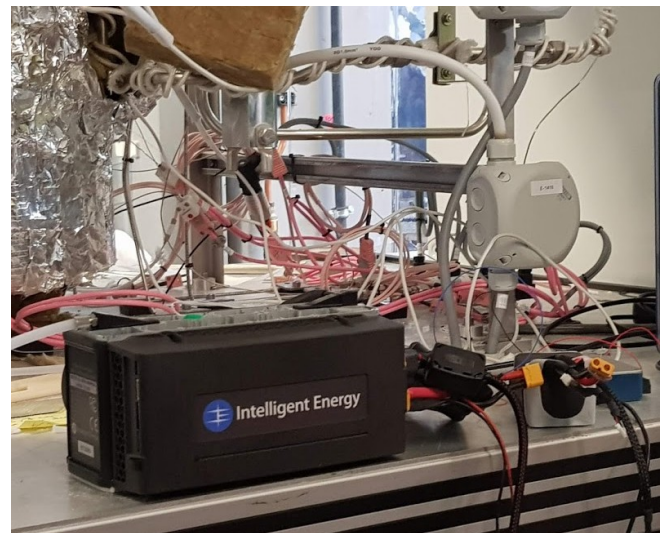


Figure 5: Testing of the fuel-cell in the lab and measuring the current and voltage output under different loads.

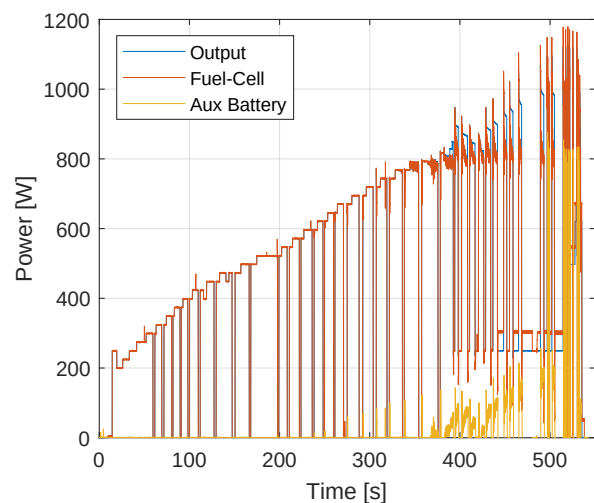


Figure 6: Testing of the fuel-cell in the lab and measuring the output power. When more than 800 Watt is required, the auxiliary battery starts (yellow) to deliver power as well. Every time the power required became larger than 1100 Watt, the system would shut down.

phases, an extra battery is added to the total system. This Lithium-Polymer battery is sized to allow 5 minutes of hovering and is recharged during low power cruise flight when the fuel cell has spare power.

Besides the selection of the fuel-cell, the selection of the tank is a crucial design component. A *CTS Composite Technical Systems* 6.8 Liter 300 bar tank was selected. The weight of the tank is 3.3 kg. At 300 bar it contains 140.7 gram of hydrogen. This results in a system with an efficiency 1415.5 Wh/kg and 4.25 wt%/h². With a total energy content of 4671 Wh and an estimated 55% fuel-cell efficiency this results in 2569 Wh usable. At the 25V output this results in a 103Ah 6-cell LiPo equivalent.

5 TEST FLIGHT

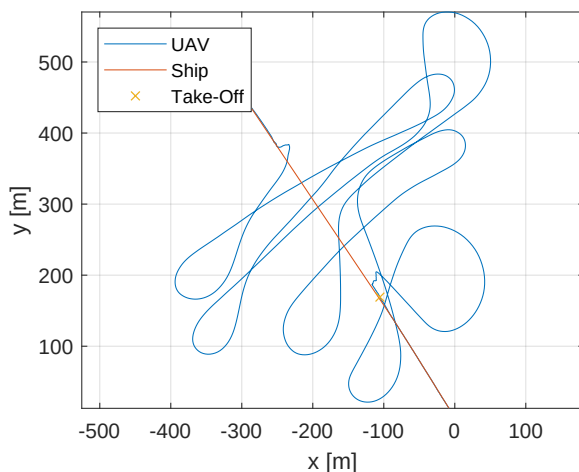


Figure 7: Ground track from a flight from a ship on the North Sea. Stable hover above the moving ship was possible and very stable and smooth forward flight was shown in figures of eight following the moving ship.

The UAV was equipped with a Pixhawk 4 autopilot running Paparazzi-UAV software [16, 17]. The motor controllers equipped with CAN drivers were programmed with an implementation of UAV-CAN with own messages. The datalink consists of a Herelink 2.4GHz + 433MHz (backup), capable of transmitting both video and telemetry. The radio control is a TBS Crossfire Diversity 868MHz.

Before more dangerous test flights are attempted with fuel-cells onboard, the NederDrone was equipped with Lithium-Ion batteries for testing. The hover controller was first tuned in an indoor flight test facility of the TUDelft. Once the hover loop was tuned, the NederDrone was tested outdoors. The hover gains were also good for slow forward

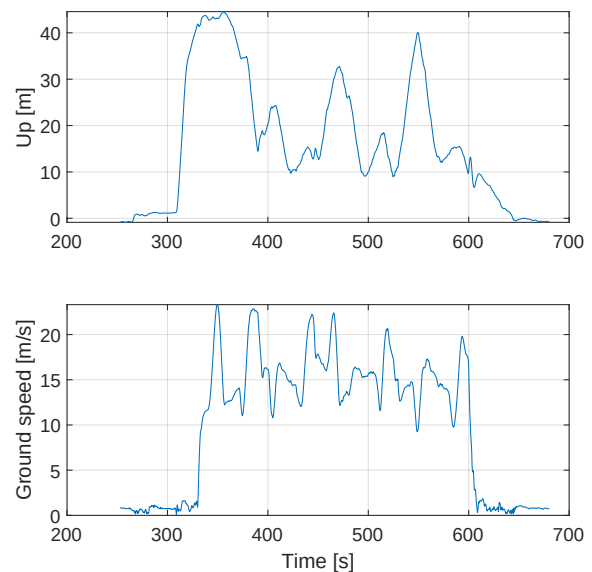


Figure 8: Height and ground speed of a test-flight from a ship.

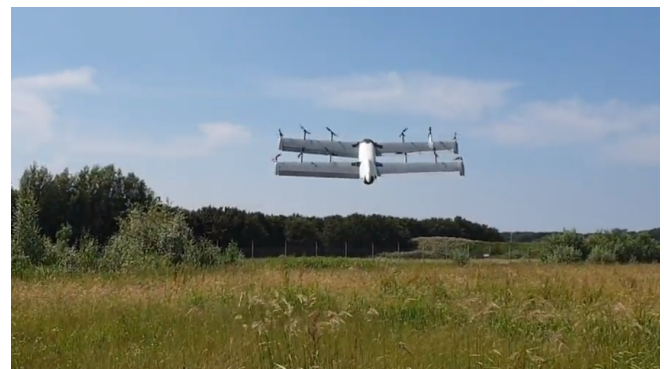


Figure 9: NederDrone2 in-flight.

flight, and for faster flight the forward gains were reduced until stable flight was achieved. Figure 9 shows the NederDrone2 in-flight.

6 CONCLUSIONS

A new transitioning tandem wing UAV concept was proposed which is in between a quad-plane and a tailsitter. The tandem wings give it excellent stability despite the huge moment of inertia in the pitch direction due to the long pressure tank and fuel-cell. The orientation of the wing allows very good passive stability when laying on the ground and eliminates the risks of tipping over that are associated with tailsitters. At the same time the NederDrone2 can take-off vertically. The 12 hover propellers give it excellent redundancy and the forward flight capability further increases the resilience to failures in flight. The same propellers can be used during forward flight, where 8 of the 12 propellers fold

back.

7 RECOMMENDATIONS

While the concept was shown to fly very successfully, it has not flown using hydrogen power yet. Many other aspects remain to be investigated in more detail. Test flights with a missing propeller were already performed but a detailed analysis is still needed how many props may fail. Recovering from hover to forward flight is also a maneuver that requires more investigation. Finally, working with hydrogen is a significant operational challenge requiring a lot of research and development.

ACKNOWLEDGMENTS

The authors would like to thank the Royal Netherlands Navy for making this research possible.

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APPENDIX A: SPECIFICATIONS



Figure 10: A composite photo from a NederDrone 1 prototype in hover and subsequently in forward flight, operated from a ship on the North Sea.

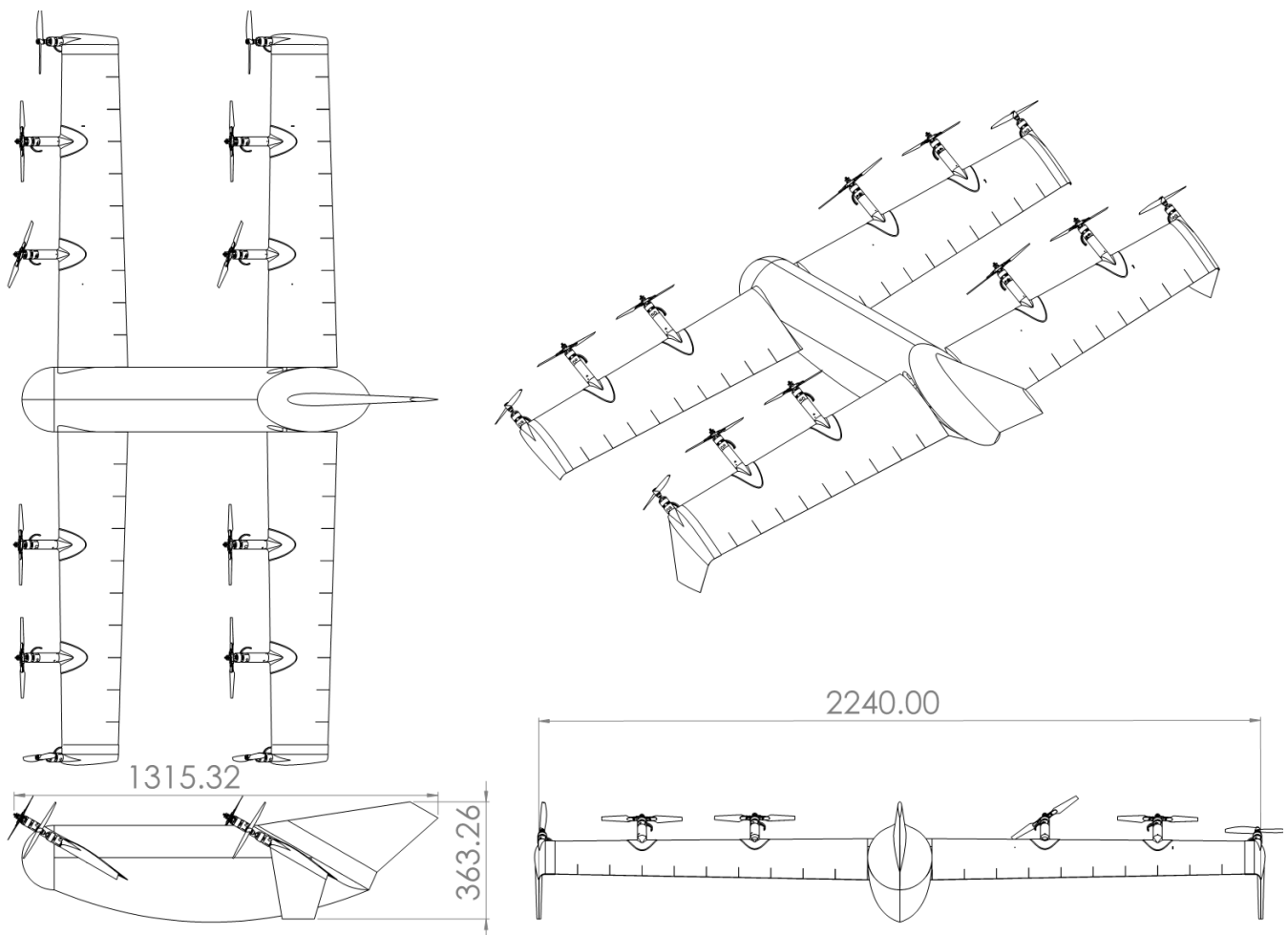


Figure 11: NederDrone2 top, side, back and isometric views. The hydrogen tank forms the main part of the fuselage while the tandem wings are placed at an angle to combine high passive stability on the ground with the possibility of automatic vertical take-off. The span is 2m24 while the length is 1m31.