24. AIgle drone - Open-Source Hardware Robotic Racing Drone for Future AI Competitions


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## 24.1 Introduction

Drone racing has gathered increased attention and interest in the past few years, establishing itself as a sport on par with more traditional ones such as Formula 1. A subset of it, autonomous drone racing, has been growing rapidly in popularity, recently capturing the interest of both the industry, the general public, and the scientific community. Since its beginning in 2016 with the IROS Autonomous Drone Race, the number of competitions has expanded, with more industry players such as the Drone Racing League (DRL) hosting its competition in 2019, to fully virtual drone races being held by NeurIPS (also in 2019).
The essence of these competitions has however remained the same. Teams compete to develop the most effective software to pilot a standardized drone as quickly as possible over a given circuit. The drone hardware being standardized is a critical aspect of the competition, as it ensures that the software is the sole deciding factor. During the DRL races, the competition host provides the drones that competitors would be flying, to ensure no drone has a mechanical advantage over its opponents. This however brings about several issues. The cost of hosting a competition goes up drastically, as the cost of producing, maintaining, and repairing the drones then becomes the responsibility of the host. It also means competitors would not be able to effectively test, adjust, and optimize their algorithms before the race, reducing the team's potential ability to compete. To alleviate these issues, group 19 of the TU Delft 2020 DSE aims to propose an open-source hardware solution for race organizers and teams to be used in future autonomous drone racing competitions. The end goal of the project is to facilitate a worldwide collaboration on the development of artificial intelligence in agile autonomous drone flight.

## 24.2 Objectives and requirements

**Objectives**

The mission need statement of the project was to:

*"Facilitate a worldwide collaboration on the development of artificial intelligence in agile autonomous drone flight, accomplishing faster decision making than human pilots."*

Much like with other technical disciplines, the best platform for advancing autonomous drone technology is through competitions. The two biggest AI drone races are those organized by DRL and IROS. The first one supplies the teams with standard hardware that is not available pre-race, while the other competition requires the teams to develop their own hardware. Both solutions are suboptimal as the teams either cannot test their software on the drone or they have to design both the hardware and the software, while the focus should be on the AI development. The solution to this problem is simple and is summarised in the project objective statement:

*"Provide an open-source hardware racing drone design and demonstration software for the artificial intelligence robotic drone race competition by eleven students in ten weeks."*

Once this goal has been achieved, the teams would be able to easily manufacture the drone and test their software extensively pre-race. This would allow the AI racing sector to fully focus on perfecting the AI algorithms instead of allocating time to the design of hardware as well. This should encourage faster development in the sector.

**Requirements**
Besides the project objectives shaping the design, a collection of user requirements also have a crucial influence on it. The customer expects the drone to:

- Have a maximum speed of at least 30 m/s.
- Make a 3-meter radius arc while flying at 10 m/s
- Linearly accelerate at 19.61 $m/s^2$ from zero velocity
- Fly for 1 minute at full throttle and remain idle for 2 minutes
- Have enough computational power to process images at 60 Hz and calculate a flight path
- Have manual take-over capability
- Suffer no damage to on-board systems or structure if the drone is dropped from 3 meters onto a concrete floor
- Suffer no fracture, plastic deformation or loss of electronic function if the drone flies into a gate at maximum flight speed
- To be optimised for sustainability
- Have components that can be replaced individually
- Be no heavier than 1 kg
- Have its maximum dimension smaller than 50 cm
- Have at least one front-facing camera with a frame rate of at least 60 Hz
- Cost up to 2500 euros
- Be manufacturable using 2D milling, 3D printing, and printed circuit board machines
- Use on-board computation only
- Use the ’Betaflight’ program as attitude controller
- Have a telemetry option
- Be able to be repaired/replaced in at most 2 minutes

## 24.3 Conceptual design

In the initial design phase, five concepts were considered, as seen in figure 24.1. A concept focused on computing power, a sensor-heavy concept, a very durable concept, and two lightweight concepts: a lightweight quadrotor and a lightweight tri-rotor. These five concepts were evaluated on six different criteria: Autonomous Navigation Performance, Flight Performance, Risk, Sustainability, Mass, and Cost. These criteria were given a weight, with the most important criterion being the Autonomous Navigation Performance as it has been the bottleneck for past autonomous racing drones. Subsequently, a trade-off was performed for which the durability concept came out as the winner since the durability concept was able to combine flight and computational performance, together with good sustainability and the ability to survive accidents during testing. All in all, the durability concept was chosen to be worked out in detail during the detailed design phase.

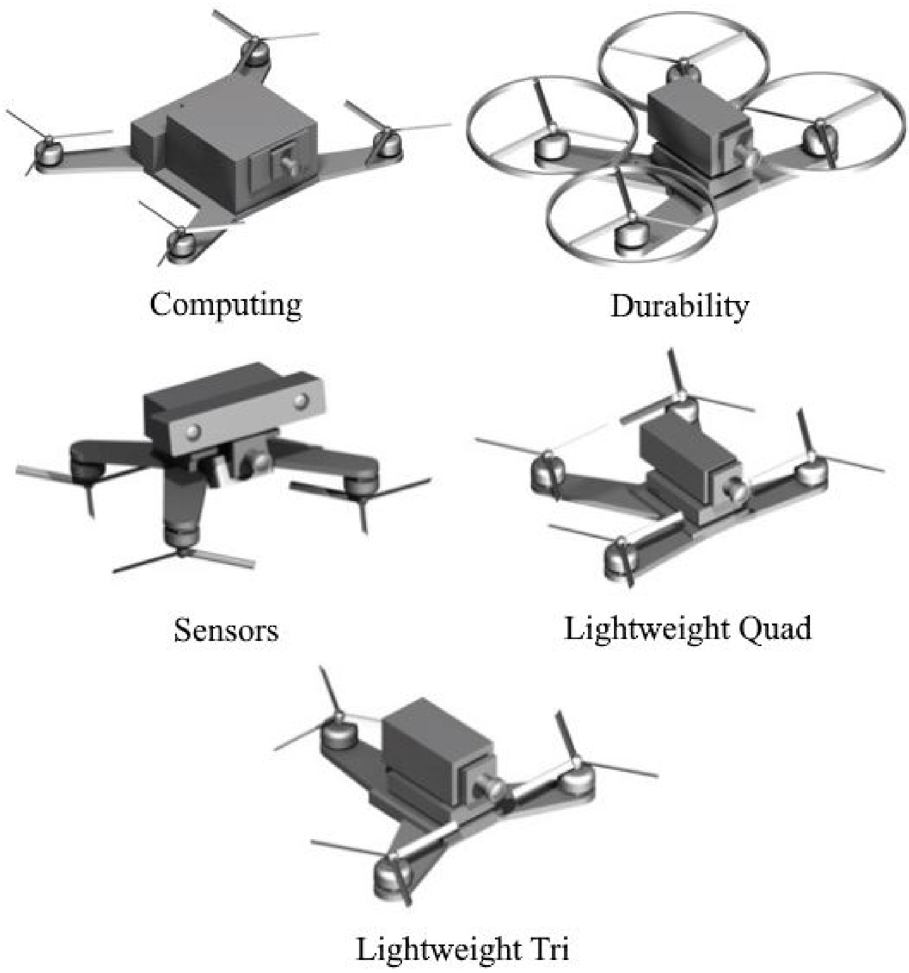


Figure 24.1: Five evaluated design concepts

## 24.4 Detailed design

In order to obtain a detailed, robust, and sustainable design for the drone, its main hardware components were divided up into 3 subsystems to be designed parallel and concurrently to each other. These are Power & Propulsion, Electronics, and Structures. Similarly, the software department was divided into Machine Vision & State Estimation, Navigation and Control & Stability.

**Power and propulsion**

First of all, the propulsion and power subsystem provides both the thrust and power of the drone. The designing process started by obtaining databases of off-the-shelf propellers, brushless multirotor motors, and batteries. After these databases were set up, the next step was to assess the motor and propeller databases in order to find optimal motor and propeller duo's which would provide the desired performance during flight. After these duos were identified, a suitable battery had to be added, effectively creating a triplet. This battery was chosen by investigating the drone's needs with regard to power, voltage, and current. The drone's needs were combined with the desired flight time and this consequently determined the size of the potential battery. After obtaining suitable batteries, the most lightweight option was chosen to complete the triplet. This matching process was automated with code, which allowed for frequent iteration and was consistently able to select triplets that can achieve the desired flight performance characteristics. The final iteration consisted of the following components: an APC 6x4E propeller, a SunnySky Edge R2306 motor, and a Tiger Power 3600 mAh battery. This configuration yields a thrust to weight ratio of at least 4 in dynamic conditions. Furthermore, it is predicted the drone is able to achieve a maximum speed of 32.1 m/s.

**Electronics**

Secondly, the electronics are the brain and the nerves of the drone, as it has to provide environmental sensing, computational power, and power distribution. The design process started by performing a trade-off concerning mass and repairability for the overall architecture. This has lead to a low-mass architecture, which consists of a 4-in-1 electronic speed controller (ESC), a flight controller, and a "companion" computer. Since processing should only be performed onboard the drone, a companion computer is needed that can handle the heavy processing of machine vision and deep learning algorithms. The chosen companion computer is the NVIDIA Jetson Xavier NX for its state-of-the-art computational capabilities while having a low mass and a small form factor. This companion computer requires a separate carrier board that provides power regulation and enables connections to the camera, flight controller, and the WiFi module. It was decided to design a custom carrier board as it saves mass and volume. As a result, the custom carrier board saved at least 26% in mass compared to off-the-shelf solutions. Furthermore, a microSD card was implemented for data storage of all flight data including video data, as well as all other sensor data from the flight controller and ESC. This data can be used to debug and improve on the drone. Additionally, two receivers - one for backup - were connected to the flight controller to allow for manual take-over of the drone in case it loses control. Finally, cables and connectors were sized based on the current flow, to allow them to withstand the heat associated with flying at full throttle for the full flight time of the drone.

**Structures**

Finally, the structure of the drone was designed to protect the sensitive electronics when being subjected to a drop of 3 meters and not to break when crashing in a gate at 30 m/s. The chosen frame layout to achieve the crash requirements and provide a stiff drone body is a 'DeadCat' frame. This is a frame in X-shape, with the forward-facing arms bent at a wider angle than the aft arms. It allows the camera a large field of view, while still protecting especially the camera from head-on crashes. The mainframe is a monocoque frame, meaning that the main body of the drone is one enclosed box. This is 3D printed out of strong PolyEther Imide (PEI) filament and helps to protect the inner electronics from direct impacts. It has a top cover that can be taken off to access the electronics as well as a back cover through which the battery can be mounted. The arms are made out of carbon fiber tubes, which are very strong and lightweight. The motors can then be mounted on top of the arm via tangent tube mounts which are also made out of carbon fiber. As the electronic components can only withstand impact loads of up to 50g, a dampening system has been designed to reduce the impact forces, which can only be achieved by having a 'crushing' or 'cushioning' zone. The design of the electronics protection system has been done for the scenario of a 3m drop onto concrete and the cushioning system consists of multiple stages. This is first of all, at the points of contact with the object the drone crashes into. Those are naturally the arms and the underside of the drone. Therefore propeller guards are attached at the motor mount in order to provide cushioning of the electronics, but also to protect the propellers from injuring their surroundings, making it safer for humans to handle the drone. Furthermore, a landing gear out of rubber has been added, which cushions the entire drone from hard impacts unto its underside. They were placed below the mainframe and are 3D printed, similar to the propeller guards which are 3D printed out of the stronger PEI filament. The innermost layer of protection consists of the standoffs for the most sensitive electronics such as the carrier board, the processor, its cooler, and the camera. Those components are mounted on four of these standoffs which act each as a little spring-damper connection that allows a maximum deflection of 8 mm. This means that the processor and other electronic parts are able to shift up to 8 mm inside the mainframe housing.

**Software**

To showcase the capability of the drone, demonstration software has been developed. The software is split into three parts; Machine Vision & State Estimation, Navigation, and finally Control & Stability. Machine Vision & State Estimation uses the data from the camera to determine the location and velocity of the drone with respect to gates that are in view. Navigation uses this data to determine the path the drone should take. The waypoints the drone is to go through are used by Control & Stability to give actual commands to the propulsion system to execute so the drone reaches the gate efficiently.

Machine Vision & State Estimation managed to identify the pixels of the gate from a single image, using a snake algorithm, by following the gate through the image until all four corners are found. This works even under a roll angle of up to 26°. Using the found corners of the gate and the gate's known size, the location and orientation of the gate can typically be found with errors no greater than 5% by means of a Perspective-n-Point algorithm. The states are then stored in a database to be accessed later. This is used to find the speed of the drone which can be used by other programs.

Navigation has investigated and developed multiple methods from various fields to determine the path the drone should take. The varying complexity and methodology demonstrate the variety of approaches and implementations teams using the AIgle racing drone can use. This includes deep learning techniques such as Double Deep Q learning, or Deep Deterministic Policy Gradient for fully autonomous intelligent navigation. Furthermore, by demonstrating the applicability of deep reinforcement learning, a baseline has been provided for future teams that wish to build their own autonomous navigation protocol.

Control & Stability developed the software responsible for translating desired waypoints to actual actions for the drone to take. This is demonstrated using a method based on the algorithm by D. Melinger, which generates the required inputs for Betaflight - the firmware that runs on the flight controller where commands for the ESC are determined. Betaflight was chosen due to it being the top notch firmware in the area of drone racing, for which it has been optimized in recent years. Using this method, high levels of accuracy can be reached; waypoints are reached with disparities no greater than 8 cm, and velocity and acceleration errors in the program are no greater than just 0.10 m/s and 0.01 m/s$^2$, respectively. Since this algorithm was combined with the performance limits set by the propulsive abilities of the drone, a realistic overview of the drone's abilities with regard to control and stability was obtained.

## 24.5 Results

The aforementioned mentioned design decisions resulted in the overall specifications, such as cost, mass, maximum speed, and others, presented in table 24.1. A render of the complete autonomous racing drone design is shown in figure 24.2. Finally, 3-view drawings can be seen in figure 24.3.

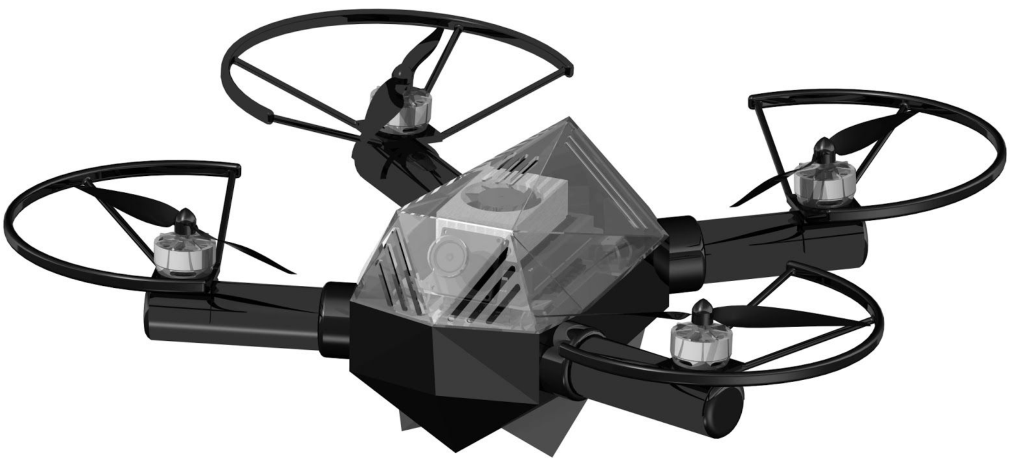

Figure 24.2: CATIA render of the final design

Table 24.1: Characteristics of final drone design

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|---|---|
| Mass | *1.3 kg* |
| Cost | *1410 €* |
| Thrust to weight | *4.1* |
| Top speed | *32 m/s* |
| Flight time (at max. throttle) | *63 s* |
| Power | *2150 W* |
| Maximum Dimension | *46.6 cm* |
| Materials | *Polyether Imide (PEI)*<br>*Carbon Fibre* |

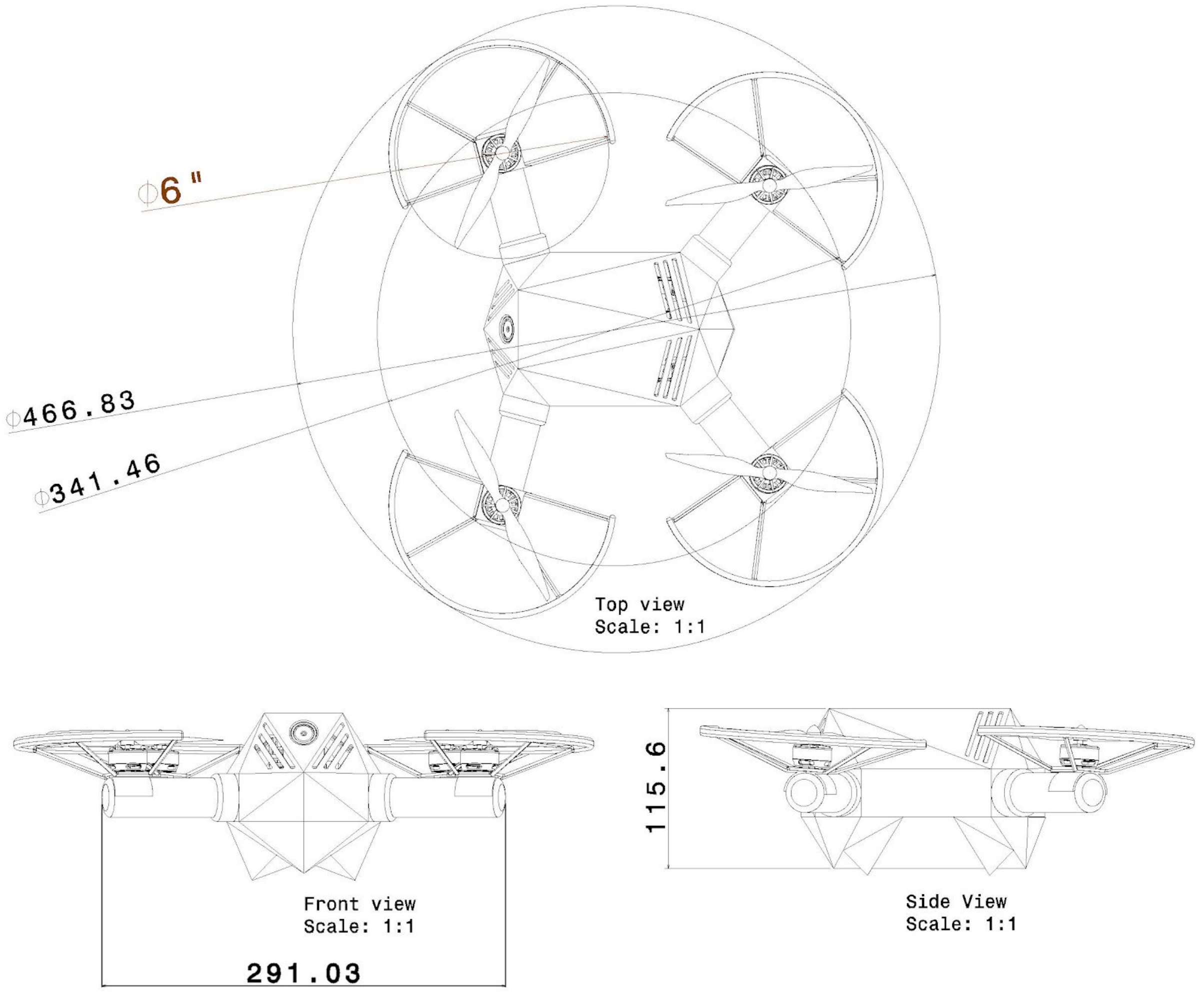


Figure 24.3: 3-view drawings of drone design

24.6 Conclusion and recommendations

Reviewing the project objectives and user requirements, it was concluded that some requirements were not met such as the total mass and the ability to remain functional after gate crash at maximum speed. However, considering the state-of-the-art components on board, as well as the additional mechanisms to protect the sensitive hardware, the increase in mass is considered justifiable. Furthermore, the flight performance of the drone is uncompromised and is, consequently, able to correctly carry out all maneuvers it is designed for. In addition, the software provided adequate proof of concept with regard to tracking, navigating, and control. Therefore, it can confidently be stated that the drone is fully capable of meeting the project objectives and thus provides a sustainable platform for the further development of AI racing. Post-DSE testing should take place to validate both the hard- and software of the design.

In the future, it is recommended that, if further iterations are to take place, a focus should be upon decreasing the mass as much as possible even at the expense of total cost.