2021 TÜBİTAK INTERNATIONAL UNMANNED AIR VEHICLES TURKEY COMPETITION

AGH SOLAR PLANE 3.0

Detailed Design Report

TEAM NAME: AGH Solar Plane 3.0
VEHICLE TYPE: ROTARY WING
UNIVERSITY: AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY IN CRACOW
TEAM CAPTAIN: MONIKA MALINOWSKA

1. PROJECT SUMMARY

1.1.Method Followed in Design

The scope of the study is the design of an autonomous unmanned aerial vehicle in the form of a quadrocopter in the X4 system. It is powered electrically from a lithium polymer battery in the 6S1P configuration.

The main assumption of the project was to build a drone by the requirements of the regulations with a maximum takeoff mass (MTOM) of no more than 4 kg. The concept developed by the team assumed the construction of a drone with the lowest possible weight of the structure itself to equip the drone with a tank with the largest possible capacity.

The frame of the drone consists of two extremely lightweight carbon fiber plates. The arms and engine mounts are made of the same material. Carbon fiber on the arms is a twill weave, so that we have obtained increased torsional and vibration stiffness, which is extremely important when using a relatively thin and light arm and large propellers and high-torque motors. To reduce weight, the water tank is made of composites. This made it possible to obtain a structure weighing ~ 2 kg that could fit and transfer up to 2 litres of water into the tank.

The second assumption was adopted by the construction team and concerns the maximum dimensions of the drone to ensure convenient and safe transport of the structure to the competition site. Due to the use of higher-quality materials for the construction, and thus lower weight, it was possible to increase the dimensions of the drone from 500 mm (designed dimensions, presented in the concept report) to 790 mm, which has a positive effect on the structure itself and allowed the use of 15 ”propellers. Such dimensions also allowed to increase the stability of the drone by as much as 20% compared to the one designed and described in the conceptual report.

The application of Computer Vision algorithms made it possible to detect objects in real-time using the Raspberry Pi. This enables autonomous recognition of objects related to the second mission. (i.e. pool and drop system)

1.2.Team Organization

The diagram below shows the division of the team into individual roles. Team captain - Monika Malinowska, coordinates and controls the work in the team. Her role is to distribute tasks to individual sections and monitor progress. She is responsible for the positive course of the mission. Szczepan Malaga, the Construction Team Leader, takes care of the overall design of the UAV. In addition, he was responsible for procuring the components needed to build the drone and accounting for purchases by national and university legal procedures. He is assisted by the two constructors Filip Pieniążek and Piotr Guzdek. They are in charge of the direct construction of the unmanned aerial vehicle. The Leader of the Power Supply Team - Dominik Patyk, is responsible for the electrical design of the UAV. That design is made by an Electrician - Aleksandra Szeląg. In addition to the design itself, this two-man team was also tasked with wiring the drone and assembling and connecting all the electronic components and devices on board. Marcin Mucha, Programming Team Leader, manages the work of the Programming Team. He cooperates with programmer Paweł Świder. One of their main tasks was to design the system and develop algorithms for detecting the place of water intake and discharge. As well as to create flight surveillance software. Documentation Team Leader - Anna Gęca work along with each member to create all the necessary documentation. She manages to develop the technical documentation of the drone and its system. Kacper Adamus is the UAV Pilot in the team. He is responsible for controlling the unmanned aerial vehicle and supervising autonomous flight. During many months of preparations for the competition, he was also responsible for conducting numerous tests and calibrating the onboard computer. A diagram of team organization is attached on page 18.

1.3.Milestone Chart: Planned and Realized

The conceptual report assumed a completion time of 11.07.2021. The schedule included 3 main milestones: Design and construction, Electronic equipment and The UAV test. Due to protracted equipment deliveries and difficult contact with team members due to the pandemic, the timing of the first two milestones will drag on. The original timeframe for Design and construction changed from 13.01.2021-15.03.2021 to 13.01.2021-30.04.2021, while the timeframe for Electronic equipment changed from 13.01.2021-30.04.2021 to 13.01.2021-21.06.2021. Although some of the tests took longer than originally planned, the project was eventually completed on schedule on 11.07.2021. The original and final schedules are attached on page 19-20.

2.DETAIL DESIGN

2.1.Dimensional Parameters of the Design

The span of the drone without propellers is 790 mm. On the other hand, the maximum span with the propellers, measured from the end of the propeller to the opposite end of the propeller, is 1140 mm. The weight of the drone itself for flight is 1400 g. The drop system weighs 550 g, and the mass of the load (water) is 2000 g, which gives the total maximum weight of the drone in the air of 3950 g. This is the optimal weight within the limit of 4 kg.

Table A. Rotary Wing UAV Part and Total Weight Table

№	Part Name	Weight [grams]	Pieces	Total Weight [grams]
1.	Engines	68	4	272
2.	Propellers	21	4	84
3.	Speed regulators	10	4	40
4.	Boom blocks	10	16	160
5.	Pixhawk + Power Module	100	1	100
6.	GPS with mount	100	1	100
7.	LiPo	300	1	300
8.	Frame	150	1	150
9.	Telemetry	15	1	15
10.	Receiver	10	1	10
11.	Wires and connectors	170	1	170
12.	Drop system	550	1	550
	Total			**1951**

Table B. Fixed or Rotary Wing UAV Material Weight and Balance Table

№	Part Name	Weight [grams]	X distance [mm]	Y distance (mm)	Z distance (mm)
1.	Front left engine	68	260	260	50
2.	Front right engine	68	-260	260	50
3.	Back left engine	68	-260	-260	50
4.	Back right engine	68	260	-260	50
5.	Front left propeller	21	260	260	60
6.	Front right propeller	21	-260	260	60
7.	Back left propeller	21	-260	-260	60
8.	Back right propeller	21	260	-260	60
9.	Front left Speed regulator	10	260	260	21
10.	Front right	10	-260	260	21
11	Back left	10	-260	-260	21
12.	Back right	10	260	-260	21
5.	Pixhawk + Power Module	100	0	0	60
6.	GPS with mount	100	60	0	110
7.	LiPo	300	0	0	-20
8.	Frame	150	0	0	-90
9.	Telemetry	15	-85	0	40
10.	Receiver	10	90	0	0
11	Drop system	170	0	0	-195

Centring of the centre of gravity is done by micro-adjustment of the battery position.

Figure 1. Determination of the centre of gravity of the drone.

2.2. Body and Mechanical Systems

The foundation of the multirotor is the frame on which all components are mounted. The UAV frame was designed in a symmetrical X4 configuration, maintaining an even distribution of the weight of the components and keeping the center of gravity of the multicopter in its center. The material used to build the drone is carbon fiber. Despite its high price has several significant advantages. The most important one is its weight, which must be limited according to competition regulations. Composites based on carbon fiber are much lighter than solid metal structures, but also undoubtedly stiffer and more durable than plastics. The drone's arms are constructed from 20mm diameter carbon tubes.

For the construction of the UAV, it was decided to use parts mostly from the same company - T-MOTOR. Thanks to this, the drone has compatible elements, which translates into the quality of their cooperation. The selected engine model is Antigravity MN4006-23 KV380 with 380W power. The motors used in the construction are the Outrunner brushless BLDC motors, popular and widely used in modern multi-rotors. They are synchronous motors powered by direct current. The team focused on a proven solution in the form of BLDC due to its high energy efficiency and advantage over brushed motors. Compared to brushed motors, they last longer and are less prone to failure due to the use of high-speed bearings and the removal of frequently wearing brushes. At the same time, this model is extremely light and has a very high thrust-to-weight ratio, thanks to which, with properly selected propellers, it reaches up to 2228 grams of static thrust at 6177 RPM. The design has 4 motors in the X4 flat system. According to the standards, motors with different directions of rotation are arranged alternately.

The propellers of the above-mentioned brand were also used because they are characterized by high quality, very good balance while maintaining a low weight. They are 15 inches in diameter and relatively large. As a result, the motors operate at lower revolutions, which ensures the high efficiency of the drive. This way, energy consumption is reduced, which in turn translates into less weight and size of the battery and allows more load to be carried.

The flight control unit is Pixhawk 2.1, which offers many flight modes, such as position hold, stabilization, manual flight, flight on a planned route, circling, and autonomous flight. Telemetry is based on the RFD system, which offers the unmatched range and link stability. For powering, lithium-polymer batteries have been used, which have a high energy density both by volume and weight.

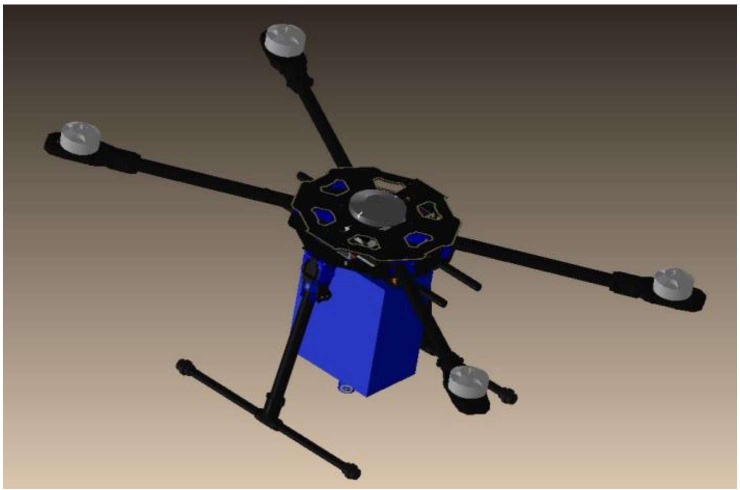

Figure 2 The view of the drone

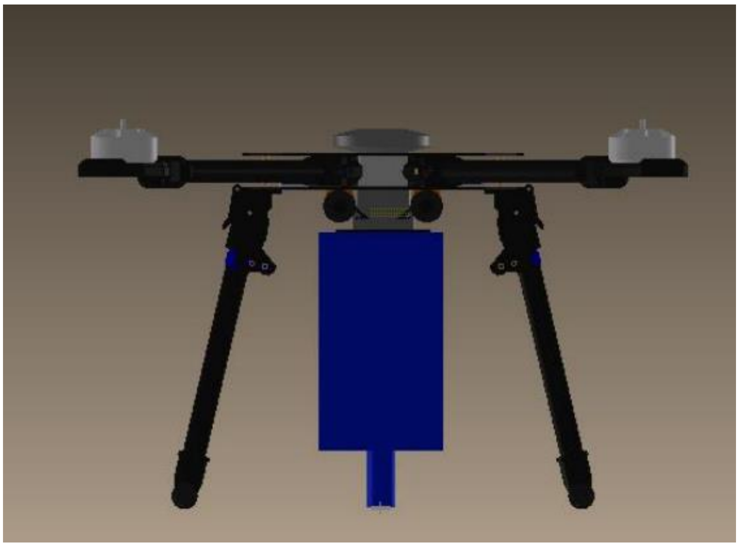

Figure 3. The view from the side

Figure 4. The view from the top

2.3.Aerodynamic, Stability and Control Features

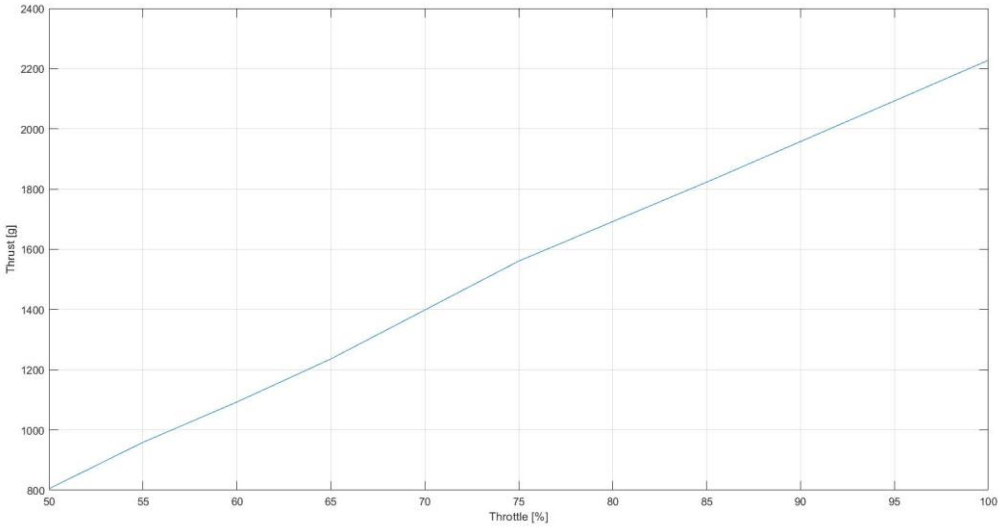

Figure 5. Throttle – Thrust Relationship

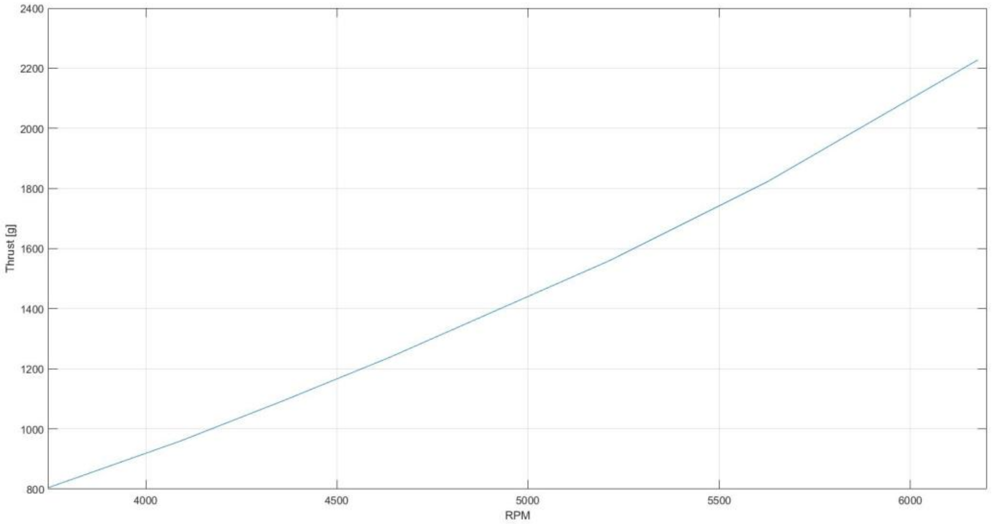

Figure 6. RPM – Thrust Relationship

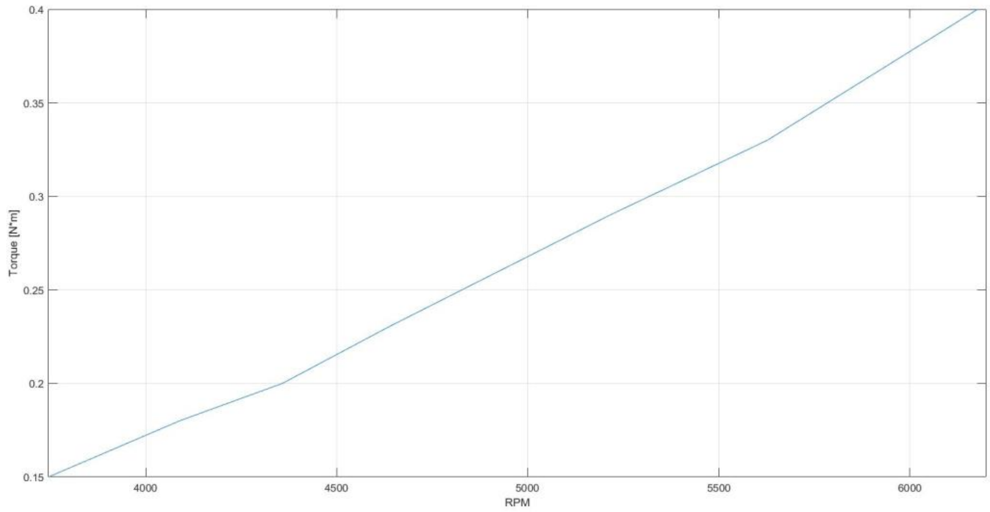

Figure 7. RPM – Torque Relationship

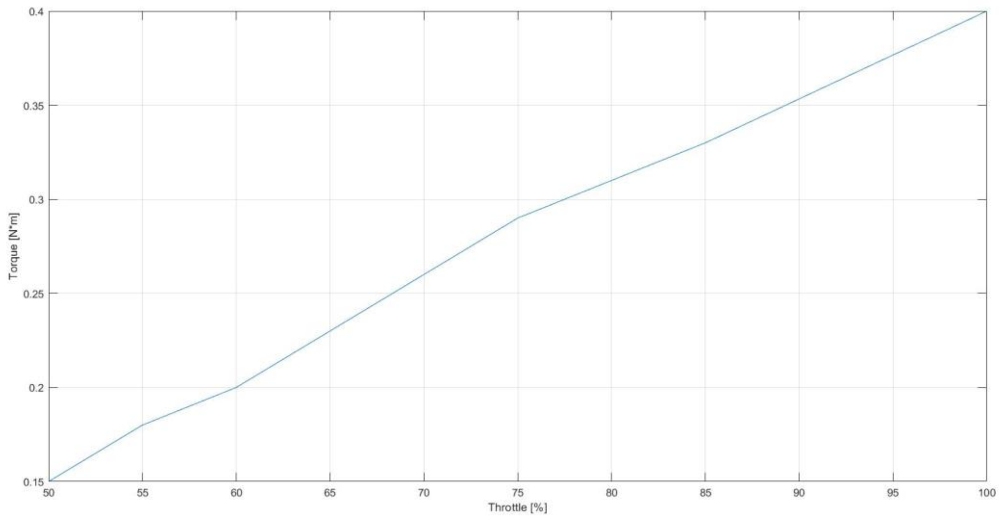

Figure 8. Throttle – Torque Relationship

2.4.Task Mechanism System

The pump module controls pumps and water sensors placed at the top of the tank and at the end of the tube. The task mechanism has been divided into two parts related with physical interpretation. First of all the tank contains a water sensor and pump. The second one includes a tube, pump and water sensor mounted outside the tank. Components placed in the tank are responsible for checking the water level and pumping out the liquid. The sensor outside the drone checks whether the tube reached the water while the pump draws it from the pool. The algorithm responsible for the pumps is implemented as a finite-state machine, accepting messages from the main module as an input. After ending each operation, the module sends the feedback.

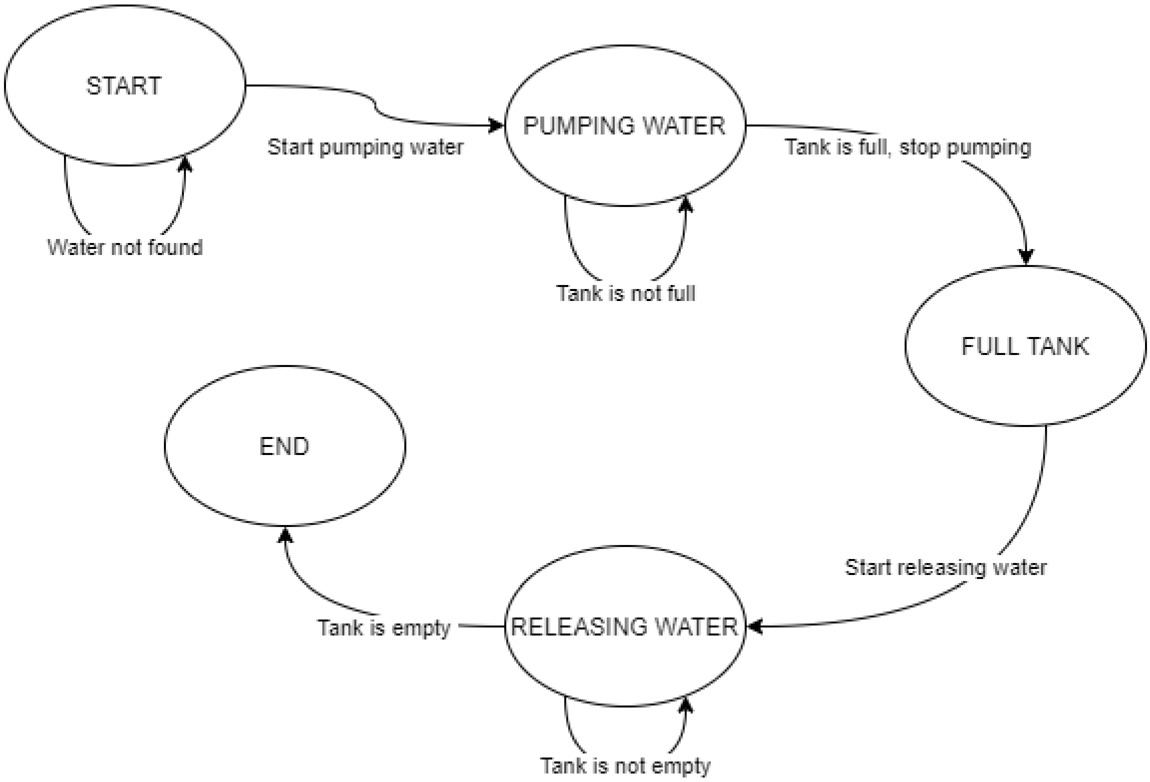

Figure 9. Finite-state machine

Once the tank is filled, the main module drives the drone towards the payload using the methods previously described. After reaching the target and emptying the tank, the drone returns to the pre-planned mission, heading towards the end of the lap.

The sensor water monitors the flow of water and reacts for resistance changes. To receive data from the sensor the analog - digital converter has been used. The pump is meant for pumping and releasing the water. In terms of voltage parameters the pump works with 12V voltage. To estimate voltage the pump input is connected to the step-down converter.

2.5.Electrical Electronic Control and Power Systems

The drone in manual flight is controlled by a 24-channel RC transmitter operating at 2.4GHZ - Taranis X-Lite Pro, working in the FrSky ACCESS protocol. It has a great range, as well as high signal quality and stability.

Pixhawk Cube Orange version 2.1 with GPS module is responsible for flight control. It has internally isolated vibration sensors, which allow it to be rigidly attached to the flying platform frame. For this reason, readings will be very precise. This has a positive effect on the behavior of the UAV and improves its stability. The flight controller also has a fail-safe function. This ensures that the drone behaves predictably in case of loss of control. Telemetry data is transmitted to the ground using the recognized RFD telemetry. The data is displayed on the screen and stored in the Mission Planner.

The model can be controlled in three ways:,

- using the modeling apparatus,
- using a computer (fly-by-wire),
- - in fully autonomous mode.

The power supply uses a pack of lithium polymer batteries connected in a 6S1P configuration to reduce current and increase the efficiency of the drive. High-torque low-speed motors were used so that large propellers could be used, thus increasing the efficiency of the overall drive. The drone's electrical installation was based on silicone cables, due to their higher bending, twisting, and vibration coefficient, as well as their far greater abrasion resistance. This reduces to a minimum the possible breakage of the insulation and the creation of a short circuit. The signal wires will also be silicon copper wires in a twisted pair configuration, so they can be thinner. The thickness of the wires to the motors feeding on the pack to the motors will be 1.5 mm^2. The battery will supply the drone's electronics with 20 A at full load and 10 A when flying empty. The battery is mounted on top of the drone for easy access. The battery will have cells connected in a 6S1P configuration with a nominal voltage of 22.2 V and a capacity of 2200 mAh. This will allow for a flight time at the full allowable load of 7 minutes and an uncharged drone flight time of 14 minutes to 15 minutes. The 4-in-1 speed controller built into the platform is responsible for controlling the motor speed. This means that we control all 4 motors with one system

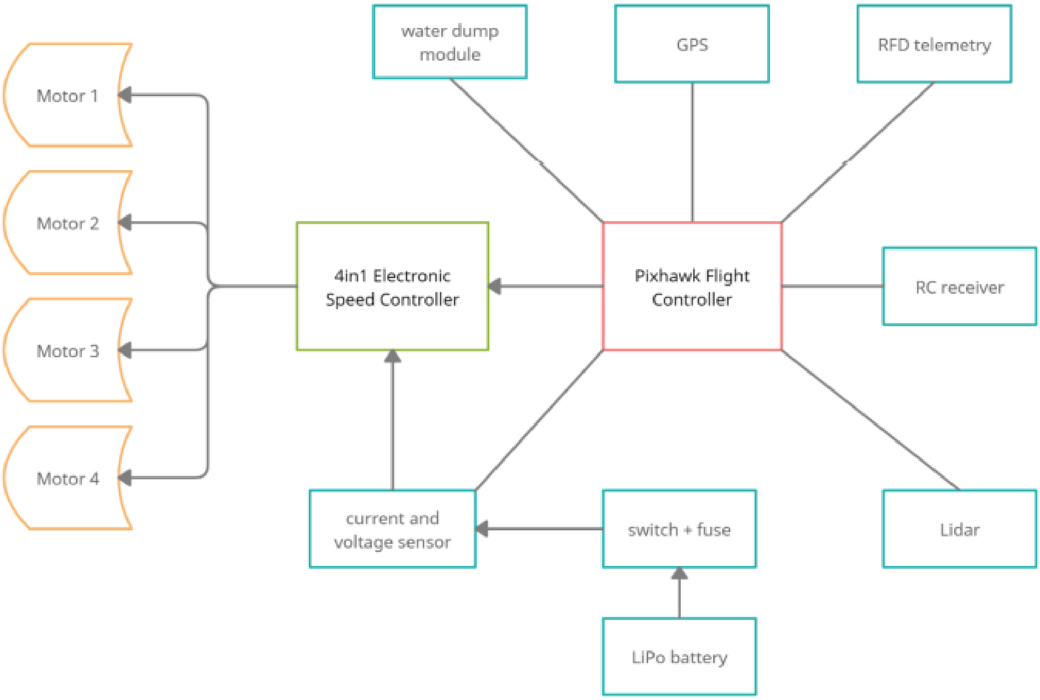

Figure 9. Block diagram of the drone's components

2.6.Target Detection and Recognition System

The detection system is based on a multithreaded algorithm implemented in the Python programming language. Every thread is responsible for other tasks, communicating with each other using queues. The main module dispatches commands to the appropriate components using slave/master architecture.

The mission begins with the initialization of the pre-planned flight in the Pixhawk system. During the first lap, the OpenCV module detects the potential drop system and pool using the camera placed at the bottom of the drone, directed vertically down. The module detects potential zones using algorithm following algorithm:

1. get the latest frame from the onboard camera,
2. convert the image from RGB colour model to the HSV,
3. create binary mask responsible for detecting desired colour (blue for the pool, red for the drop zone),
4. detect the potential area in the shape of the ellipse in the mask,
5. send centre coordinates of the detected zone

Coordinates evaluated by the OpenCV module are relative, measured as the pixel offset from the centre. These points are converted by the main module using the telemetry provided by the Telemetry module.

After finishing the pre-planned flight, the dronekit module changes pixhawk mode from AUTO to GUIDED, taking direct control over the drone. During this stage, the main module corrects the trajectory towards the pool using continuously delivered data from the telemetry module. After reaching the pool, the drone descends itself, preparing for filling the tank.

In order to simultaneously control the drone and provide the data to the main module, two separate threads interacting with Mavlink API were designed. In this implementation dronekit module requests data from the telemetry module. Due to the non-straightforward nature of this solution, the Message router was implemented with the intention of hiding the routing mechanism between the telemetry module, dronekit module and the main module.

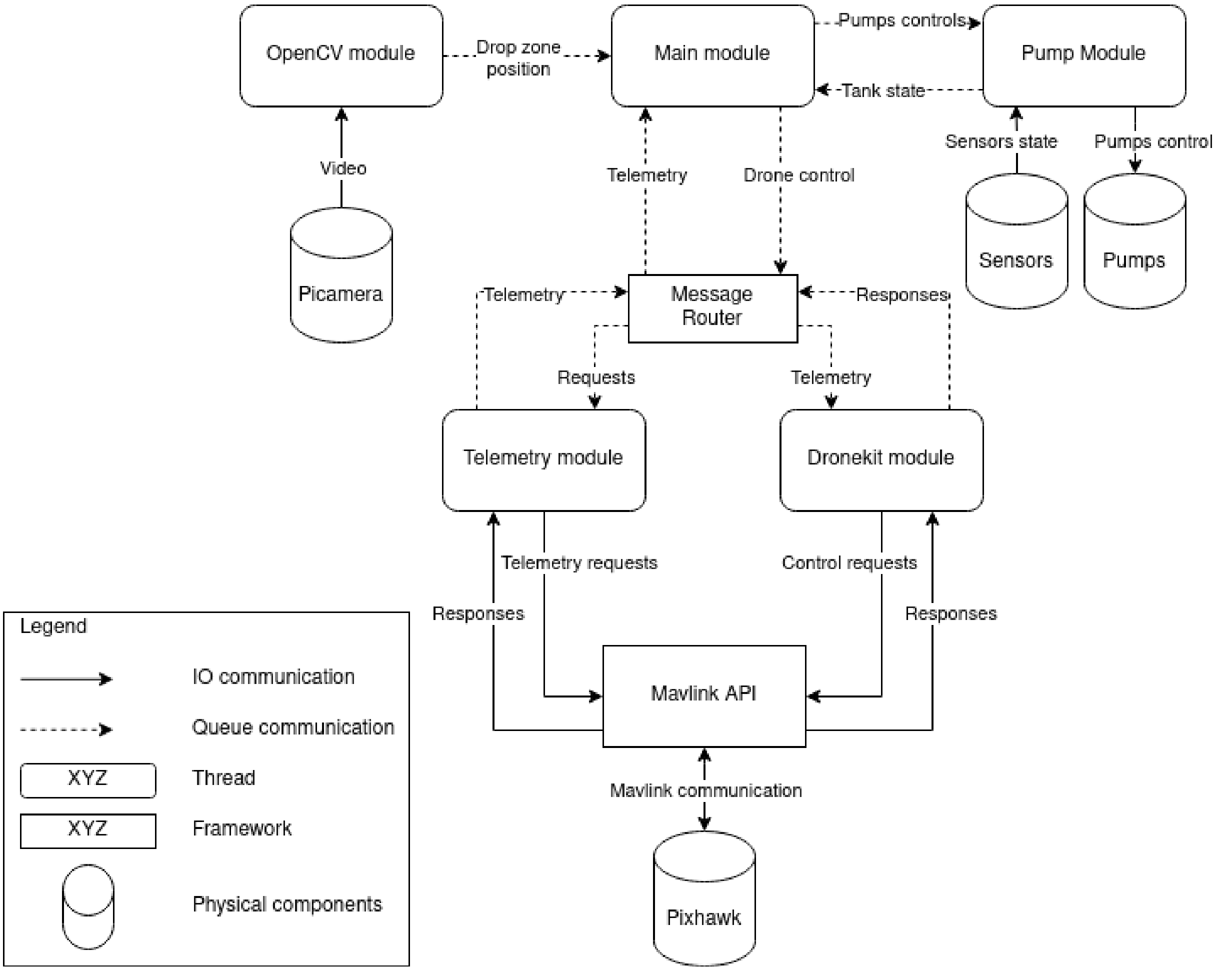

Figure 10. Drone Algorithm Architekture

Components used for the detection are Raspberry Pi 3B+ as the onboard computer and Raspberry Pi Camera Module V2 as the camera.

2.7.Flight Performance Parameters

Current per engine without the payload:

$$I_{E1} = 2.5A$$

Current per engine with the payload:

$$I_{E2} = 5A$$

Number of engines:

$$N = 4$$

Total engines current without the payload:

$$I_1 = NI_{E1} = 10A$$

Total engines current with the payload:

$$I_2 = NI_{E2} = 20A$$

Battery capacity:

$$C = 2.2Ah$$

Battery operating time formula:

$$T[h] = \frac{C[Ah]}{I[A]}$$

Total time without the payload:

$$T_1 = \frac{2.2Ah}{10A} = 0.22h \approx 13.2minutes$$

Total time with the payload:

$$T_2 = \frac{2.2Ah}{20A} = 0.11h \approx 6.6minutes$$

Reference voltage:

$$U = 22.2V$$

Engines power without the payload:

$$P_1 = 22.2V \cdot 10A = 222W$$

Engines power with the payload:

$$P_2 = 22.2 \cdot 20A = 444W$$

2.8.UAV Cost Distribution

Table 1. UAV material cost table

No	Component Name	Unit price (TL)	Quantity	Total price (TL)
1.	Boom block	12,44	16	199,04
2.	Brushless Motor	765,46	4	3061,84
3.	Camera Raspberry Cam V2	297,69	1	297,69
4.	Carbon fiber propellers	285,31	4	1141,24
5.	Carbon fibre tubes 20 x 18 1000	295,06	3	885,18
6.	Carbon-fibre plate	1103	0,25 m^2	1103
7.	Electrical plugs and connectors and small electrical accessories	-	-	55,13
8.	Electronic speed controller	305,35	4	1221,4
9.	Motor wires 26AWG - black	1,96	6 m	11,76
10.	Motor wires 26AWG - red	1,96	6 m	11,76
11.	Pixhawk Cube Orange 2.1	3198	1	3198
12.	Pump	33,08	2	66,16
13.	Raspberry 3	374,87	1	374,87
14.	Telemetry	3528,16	1	3528,16
15.	RC receiver	330,76	1	330,76
16.	silicone hose	4,41	1,5 m	6,62
17.	Batterry	1102,55	1	6,62
	TOTAL			**15499,23**

2.9.Originality

There is no work within the scope of originality.

Attachment 1

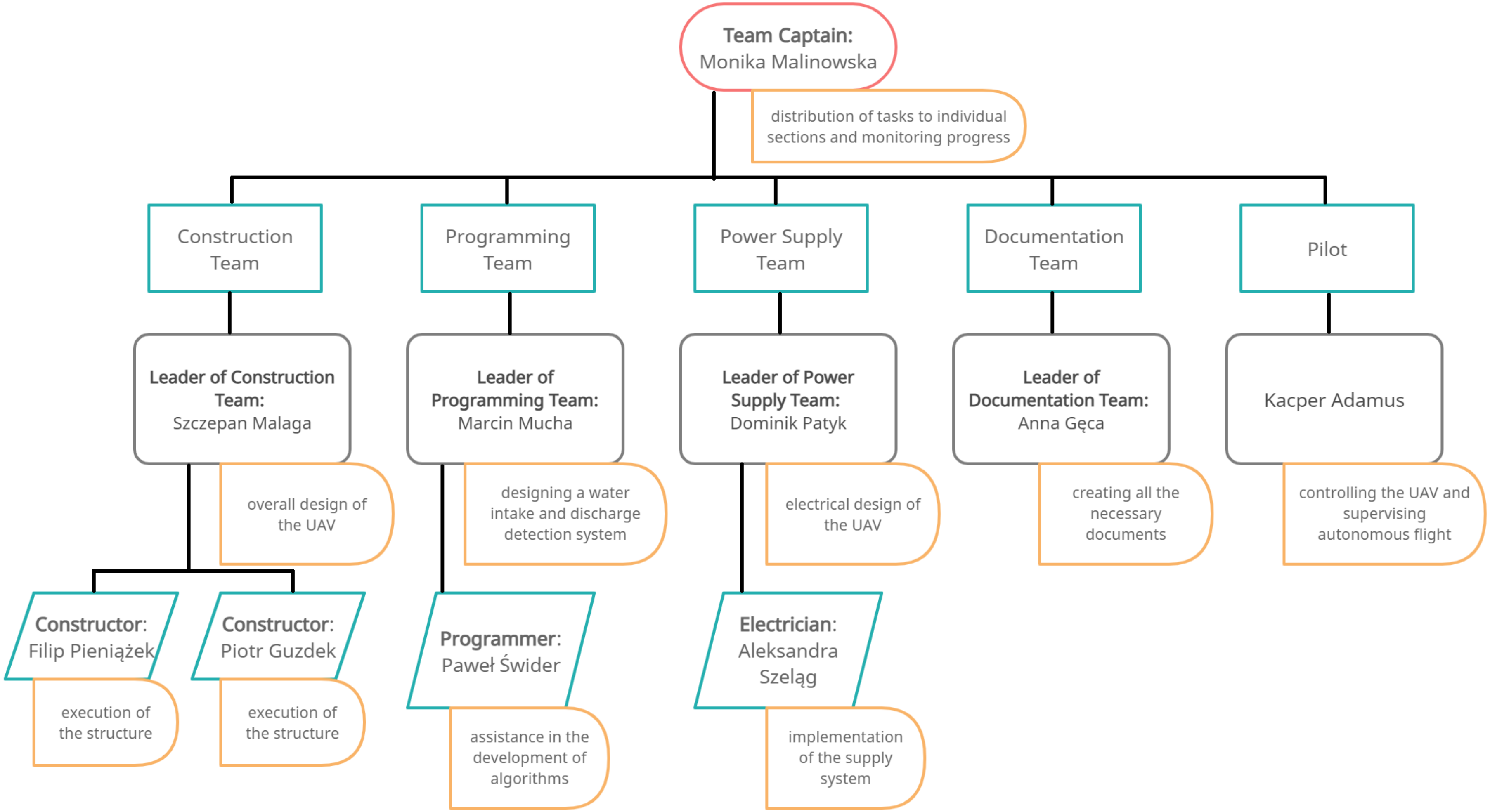

Figure 10. Team organization

Attachment 2

AGH SOLAR PLANE 3.0, ROTARY WINGS, AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY IN CRACOW													
PROJECT TIMELINE													
WORK PACKAGES AND ACTIVITIES		Start Date	End Date	Duration (Day)	January	February	March	April	May	June	July	August	September
1.	**Design and construction**	**13.01.2021**	**15.03.2021**	61									
1.1	Execution of frame design and calculations			35									
1.2	Milling of carbon fiber elements			18									
1.3	Assembly of the frame structure			26									
2.	**Electronic equipment**	**13.01.2021**	**30.04.2021**	107									
2.1	Calculation of the required drive and power			28									
2.2	Assembly of electronic component			17									
2.3	Connection of data transmission systems			8									
2.4	Programming of the flight controller			33									
2.5	Design of the water discharge system			10									
2.6	Execution of the water discharge system			25									
3.	**UAV tests**	**15.04.2021**	**11.07.2021**	87									
4.1	Tests of the manual flight correctness			11									
4.2	Tests of the autonomous flight correctnesss			27									
4.3	Tests of the water intake and discharge system			35									
4.4	Possible corrections			31									

Figure 11. Original timetable

Attachment 3

AGH SOLAR PLANE 3.0, ROTARY WINGS, AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY IN CRACOW													
PROJECT TIMELINE													
WORK PACKAGES AND ACTIVITIES		Start Date	End Date	Duration (Day)	January	February	March	April	May	June	July	August	September
1.	Design and construction	13.01.2021	30.04.2021	107									
1.1	Execution of frame design and calculations			39									
1.2	Milling of carbon fiber elements			23									
1.3	Assembly of the frame structure			45									
2.	Electronic equipment	13.01.2021	21.06.2021	159									
2.1	Calculation of the required drive and power			36									
2.2	Assembly of electronic component			23									
2.3	Connection of data transmission systems			13									
2.4	Programming of the flight controller			41									
2.5	Design of the water discharge system			18									
2.6	Execution of the water discharge system			28									
3.	UAV tests	15.04.2021	11.07.2021	87									
4.1	Tests of the manual flight correctness			11									
4.2	Tests of the autonomous flight correctnesss			27									
4.3	Tests of the water intake and discharge system			35									
4.4	Possible corrections			31									

Figure 12. Final timetable