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

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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 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 wingspan to minimize 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 vortexes. The propulsion is tested on a force balance and the selected fuel-cell is tested in the lab. Finally, a prototype is built and tested in-flight. Stable hover, good transitioning properties, and stable forward flight are demonstrated.

Keywords: UAV, Hydrogen, Pressure Tank, Pressure Cylinder, Fuel-Cell, Hybrid UAV.

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 [1–4]. To achieve a 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 aircraft [7–9]. 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 UAVs [9, 11]. These concepts are great but have difficult control properties and require a complex wing actuation mechanism. The wing mechanism also forms a single point of failure.

Fig. 1. NederDrone2 with 12 propellers of which 8 are foldable 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.

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

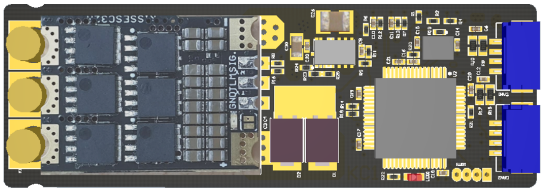

Fig. 2. Dual power bus and dual CAN controller area network brushless electronic speed controller.

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 over the controller housing (See Figure 11).

Also during forward flight, the heavy, bulky and long hydrogen pressure tank places a lot of constraints on the airframe. 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 an equal wingspan. 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. Nederdrone2 specifications

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

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 vortexes. 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.

A Hacker A20-38L motor was selected 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.

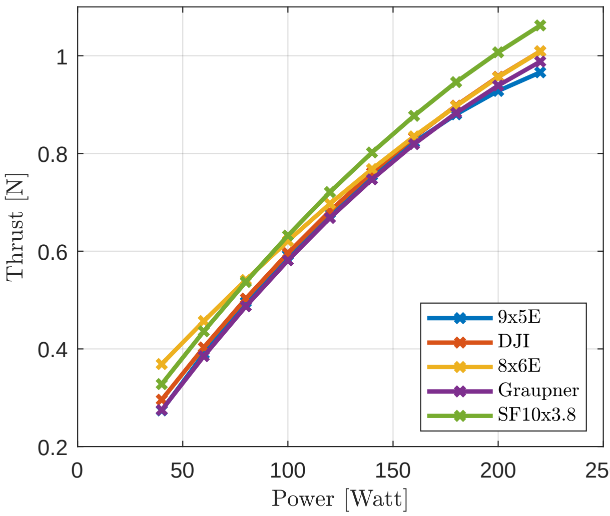

Fig. 3. Thrust in function of power for a selected combination of propellers.

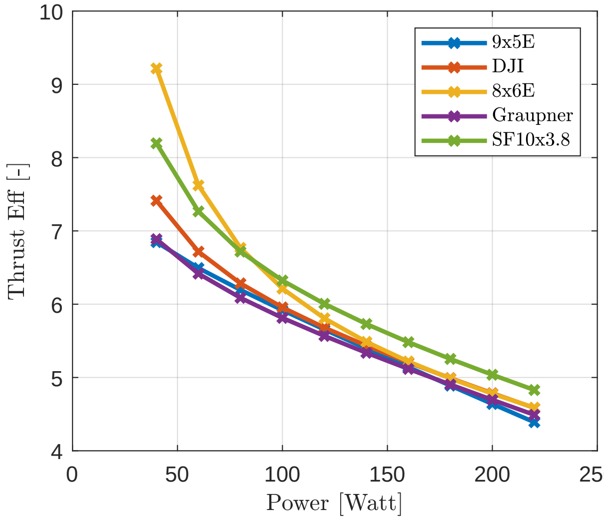

Fig. 4. Thrust efficiency in function of power for a selected combination of propellers.

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 5 shows the test setup with the fuel cell. Specifications of the cell are given in Table 2.

Table 2. Fuel-Cell specifications

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

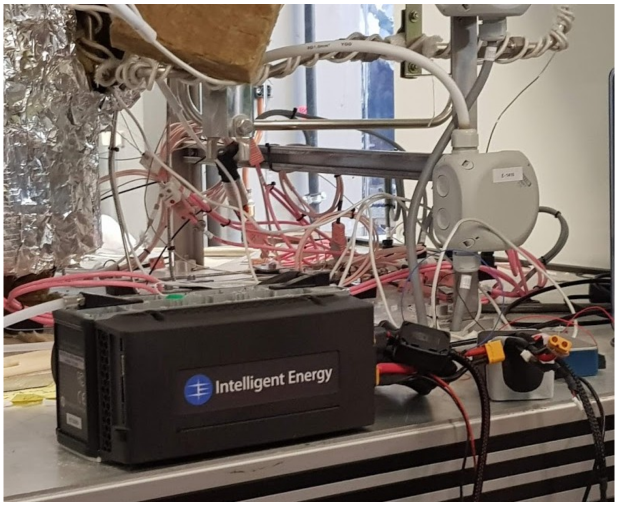

Fig. 5. Testing of the fuel-cell in the lab and measuring the current and voltage output under different loads

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. (See Figure 6)

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 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 grams of hydrogen. This results in a system with an efficiency of 1415.5 Wh/kg and 4.25 wt%/H_2. 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.

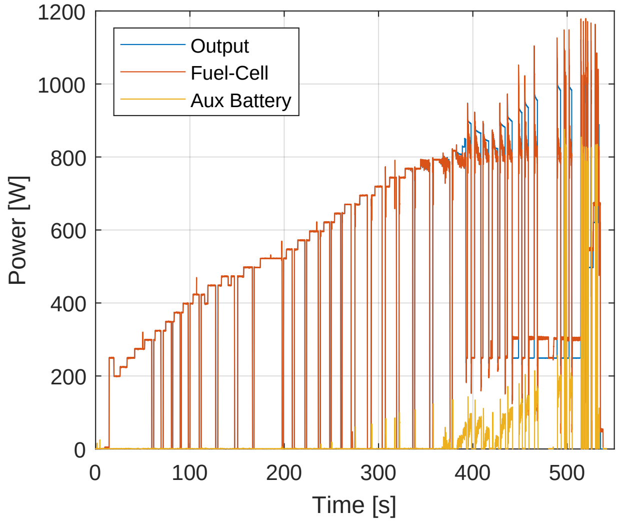

Fig. 6. Testing of the fuel-cell in the lab and measuring the output power. When more than 800 Watt is required, the auxiliary battery starts (yellow) to deliver power as well. Every time the power required became larger than 1100 Watt, the system would shut down.

5. Test flight

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 the implementation of UAV-CAN with own messages. The data link consists of a Herelink 2.4GHz + 433MHz (backup), capable of transmitting both video and telemetry. The radio control is a TBS Crossfire Diversity 868MHz.

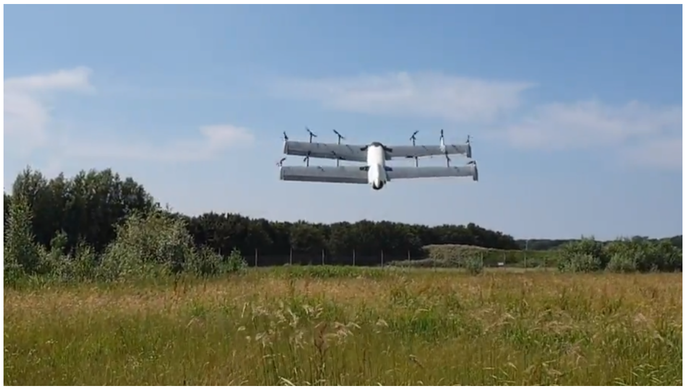

Fig. 7. NederDrone2 in-flight.

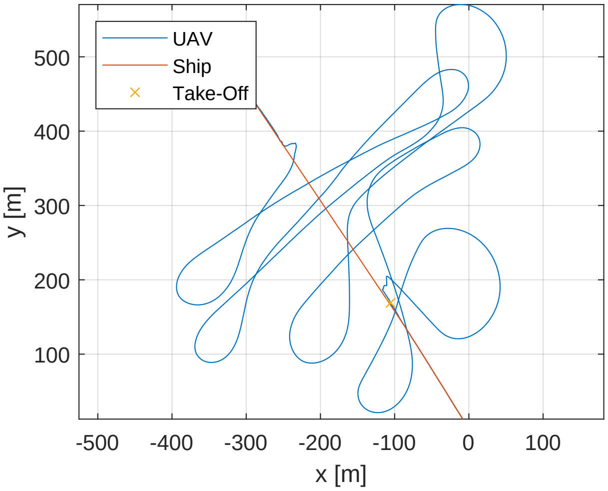

Fig. 8. Ground track from a flight from a ship on the North Sea. Stable hover above the moving ship was possible and very stable and smooth forward flight was flown in figures of eight following the moving ship.

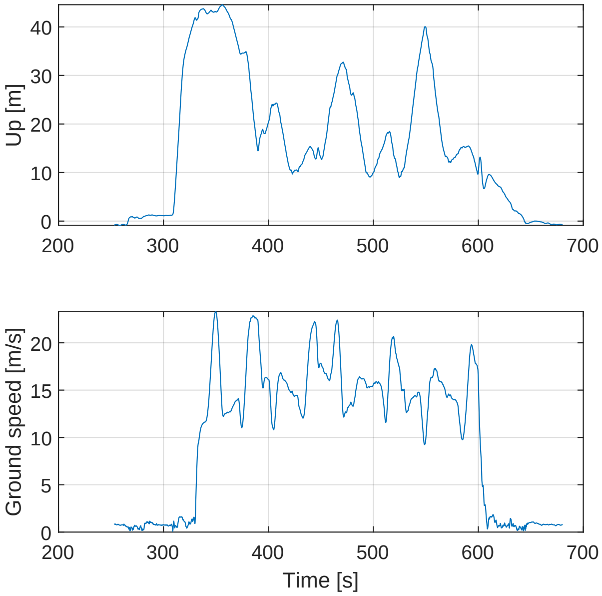

Fig. 9. Height and ground speed of a test-flight from a ship.

Before more dangerous test flights are attempted with

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

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 flight, and for faster flight the forward gains were reduced until stable flight was achieved. Figure 7 shows the NederDrone2 in-flight.

To test the vertical landing capabilities, flights were performed from a ship on the North Sea. Figure 8 shows the ground track of a ship and the ground track of the RPAS in-flight. Figure 9 shows the corresponding height and ground speed profile. Figure 10 shows a flight from a ship.

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

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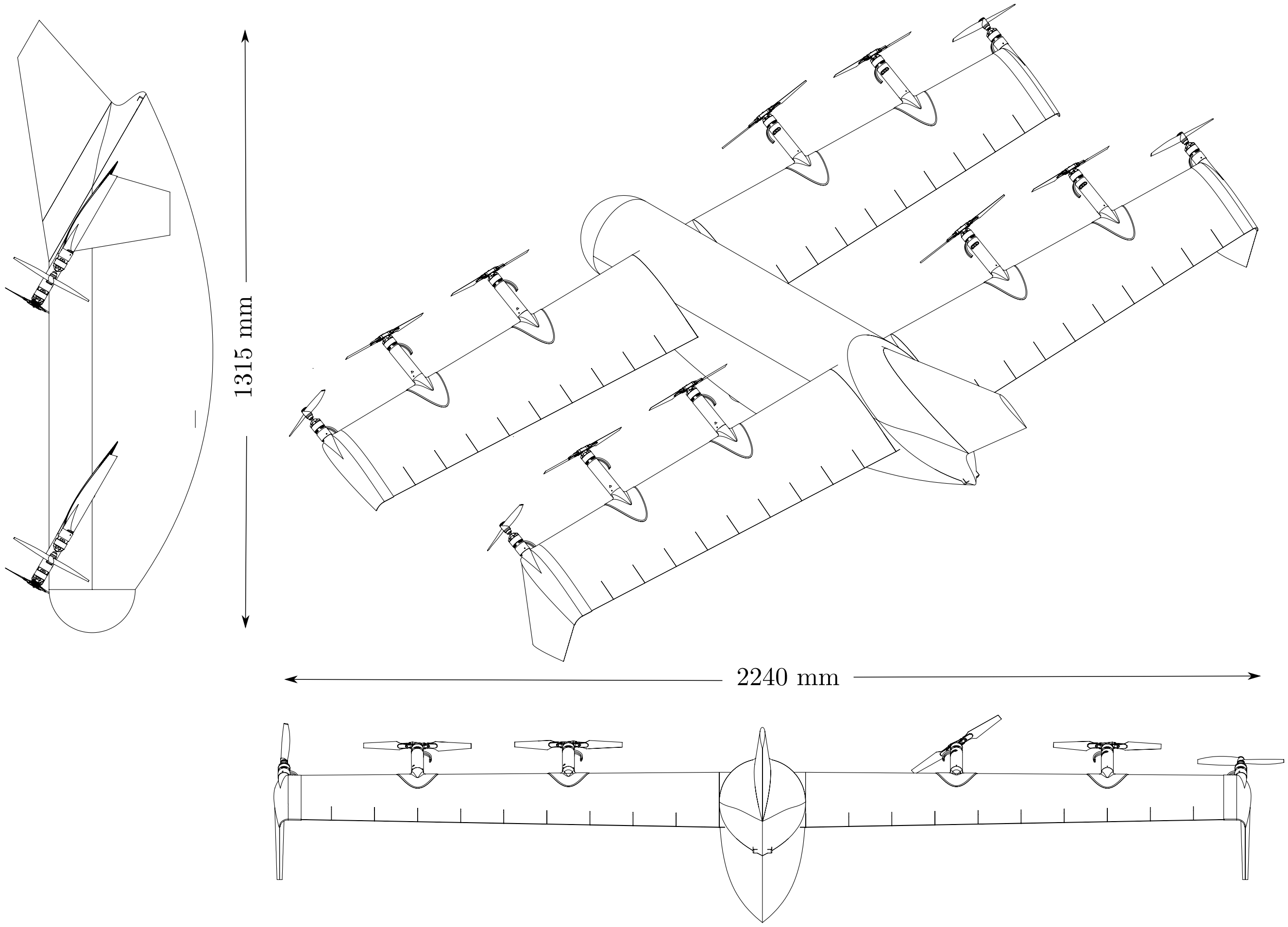

Fig. 11. NederDrone2 left, back and isometric views. The hydrogen tank forms the main part of the fuselage while the tandem wings are placed at an angle to combine high passive stability on the ground with the possibility of automatic vertical take-off. The wingspan is 2m24 while the length is 1m31.

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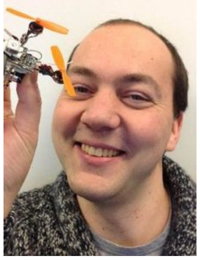

Bart Remes received his M.Sc. in Aerospace Engineering at the Technical University of Delft on the topic of Aerospace for Sustainable Engineering and Technology. He then joined the Aerospace Software and Technologies Institute and was involved in the design and construction of various Micro Air Vehicles, such as the DelFly II and the DelFly Micro. Both these Micro Air Vehicles (MAVs) have won multiple awards including a mentioning as the “Smallest Camera Airplane, DelFly Micro” in the Guinness Book of records, 2009. Currently, he is project manager at the Micro Air Vehicle lab. Besides flapping-wing MAVs, he has worked on hybrid air vehicles and the design of the smallest open-source autopilot in the world, the “Lisa S”, a 2x2 cm device.

Rick Ruijsink obtained his M.Sc. in aeronautical engineering at the Technical University of Delft and graduated in theoretical and wind tunnel research of propellers for UAVs. After a professional life in automotive aerodynamics at Volvo Car, he has worked as an independent aerodynamic consultant since 1994. He has designed and flown many competition model aircraft up to world championship level. Besides, he designed, produced and marketed the first micro-size multichannel proportional radio gear to be used in indoor flying model aircraft in the beginning of the ‘90s, breaking the ground for the current Micro Air Vehicles. Since 2005 he has been working part-time for the MAV-lab of Delft University as a technology integrator. He is a key member of the NATO AVT 184 on flapping wing technology.

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Erik van der Horst received his HBO degree from the HTS Leeuwarden, in 1986. Worked as consultant at France telecom and numerous other telecom firms as IT specialist. Since 2012 he is Engineer at the Micro Air Vehicle Lab.