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Artificial Intelligence of Things-Based Modular Avionics System Solution for Swarm Unmanned Combat Aerial Vehicles (SUCAVs)

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Abstract. In this study, a modular avionics system solution is presented for fixed-wing fully autonomous controlled swarm unmanned combat aerial vehicles (SUCAV) that can successfully detect within-visual and beyond-visual targets in the mission area as many times as possible thanks to deep learning, lock on to the target for the desired period of time and destroy it, evade the locks of other armed unmanned aerial vehicles with maneuvers and continuously transfer the information it receives to ground stations. Armed unmanned aerial vehicles provide reconnaissance, surveillance and intelligence opportunities as well as detection and confirmation of within-visual and beyond-visual targets in risky, complex conflict zones. Avionics system architecture consists of three units: the air platform consisting of swarm unmanned aerial vehicles, the ground station where swarm unmanned aerial vehicles are tracked throughout the mission flight and the IoT platform. Swarm armed unmanned aerial vehicles can take off autonomously and calculate the orientation and direction information of all aircraft in the airspace. Accordingly, the locking process is performed via the high-resolution/wide-angle imaging system by focusing on the appropriate aircraft that can be tracked. With the artificial intelligence (AI) algorithms to be developed for the continuity of the locking process, it is ensured that the swarm armed unmanned aerial vehicles can perform appropriate maneuvers. Aircraft equipped with appropriate systems for autonomous flight have a mission computer to run the algorithms related to the task. A joint study is carried out with the ground station and IoT platform to ensure the controllability and tracking of the system during the tracking of the swarm armed unmanned aerial vehicles. In order for these specified design points to be successfully performed during the mission, the system has a stable and agile flight control.

Keywords: Swarm Unmanned Combat Aerial Vehicle, Fixed Wing Unmanned Aerial Vehicle, Avionics System, Artificial Intelligence of Things, Internet of Things, Deep-Learning, 5G Technology.

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1 Introduction

Since the first manned aircraft was produced, aircraft have been used intensively for military purposes as well as for civilian purposes [1-3]. Combat aircraft have developed and acquired important features such as high maneuverability, advanced electronic systems, low radar visibility and payload carrying capacity [4,5]. Unmanned aerial vehicles (UAVs), which have emerged in the recent past in parallel with the developments in technology and have shown that manned combat aircraft can undertake future tasks, are currently used by security forces for reconnaissance-surveillance and attack purposes [6-8]. Another application area that requires high autonomy and is one of the hot research areas worldwide is to provide UAVs with the ability to do dogfights performed by fighter jets [9-12]. While ten years ago, worldwide surveillance activities largely consisted of manned platforms, today, developments in areas such as high environmental awareness, decision-making ability and planning ability in dynamic environments are effective in UAVs performing air-to-air combat maneuvers [13-16]. Based on the idea that the air force structures will be entrusted to unmanned fighter aircraft in the new conjunctures of the armies over time, solutions are being created for UAVtechnologies in combat [17-20].

While these developments continue in the field of aviation, a new concept called Artificial Intelligence of Things strengthens human-machine interactions by performing Internet of Things (IoT) operations more efficiently together with the digital transformation, where all components of technology are changing rapidly [21-23]. It combines artificial intelligence (AI) technology with IoT infrastructure to improve data management and analytics [24-27]. The value of the data produced by devices using the Internet of Things goes beyond the limits with the support of artificial intelligence. However, artificial intelligence alone has serious difficulties without the data provided by the Internet of Things. The combination and harmonious operation of these two concepts increases customer experiences in the consumer world and improves business performance [28,29]. As businesses grow, the interest in competition, innovation and agility also increases. Therefore, examining information quickly and coming up with new commercial ideas becomes the primary priority. However, since IoT data is physically impossible for a human to analyze, artificial intelligence support becomes inevitable [30]. Combining different technologies has become a trend rather than a business strategy [31]. AIoT also emerges as a result of this trend [32,33]. The values that emerge with AIoT add value to products and business structures in every sector [34].

The Industrial Internet of Things (IIoT), which is currently used in industrial systems, enables networks to operate much more efficiently in communications established between machines or between humans and machines [35]. It is expected that supply chains and systems with stronger, healthier and lower margins of error will emerge with the artificial intelligence technologies to be added to these systems [36]. With the application of AIoT to systems, large amounts of data can be processed and calculated in a very short time. In this way, the necessary measures to increase efficiency in the workplace can be determined quickly, while insufficient productivity problems can be eliminated. Based on this, IoT sensors and artificial intelligence analytics are used for the predicted maintenance operations of the devices used in companies serving in the aviation and other transportation sectors [37,38]. However, as AIoT devices develop and become part of operations, systems and devices become smarter with algorithms they develop by learning from intense data flows, and can optimize operations and even perform self-maintenance operations when necessary.

Bringing these developments online faster, with less delay, more securely and at a lower cost in terms of infrastructure, 5G has the potential to lead to radical changes in the aerospace defense field, as in every sector. 5G has extremely high speed, low latency and a very wide bandwidth [39]. Thus, it can use higher level encryption without compromising the connection speed. In this way, it can establish more secure communication [40]. The new 5G infrastructure can be portable, and 5G antennas can be mounted on vehicles and even unmanned aerial vehicles [41,42]. In this way, fast and reliable connection can be brought to the front line, and high-bandwidth access and communication can continue uninterrupted despite dense urban areas, difficult geographical and climatic conditions [43]. Thanks to sensors, data flow can be provided about sensitive points. Command and control mechanisms can make fast decisions, coordination can be provided in complex processes, and dangerous missions can be carried out without the need for human intervention.

As emphasized in the examples in question, in today's world where interest in UAVs is increasing day by day, this study aims to understand what kind of avionics system the vehicles currently have and to understand the artificial intelligence structure created with deep learning capability and its impact on IoT. Developed in line with these objectives, this study includes a modular solution for swarm armed unmanned aerial vehicles that can provide formation, tracking, mission, intelligence, reconnaissance and communication capabilities, recognize and destroy enemy targets with a deep learning system, and collect data remotely from the sky with an IoT and ground platform and transmit it in real time. Also, authorized servers can receive mission orders on the IoT platform, report enemy target sets and have mission destructions. In SUCAVs designed for destruction, reconnaissance, surveillance and intelligence purposes, industrial data exchange and production technology context is created with engineers and designers from different disciplines after each mission flight. These concepts are an operational solution for unmanned aerial vehicles with artificial intelligence of objects created by combining deep learning, machine learning and artificial intelligence technologies with the Internet of Things infrastructure that simulates the behavior of the human brain by learning from data sets. It offers a military alternative model for UAVs that includes productivity, increased efficiency, savings, improved safety and security, and the collective swarm intelligence that emerges in future agent communities.

The main hypothesis of the study is that AIoT-supported SUCAV systems significantly increase operational efficiency compared to traditional unmanned aerial vehicle solutions. In this context, experimental studies were conducted on various metrics such as target detection accuracy, effectiveness of evasive maneuvers and data transfer rates, and the contribution of AIoT to operational efficiency was analyzed in detail in line with the results.

2 Related Work

[44] focuses on collaborative multi-robot systems for military applications. The study focuses on how multi-robot systems can be used in military operations. Collaborative multi-robot systems are systems where different robots work together to perform a task and create synergy. These systems can be used in various tasks such as reconnaissance, surveillance, explosive ordnance detection, and rescue in military operations. A review of the potential of 5G and satellite systems for UAVs is presented in [45]. The paper focuses on the command and control, navigation and surveillance systems of UAVs. It also discusses how 5G and satellite systems can enhance the navigation capabilities of UAVs. It also examines how 5G and satellite systems can enhance the surveillance capabilities of UAVs. In [45], a review is presented on unmanned aerial vehicle (UAV) swarm system coordination and communication. In general, it examines the current status, methods and future development potentials in the field of coordination and communication of UAV swarm systems in detail. This study examines the methods used for effective coordination and communication of UAV swarms. However, unlike Singh et al., the current study presents a system that can be optimized according to specific mission requirements due to the customizability of UAV swarm coordination and communication systems.

[46] presents a comprehensive review of swarm intelligence algorithms for the cooperation of multiple unmanned aerial vehicles (UAVs). In this study, various swarm intelligence algorithms used for the interactive and coordinated operation of UAVs are examined. In general, the swarm intelligence algorithms used for the cooperation of multiple UAVs are examined in detail. These algorithms include methods such as ant colony optimization, particle swarm optimization, bee colony optimization, and firefly algorithm. The working principles, advantages, and disadvantages of each algorithm are discussed. In addition, different methods and strategies used for the cooperation and coordination of UAVs are discussed. These strategies include leader-following, task sharing, communication protocols, and routing techniques. Unlike Tang et al.'s study, the current study can increase coordination and perform tasks more effectively by using swarm intelligence algorithms for cooperation among UAVs. In [47], unmanned aerial vehicle (UAV) swarm design, flight patterns, communication types, applications and recommendations are discussed. The aim of the study is to provide design guidelines for UAV swarms and to evaluate the current applications in this field. Topics such as UAV swarm design, swarm communication, swarm management and flight patterns are examined. While the current study presents a more specific and detailed modular avionics system design, the study of Myjak and Ranganathan provides a more general review. In addition, the current study focuses on more advanced technologies such as deep learning, artificial intelligence and target acquisition/locking capabilities.

In this context, the current study uses more advanced hardware to design a modular avionics system for swarm unmanned aerial vehicles. This distinguishes the study from other studies and provides a more advanced level of technology and hardware. Advanced hardware provides higher performance, reliability and flexibility, allowing it to be used more effectively and efficiently in military operations. In addition, it focuses on the target detection and destruction capabilities of unmanned aerial vehicles. This provides an advanced approach to the process of accurately detecting and effectively destroying targets, which are of great importance in military operations. These capabilities enable military forces to conduct their operations more safely, quickly and effectively. In addition, the use of deep learning and artificial intelligence techniques brings advanced techniques used to analyze the data of swarm unmanned aerial vehicles, perceive their environment and enable them to make more intelligent and autonomous decisions. Deep learning and artificial intelligence enable the study to provide a more efficient, flexible and customizable system. The application areas of the study include target detection and destruction capabilities in risky and complex conflict zones. This provides a system that can perform vital tasks in military operations. The applicability and importance of the study is aimed to help support the operations of military forces in real-world conditions. These advantages emphasize the future benefit and importance of the study. Advanced hardware, target detection and destruction capabilities, deep learning and artificial intelligence techniques provide a system that can be used more effectively, safely and efficiently in military operations. In the future, it is expected that such advanced technologies will be more widely accepted and used in military operations.

Compared to traditional methods, AIoT-supported swarm armed unmanned aerial vehicles (SUCAV) offer various innovative components that increase operational efficiency. First of all, the real-time data processing capacity of these systems enables faster and more accurate decisions to be made in target detection and tracking processes. While decision mechanisms in traditional systems are usually directed by human operators, AIoT-based SUCAVs analyze the data they acquire during flight instantly to optimize threat detection, avoidance and target destruction processes. However, thanks to the IoT infrastructure, high-speed data sharing is realized between individual unmanned aerial vehicles in the swarm and the need for a central command and control system is minimized. This allows operations to be conducted more flexibly and autonomously, especially in dynamic conflict environments. In addition, the continuous learning capability of AI-supported systems improves flight and maneuver algorithms in line with the data acquired in the field and increases mission success rates. As a result, the benefits offered by the current study create a system that has aspects that are potentially prominent and can be used successfully in the field of UAV swarms. Focusing on topics such as cooperation, swarm intelligence algorithms and communication/coordination of UAVs, the study has the potential to make a significant contribution to the development of UAV technology and the expansion of its application areas.

3 Aerial Platform

The avionics system architecture given in Fig. 1 is built on three units in order to fulfill the flight and mission requirements in a healthy way. These are UAV with full autonomous driving capability that will identify and lock on to targets and perform the shooting, ground control station where the mission and flight can be monitored and executed in a healthy way and IoT platform where the desired information is transferred to remote servers and the target is reported. In addition, various subsystems that provide the necessary communication have been established so that all of them can work together and in coordination according to different requirements. In order for the mission to be fulfilled successfully, all these systems must work in harmony with each other. Therefore, special attention was paid to compatibility during the selection of hardware. The aerial platform consists of swarm unmanned aerial vehicles equipped with different electronic equipment and advanced artificial intelligence robotic systems that fly in the air for a certain period of time. Swarm unmanned aerial vehicles will take off autonomously, correct their position and remain in the air. Swarm unmanned aerial vehicles will calculate the orientation and direction information of all targets within the mission area. In case of incoming targets from the ground station or IoT platform, they will start the mission by analyzing the information of the targets and developing an attack strategy and formation.

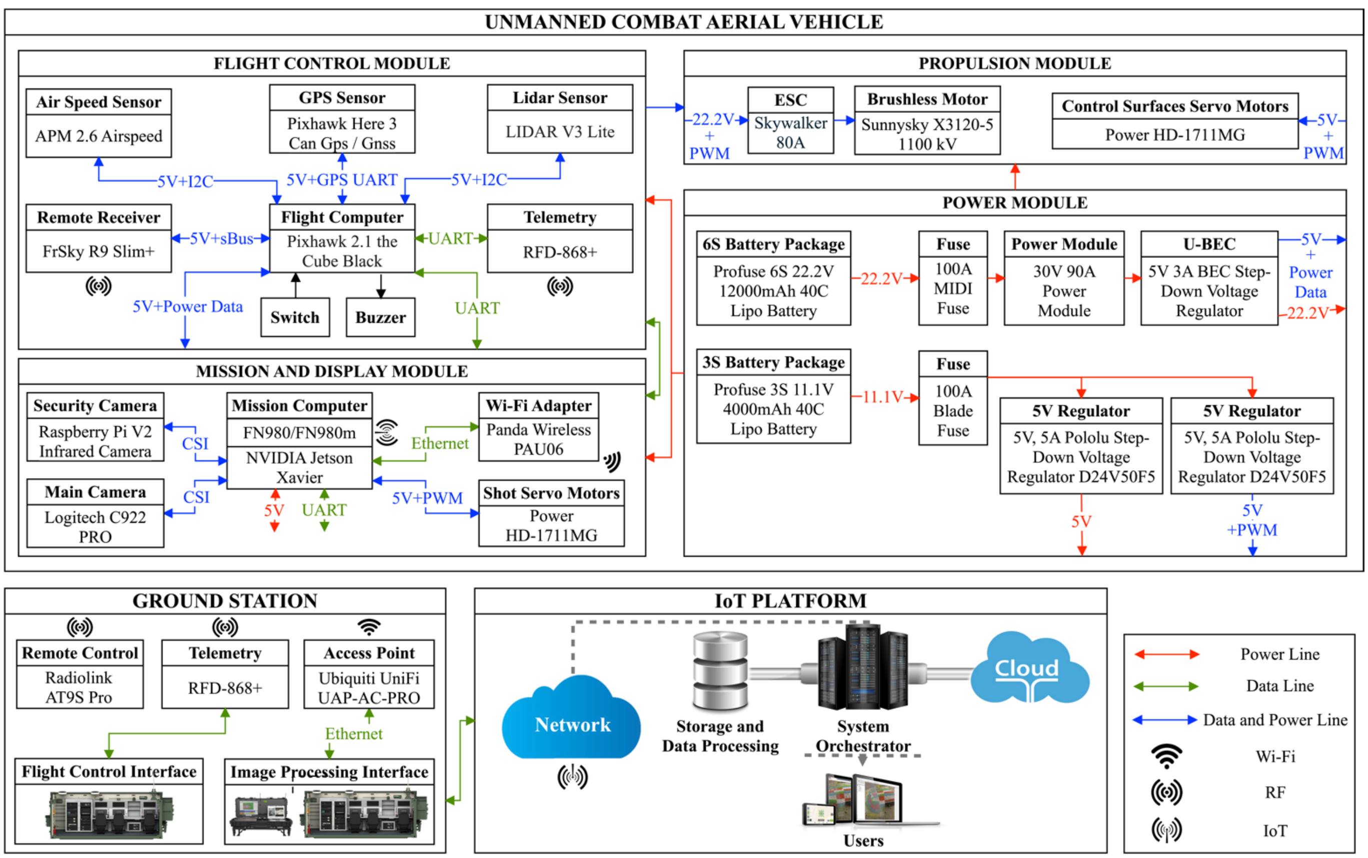


Fig. 1. Block diagram and system architecture of all components of the UAVavionics system.

Swarm unmanned aerial vehicles that start the mission will determine the most suitable targets for themselves from the location information of the targets they receive via telemetry from the ground station and will be locked on via the imaging system with the tracking algorithms used with their cameras and the shooting will be carried out. The continuity of the autonomous locking process on the target and the artificial intelligence algorithms developed to avoid being targeted by the enemy and being locked on, have ensured that the platform can perform appropriate aggressive maneuvers. During the flight, location, altitude, speed, axis inclination, acceleration value and similar data will be sent to the ground station with 868 MHz telemetry at a minimum rate of 1 Hz per second. At the same time, it will process the image taken from its 8-megapixel camera on its NVIDIA Jetson computer and instantly transmit it to the ground station as analog video. In addition, a joint study will be carried out with the ground control station and the IoT platform to ensure controllability and tracking of the system during the time the swarm unmanned aerial vehicles are tracking. The flight computer and image information coming from the air platform to the ground antennas will be made meaningful to the ground control station and sent to the IoT platform in the desired format. In order to ensure control of the air platform in an emergency, the safety pilot commander will be able to manually direct the ground control station. It will be able to land autonomously or manually after the mission flight. The air platform is designed to consist of 4 units, namely flight control unit, mission unit, thrust unit, and power unit, based on the specified mission and flight requirements. In order to meet these requirements, the system boundaries are determined according to these requirements during the conceptual design process of avionic systems. The boundaries of the avionic system for the air platform are also determined for subsystems such as the amount of power requested and the amount of power the avionic system can provide. Within these system boundaries, the boundaries of the avionic system, especially against external effects such as thermal and electromagnetic, are also determined.

Mission control system; It provides evaluation of target information coming from IoT or ground station and images coming from camera, tracking of mission algorithm in the most appropriate way, management and administration of escape and other sub-algorithms. With mission control system, images obtained from camera can be interpreted with target detection algorithms and necessary inputs for control system can be obtained. Data of rival vehicles obtained from IoT or ground station will be evaluated with algorithms to be executed in ground station and target information which is most suitable for orientation of swarm unmanned aerial vehicles will be transferred to mission control system. Both outputs obtained from camera and outputs obtained from evaluation of information transmitted from ground station will be transmitted to flight control system for systematic orientation of vehicle by mission control system. Correct management of these operations requires mission control system to process the information transmitted to it correctly. Main component of mission control system is mission control computer. Nvidia Jetson Xavier NX is used as mission control computer. The most important factor in choosing this computer is that the graphics processing units (GPU), which are the most important structure in running artificial intelligence and detection algorithms, can be run much more efficiently and quickly with Jetson Xavier's CUDA technology. Since the operation that will create the most load on the computer will be the execution of vehicle detection algorithms, it is very important to have CUDA technology. Jetson Xavier NX, which is used to cope with the processing load brought by the tracking and image processing algorithms developed in unmanned aerial vehicles, is a powerful AI Edge computer produced by Nvidia. This compact device is optimized for high-performance artificial intelligence applications. Jetson Xavier NX has a GPU based on NVIDIA's Volta architecture. It supports 512 CUDA cores, 64 Tensor Cores, and fast Input/Output (I/O) speeds of up to 750 GB/s. This powerful GPU can perform deep learning and artificial intelligence operations quickly and effectively. This computer is powered by an 8-core NVIDIA Carmel Arm® v8.2 64-bit CPU. Jetson Xavier NX is equipped with a variety of general-purpose input/output pins, pins and ports that support communication protocols. This allows it to work with additional hardware and support a variety of connection options. In addition, Jetson Xavier NX is equipped with a 500 GB SSD memory module to provide sufficient storage space. This allows you to store larger software files and data sets and increase processing capabilities. There are two camera systems on the mission computer to be placed in front of and behind the unmanned aerial vehicles. Logitech C922 PRO Web Camera, which is introduced and connected as a webcam with 1080p/30fps-720p/60fps high resolution and fps with anti-shake systems, is used in front of the vehicle for basic mission execution. At the rear of the vehicle, a Sony IMX219 8-megapixel, 90 FPS, 1080p resolution, high viewing angle (horizontal: 62.2°, vertical: 48.8°), lightweight Raspberry Pi V2 camera module compatible with the mission computer is used to enable the vehicle to escape from enemy vehicles.

The flight control system processes the meaningful information coming from the mission control system and sends the necessary commands to the swarm unmanned aerial vehicles. The Pixhawk Cube Orange flight control card is used, which contains up to three 10-axis IMUs with signal vibration suppression, an integrated FMU, and a large number of various I/O ports (PPM, SBUS, UART, etc.) with a heating system for low-temperature flight. The flight control system requires different sensor information to operate correctly. ArduPlane 4.0.8 flight control software is run over the Pixhawk Cube. The airspeed information coming from the pitot tube and the global position information provided by the GPS feed the ArduPlane flight control software, which will run within the flight control computer. Thanks to ArduPlane's open source code, it allows the addition of new flight modes and new controllers, and it is a stable controller, it can effectively implement different control theories in discrete time, the relevant controller coefficients (PID coefficients of 'Attitude Controller') can be easily determined thanks to an internal flight mode ('Auto-tune' mode), it has a fail-safe flight mode, and it has filtering algorithms applied in non-linear systems such as 'Extended Kalman Filter', facilitating flight control. Thanks to flight modes such as "Fail-Safe" and "Advanced Fail-Safe" for possible emergencies, it allows the aircraft to return to the flight area autonomously when it leaves the predetermined area and to stall and crash in a potentially dangerous situation. However, since there is no flight mode with tracking feature in the ArduPlane software, a flight mode called "Automated Flight Following" was developed and added to the control software. APM 2.6 Airspeed Sensor compatible with Pixhawk is used. The APM 2.6 Airspeed Sensor communicates with the Pixhawk Cube Orange using the I2C protocol. In order to prevent the swarm of unmanned armed aerial vehicles from hitting enemy vehicles and to perform their own self-defense, there is a LIDAR V3 Lite lidar distance sensor at the front and back. The location information is provided by the Here 3 GPS module, which provides precise location data thanks to the u-blox M8 high-sensitivity GNSS receiver that can work in harmony with the Pixhawk Cube Orange. The Here 3 GNSS module is connected to the I2C port because the use of these ports provides higher efficiency when adjusting the parameters of the autopilot card. The Here 3 GPS module carries the safety button used for safer operation of the vehicle. During lock-on, maneuver management is again performed by the flight control system according to the MAVLink messages from the mission computer.

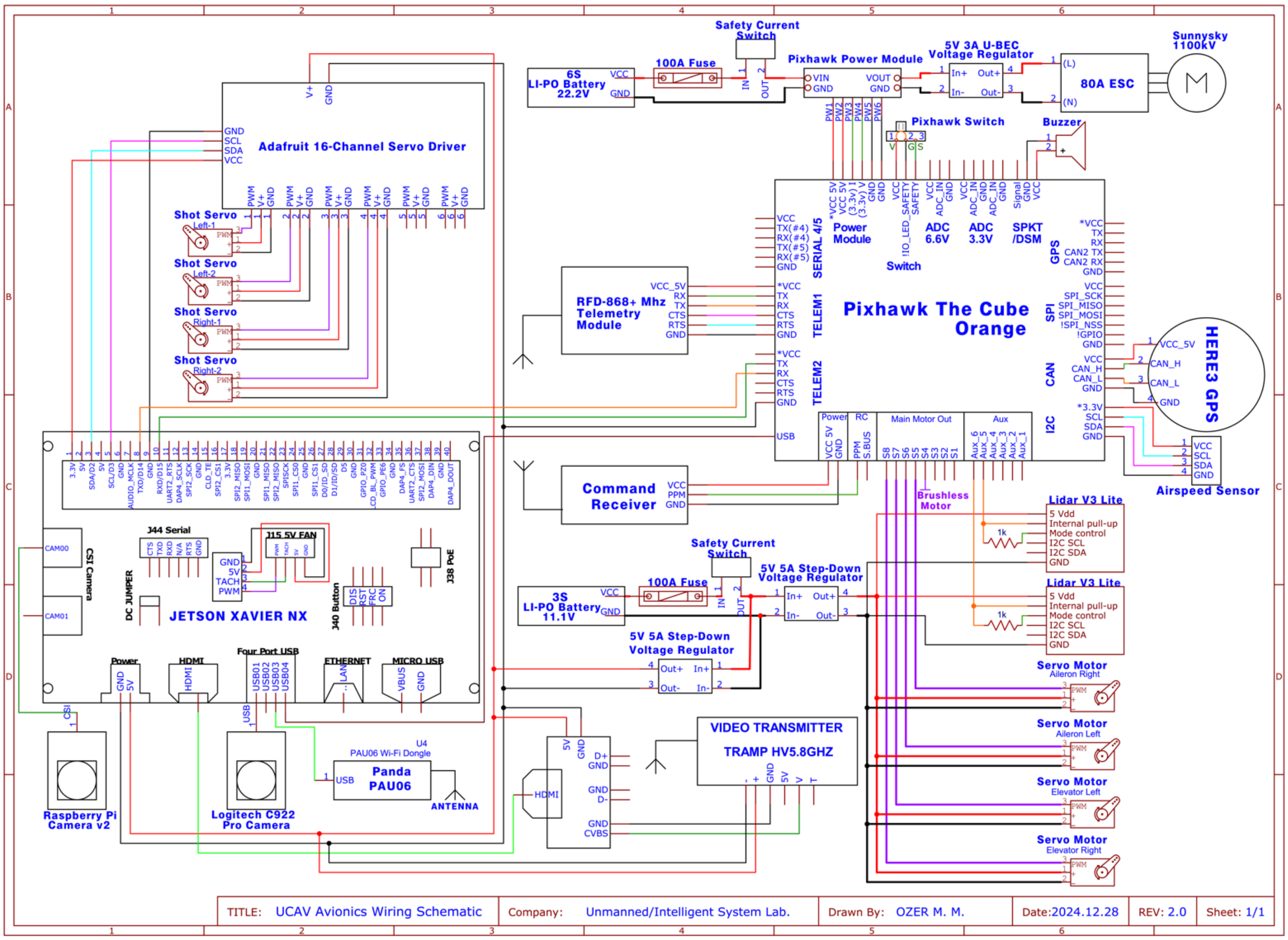


Fig. 2. Unmanned combat aerial vehicle avionics system circuit wiring diagram.

In order for systems to work healthily with each other, communication between them must also be carried out healthily and uninterruptedly. Four different communication processes take place on the swarm unmanned armed aerial vehicles, at the ground station and on the IoT platform. One of these systems is carried out in a wired manner in accordance with the UART communication protocol between the mission computer and the flight control system. The cables coming out of the RX (receiver) and TX (transmitter) pins of the Nvidia Jetson Xavier NX are connected to the telemetry port of the Piwhawk Cube Orange together with the grounding line. The other two communication processes take place between the swarm unmanned aerial vehicles and the ground station. The safe and accurate transfer of sensor data on the aircraft to the ground station during autonomous flight is important both in terms of flight safety and autonomous flight performance. Telemetry information is provided by connecting RFD-868+ telemetry modules, which can broadcast up to 40 kilometers and are compatible with the ground station having a powerful processor and can transfer much more sensitive data thanks to its low-pass filter structure, to the Pixhawk Cube Orange and the computer in the ground station. Manufactured by Pixhawk and having a maximum shooting range of 40 km, this module operates at a frequency of 868 MHz. Another communication process that takes place between the systems is between the mission computer and the ground station for the transfer of image and lock information. This process is carried out by the ground station and the mission computer being connected to the same network. In order to ensure a healthy network connection, a Wi-Fi USB Adapter is used on the vehicle and an access point is used in the ground station. The Panda Wireless PAU06 300 Mbps Wireless

N USB Adapter connected to the Jetson Xavier NX on the UAVs supports the IEEE 802.11n wireless standard and operates in the 2.4 GHz frequency band. It provides a maximum data rate of 300 Mbps. It offers the opportunity to use different types of antennas to ensure that wireless signals spread over a wider area. In addition, the Ubiquiti UniFi UAP-AC-PRO access point located in the ground station supports the IEEE 802.11ac wireless standard and can operate in the 2.4 GHz and 5 GHz frequency bands. It offers a maximum data rate of 1750 Mbps and the opportunity to use with internal or external antennas for wider coverage. The final communication between the systems is the IoT connection between authorized smart devices and 5G Telit FN980/FN980m, which includes both Sub-6 and mmWave technologies with LTE, WCDMA, GNSS support for service providers working with professional mobile high-definition video broadcasting equipment and more that can be directly integrated to Nvidia Jetson Xavier NX. In this way, high-power fixed wireless access, enterprise routers and gateways, professional broadcasting and surveillance are provided. The FN980m also supports the Qualcomm QTM525 mmWave antenna module for low-power indoor and outdoor applications near the ground, and the Qualcomm QTM527 mmWave extended-range antenna module for high-mount outdoor applications.

The vehicle provides the necessary thrust with a SunnySky X3120 1100 kV brushless motor. Haoye 11x5.5 cm propeller is used to meet the thrust requirements. All electronic systems and the power required for the brushless motor are provided by Profuse 6S 12000 mAh 40C and Profuse 3S 4000 mAh 40C Li-Po batteries with high energy efficiency and light mass. In order to obtain high RPM in the motor used to provide thrust, it was decided to use a 6S Li-Po battery that can be used at maximum, and a 3S Li-Po battery for the servo motors. The remaining systems in the vehicle are also powered by these two batteries. An 80A Skywalker ESC is used to accurately control the power from the battery to the motor and to direct the flight. A 30V 90A power module is used to protect the flight control subsystem. In order for the pilot to take control of the armed unmanned aerial vehicles as quickly as possible in the event of an adverse situation during autonomous flight, there must be a sufficient number of keys on the control to provide mode transition. FrSky Taranis X9D Plus control is used to provide these features expected from the control system. There is a FrSky R9 Slim+ receiver on the vehicle for communication with the control. The receiver establishes wired communication with the flight control computer in accordance with the SBUS communication protocol. As shown in Fig. 2, the distribution of the cables that provide power distribution for all electronic systems of the armed UAV within the fuselage is intended to be made in a way that will affect the sensors as little as possible.

4 Ground Station

Although the designed UAV platform performs its tasks completely autonomously, it requires a ground station to monitor the system, make autonomous flight configurations of the vehicle, examine its data and establish a connection with the IoT platform. As shown in Fig. 3, this communication is displayed on the ground station and transferred to the IoT platform for flight data from the unmanned aerial vehicle. In addition, the information received from the IoT platform is processed and plays a role in determining the commands sent to the vehicle. In addition, a serial connection is established between the flight and mission computers in the vehicle to transfer the commands that direct the flight for the successful execution of the mission. The ground station is classified and separated in two different ways. The first of these is the flight control interface, which will enable the adjustment of the basic parameters of the vehicle and send the necessary data for autonomous flight. The communication system on the vehicle has three separate communication systems. These systems provide communication between the mission computer and the ground station for image transfer and locking information transfer, communication between the flight control card and the ground station, and communication between the remote control that will be under the control of the pilot and the receiver on the vehicle for manual control of the vehicle.

4.1 Telemetry Communication

In order to transfer health, location, gyroscope, sensor and calibration data from UAV sensors to the ground station, a telemetry communication system that can work in harmony with the autopilot system is needed. Since telemetry packages do not have large dimensions, the RFD 868x telemetry module with low frequencies is used to transmit telemetry information between the flight control card and the ground station, since it has a range greater than the minimum distance considered safe for a mission flight. The RFD 868x can operate properly in the 868-869 MHz band, where there are no legal restrictions on its use. The system with 1 W output power can operate at different air data transfer rates and UART data transfer rates. The device is used at the default air data transfer rate of 64 kbit/s and the default UART data transfer rate of 57600 baud. These and other similar settings can be made on the module using AT commands. The fact that the RFD 868x module supports the ArduPilot flight control software to be run within the flight control card provides an advantage in terms of system integration. In addition, in order to avoid any disruptions and problems in communication during a mission flight where more than ten vehicles will be in the air in swarm missions, the RFD 868x has the Frequency Hopping Spread Spectrum (FHSS) feature, which prevents possible confusion and data loss that may arise from other data transfers taking place on the same frequency. With the FHSS feature, it transmits the information it will send using a large number of sub-frequencies formed by dividing a wide frequency range. In addition, the system is encrypted to prevent interference with other telemetry devices and possible radio signals in the vicinity. The connection between the RFD 868x and the Pixhawk Cube on the vehicle is provided via a serial connection in the UART communication protocol standard.

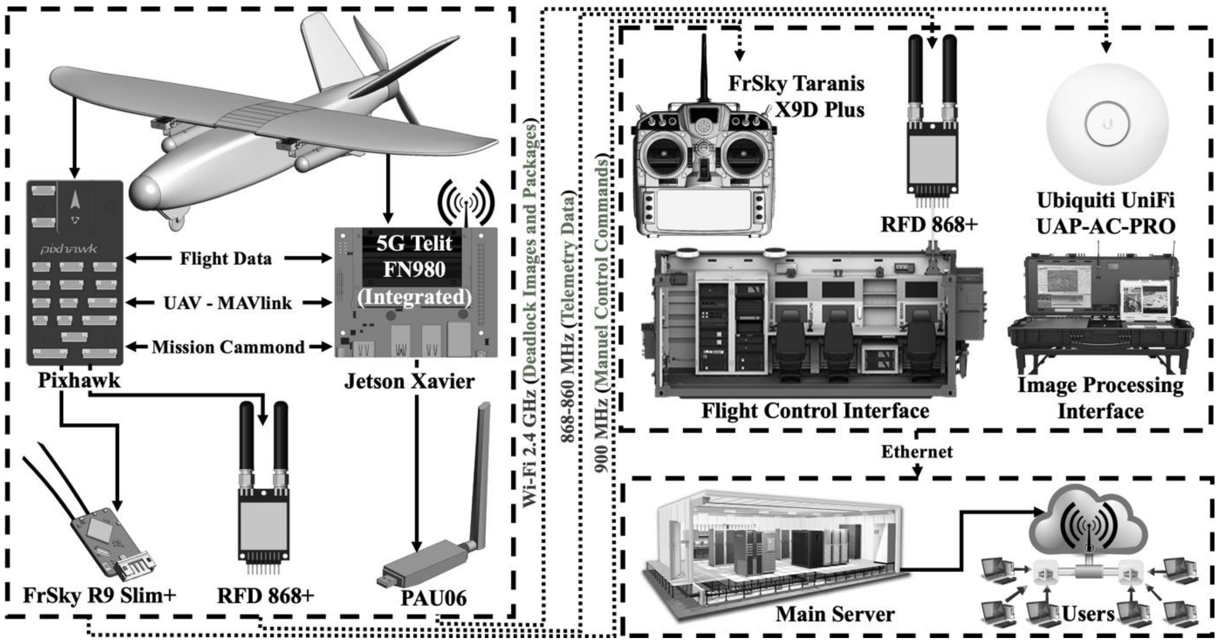


Fig. 3. UAV communication block diagram.

4.2 Wi-Fi Communication

One of the mission requirements is to transfer images from the vehicle to the ground station. In order to meet this requirement, a Wireless Wireless N USB Adapter connected to the mission control computer is placed on the vehicle. In addition, a network is established between an access point with an antenna on the ground station and the ground station. Thus, data transfer can be made between two computers connected to the same network. The Panda Wireless PAU06 300 Mbps Wireless N USB Adapter hardware is used on the unmanned aerial vehicle and the Ubiquiti UniFi UAP-AC-PRO 1750 Mbps Access Point is used on the ground station. Both systems can operate in the 2.4 GHz band and transfer data at speeds of 300 Mbps. The systems support 801.11 n/ac Wi-Fi standards. In order to provide image transfer at a sufficient range, the antenna used in the ground station is selected from models that can detect directional signals. Since the antenna is directional, it needs to follow the vehicle during flight. Therefore, a vehicle tracking system is being developed for the antenna located in the ground station. Real Time Streaming Protocol (RTSP) is used in video transmission over the network with the help of Gstreamer library. Since the factors that may cause the connection between the access point and the wireless USB adapter to be disconnected in this system established for image transmission over the wireless network are not clearly known, the image is transferred analogously using FPV image transmission systems to transfer the relevant image. In this way, precautions are taken against possible problems. The receiver at the ground station of the FPV system is RC832, and the transmitter on the unmanned aerial vehicle is the TS832 module. This system operates in the 5.8 GHz band and also supports the transmission of the image in analog NTSC or PAL format.

The access point provides reliable transmission of data sent by Jetson Xavier NX. The ground station software is the interface used in the ground station and manages the data communication between Jetson Xavier NX and the access point. The information collected by the UAV, such as images, object detection and tracking data, is transmitted to the YKİ software via the access point. This software allows the user to control the UAV and take the necessary actions according to the received data. In this way, using Jetson Xavier NX with the Panda Wireless PAU06 adapter and Ubiquiti UniFi UAP-AC-PRO access point enables the UAV to transfer image data and object detection and tracking data reliably with the ground station. The QGroundControl software manages this data, optimizes the control of the UAV and makes the necessary decisions based on the received data. In order to transmit flight, image, locking data to the ground station using Wi-Fi and telemetry communications from the transmitter in the vehicle, to give commands to the aircraft and to transfer the data to the IoT platform, a ground antenna must be used at the ground station. For this purpose, two separate antennas are used: a video receiver ground antenna that provides faster video from the air platform to the ground station with the Wi-Fi module and telemetry sensors, and a telemetry ground antenna that provides different flight data from the air platform to the ground station with the telemetry module. In order for the Wi-Fi and telemetry communication used to transmit data in a healthy way, the antenna must look at the swarm of unmanned aerial vehicles during the flight. In order to overcome this difficulty, a mechanism that follows the aircraft carries the ground antenna. The established system will follow the aircraft autonomously and ensures that the antenna looks at the aircraft at all times. The telemetry data and images coming to the ground station via the antenna are instantly transmitted to the IoT platform.

4.3 Control Command Communication

Although the established system has autonomous maneuvering and flight capability, in emergency situations, remote pilot intervention may be required for the vehicle to fly and perform various side tasks. At this point, in order to ensure that the aircraft can be controlled by the pilot, the FrSky R9 Slim+ remote control receiver placed inside the unmanned aerial vehicle is accessed directly or via the flight controller to the servo motors that move all control surfaces, via the FrSky Taranis X9D Plus transmitter remote control with joysticks and switches. Thus, a more secure and stable system is established. There is a secure connection between these two components, which communicates at 2.4 GHz frequency and 900 MHz bandwidth, even over long distances. In addition to providing servo movements with PWM signals, Pulse Position Modulation (PPM) can perform the movement of multiple servos from a single signal cable. In this way, both cable confusion is eliminated and the system is made more stable. The autopilot system used receives modulated PPM outputs from the SBUS output of the control receiver in the Pixhawk The Cube Orange system architecture and enables the rotation of the servo motors that provide the maneuvers of the vehicle. The servo signals coming from the control receiver to the control receiver are processed and received as an input signal. These incoming signals are Pulse Width Modulation (PWM) signals and the incoming servo signals are converted to PPM signals by inserting a monostable multivibrator. The control receiver separates different points of a full pulse for each servo according to its own channel number. Then, depending on which channel the incoming servo signal is from, it places that signal where it should be in the PPM signal and adjusts its width according to the servo rotation angle in the PWM signal. In this way, all servo motor controls can be performed with a single signal cable.

4.4 Iot Platform

Although the main mission of a swarm UAV is to destroy enemy targets, it should also collect data from remote locations for tasks such as reconnaissance, surveillance and intelligence. The transmission of this data to authorized smart devices on the ground and in different regions requires having IoT devices to provide destruction mission orders to UAVs, enemy target set notifications and real-time tracking of the destruction mission. In addition, a reliable data transmission system is needed to share the data collected from the sensors and cameras on the UAV with other UAVs, ground stations and authorized smart devices in the network. In addition, an integrated IoT platform needs to be mounted on the swarm armed UAVs to collect and transmit IoT data with sensor and camera modules at a certain altitude and use IoT devices. For this reason, an IoT gateway is being developed with an Nvidia Jetson Xavier NX that allows different IoT devices to be connected, installed and activated, as shown in Fig. 4.

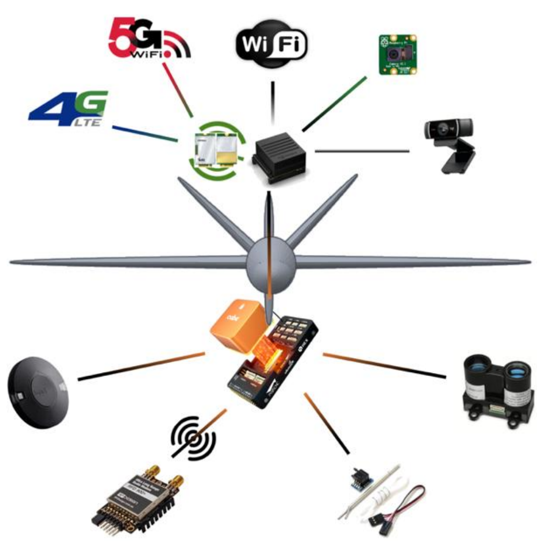


Fig. 4. UAV equipped with various IoT devices, sensors and modules.

Using the platform, when IoT devices are activated at the intended locations, IoT data can be collected remotely from the sky or transmitted in real time. Also, depending on the need, the collected data can be processed locally on the UAVs or transferred to an authorized server on the ground. In fact, mounting such an IoT platform on a swarm of armed drones enables them to provide value-added internet of things services (VAIoTSs) from the sky. When these UAVs are massively deployed, organizing them to provide VAIOTS becomes a complex problem, although each armed drone has multiple IoT devices, so each armed drone has a different type of access technology (e.g., a cellular system or Wi-Fi). Therefore, it uses a central system orchestrator that organizes the UAVs and their on-board facilities, and an efficient communication architecture that enables the UAVs to connect to the system orchestrator or other UAVs, as shown in Fig. 1. In addition, it also includes mission lock information and instant flight status information of the vehicle by establishing a data connection with the help of a router to transfer data related to the mission/flight between the nearby servers and the ground station to the server and to increase the success of the mission during the mission. The process of receiving data from the server, processing it, creating orders to go to the vehicle and transferring the data coming from the vehicle to the server with a minimum frequency of 1 Hz is automated with a pre-prepared Python interface. Python - Request module is used for communication with the server and MAVSDK library is used for communication with the vehicle.

5 Autonomous Deadlock

After the unmanned aerial vehicle determines an attack strategy during flight, the lock-on algorithm is also put into operation. The term autonomous flight algorithm is used to describe the algorithm that manages the decisions and maneuvers made by the aircraft within the strategies it will implement independently of external interventions in a holistic framework; while the term lock-on algorithm is used to describe the entire decision mechanism that enables the aircraft to perform actions such as location detection, visual detection, tracking and profiling of targets with the holistic use of data from the IoT and ground station and internal sensors while the aircraft is in autonomous flight. These two algorithms, which operate in real time, will continuously strategically evaluate the rival aircraft whose location is detected and decide on the action to be taken. The autonomous locking algorithm basically consists of 2 steps: autonomous detection and autonomous tracking.

The general working principle of the algorithm given in Fig. 5 starts with target detection during flight. After the target is sufficiently approached, the location of the target that enters the camera image is detected on the image using deep learning-based object detection algorithms. Then, the horizontal and vertical location of the target on the image is transferred to the ground station with the information that the detection has been made. Finally, continuous tracking is provided by the maneuvers of the swarm armed unmanned aerial vehicles in the necessary roll and pitch axes according to the incoming data. Since autonomous detection and tracking sections include research and method processes, they are examined under two separate headings. Autonomous approach to the target is provided by giving GPS data of the opponents that send healthy telemetry data as a reference to the swarm unmanned armed aerial vehicles. Whether the opponents send healthy telemetry data is understood by the time difference parameter specified in the communication document.

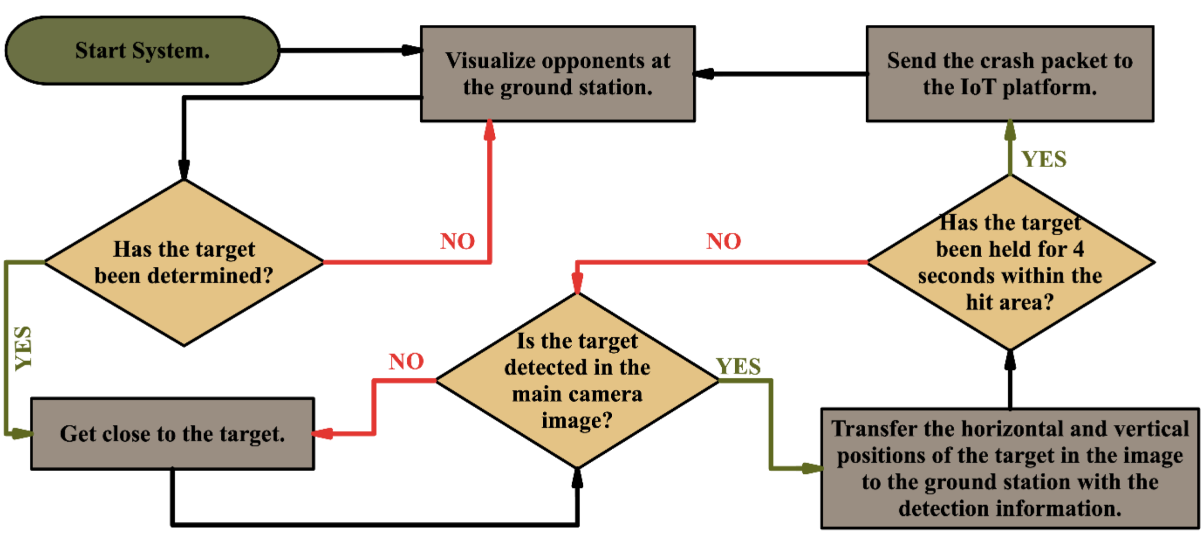


Fig. 5. UAV real time autonomous object and vehicle deadlock algorithm block diagram.

5.1 Autonomous Detection

The purpose of autonomous detection is to receive the image from the camera and transmit the information that the detection has taken place to the ground station in addition to the horizontal and vertical position of the target on the image. First, the target needs to be detected autonomously on the incoming image. For this case, target detection can be done using the window shifting method on the image with algorithms such as Support Vector Machines or Random Forests, as well as target detection can be done using deep learning-based object detection algorithms. Since deep learning-based object detection algorithms are superior in terms of both success and speed, they are used in swarm unmanned armed unmanned aerial vehicles for autonomous detection. Among deep learning based neural networks, algorithms such as YOLO, Single Shot Detector (SSD) and Faster Recurrent Neural Network (Faster R-CNN) have come to the fore. In order to determine the most effective algorithm, various comparisons were made in different system configurations and according to the results, it was determined that the YOLO algorithm is more successful than other algorithms in terms of accuracy, speed and compatibility with tracking systems. These algorithms have different methods for finding objects on images. The descriptions, features, success and speed (FPS) rates of the most commonly used of these methods are given in Table 1. When the algorithms were compared in terms of success rate and disadvantages, it was decided to use the YOLO algorithm since YOLO stands out [49].

Table 1. Comparison of UAV Object Detection Algorithms According to Method, Disadvantage, Success Rate and Frame per Second.

Name of Algorithm	Method	Disadvantage	Success Rate	FPS
Single Shot Detector (SSD)	It approaches the image at a rate determined by the user and divides it into squares at the specified rate. Image processing is performed on these divided images to obtain object class and location estimates.	In general, it has difficulty finding objects.	93.7%	46
You Only Look Once (YOLO)	The image is divided into frames at a specified ratio. After this division, each frame makes an estimate of the position of 5 objects and its certainty in this decision. From the combination of the estimates, the position of the actual object is obtained.	Has difficulty finding objects that are very close to each other or small in size.	95.4%	54
Faster Recurrent Neural Network (Faster-RCNN)	It creates new images by cutting out the locations that could be objects with the region proposal network. Then, it makes predictions.	Many region proposals are required to detect several different objects on the captured image. For this reason, it is slower than other methods.	96.1%	23

The YOLO algorithm stands out as one of the most advanced deep learning algorithms that can detect objects in real time and works with GPU support. One of the most striking features of this algorithm is that it can analyze each frame obtained from the image in a single process step and thus complete the object detection process without any loss of time. Since its first launch, it has been continuously developed according to user needs and more efficient versions have been produced and made available for use. As its name suggests, the You Only Look Once (YOLO) algorithm can perform object recognition and detection quickly in one go. When the YOLO algorithm works, it detects the locations of objects in images or videos at the same time. Images consist of a single frame, while videos consist of multiple frames combined. While the algorithm works repeatedly in videos, it works for a single frame in images. The YOLO algorithm first divides the image into regions. Then it boxes the objects it finds in each region. This boxing process is called ‘bounding boxing’.

These bounding boxes write the name of the object it finds and its probability of being found outside the frame, usually on the top left or in the middle. After deciding to use the YOLO algorithm, different trainings are carried out to decide which version of this algorithm will be used. When choosing this algorithm, the first thing to consider is accuracy, followed by the number of operations that can be done per second, or in other words, the number of object tracking per second. One of the most important reasons for using the YOLO v5 model is that it provides both faster and more accurate results than YOLO v3 and YOLO v4, as shown in Fig. 6.

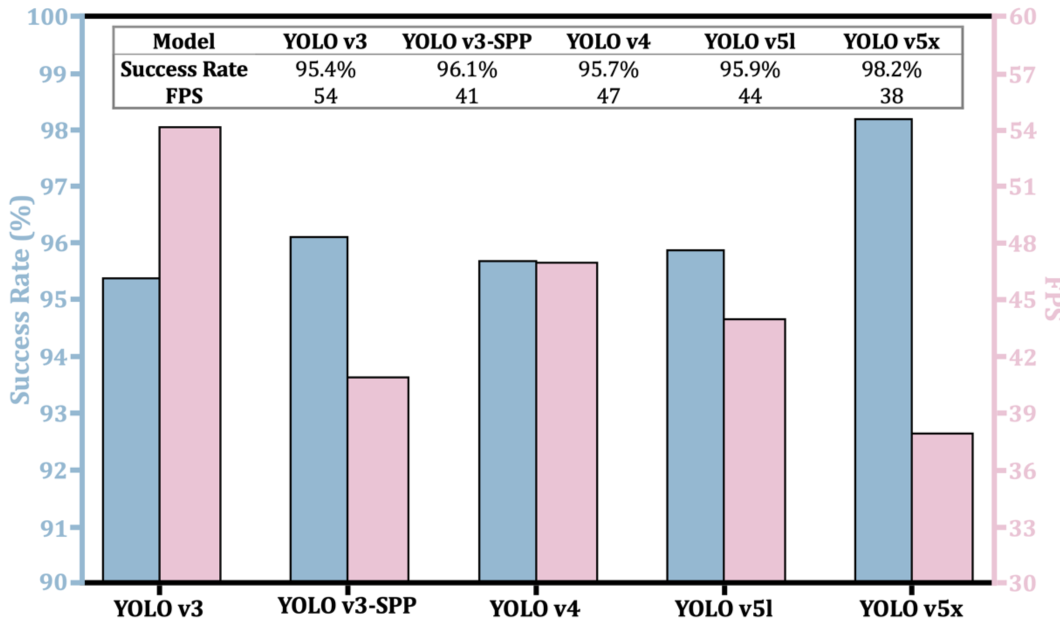


Fig. 6. Comparison of different YOLO models education test results according to succes rate (blue, left label) and FPS (pink, right label).

The YOLO v5 model also has model differences among itself. The YOLO v5 algorithm, various parameters of which are given in Table 2, has different models such as YOLO v5s, YOLO v5m, Yolov5I and YOLO v5x. Since the Nvidia Jetson NX Javier card selected for some operations to be performed by the armed unmanned aerial vehicle such as artificial intelligence, image transfer and communication has the memory that the algorithm will need together with the 500 GB SSD memory module installed, memory parameters are not important. The most striking of these model differences is the high or low mAP value. In order to evaluate object detection models such as YOLO, the average sensitivity (mAP) is used, which gives a score by comparing the ground reality bounding box with the detected box. The higher the score, the more accurate the model detections are. When the mAP values of these models are compared, it is seen that the average sensitivity value of the YOLO v5x model is higher. However, when the latency times are compared, it shows that YOLO v5s is the most efficient in the GPU FPS values obtained.

Table 2. Comparison of training test results of different versions of the YOLO v5 model selected for use [50].

Model	Size (pixels)	FLOPs @640 (B)	mAP^{val} 0.5:0.95	mAP^{val} 0.5	$Speed_{CPU}$ b1 (ms)	Speed V100 b1 (ms)	$Speed_{GPU}$ V100 b32 (ms)	FPS_{GPU} V100 b32 (1000/ms)
YOLO v5n	640	4.5	28.0	45.7	45	6.3	0.6	1666
YOLO v5s	640	16.5	37.4	56.8	98	6.4	0.9	1111
YOLO v5m	640	49.0	45.4	64.1	224	8.2	1.7	588
YOLO v5l	640	109.1	49.0	67.3	430	10.1	2.7	370
YOLO v5x	640	205.7	50.7	68.9	766	12.1	4.8	208

The performance comparison of the models belonging to the YOLO v5 family was performed considering various computational and accuracy metrics. Size (pixels) indicates the resolution used by the model while processing the input image, and while higher resolution generally provides better detail capturing capacity, it can increase the processing time. FLOPs @640 (B) indicates the number of Floating-Point Operations (FPOs) performed by the model on an input size of 640 pixels and helps determine the computational complexity of the model. mAPval 0.5:0.95 measures the overall object detection accuracy of the model over a wide range of thresholds, allowing performance evaluation at various difficulty levels. mAPval 0.5 provides a basic reference, especially in applications where fast decisions are required, by showing the accuracy at a single threshold value (IoU=0.5).

Various parameters determining the processing time and speed performance of the model were also analyzed. Speed CPU b1 (ms) indicates how long the model processes a single image using the central processing unit (CPU) and is a critical factor especially in systems with low hardware requirements. Speed V100 b1 (ms) and Speed GPU V100 b32 (ms) allow to evaluate hardware-based optimization possibilities by comparing the speed of the model with NVIDIA V100 graphics processing unit (GPU) in single and multi-threaded scenarios. Finally, FPS GPU V100 b32 (1000/ms) metric shows the number of frames per second that the model can process, indicating how effective it is in real-time object detection applications. When all these metrics are taken together, a detailed analysis is made of how different YOLO v5 versions offer a balance between computational requirements, accuracy levels and processing speeds.

After these tests and evaluation, it was decided to use YOLO v5x in target detection because it has both high average sensitivity and ideal FPS values. 60 FPS value is easily obtained with the model trained using Nvidia Jetson NX Javier card. It is also trained without adding the image of the armed unmanned aerial vehicle to the data set. When the video of the armed unmanned aerial vehicle is loaded into the model, it recognizes it with high accuracy and successfully locks on the image. The distances of the targets to the armed unmanned aerial vehicle can be found from the area it covers within the specified frame on the main camera. For example, a target with a wingspan of 2 meters covers on average half of the determined frame from 5 meters away. This means that the distance of the armed unmanned aerial vehicle should be kept constant. When the target starts to move away from the armed unmanned aerial vehicle, it increases the engine power and approaches the target as soon as it detects a decrease in its size on the screen.

One of the machine learning models is used when creating the locking algorithm. The most important feature of machine learning, which is one of the sub-branches of artificial intelligence, is that it needs data. As the main logic, it applies what it has learned from the data set. Therefore, it does not have the feature of learning from its mistakes as in artificial intelligence algorithms. For this reason, the quality of the data set ensures that the machine learning model is also of high quality. While creating the data set of the vehicle's locking algorithm, 2 sources consisting of ready data sets and data collected by the relevant units are used. As shown in Fig. 7, 50,000 (developers' success rates of labeled photos with the YOLO v5 algorithm) photographs of unmanned aerial vehicles, land, air, and sea vehicles were collected from different platforms for the data set. Labeling is performed on these photographs using the website (makesense.ai). As a result of labeling, the object coordinates obtained from the photograph are converted into a format that the algorithm can understand. 81% of the labeled data is separated as training (train) data and 19% as test data and loaded into the algorithm. With this labeling, the algorithm has become able to detect targets on video. In addition, the number of photos has been increased by adding ready-made Common Object in Context (COCO) data sets to the data set. The aim here is to ensure that the vehicle can make the right decisions during the mission by recognizing not only the determined targets but also different objects.

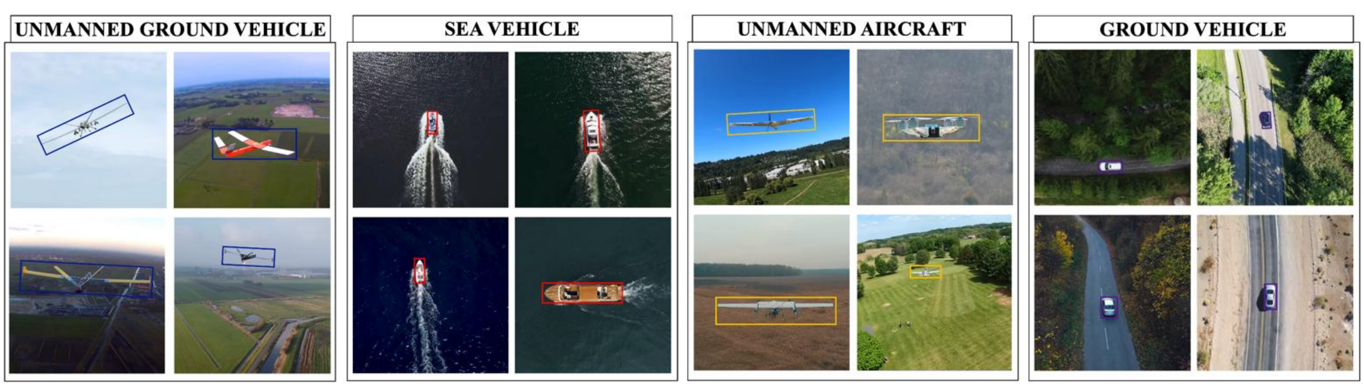


Fig. 7. Different vehicle sample of dataset used in training of the deadlock algorithm for understanding detection and deadlock.

After the objects are obtained, they are given to the deep learning algorithm and the prediction is made. In this way, the targets on the image can be detected. After the targets are detected, there are different methods to ensure that each group of armed unmanned aerial vehicles locks onto a single target and prevent multiple targets from being locked at the same time. The first of these can be considered under three methods: constantly determining the target closest to the horizontal and vertical center point in the image as the enemy, the second of these is determining the target detected with the highest stability rate as the enemy, and the last of these is first selecting the horizontal and vertical center point of the image as the center, determining the target closest to the center as the enemy and determining its position as the new center point for the next image.

Since armed unmanned aerial vehicles include instant maneuvers during combat, the unmanned aerial vehicle that is not instantly tracked can pass closer to the center of the camera image than the desired one. Therfore, the first method was abandoned since the tracking would be interrupted continuously. For the same reason, if the accuracy rate of the randomly detected target is higher than the one desired to be tracked, the tracking will be continuously divided. Consequently, the second method was also abandoned. The purpose of updating the continuous center point specified in the third method is that the target closest to the center in the next image is the one that is intended to be tracked. If other targets enter the image, the distance between them and the center point determined in the previous image will be greater than the target that is being tracked, thus providing continuous locking on a single target. The flow chart given in Fig. 8 shows step by step the transmission of the information that a single target has been locked on and the horizontal and vertical position of the target on the image to the ground station.

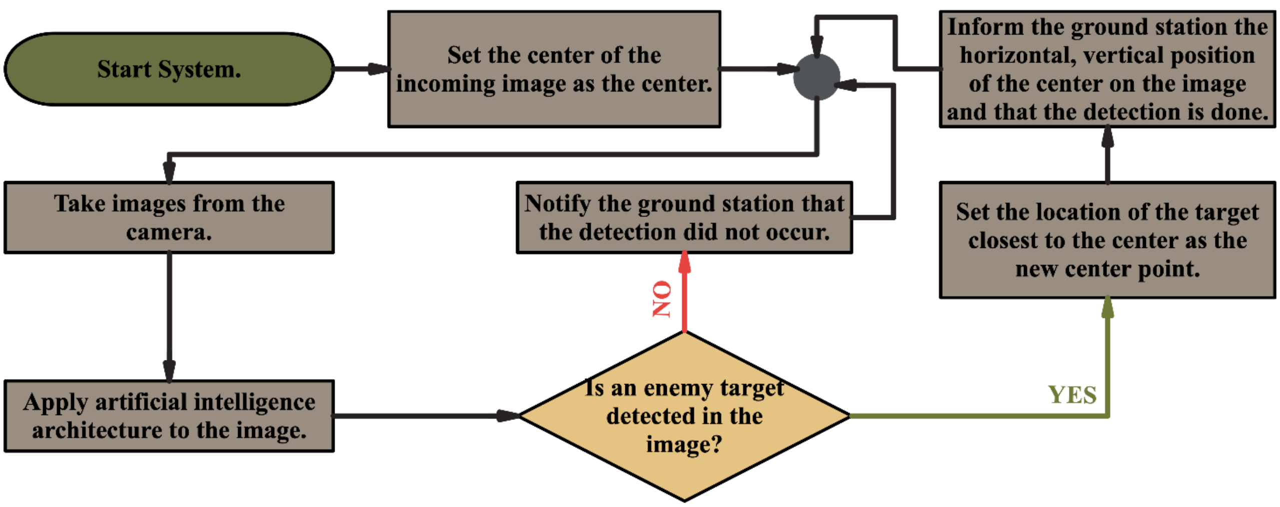


Fig. 8. UAV real time autonomous object detection algorithm block diagram.

5.2 Autonomous Tracking

After the detection process, the autonomous tracking process is activated. The swarm unmanned aerial vehicle must select a fully autonomous target during the mission, detect the target and start tracking by locking onto it via the image. There are different methods for tracking. The first of these is to give the GPS data sent by the detected target to the server as a reference to the controller, the second is to calculate the location of the detected target with a “Geo-Location” algorithm by measuring its distance with the help of a depth-measuring camera and give it to the controller as a reference, and the last of these is to produce a reference in the roll and pitch axes according to the “Pixel” change on the screen of the detected target and give it to the controller. The first method gives the lowest performance result compared to the other methods, and it is not possible to be sure that the target is transmitting proper data to the platform. In addition, even if it transmits data to the server, doing this with 1 [Hz] means that the location data can be received from the server only once a second at best. However, it is not possible to keep the opponent in the locking quadrant with a reference signal that will come once a second. Compared to the first method, the second method makes it possible to reach the location data independently of the target's ability to transmit data to the server. However, in addition to the fact that depth-measuring cameras are quite expensive, the result from the "Geo-Location" algorithm is not as accurate as the GPS data transmitted to the server and can only approximate. Compared to the disadvantages of the second method, the third method does not require high additional costs and allows working independently of the target's communication ability and at the desired sampling time allowed by the hardware. However, it is necessary to develop an optimized tracking algorithm in the third method. When these three methods were evaluated, the third method was selected due to its advantages.

The third method, the stages of which are given in Fig. 9, is carried out in 2 different stages: a "Following Algorithm" that generates references in the roll and pitch axes according to the "Pixel" positions of the detected target, the rate of change of their positions and their acceleration, and the "Automated Flight Following" flight mode developed by us, which enables the tracking of the references resulting from this algorithm.

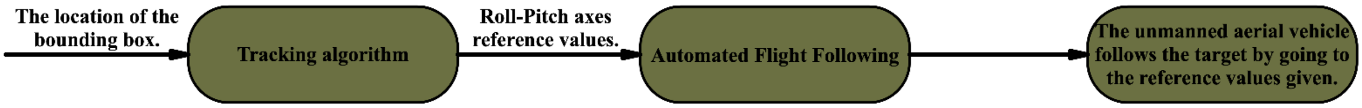


Fig. 9. UAV real time autonomous object tracking algorithm block diagram.

5.3 Tracking Algorithm

For the roll and pitch axis, it is desired to produce a reference angle according to the position of the detected target on the screen, the rate of change of the position and the acceleration. In this case, it ensures that it reacts not only according to the current position of the detected target but also according to its orientation. The center of the 800x450 [px] screen is determined as the origin on a 1600x900 [px] screen. Then, in the tracking algorithm given in Eq. 1, the distance to the center of the detected target on the X axis is defined as the error in the X axis e_x, and the distance on the Y axis is defined as the error in the Y axis e_y. θ is the value produced in the roll axis and sent to the flight controller as a reference, and φ is the reference value to be sent to the flight controller on the pitch axis. An equation depending on certain coefficients is created according to the position of the detected target on the screen, the change of position and acceleration, and then an energy-based controller is designed based on that equation.

$$\begin{bmatrix}\theta\\ \varphi\end{bmatrix} = \begin{bmatrix}A_x e_x\\ A_y e_y\end{bmatrix} + \begin{bmatrix}B_x \dot{e}_x\\ B_y \dot{e}_y\end{bmatrix} + \begin{bmatrix}C_x \ddot{e}_x\\ C_y \ddot{e}_y\end{bmatrix} \quad (1)$$

Using this equation, a discretized and then Lyapunov based proportional controller is designed. As a result of the process, the value obtained for the roll axis is sent to the flight computer via the ground station as an angle, and the result obtained for the pitch axis is sent as an altitude difference. Since the L1 controller, which controls the lateral acceleration in the flight computer, has a maximum operating speed of 50 [Hz], the tracking algorithm is added to the image processing interface with a sampling time of 40 [ms] (25 [Hz]). In addition, it changes the operating frequency to optimize performance in each cycle. Therefore, the system is fed for half of the 50 [Hz] period as a safety factor. If the tracked target leaves the screen, the algorithm continues to work for 2 seconds according to the data of the last 3 cycles of the target. If no detection is made in the elapsed time, the algorithm stops working. The general diagram of the tracking algorithm shown in Fig. 10 operates with 3 data streams: "Detection Yes/No", "Reference on Rolling Axis", "Reference on Pitch Axis" from the image processing interface to the ground station and from there to the unmanned aerial vehicle.

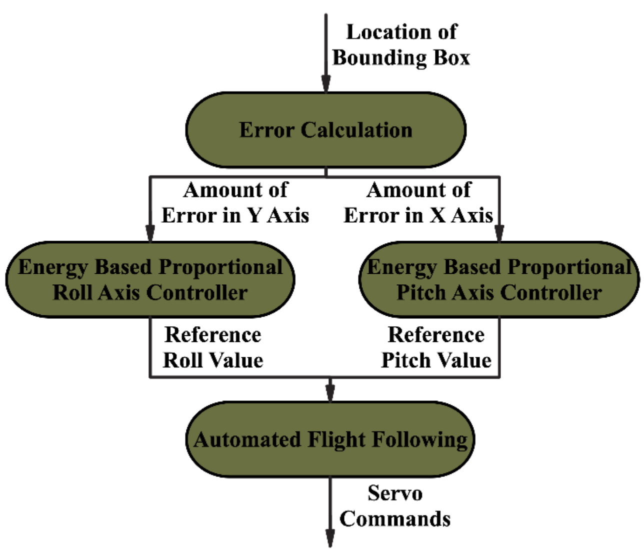


Fig. 10. UAV real time autonomous tracking algorithm block diagram.

5.4 Automated Flight Following Flight Mode

There is no flight mode in the "Ardupilot" control software that will meet the requirements for autonomous tracking. Therefore, a flight mode is being developed that has an autonomous flight mode called "Automated Flight Following", that allows easy entry/exit to/from the flight modes defined in the system, that can stay in "Level" when the roll and pitch axes reach 0, that can follow the reference values given in the roll and pitch axes with a low steady-state error, and that can exit the mode if it falls below a certain height limit. An extra controller is not designed while developing the mode. The new mode is added by changing the reference values given to the existing controllers in Ardupilot. The value coming for the roll axis is given to the controller as a direct angle value, and the reference coming for the pitch axis is given as a height difference. There are 4 different parameters controlling this new designed mode:

1. Auto_Follow_Active: It takes values between 1 and 0. When it is 1, if the unmanned aerial vehicle is in "Auto" or "Guided" mode, it switches to "Automated Flight Following" (if the height requirement is met). When it is 0, the unmanned aerial vehicle assigns a GPS point in the heading angle direction and enters "Guided" mode and continues its movement in the current height and heading angle direction until a new command is received. When a detection is made from the image processing interface, this is transmitted to the aircraft and this parameter is automatically set to 1 via the flight control interface to enter the mode, and when it is 0, the mode is exited.
2. Auto_Follow_Min_Alt: Determines the altitude limit for Automated Flight Following mode in meters. Even if "Follow_Enable" is 1 below this limit, it will not enter the mode. If it falls below this limit while in "Automated Flight Following" mode, it will exit the mode.
3. Auto_Follow_Roll: This parameter is limited to ±45 degrees. The value obtained from the tracking algorithm for the roll axis is written directly to this parameter, and whatever this parameter is, it is given as a reference to the controller controlling the roll axis, allowing the unmanned aerial vehicle to roll that much.
4. Auto_Follow_Pitch: This parameter takes a value between ±10. The value coming from here is added to the current height of the aircraft and given as a reference value to the controller controlling the height, and the unmanned aerial vehicle moves on the pitch axis to reach that height.

In addition, Ardupilot's defined parameters are also used in this mode to ensure autonomous flight. The general operation diagram is given in Fig. 11. In the Automated Flight Following mode, the position of the unmanned aerial vehicle on the screen detected from the Image Processing Interface (GIA) is provided to the aircraft according to the rate of change of the position and its acceleration, and it is ensured that the aircraft receives accurate autonomous responses.

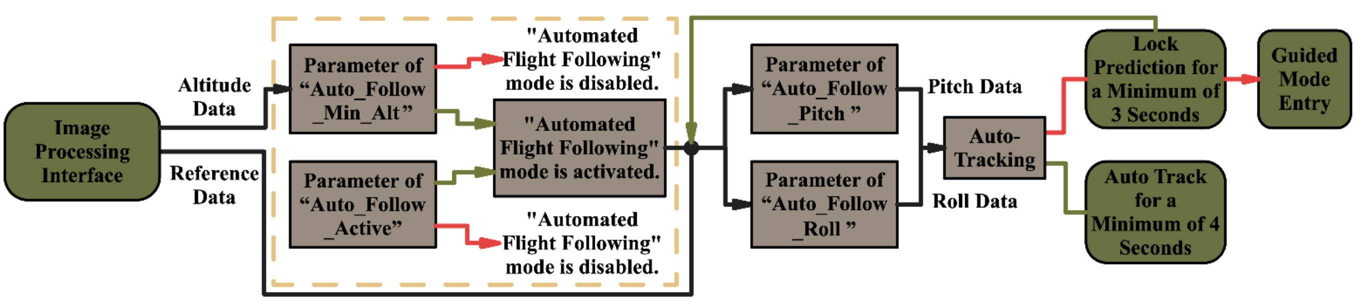


Fig. 11. UAV real time autonomous tracking algorithm block diagram.

6 Results and Validation

In this section, comprehensive tests were conducted to evaluate the compatibility and performance of the selected specific hardware and network application. The study deeply examines the effects of the power consumption, network range and efficiency of a drone operating on the aerial surveillance flight model with a UAV with swarm intelligence. In this study, different scenarios were tested using various configurations. During the tests, precise measurements were made to analyze the effects on the energy consumption of each UAV in the swarm. In addition, the potential of optimizing the communication range and data transfer of the drone with different network configurations was investigated. In this way, it is aimed to develop methods for operators to achieve longer flight times and collect data in a wider area in aerial surveillance activities. The obtained results show that various strategies can be applied to increase the performance and integration of the hardware and network application. This study aims to contribute to the more effective and efficient operations in this field by increasing the energy efficiency and communication capabilities of aerial surveillance drones.

While developing on the platform, it progresses step by step and tests are performed in real life and simulation environments to detect design and software deficiencies. While hardware performance adequacy and platform durability tests are performed in the field by creating appropriate security conditions, the software presented in the theoretical development process is subjected to debugging processes on the simulation many times and is presented to the field when it reaches its stable version. ROS-Gazebo robot physics simulation is used in the software development process.

6.1 Hardware Test Methods

The communication, propulsion and power distribution systems are designed in accordance with the requirements of the relevant equipment. In this direction, the power line diagram was created and the cable sections were determined to meet the required power during transmission. During the installation of the equipment inside the body, the distances between the subsystem elements were optimized in order to minimize power transmission losses. The antennas of the communication system were mounted outside the body to maximize signal isolation. Before the integration of the equipment, the entire system will be installed and tested outside the body, and then the propulsion system components and the batteries that feed this system will be integrated. After the installation of the propulsion system is completed, the autonomous system and the relevant power components will be included in the system, and in the final stage, the integration of the hardware that will enable the execution of the mission will be carried out.

Although the adequacy of the propulsion system is analyzed in line with theoretical calculations, it is of great importance to test it under real-world conditions. An inadequate propulsion system may cause the UAV to make unexpected maneuvers. In this direction, after all the components of the system are provided, a propulsion test is applied to verify the accuracy of the calculations. Before the test flight, it is verified that the engine, speed controller (ESC) and propeller are working as expected and that the maximum thrust, they provide is compatible with the calculated values. In order to determine the range of the telemetry module, two telemetry modules are placed on an RC drone and the test process is carried out. Within the scope of this test, two separate ground control stations are established, one close to the drone and the other further away. The nearby telemetry module provides data flow by transmitting the UAV's flight data to the nearest station. The other telemetry module sends data to the ground control station located further away to determine when the signal will be cut off and to determine the maximum transmission range of the system. The visual lock-on test aims to detect potential problems and take the necessary precautions by measuring the accuracy and latency of image processing algorithms. Within the scope of this test, the onboard camera is connected to a computer in a laboratory environment and various videos with high frame rates are transferred to the camera. During the test, the image processing algorithm is run on the computer and the data obtained by the camera is processed. At the end of the tests, the accuracy level of the algorithm is evaluated and it is analyzed whether it contains any bias towards certain conditions.

6.2 Omnidirectional Antenna Selection and Gain

When swarms of UAVs are constantly moving and need to be connected to each other, the installation of omnidirectional antennas on UAVs is considered a suitable solution. At the ground control station, both types of antennas can be used depending on the expected flight patterns. If the entire swarm needs to fly together in a certain direction, it is possible to increase the communication range of the swarm by using a directional antenna. The disadvantage of this approach is that an additional person must be assigned to direct the antenna towards the swarm or a system must be installed to monitor the antenna. On the other hand, if the swarm is expected to remain close to the control station or fly around it, an omnidirectional antenna can still provide good range and eliminate the need for a tracking system. Antenna gain is a factor that affects the radiation pattern of an antenna and varies depending on the antenna type. Antenna gain is usually measured in hertz (kHz) or decibels (dBi). Antennas with higher gains can generally transmit signals farther, but tend to narrow the direction of transmission. Increasing the gain of a directional antenna focuses the transmitted signal to a narrow area. Increasing the gain of an omnidirectional antenna, on the other hand, increases the horizontal range of the signal while decreasing its vertical range. Antenna gain is determined by the specific application and expected flight patterns. If all drones are expected to fly at the same altitude, using multiple directional antennas with high gain can extend the horizontal range of the swarm. However, if UAVs are expected to fly at different altitudes, a lower gain antenna is more appropriate. While a lower gain antenna will reduce the range of the UAV, the connection between UAVs becomes more stable as the altitude of individual UAVs changes.

To investigate the effects of directional antennas, first the differences in network range and throughput between 10kHz and 5kHz gain omnidirectional antennas were tested. Higher gain antennas have the ability to focus signals in the direction of transmission for longer range communication. Increasing the gain of the antenna usually results in an increase in the size of the antenna. Therefore, the purpose of the test was to determine whether the increased range provided by the 10kHz antenna could compensate for factors such as added weight and size. The experiments were conducted in an open area with direct line of sight. Both antennas were positioned at the same height and directed their signals along the same plane. The tests were performed using a command line tool that allows measuring the maximum bandwidth between devices on a Local Area Network (LAN). Bandwidth measurements were taken at various distances in 15m increments until the bandwidth could not be estimated due to weak signal strength. At each distance, the software was run for 50 seconds and the average throughput over 50 seconds was recorded, yielding the experimental results shown in Fig. 12.

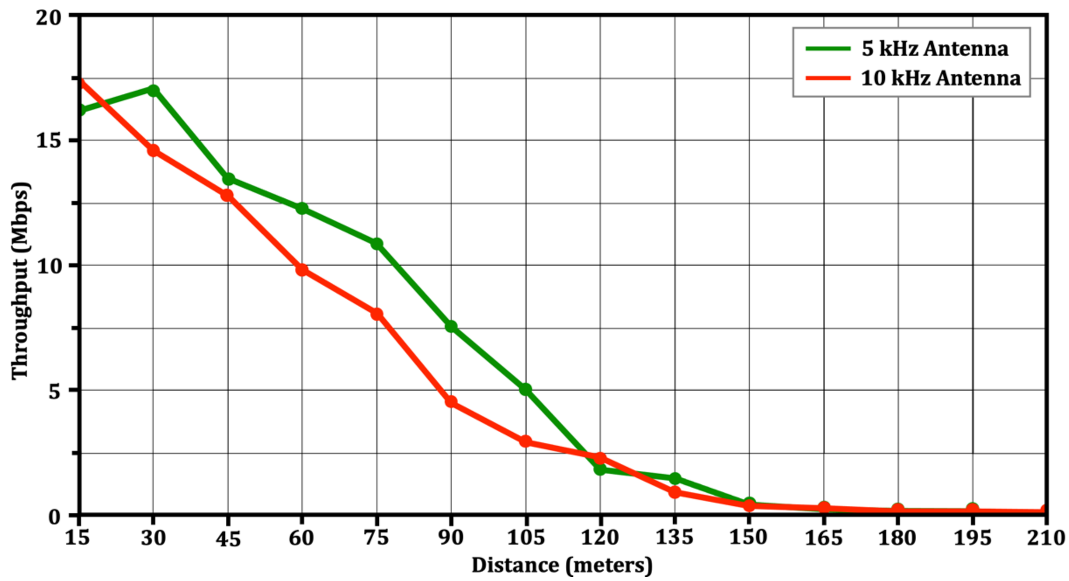


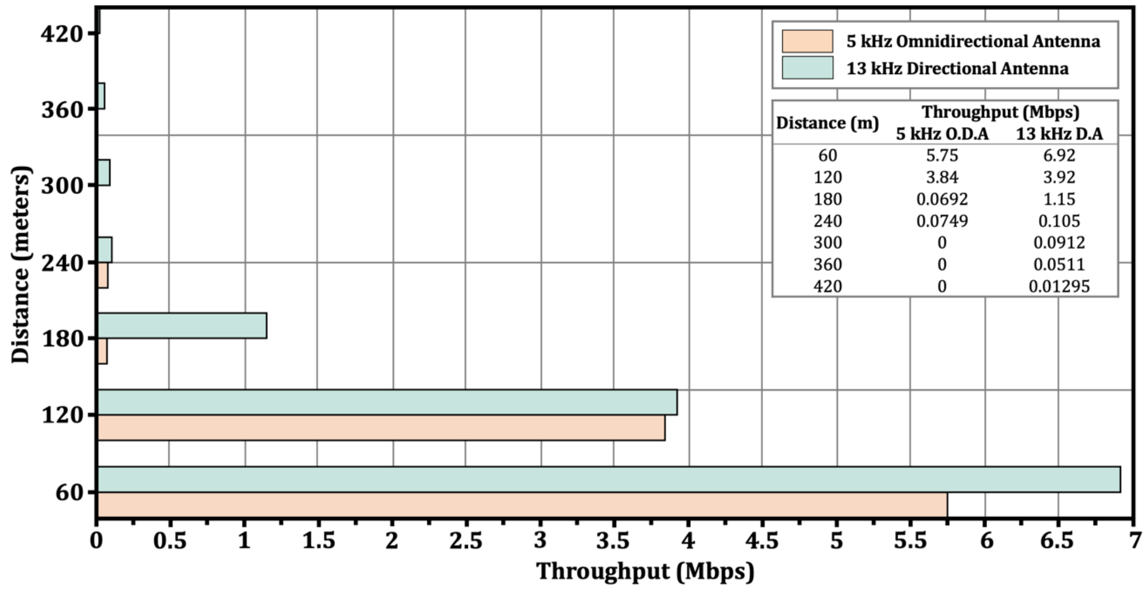
Fig. 12. Antenna of UAV's Wi-Fi module throughput for omnidirectional antennas of 5 kHz (green) and 10 kHz (red) decibels.

Tests on the performance and effects of directional antennas have shown that when these antennas are focused in a certain direction, they increase communication performance and provide longer ranges. When the performance difference between two antennas with different decibels is examined, as shown in Fig. 12, it is seen that the antenna with lower gain provides better efficiency at distances below 150 meters. On the other hand, although the 10kHz omnidirectional antenna offers 30 meters more range than the 5kHz omnidirectional antenna in terms of maximum range, this additional range gain is not preferable because it is insignificant enough to compensate for the cost of installing a heavier antenna on the UAVs. Therefore, the efficiency and advantages obtained are optimized by installing 5kHz omnidirectional antennas on each UAV in the swarm.

6.3 Network Performance Evaluating

In order to verify the performance of the network application with the designed hardware, the Panda PAU06 USB Wi-Fi adapter swarm UAVs connected to Jetson Xavier NX were assigned for aerial observation at an altitude of 45 m, and the measured results depending on the horizontal distance from the GCS with 5 kHz omnidirectional antenna and 13 kHz directional panel antenna are shown in Fig. 13.

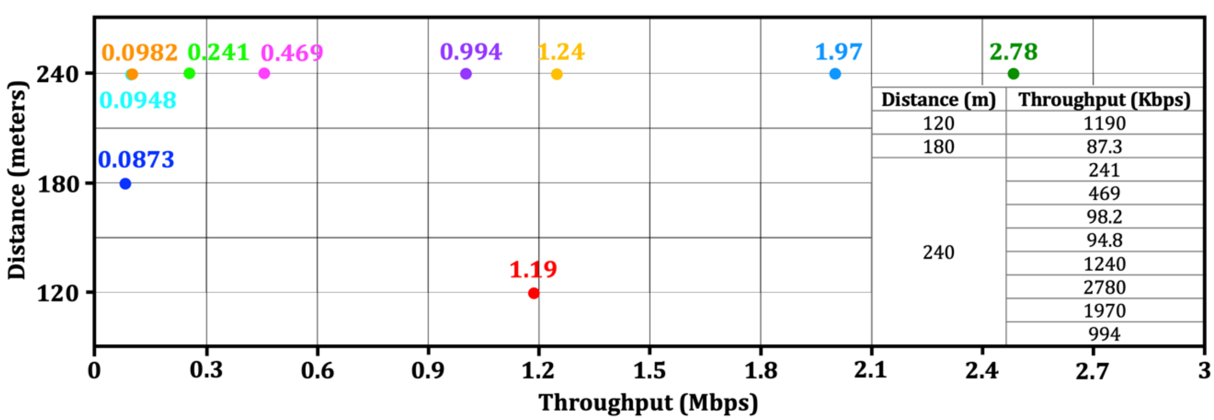
During the ground station and omnidirectional antenna test, SiK telemetry radios were used to measure the efficiency and maximum range of the connection from the ground station to a UAV, and it was aimed to prevent telemetry data from affecting the efficiency measurements. In order to perform the test, a 5 kHz omnidirectional antenna was first mounted on the Panda PAU06 Wi-Fi adapter connected to the Jetson Xavier NX and subjected to a test flight. In this context, the test results obtained showed that the 5 kHz omnidirectional antenna could successfully maintain its performance up to approximately 120 m, while a high amount of loss in efficiency occurred after this range. In addition, the network was able to establish the last communication at approximately 240 meters with 0.0749 Mbps in the measurement ranges. In the meantime, the telemetry data connected to the mesh network was measured as 275 m, which was determined as the maximum communication range via the ground station software. After the completion of the first test, a second test was performed by connecting a 13 kHz directional antenna to the Panda PAU06 Wi-Fi adapter connected to the Jetson Xavier NX. In this context, the test results obtained clearly demonstrated that directional antennas are more successful in long-range missions than omnidirectional antennas. Here, it was determined that the network efficiency obtained for every 60 m difference in range received with the directional antenna was higher than the omnidirectional antenna. In addition, it was clearly demonstrated that the network could maintain communication at measurement ranges within the 420 m flight zone. When the directional antenna was used, it was observed that the maximum communication range increased from 275 m to 300 m while telemetry data connected to the mesh network was received via the ground station software. Although this seems to make the use of the directional antenna advantageous, the directional antenna must be directed towards each UAV in the swarm in order to maintain the connection healthily in long-range missions. Otherwise, the connection of the UAVs in the swarm may be lost. This makes it easy to explain the difference between the ground station software and the command line tool used for network throughput measurement.



Distance (m)	Throughput (Mbps) 5 kHz O.D.A	13 kHz D.A
60	5.75	6.92
120	3.84	3.92
180	0.0692	1.15
240	0.0749	0.105
300	0	0.0912
360	0	0.0511
420	0	0.01295

Fig. 13. Antenna of UAV's Wi-Fi module throughput for omnidirectional antennas of 5 kHz (musk melon) and 10 kHz (water green) decibels according to increasing mission area distance.

After these tests, an additional test was performed to compare the range of the SiK telemetry module used to send telemetry data with the range of the Wi-Fi module. To do this, the individual UAV started the test flight at an altitude of 45 meters and measured in a straight line every 60 meters. The results showed that the SiK telemetry module was able to successfully transmit telemetry data within a 1 km area. Although this does not seem healthy for the transmission of data other than flight data, it was clearly demonstrated that it can be used as a successful additional communication path for individual UAVs that cannot maintain a mesh network connection. In order to realize multi-hop communication, a study was conducted by attaching a 5 kHz antenna connected to a Panda PAU06 Wi-Fi adapter to two UAVs belonging to a swarm. One of the two UAVs was placed at the farthest point of the range, while the other UAV was positioned in the middle with a UAV at the same altitude as the ground station. The SiK telemetry module was not installed in the swarm, whose control was carried out via the ground station, in order not to create a connection problem at the same time. However, in order to overcome this deficiency, it was decided to transmit telemetry data over the mesh network, which was preferred despite the fact that it was thought that this could cause performance problems since it required wide network bandwidth. As shown in Fig. 14, the results obtained for 120 m and 180 m showed that transmitting telemetry data over the mesh network caused a lower network efficiency than the previous tests.



Distance (m)	Throughput (Kbps)
120	1190
180	87.3
240	241
	469
	98.2
	94.8
	1240
	2780
	1970
	994

Fig. 14. Communication network throughput of two UAVs in the swarm according to increasing mission area distance.

Repeated measurements were taken for 240 m. The first four values out of the total of 8 results obtained provided lower efficiency due to the fact that the UAV in between was not used in message transmission due to being within range of the ground station with the farthest UAV, while the last four values provided higher efficiency due to the fact that the data transfer was obtained after being out of range of the ground station, which shows the performance of multi-hop communication. In addition, thanks to the Hybrid Wireless Mesh Protocol, when it could not find a route to the ground station, it created a route planning and created a way to explain the higher efficiency passing through the intermediate UAV. The fact that the tests obtained here were provided for short ranges goes beyond the fact that the command line tool used affects the telemetry data and affects the connection of the ground station software.

6.4 Improvement of Image Processing Precision and Recall

The parameters of the YOLO algorithm, the parameters of the training and test results of Yolov5x are shown in Fig. 15. The precision value expresses the accuracy rate of the algorithm's predictions in image processing. The Intersection Over Union parameter indicates the ratio between the predicted detection box and the actual detection box. This ratio is used as a boundary in the training phase and expresses the accuracy of the prediction to the artificial intelligence architecture. The intersection over union parameter is used for the non-maximum suppression parameter in the completed artificial intelligence model, thus avoiding detection boxes surrounding the same object one on top of the other. The Confidence parameter returns a value between 0 and 1, indicating the certainty of whether there is an object at the predicted location. In order to avoid possible errors and accidents, it was found that the most appropriate value was 0.65 after testing different ratios.

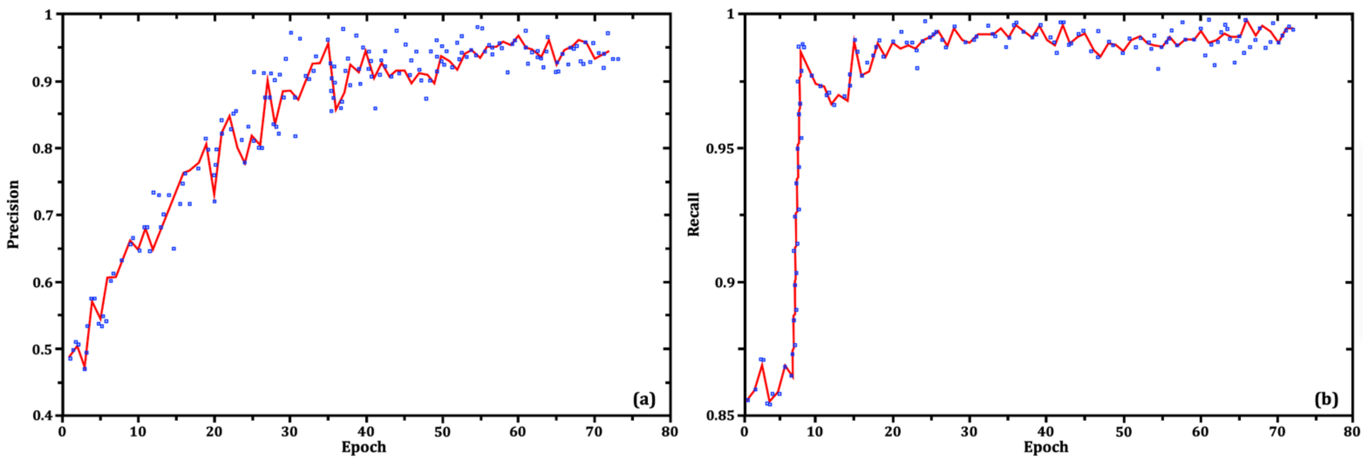


Fig. 15. Incremental evolution data of the YOLO v5x model selected for use in UAV (a) Precision Parameter Evolution (b) Recall Parameter Evolution over epochs.

6.5 Autonomous Tracking

During the autonomous tracking test, a platform is needed that allows UAV and Pixhawk codes to be tested together. In this context, it was decided to use the ROS + Gazebo platform, which allows instant camera images to be taken as ROS headers without any performance loss. In order to perform a simulation of the mission area, the simulation environment must be able to run the Ardupilot software loaded onto the vehicle, instant FPV camera images can be taken from the aircraft, multiple vehicle animations can be made for escaping and chasing aircraft, and image renewal must be provided at a speed of at least 25 [fps] to send data 25 times per second using the tracking algorithm. ROS + Gazebo is used in Autonomous Tracking Tests because it provides performance above 60 FPS and allows image transfer and swarm applications.

Ardupilot SITL and Gazebo environment are communicated with the “plugin” specified in the Ardupilot documentation. For the tests, escaping and chasing objects are created with a fixed-wing UAV and the necessary tracking algorithm tests are performed. The purpose of this test is to observe whether the designed controller algorithm works stably and to optimize the system with different parameters. The system was optimized with tests performed by creating different scenarios in the Gazebo environment. When the target aircraft enters the image, the target is detected and included in the locking quadrilateral and an error vector is drawn from the center of the image to the center of the locking quadrilateral. As shown in Fig. 16, the tests were performed by two or more UAVs performing mission flights simultaneously. During the test, all computers are connected to the same local network and communicate with each other via UDP protocol. The simulation computer is used to simulate the mission area.

Models of UAVs, simulation environment and autopilot software are run here. The image taken from the simulation is sent to the Image Processing Computer via ROS. Target detection is performed here and the desired reference data is produced. The produced references are sent to the interface controlling the tracking aircraft. Auto-Follow mode inputs and outputs are tested on the target UAV control interface. The Tracking and Target UAV Interfaces are connected to the simulation environment again via UDP and telemetry exchange is provided. The experiments were repeated to determine the optimum controller coefficients to be used in the tracking algorithm and tracking was successfully provided in a stable manner. In this context, the controller coefficients reached were determined as the proportional coefficient for the horizontal axis as 0.78,

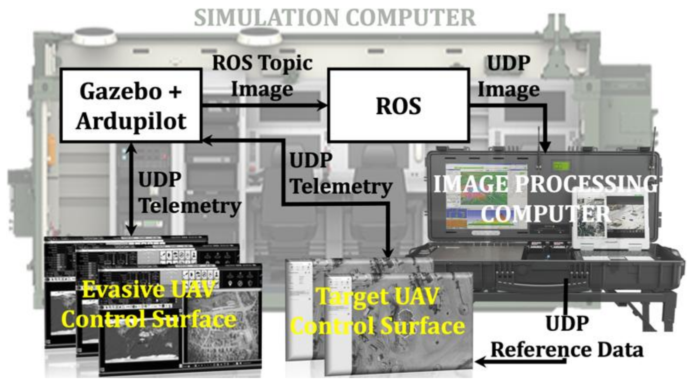


Fig. 16. Swarm UAV ground control unit environment equipments connection diagram to be used in operation.

A value as 0.15, B value as 0.37 and C value as 0.17. For the vertical axis, the proportional coefficient was determined as 0.28, the A value as 0.5, the B value as 0.24 and the C value as 0.18. As shown in Fig. 17, it shows the positions of the target hit area and the locking rectangle. Since the image was processed in 1600x900 pixel dimensions, the graphic was created between -800 and 800 horizontally and -450 and 450 vertically. The moving target was placed in the target hit area within 3 seconds after entering the field of view and tracking was successfully continued for 7 seconds. After this period was deemed sufficient for tracking, the tracking test was terminated.

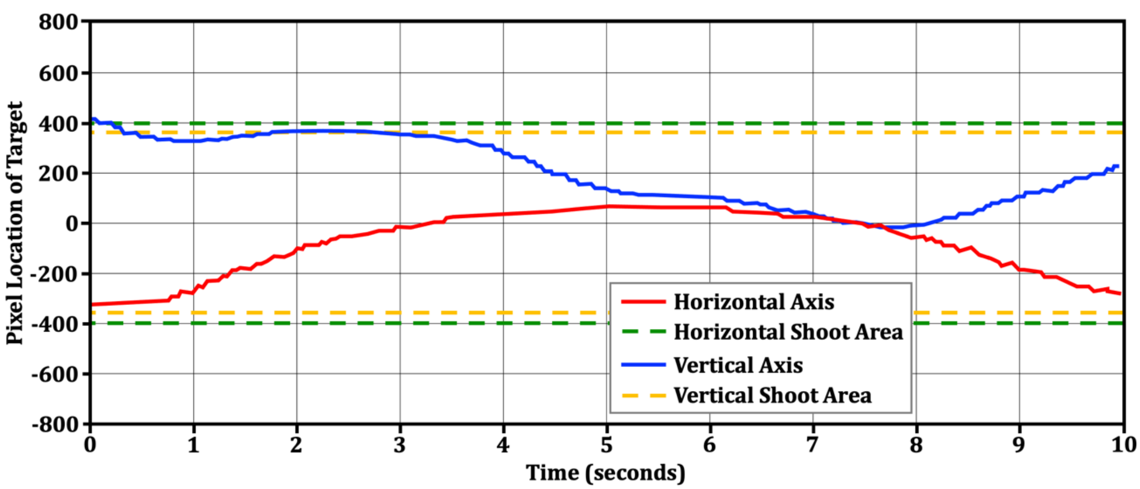


Fig. 17. UAV Locking Quadrant Position Graph on Horizontal and Vertical Axis of the target hit area and the locking rectangle.

6.6 Safety

Certain precautions are taken and implemented to protect the researcher and the materials against accidents that may occur during work. Based on this, cable thicknesses suitable for the high current values that the motors used will draw are selected and insulation is provided by attaching tubes to the areas where these cables are soldered. Short circuit control of transmission lines is meticulously carried out. In cases where intervention is required on the UAV, a fuse and current breaker unit is placed in an accessible location to prevent the dangers that high current may cause. In order to prevent accidents that may occur during production and assembly, equipment such as protective glasses and masks are used during work. The propellers of the motors are not installed during calibration and tests.

In addition, a first aid kit is kept in the work environment for unforeseen accidents. A fireproof battery bag is used to protect the Li-Po battery in the event that the UAV breaks down, and the battery is also stored in this bag when not in use. Despite all these precautions, a dry chemical powder extinguisher is kept in the laboratory environment in case the battery burns. During soldering or intervention, an antistatic wristband is used to protect the materials from static electricity. During the flight, the boundary conditions within which the SİHA can navigate are determined so that it does not go outside the designated area and damage anywhere or get lost. When the battery drops to critical levels, the UAV can give warnings to the ground station and the controller and land.

7 Conclusions

A modular avionics system has been presented for fixed-wing fully autonomous controlled swarm unmanned aerial vehicles that can successfully detect in-line-of-sight and beyond-line-of-sight targets as many times as possible, lock onto the target for the desired period of time and destroy it, evade the locking of other armed unmanned aerial vehicles with maneuvers and continuously transfer the information it receives to ground stations. The mission requirements of the swarm armed unmanned aerial vehicles for which the system design was made have been determined in detail and 3 platforms, namely air, ground and IoT, have been established within the scope of meeting the determined requirements. Based on the performance-power-quality-success index, modular systems that can be integrated into different types of fixed-wing aerial vehicles that offer high mission capacity, fully autonomous mission flight, successful swarm strategy, real-time data transfer, defense reconnaissance, surveillance and intelligence have been developed. The mission-success capability of a fixed-wing UAVequipped with an artificial intelligence and deep learning-based development card and various sensors has been maximized and different challenging maneuvers such as dog fight have been achieved. Thanks to its integrated cameras and high computational processor, it destroys enemy targets accurately. The images and flight data captured during tracking are used for the development board and behavior optimization of the UCAV with an AI-based algorithm. By establishing effective communication with the ground station, it provides both more effectiveness in air combat, manual control, image processing, data processing and transfer to servers, and information exchange during reconnaissance and area scanning. In order to ensure this, correct data exchange tests were performed on sensors connected to computers, and communication modules were enabled to communicate to provide real-time data exchange. The necessary connections and coding were made for the integrated operation of mission and flight computers. In addition, information is received from the satellite reliably via the IoT platform and transmitted to smart devices, while mission orders and instant mission tracking are provided. In addition, thanks to the proposed avionics architecture, critical mission data obtained from sensors can be transferred to the cloud and controlled independently of location. It has been verified that the data obtained from the cloud can be easily followed via the software platform. In addition, an Ethernet connection has been connected between the ground station and the nearby servers in order to transfer the requested information to authorized nearby servers.

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