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# HAMAV

High Altitude Micro Air Vehicle

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# Defining the problem

## Identification of the problem

The problem that we, the 3-SAT tech team, decided to solve is stratosphere experiment payloads being blown away by the wind, which may cause difficulties in recovering the payload, and uncontrolled landings, which may even destroy the experiments. These significantly increase probability of mission failure.

## Technical Overview

The common way of transporting scientific payloads, measurement instruments or, as in our case, biological experiments to the stratosphere are simple stratospheric probes. They consist of capsule, containing the payload, and onboard computer with GPS and radio transmitter. The probes are lifted to stratosphere with use of high-altitude balloons.

These probes have many drawbacks, but the worst one is complete lack of controllability. Probe begins the fall when balloon bursts, it is impossible for it to detach before this happens. Because of effect of the wind on balloon, and after burst, the parachute, probe can land as far as 100 kilometers away from the launching site. It is crucial to track the probe during flight and to send a party to recover it afterwards. The probes often land in inaccessible places, for example on trees or on private property, and the recaptures are difficult. Furthermore, the payload might be damaged or even stolen.

There exist other, more advanced solutions; however they are not available for most. They are used by major space agencies, large corporations and military. These solutions include for example, NASA Global Hawk and Airbus Zephyr. (see Photography 2 in Graphical Content)

## Criteria

We set the construction of platform for scientific experiments, capable of reaching to and returning from stratosphere, as our goal. To better simple stratospheric probes, we created a list of criteria out solution needed to fulfill:

1. Stratospheric flight at altitude greater than 9 km AGL[[1]](#footnote-1)
2. Return to the launching site (maximal error 300 meters)
3. Capability of transporting a scientific payload
4. Autonomous flight
5. Good and stable radio link
6. Failsafe
7. Low battery usage

Our platform had to be able to reach stratosphere, carrying scientific payload of considerable size of 16 test-tubes. To avoid problems of burdensome recapture and uncontrolled landing, the construction had to be able to return not further than 300 meters form the launching site. We wanted it to be autonomous, for easier operation. The communication had to allow receiving satisfying amount of frames[[2]](#footnote-2) of telemetry and good RSSI[[3]](#footnote-3) of RC link on a level at least of 40%, and real-times video feed allowing full control over the platform. The battery should not ever drop below 20% because of safety concerns. Platform should also boast a failsafe, to ensure security even in an event of unexpected failure.

# Project description

## Overview

Our response for set criteria is HAMAV – a project of autonomous stratospheric drone.

HAMAV is an UAV, that can be attached under high-altitude balloon and detach at given height, beginning autonomous flight in the direction of the launching site. Onboard, under the wings, are located two cavities allowing to mount experimental payload of up to 200 cm3. To show this functionality, we decided to affix 16 test-tubes of biological payload, however any other payload is possible

All autonomous functions of HAMAV are controlled by flight controller, located in electrically-heated hull.

We used 3 radio links for communication: one for telemetry data, second for video feed, and third for controlling the UAV from the ground station during landing.

When HAMAV, lifted by high-altitude balloon, reaches the given altitude, the crew at ground stations sends the command to detach from special rig connecting it to the balloon. In case of malfunction of radio link, HAMAV detaches by itself. When rig is decoupled, the UAV enters into the gliding flight and, using built-in GPS receiver, it heads towards launching site. If the gliding flight turns out to lack distance to reach the destination, the motor powered by a large set of lithium-ion batteries engages. Aside from main power supply, there is a backup power supply in the hull, that can power all systems needed for a controlled gliding flight. (see Photography 3 in Graphical Content)

## Detailed description

### Onboard electronics

(see Scheme 1 in Graphical Content)

#### Power supply

The UAV boasts two power supplies. The first one is main accumulator, consisting of Li-Ion batteries Panasonic NCR18650B (3400mAh) in configuration 6S2P[[4]](#footnote-4). The main power supply powers the flight controller, the heating system, the electric motor and cameras. The smaller accumulator consists of the same batteries, but in configuration 3S. The doubled power source is the first multi-level failsafe onboard. The main accumulator power entire platform, but if it is emptied or damaged, every circuit needed for the gliding flight switches to backup power supply. Every subsystem has two voltage regulators, and uses primary one as supply by default, but in the event of its destruction the subsystem automatically switches to the other regulator. This multi-level system of precautions increases reliability, because the UAV is always able to land in a controlled manner, even if the motor usage drains the whole main power supply. (see Photography 4 in Graphical Content)

#### Flight controller

The HKPilot 32 flight controller is the brain of the UAV. It uses a current sensor and UBLOX NEO-M8N GPS. It is also connected to Pitlab OSD, which overlays flight parameters onto the video feed from RunCam Swift camera. The flight controller allows the UAV to function autonomously, for example enables active flight stabilization or autonomous return.

#### Heating system

The heating system is built from Arduino computer, relay, thermostat and heating mat originally for car mirrors, of power of 12W. When the temperature decrease below 20 degrees Centigrade is detected, Arduino activates heating mat through the relay to heat the batteries and circuits. This averts error in gyroscope measurements. (see Photography 5 in Graphical Content)

#### Communication modules

There are three ways to communicate with the UAV via radio: RC, FPV and telemetry. RC allows to directly control the UAV using the apparatus in the ground station, FPV ensures the live video feed, and telemetry can be used to transmit flight parameters and give the UAV complex commands. The use of three radio links is another multi-level precaution – it raises the reliability of the platform, as in case of a malfunction and loss of one of the links, the drone is still controllable through the other two.

The RC system consists of eLeRes MAX transmitter (1W), connected to Yagi antenna and eLerEs reciver connected to dipole antenna 2.2 dBi. The system uses the frequency of 425 MHz.

The FPV system works on frequency 1.28 GHz. The LawMate 1W with dipole antenna of 2.2 dBi is the transmitter, and RX-1260CK with biquad antenna of 11dBi is the receiver.

Telemetry consists of two RDF868x transceivers[[5]](#footnote-5) of power of 1W. The system uses two dipole antennas of 3dBi, and the ground station uses two Yagi antennas.

### Software

#### Flight controller software

The flight controller uses an open-source software ArduPlane. It gathers flight data from different sensors, such as gyroscopes, barometers and GPS, and then it analyses them and uses the motor and control surfaces, ensuring a stable flight and allowing autonomous functionality. The system is equipped with failsafe, which detaches the UAV and commences flight after loss of signal for longer than 120 seconds.

#### Heating system control loop

The heating system software is a simple control loop. When temperature rises above 20°C, the system disengages, and is turned again on when the temperature drops again below the limit.

### Mechanical parts

#### Frame

The drone frame is in flying wing configuration, as it is the most aerodynamic profile, and low drag ensures best efficiency. That allows for travelling long distances. The used model is FX-61 EPO frame of wingspan of 155cm. It was heavily modified with ABS 3D prints (electronics containers, payload mount and other systems), and enforced with carbon profiles and composite material (glass fiber laminate), to make the construction more durable. The reinforcement protects the frame from potential damage caused by huge acceleration if the UAV was to tailspin in stratosphere. (see Photography 6 in Graphical Content)

#### Propulsion

The propulsion system is the Quantum MT Series 4108 700KV brushless motor and APC 10x10E propeller, which allows for achieving high efficiency at high speeds, and therefore increases distance the UAV can cross. The brushless motor is controlled by ZTW Spider Series 60A Opto ESC (electronic speed control).

#### Control surfaces

The ailerons were reinforced by the use of plastic hinges, glass fiber tape and PVC. They are controlled with digital servos Corona DS-918MP, with lubricant replaced with antifreeze. (see Photography 7 in Graphical Content)

#### Detaching mechanism

The decoupling system consists of detaching mechanism and stabilizing print. The mechanism is digital serco Corona DS-918MP, which activates after command through RC link or telemetry, retracting the lace and freeing the balloon wires. Mechanism is on the back of the UAV, and the wires go out through carbon rubes. The role of stabilizing print is to prevent wires entangling with motor and propeller. It also protects propeller from being damaged by tense wires. It also eases the tension on mechanism, decreasing a change of damage. (see Render 1, Render 2 and Photography 8 in Graphical Content)

#### Scientific payload

The scientific payload is mounted in two 3D printed containers in cavities under the frame’s wings. The prints are aerodynamic, to decrease the drag coefficient, and the majority of payload is enclosed. Each container can fit 100 cm3 of payload, or 16 test-tubes. (see Render 3 in Graphical Content)

## Procedure

All points of procedure of preparing the HAMAV operation are listed below:

1. Deployment of ground station
2. Installing of:

- payload

- accumulators

- propeller

- wires in detaching mechanism

1. Plugging the accumulators in
2. Check-up of:

- Steering of control surfaces via RC

- Steering of control surfaces via autopilot

- Motor

- Detaching mechanism

- Radio communication

1. Closing the cover and securing it with tape
2. Calibration of sensors
3. Arming of autopilot
4. Fixing the wires to high-altitude balloon
5. Freeing the balloon (lift-off)
6. Detaching from the balloon at target altitude
7. Activate autonomous return to launching site
8. Assuming manual control and landing

(see Scheme 2 in Graphical Content)

# Evaluation

## Tests

The platform was tested to ensure that it fulfills all the set criteria. Testing has been completed in four phases:

* Phase 1 – VLOS flight at 750m AGL, 16 June 2018. It was a full success. The UAV landed 50 meters from the balloon launching site.
* Phase 2 – BVLOS flight at 6km AGL, attempted 20 September 2019. Unfortunately, very unfavorable weather conditions forced the crew to abort the launch. The test was called off.
* Phase 3 – BVLOS flight at 11.5km AGL, 20 October 2018. The test was successful. The drone returned from stratosphere and landed 20 meters from the launching site.
* Phase 4 – BVLOS flight at 30km AGL, planned 8 June 2019. Permission for test was already given by Polish Army.

(see Photography 9 in Graphical Content)

To make sure the tests did not break any laws and were performed in safe conditions, the phases 3 and 4 require obtaining permission from Polish Air Navigation Services Agency and Polish Army.

Below are listed all criteria set for HAMAV, and the results from the tests.

Table 1 – list of criteria for HAMAV and the results of testing

|  |  |
| --- | --- |
| Criteria: | Result: |
| Stratospheric flight | Altitude > 9km AGL |
| Scientific payload | 1. Volume of container with payload ≥ 200 cm3, 2. Payload ≥ 24 g |
| Return to the launching site | Distance <300m |
| Autonomous flight | Yes |
| Radio communication | Received frames of telemetry > 40%  Live video feed and RSSI of RC link > 40% |
| Failsafe | Working |
| Battery charge used | <80% |

## Prototype

Prototype was built for the purpose of the four phases testing. The name of prototype is IKAR. (see Photography 10 in Graphical Content)

The mass of IKAR is 2685g. The battery usage in rest equals 11W. The battery usage with the motor at full power equals 350W. Cruising speed is 13 m/s.

The prototype is able to fly to stratosphere, carried by the balloon, and return to the launching site.

## Testing and the results of phase 3

Phase 3 was so far the highest flight of HAMAV, so the results from it will be discussed below.

### Stratospheric flight

The stratospheric flight is an obvious requirements for a stratospheric drone, whose purpose is to carry payload to stratosphere. We took the altitude of 9km as a minimal target, as it is the lower boundary of stratosphere. The altitude of platform was measured with GPS and barometer from flight and telemetry records. During the test on 20 October 2018, balloon lifted the UAV to an altitude of 11.550km. The difference of 770m between barometer and GPS logs was due to increase of the uncertainty of GPS with height. Regardless, both sensors showed the UAV reached above our target altitude. (see Simulation 1 in Graphical Content)

### Scientific payload

One of the most important criteria we set for ourselves is practical functionality of platform – an ability to carry scientific experiments onboard. The volume of 200 cm3 is sufficient to feature interesting experiments. According to 3D modeling software Fusion360, the volume of 3D printed payload containers we used is 212 cm3. We also agreed that the minimal possible mass of 20 g should be satisfying. During test flight there were 16 test-tubes, 1.5 grams of biological material each, on board, for a total experimental mass of 24g. The platform fulfilled both volume and mass criteria. (see Photography 11 in Graphical Content)

### Return to the launching site

Return to the launching site is a crucial functionality of the platform, as it eliminates possibility of very difficult or even impossible recovery due to terrain features in the place of landing. We assumed the distance of 300 meters from the launching site is accurate enough for recovery to be relatively easy and quick. After detaching from balloon, the UAV glided to the launching site and landed about 20 meters from ground station. The requirement was fulfilled.

### Autonomous flight

The autonomous flight functionality allows for return to the launching site without any action from the pilot, therefore the procedure is much more reliable and easier to perform. Even the half-autonomous flight stabilizes the UAV in-flight and makes piloting easier, again, increasing reliability. During the test on 20 October 2018, the UAV travelled to the launching site on its own, without any problem and with pilot passively observing the process. The requirement was therefore fulfilled. (see Photography 12 in Graphical Content)

### Radio communication[[6]](#footnote-6)

The communication with drone is very important, as it updates the ground crew on current status of mission and allows them to steer the UAV, if need arises. Moreover, it is a legal requirement for any drone operation. The quality of telemetry link during flight was measured with percentage of received amount of frames with data. A signal with 40% of frames received is considered to be of good quality. The measurement was taken from telemetry. The quality of FPV signal was judged visually, based on quality of received feed, and quality of RC signal was measured with RSSI. During phase 3 test there were multiple occasions on which RC RSSI dropped below 10%. The telemetry was lost once for a brief time, before restoration. The video feed was lost at the altitude of about 4km. The requirement was not fulfilled. The reason for this failure was incorrect setup of RC transmitter, which worked with power of 200 mW instead of 1 W. Furthermore, the UAV experienced turbulences that negatively impacted the signal strength as the polarization of antennas was incorrect. Another reason for unsatisfactory performance was dense and low clouds at the height of 2km AGL that suppressed and reflected some of the radio waves. (see Photography 13 in Graphical Content)

### Failsafe

The functionality of failsafe directly impacts the safety of operation and payload and the reliability of drone. In case of signal loss, the UAV waits 20 seconds, and if the signal is not regained by then, the UAV detaches itself and begins an autonomous flight towards the launching site. The failsafe ensures that even the total loss of signal does not impact the operation. During the return flight the RC link was lost and the UAV activated the failsafe, continuing the flight. The requirement was fulfilled.

### Battery usage

Appropriate level of battery usage is important for HAMAV. Fully drained charge negatively impacts accumulator and might even damage it. In the worst case scenario, the UAV might fall down if the battery is drained. The battery charge should not drop below 20%. The charge of both power supplies was measured before and after flight. The main power supply lost 1500mAh from the total of 6800mAh at the beginning (only 22% of charge drained). The requirement was therefore fulfilled with a large margin, which can be also credited to very advantageous flight conditions during return, as because of them the UAV did not need to engage the propulsion at all.

## Prototype assessment

The UAV fulfilled six out of seven criteria: it is capable of stratospheric flight with scientific payload onboard, autonomous return to the launching site with very small battery usage, and while maintaining every safety rule. It can be therefore assumed, that the prototype was successful and could work as functional product. However, we also identified a serious flaw – the lack of stable good quality radio communication. To fix that, during the next flight we will make sure that the RC transmitter will work on full power. We also supplemented a ground station with more directional antennas and double-checked all antenna are correctly setup and the different radio link do not disrupt each other. After the phase 3 of the test we also equipped the ground station with Antenna Tracker that precisely directs the antennas in the azimuth and elevation angles. Before this change, the antennas were directed manualy, which proved to be ineffective.

Apart from the problems listed above, the on-screen display module MinimOSD we used, failed just before launch before the flight on 20 October 2018. The most probable cause of this malfunction was incorrect setting of apparatus. OSD did not show any parameters. The backup MinimOSD we tried to use did not work at all. Minutes before take-off we decided to continue flight without OSD. That meant that if the telemetry was to fail, the manual control of the drone would not be possible and the UAV would have to fly on autopilot. After the incident the OSD was changed to PitLab OSD. Another mistake we made during that flight was skipping the use of stabilizing print in detaching mechanism. Because of that, the platform oscillated quickly during ascend, which furthermore intensified problems with radio connection, and could even lead to break of the propeller, wires being cut or damage to mechanism, which might have result in mission failure, but fortunately, none of those things happened and during next flights we will make sure to use the stabilizing print.

These problems are thus already solved, and the prototype was successful in testing. Hence, we conclude that the project was a success.

## Next steps

The next step of the project is phase 4 of testing – the 30km AGL flight. It will allow the biological experiment onboard to be tested for much longer, and will result in more credible results.

After the record-breaking flight, the schemes and instructions concerning the HAMAV, together with 3D models, will be shared online under Creative Common license, so that every institute, business or enthusiast could build a stratospheric drone and use it for scientific endeavors. Potential use case of the platform is equipping it with pollution sensors or aerogel that might allow for measurements of air pollution depending on altitude. The drone flight also makes longer, more complex high-altitude experiments possible, as a flying UAV can stay in the air much longer than a probe with a parachute. That makes cross-section examination of atmosphere much easier and efficient. The HAPS systems (High Altitude Pseudo Satellite) such as Stratobus, currently used by corporations and large scientific institutes, might also be equipped with HAMAVs in the future, to deploy them to send finished experiments back to earth.

The HAMAV would certainly find use in radio surveys that are currently used in Poland in three places, 2 to 4 times a day. Annually it accounts for 3300 stratospheric probes that are not recaptured, a considerable amount of e-waste and a costly loss. Each probes costs about 650 PLN, therefore use of the HAMAV platform might save as much as 2,000,000 PLN each year. We are in contact with Institute of Meteorology and Water Management, which expressed interest in our project. A plan of a radio survey using HAMAV is being developed right now.

There is also a possibility of implementing an active ADS-B system to the platform. It would send the position of the craft to all other airborne vehicles and increase the safety of missions. Alternative version of the drone could be built without the electric motors, as it would allow use of smaller power supply of a greater efficiency. The accumulator could consist of two Saft LSH20 cells connected in series. This version would be much cheaper, but could be used only in the most favorable weather conditions. The gliding flight would be sufficient for the return to the launching site and the mass reduction – even up to 800g – would make place for much larger scientific payload. Another possible improvement could be LIDAR system that would automatize the landing procedure, even allowing the UAV to land in an automatically chosen alternative location in the event of too low battery level. The use of Pixhawk 2, that has heated gyroscope inside, could eliminate the need for heating system and decrease the battery usage by a significant amount, which would result in longer flights. If the law in Poland changed to allow aerial operation without radio communication, the UAV without all the radio modules would function fully autonomously and would be much more battery efficient, with longer flight time and would have weight – a space for even bigger payloads. The frame could be changed to the FX-79, which has bigger wingspan and therefore bigger lift, which would allow to mount even larger experiments.

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1. Above ground level [↑](#footnote-ref-1)
2. Frame – a set of information sent by radio [↑](#footnote-ref-2)
3. RSSI – strenght of recieved radio signal [↑](#footnote-ref-3)
4. 6 pairs connected in series of 2 batteries connected in parallel [↑](#footnote-ref-4)
5. Radio modules, working both as transmitters and receivers [↑](#footnote-ref-5)
6. The described radio communication took place before major upgrades to ground station, in which more directional antennas were used. During phase 3, the RC transmitter was equipped with moxon 5.5 dBi antenna, and transceiver of ground station had only one yagi 11.5 dBi antenna. [↑](#footnote-ref-6)