

TDP: High Flyers (Poland), Outdoors Category

A. Banaszewska, M. Kaczor, K. Kozubik, K. Lewandowski, T. Stasiński, K. Stiborski, F. Strzepek and J. Tomczak
Silesian University of Technology, Gliwice, Poland

ABSTRACT

This document presents the design, development, and testing process of a multi-UAV (Unmanned Aerial Vehicle) system intended to compete in the Outdoor Category missions: Mapping of a disaster area, Transportation challenge, and Load and release, of the 16th International Micro Air Vehicle Conference and Competition. The system includes a custom-built main UAV optimized for all mission types and a set of smaller UAVs forming a swarm for collaborative transport tasks. Our approach prioritizes modularity, transportation efficiency, and robust autonomy by integrating PX4-based flight control and ROS 2 software architecture. We also propose and evaluate two distinct payload deployment mechanisms, offering flexibility for the final mission selection. Extensive simulation and real-world testing ensure system reliability and performance under competitive conditions.

1 INTRODUCTION

To address the diverse challenges presented by the Outdoor Category, our team developed a hybrid drone system consisting of a main custom-built UAV (Unmanned Aerial Vehicle) and a supporting swarm of smaller drones. The primary UAV is designed for versatility, capable of executing all three competition missions with minimal reconfiguration. Due to strict logistical constraints—such as international transportation and limited volume—we optimized the design for compactness and modularity, building the frame and critical components in-house.

In parallel, a swarm of lightweight drones is deployed for the transportation mission, leveraging real-time positioning and cooperative flight algorithms to safely carry a shared payload. All UAVs run PX4 autopilot firmware and are controlled via ROS 2-based systems that handle autonomous navigation, mission execution, and swarm coordination.

Our methodology emphasizes iterative development and rigorous testing, starting from simulation environments and progressing to field trials. This approach allows for early identification of design flaws and rapid refinement of both hardware and software components. The following sections provide a detailed overview of the MAV and system designs, competition strategies, and testing procedures.

Section 2 describes the design of the UAVs taking part in the competition, as well as the design of the modular payload

modules created for specific missions. Section 3 describes the development process of the software system that enables autonomous flight control and mission execution. Section 4 describes our intended approach to the missions in the competition. Section 5 presents the tests we incorporated into the development process to ensure the safety of the operation.

2 MAV DESIGN

To meet the demands of the missions, we decided to develop two separate types of UAVs. First, the primary drone is capable of participating in all three missions. A pair of smaller UAVs is designed to form a cooperative swarm for the transportation challenge. We also designed modular payloads to assist in the mission execution.

2.1 Main UAV frame

The main UAV is built on a fully custom-designed frame. Given the experience of the team members and the need for flexibility across multiple missions, we chose to design and develop the frame ourselves. This approach allows us to minimize the amount of separate UAVs needed to compete in the Outdoors category. This design is versatile and reduces the number of drones we need to transport internationally. Additionally, it allows us to prepare replacement parts for repairs, minimizing the risk of travel damages.

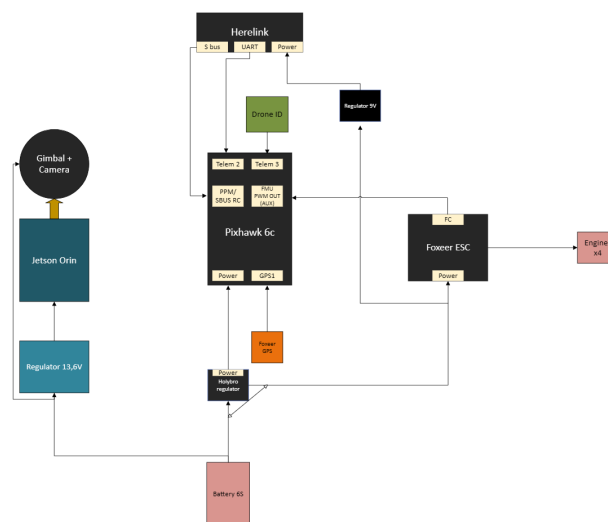


Figure 1: Main UAV components diagram

The frame consists of 3 mm carbon fiber plates for the body and 6 mm plates for four arms. These were cut in-house, providing us with the desired geometry and low mass, while

maintaining strength and stability. The lower plate features mounting points for necessary payloads, fixed in place with screws. The upper plate includes a removable hatch mounted with four screws, allowing us quick access to the internal electronics. The battery is fastened to the top of the hatch with straps. To strengthen the construction, we reinforced the arms by connecting them with 12 mm carbon fiber tubes. This design improves the rigidity of the structure and provides us with additional payload mounting points. The landing legs are removable for ease of transportation and maintenance.

The UAV is powered with 6S LiPo batteries. Converters are used to provide appropriate voltage for various electronic components. Secure and safe power delivery is ensured with XT connectors.

We use Holybro Pixhawk 6C flight controller with PX4 autopilot firmware. It was selected based on the compatibility with ROS 2 software and extensive I/O capabilities, allowing us to handle various payloads during missions.

A Foxeer M10Q GPS unit is mounted on the carbon fibre tube connecting the engines. The placement minimizes the electromagnetic interference. The communication is handled by Herelink 1.0 2.4 GHz digital transmission system.

The propulsion system consists of 1050kV T-MOTOR Velox 3115 motors paired with Foxeer Reaper 60A ESCs. This configuration has been thoroughly validated in previous projects and has consistently demonstrated high performance and reliability.

The components summary is presented in the Table 1.



Figure 2: Main UAV

2.2 Main UAV Payload

Mission critical computations are performed on the on-board NVIDIA Jetson Orin Nano microcomputer. The computer is mounted to the bottom of the lower plate with four screws and housed in the custom enclosure, enabling the fast detachment of the unit and its protection during the flight.

Frame	cutom
Batteries	6S LiPo
Flight coontroller	Holybro Pixhawk 6C
Autopilot	PX4
Motors	1050kV T-MOTOR Velox 3115
ESC	Foxeer Reaper 60A
GPS	Foxeer M10Q
Transmission	Herelink 1.0 2.4 GHz
Companion Computer	Jetson Orin Nano

Table 1: Main UAV components summary

The Jetson Nano is connected with the downfacing camera mounted on the gimbal, which ensures footage stability.

Below the computation module is the place for the secondary payload platform designed to hold the net in the Transportation challenge mission as well as the water-loading related components for the Load and release mission. The platform is attached to the carbon fiber tubes lining the arms. First prototypes of the platform are currently in the development process and are subject to refinements and improvements.

For the Load and release mission, we develop two solutions simultaneously and intend to decide upon the more optimal one after extensive system tests. The pump-based system utilizes the submerged pump, and the bambi bucket system is inspired by the real-life firefighting helicopters' approach.

2.3 Swarm UAVs

For the Transportation challenge mission we decided to prepare a swarm consisting of three drones: the leader and two smaller assistants. The Main UAV described in section 2.1 will serve as a leading drone, while assisting drones' design is described below.

Source One V5.1 5 inch frame was selected as the base for the construction, based on the compact size and compatibility with our components. Custom-made 3D printed parts provide modifications for our payload and integration requirements. T-MOTOR Velox V2808 1960kV motors powered with T-MOTOR Velox V50A ESCs (Electronic Speed Controllers) power each secondary UAV. Flight control is managed by Matek H743-Slim, chosen for small size, PX4 firmware compatibility, and the team's prior experience with the module.

For precise localization required in the internal swarm control processing, we integrated RTK (Real-Time Kinematic) technology. We use Here4 as both GPS and RTK unit, but may consider better alternatives if the budget allows it.

Onboard computing is handled by Raspberry Pi 5 CM mounted on the additional IO module, attached between the lower and upper plate and housed in the custom 3D-printed cover. The housing serves as a mounting point for the upper plate. The cover allows access to the internal drone electronics as it is removable with just a few screws.

The drones include an attachment point for the net at the bottom. The stability of the fixture is ensured with eight screws mounted on inserts and nylock nuts.

Power is supplied with a 4S LiPo battery that sits on top of the upper plate. The power is delivered to the flight controller and then supplied to the other components through it.

The summary of the components used in the swarm UAVs is presented in the Table 2.



Figure 3: Swarm's secondary UAV

Frame	Source One V5.1 5 inches
Batteries	4S LiPo
Flight coontroller	Matek H743-Slim
Autopilot	PX4
Motors	T-MOTOR Velox V2808 1960kV
ESC	T-MOTOR Velox V50A
GPS	Here 4
Transmission	Express LRS
Companion Computer	Raspberry Pi 5 CM

Table 2: Swarm UAV components summary

2.4 S900

Following the preliminary tests, we decided to use the DJI S900 frame-based drone as the fallback solution for the Load and release mission. The decision to use this UAV will be based on the water loading payload selection. S900 offers better payload capacity and flight stability; however, it requires higher power. Its larger size presents a logistical challenge and complicates international transport. If selected, it will be equipped with the Pixhawk 6C flight controller for system compatibility.

3 SYSTEM DESIGN

System design and development included creating modal software components, that can be used together to execute each mission seamlessly. Main components are flight control and swarm algorithm. Flight control enables the UAV system to command the autopilot and take control over it. Together with mission control, it allows for autonomous operation of the UAV. Swarm algorithm allows multiple drones to take decisions based on the localization of the other members of the swarm. It was designed with the transportation challenge mission in mind.

3.1 Prototyping

During the initial phase of system development, we created a prototype using the Gazebo simulation environment integrated with the ROS 2 robotics framework. ROS 2 is an industry-standard middleware widely adopted for robotic systems development, while Gazebo offers a high-fidelity simulation platform fully compatible with ROS 2.

The integration of ROS 2 with the PX4 autopilot enabled seamless bidirectional communication. This allowed us to subscribe to telemetry and state data published by PX4, monitor the internal behavior of the drone in real time, and publish control messages to influence its operation accordingly.

To support multi-agent testing, we developed a custom Gazebo world capable of simulating multiple drones simultaneously, as seen in Figure 4. This simulation-first approach enabled early detection and resolution of software issues in a controlled environment, significantly reducing risk prior to deployment. Only after validating system performance and stability in simulation did we proceed to real-world testing.



Figure 4: System prototype in the simulation environment

QGroundControl software is used as a ground control station, monitoring the drone behavior and allowing us to plan missions for simple trajectories. The system is presented in Figure 5.

3.2 Flight Control and Autonomy

To develop the autonomous system, we implemented custom software capable of interfacing directly with the PX4 au-



Figure 5: Swarm setup in QGroundControl system.

topilot. This system is built on the ROS 2 framework and is designed to monitor PX4's internal communication and respond dynamically by issuing appropriate control commands.

PX4 utilizes the uORB messaging protocol for internal topic-based communication. Through the integration of the Micro XRCE-DDS client within the PX4 firmware, uORB messages are automatically translated into a DDS-compatible format. This allows for seamless bidirectional communication with ROS 2, exposing PX4 data and control interfaces as ROS 2 topics. The communication diagram is presented in figure 6.

A core component of our system is the offboard control node, which is responsible for sending high-level trajectory commands to the PX4 autopilot. These commands can specify position setpoints, velocity vectors, or acceleration targets, enabling precise autonomous flight control [1]. Additionally, the node maintains a continuous "heartbeat" signal. If this heartbeat is interrupted, PX4 will automatically exit offboard mode and transition to position mode, handing control back to the human operator to ensure safety.

Another key module is the mission control node, which governs the high-level execution of mission logic. This component implements a Feasible State Machine (FSM) to manage the system's progression through mission phases—ranging from system arming and takeoff to task execution and safe landing—ensuring robust and predictable autonomous behavior throughout the mission lifecycle.

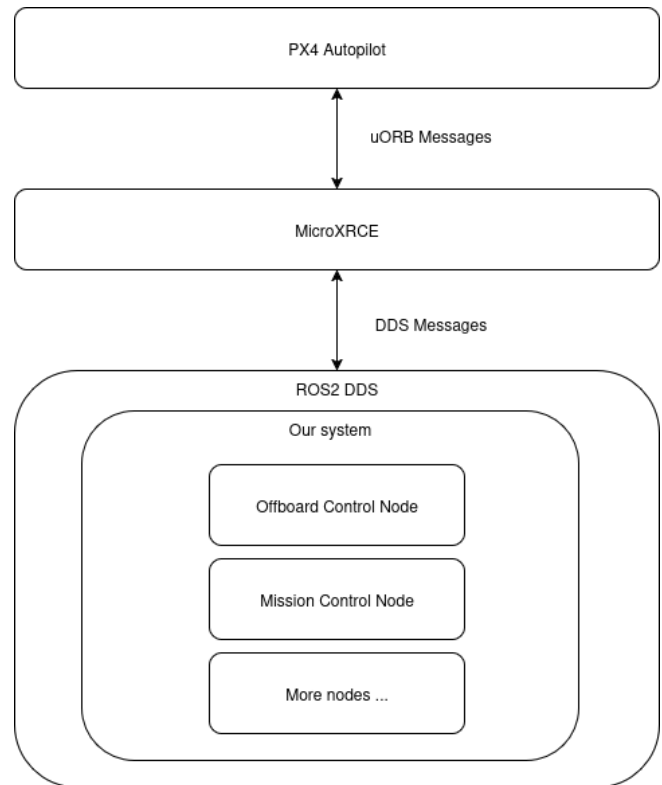


Figure 6: MicroXRCE enables ROS2 DDS communication with PX4 Autopilot

3.3 Swarm algorithm

As part of one of the mission scenarios, we developed a drone swarm capable of cooperative behavior. The primary objective of the swarm is to maintain a stable formation by preserving safe inter-drone distances, while simultaneously following a shared trajectory.

A designated Primary drone leads the swarm by determining the reference trajectory. The remaining Secondary drones follow the Primary drone, dynamically adjusting their positions to maintain appropriate spacing both from the leader and from each other.

Each UAV in the swarm operates using ROS 2 for internal flight control, leveraging the offboard control and heartbeat mechanisms described previously. Communication between swarm members is facilitated via the UDP protocol, through which drones exchange localization data in real time. This peer-to-peer communication enables each drone to make decentralized decisions regarding its flight path and velocity.

To achieve coordinated motion and spacing, each drone implements a spring-based motion model [2]. This model treats the drones as if they were connected by virtual springs, generating attractive or repulsive forces based on relative positions. The resulting force vectors determine each drone's desired movement direction and speed, ensuring smooth for-

mation control and cohesive swarm behavior.

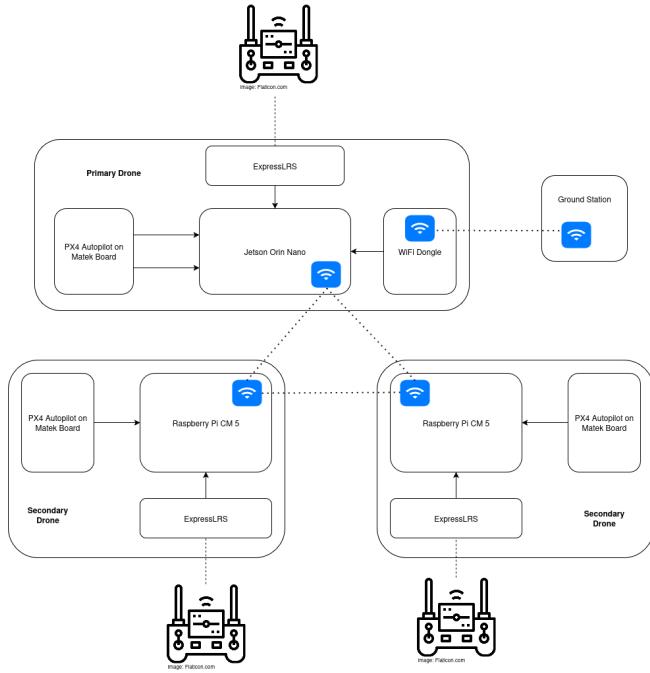


Figure 7: Swarm components connections

As presented in Figure 7, each of the swarm members has a PX4 autopilot and companion computer (either Raspberry Pi 5 CM or Jetson Orin Nano) on board. The companion computer communicates with the autopilot using ROS 2 mechanisms described in section 3.2. UAVs communicate with each other using the internal WiFi devices of the companion computers. Those interfaces allow for stable communication up to 10 meters. Using the UDP protocol, UAVs share their respective localizations in real-time. The primary UAV is equipped with another WiFi device that is able to maintain connection over larger distances. It maintains the connection to the Ground Control Station and shares the mission status data.

Apart from internal swarm communication, each of the UAVs has an Express LRS module on board, connected to the respective controllers. It allows human operators to take control of the UAV during the mission.

3.4 Swarm communication

Swarm internal communication is facilitated via the UDP protocol over a wireless network. To evaluate the performance of the onboard Wi-Fi module in the Raspberry Pi Compute Module 5 (CM5), we conducted signal strength tests of a 2.4 GHz wireless network hosted by the device. Table 3 summarizes the received signal strength indicator (RSSI) measurements recorded at varying distances from the Raspberry Pi CM5. Measurements were taken at 0.05 m (device placed side-by-side with the measurement system), 1 m,

2 m, and 5 m. At each distance, eight consecutive RSSI readings were collected using a standard laptop connected to the network, employing the iw command-line tool for data acquisition.

	0.05 m	1 m	2 m	5 m
1.	-26	-50	-53	-55
2.	-24	-47	-53	-55
3.	-24	-47	-53	-55
4.	-24	-47	-53	-55
5.	-27	-47	-53	-56
6.	-27	-47	-53	-55
7.	-26	-47	-54	-55
8.	-26	-47	-54	-55

Table 3: RSSI [dBm] measurements of 2.4 GHz WiFi network over varying distances from the Raspberry Pi CM 5 device

The same tests were conducted for a 5.0 GHz wireless network.

	0.05 m	1 m	2 m	5 m
1.	-45	-66	-58	-59
2.	-45	-64	-58	-59
3.	-45	-64	-59	-62
4.	-45	-64	-59	-62
5.	-45	-69	-59	-53
6.	-52	-65	-63	-53
7.	-52	-65	-63	-54
8.	-54	-65	-63	-54

Table 4: RSSI [dBm] measurements of 5 GHz WiFi network over varying distances from the Raspberry Pi CM 5 device

The 2.4 GHz connection is stable and reliable even for a distance of 5 meters. Swarm will be closer than that during the mission execution, as it has to carry a 1 meter wide net; the connection quality is satisfactory.

4 COMPETITION APPROACH

Taking the time limits of the competition under consideration, we decided to initially prepare to compete in three missions - Mapping of a disaster area, Transportation challenge, and Load and release. Following the successful system development and tests, we might decide to take part in the Find a person mission as well. Familiarity with the hardware and software components intended for use in the designed solution also played a part in the decision-making process. We use flight control mechanisms described in section 3.2 to conduct the missions autonomously. Each of the missions has a designated mission state machine created in the system that is responsible for executing it. Main UAV described in the section 2.1 will take part in all of the missions, assisted by

smaller UAVs described in the section 2.3 for the Transportation challenge mission.

4.1 Mapping of disaster area

Mapping of the disaster area will be conducted in two stages: a near real-time preview during flight and a high-quality reconstruction after the full dataset acquisition.

Video will be captured by a camera module (Raspberry Pi HQ with a 6mm focal length lens) mounted on a stabilized gimbal system attached to the UAV. During the test flights, the optimal altitude of flights and flight plan strategy will be determined to achieve necessary image overlap for reliable photogrammetric reconstruction. The footage is transmitted to a Jetson Orin companion computer, which extracts suitable frames, adds GPS-based georeferencing, and forwards them to the Ground Control Station. The images are processed by custom software, which stitches them into a low-resolution, preview map. This process runs nearly in real time, allowing operators to verify coverage during the mission and ensuring efficient data collection.

After the flight, the complete set of high-resolution imagery is processed offline on the ground to produce detailed mapping products. ODM(OpenDroneMap), an open-source photogrammetry platform, will be used for this task. The software provides a complete photogrammetric pipeline, feature extraction, point cloud generation, and complex reconstruction. Using the collected data, the accurate orthomosaics and, where feasible, textured 3D reconstructions will be generated. The computationally intensive offline processing stage will produce precise geospatial data to support disaster response planning.

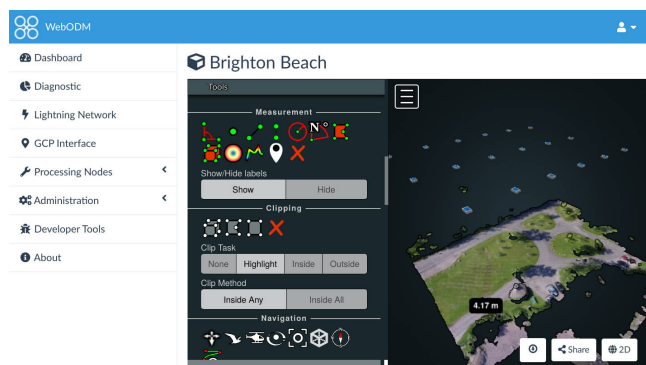


Figure 8: Web ODM system interface

4.2 Transportation challenge

During the Transportation challenge mission, we intend to carry a triangular net with the swarm consisting of three UAVs. The main UAV will serve as a leading drone, providing the swarm with the general mission trajectory. Swarm assistant UAVs will follow it while maintaining the secure distance and the net stability, utilizing the swarm algorithm

described in section 3.3. The net will be attached to the custom fixtures at the bottom of the UAVs, in their respective central mass points.

4.3 Load and release

Two different solutions for Load and release mission are currently under parallel development. After conducting extensive tests, we will decide upon using the more optimal solution.

First is the solution inspired by firefighting helicopters' approach, bambi bucket. Our implementation consists of two rings. The smaller ring is movable and fits into the bigger ring. Rings are connected with waterproof material on their outer sides. Moving the smaller ring up into the bigger one closes off the compartment, filling the material with water, forming the half torus shape. Releasing the hold on the smaller ring results in water falling out of the bucket quickly.

The rings will be 3D printed and equipped with additional weights for successful underwater operation. The system will be held by a fishing line mounted to the lower UAV plate and the motor, responsible for the inner ring pull-up and release movement.

The system's advantages are swift operation and high carrying capacity. The main disadvantage is the possibility of a sudden change in the center of mass while water is carried in the bucket. The system is currently tested on a more stable S900 UAV to mitigate that risk.

The other solution is developed on the main UAV. It utilizes a pump to move water into a designated container hung on the rubber tube. The solution offers improved stability compared to the fishing line used for the bambi bucket. Several design variations are currently under evaluation. These include the use of an electric valve for rapid water release, or a reversible pump mechanism to actively expel the water.

A key consideration is the placement of the pump. Mounting it directly to the underside of the drone would require it to draw water vertically over a distance of approximately two meters, which may exceed its operational limits. As a result, we are also testing configurations where the pump is positioned closer to the water container to reduce head height and improve efficiency.

As GPS position should be provided in advance, we intend to utilize QGroundControl system capabilities to plan the mission trajectory and reach intended loading and release locations. We aim for 2 l capacity of the bambi bucket and above 1 l capacity for the pump solution. We intend to perform multiple loading and releasing rounds.

5 TESTING

We structured our development workflow to prioritize frequent and iterative system tests. Our approach emphasizes continuous system improvement through a series of small tests, often conducted over single modules. We believe that identifying system bugs and construction failures during

tests is crucial for successful mission performance. We initially test the drone operativeness, and then move on to payload functionality tests followed by the system module tests, which were preceded by tests in the simulation environment, as described in section 3.1.



Figure 9: Field tests of the system with S900 UAV

5.1 Mapping of a disaster area

The main concern for the Mapping of a disaster area mission is the camera footage quality paired with the orthophotomap generation. Current tests include performing regular flights over versatile areas and comparing the results.

5.2 Transportation challenge

Each of the drones taking part in the swarm goes under extensive examination to ensure their smooth operability, to minimize the risk of crashes. The drones operate in close proximity to each other. Additionally, we test the weight-carrying capabilities of each of the drones and multiple drones in various combinations. The swarm algorithms are initially extensively tested in the simulation environment, as presented in section 3.1.

5.3 Load and release

Preliminary tests included ensuring the weight-carrying capabilities of the main UAV that will take part in the mission. We started by conducting several flights with a payload attached directly below the drone, increasing its weight with every flight. We followed those approximations with testing the UAV's flight behavior with a payload hanging two meters under it, as it is the requirement of the mission. As it introduces some challenges for the drone to maintain stable flight control, we moved on to testing this on a more stable S900 UAV. We introduced a servo-based payload release system, allowing us to drop the water in case of an emergency.

At the same time, we conduct the initial manual test of both bambi bucket and pump solutions. The tests will be followed by on-board payload testing.



Figure 10: Field tests of the system with main UAV

6 CONCLUSION

In this work, we have presented the design, development, and testing of a versatile multi-UAV system built to address the requirements of the 16th International Micro Air Vehicle Conference and Competition Outdoor Category missions. Our approach combined a custom-built main UAV, capable of performing target missions, with a lightweight swarm system optimized for cooperative transport.

Through modular hardware design, in-house manufacturing, and ROS 2–PX4–based software integration, we ensure flexibility, maintainability, and strong autonomy across the system. The implementation of two different payload deployment mechanisms for the Load and Release mission demonstrates our commitment to adaptability and iterative optimization.

Simulation-based prototyping using Gazebo, coupled with extensive field testing, allows us to refine our systems incrementally and identify potential failure points early in the development process. Our testing strategy emphasized safety, reliability, and performance across all mission scenarios.

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tion of existing equipment and the construction of new machines.

We would also like to thank the Ministry of Education of Poland for providing funding that enabled participation in the international IMAV competition. This support allowed a selected group of students to prepare multiple UAVs specifically for competing in chosen missions of the Outdoor Competition Category, as well as to expand their experience in both design and programming.

Special thanks are also due to the team assigned to carry out the project tasks, without whom participation in the competition would not have been possible. Experience from past competitions (national and international) allowed the team to work fast and develop a reliable system.

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