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A C4 Software for Anti-Drone System

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ABSTRACT

Mini unmanned aerial vehicles (UAVs), commonly known as small drones, have seen outstanding advancements in recent years and have been used in a variety of fields. However, their potential misuse for illegal activities and the risks they pose to safety and privacy have raised concerns. To address these issues, we propose a Command, Control, Communications, and Computers (C4) software able to manage and control anti-drone systems. Our software solution includes an easy-to-use dashboard that processes and displays video data from surveillance sensors. It incorporates AI-powered functionalities, including object detection, target tracking, and classification of small drones. At the inference stage, the network models for drone detection and classification functionalities have achieved an accuracy exceeding 96 %. We have evaluated the effectiveness of our solution by deploying it in a no-fly zone, where it successfully identified and tracked drones in near real-time. The proposed control system provides unified information with which the entire anti-drone process can be managed starting from the detection of each threat.

Keywords: Mini-UAV; Anti-drone; Data analytics; Dashboard; Deep learning; C4

1. INTRODUCTION

Mini Unmanned Aerial Vehicles (UAVs), commonly referred to as small drones, have become increasingly prevalent due to advancements in technology. These drones have found applications in various domains, such as search and rescue operations, wildlife monitoring, and border patrol[1–6]. However, their misuse of illegal activities, including espionage and smuggling, as well as their potential involvement in terrorist activities, present serious security concerns[7-8]. Furthermore, mini-UAVs can disrupt the operations of commercial and military aircraft and violate personal privacy. As a result, the development of an effective anti-UAV monitoring system is crucial to safeguard sensitive locations and mitigate potential threats.

Recently, diverse commercial anti-drone systems have been developed and commercialised[9-10]. However, only a few of these systems can detect and neutralize rogue UAVs. Furthermore, these systems rely either on radar detection which is not suitable for urban deployment, or on a combination of many sensors (radar, acoustic, and RF) which makes their prices very high in addition to being black boxes[11-12]. Moreover, related works to optic detection and AI-based drone classification use usually public datasets and common algorithms. For instance, UAV detection and classification based on the vanilla YOLOv5 model[15] were trained on public drone datasets[13,14]. Furthermore, Recent related works either develop kinetic solutions to take down the malicious UAVs[16] or address the challenge of catching them[17]. However, these approaches can have potential risks of collateral damage and do not prevent them from causing harm.

To overcome these issues, we propose a customized command, control, communications, and computing (C4) anti-drone system. C4 is a well-established term in both military and information technology domains, signifying the integration of these four essential components to enable efficient decision-making, coordination, and information exchange in a wide range of operational scenarios. Our solution provides a layered dashboard with an intuitive interface that efficiently processes and visually represents real-time video data captured by optical and thermal sensors.

The proposed C4 dashboard software can significantly improve the effectiveness of anti-drone systems in terms of real-time monitoring, data visualization, automated alerts, and integration with other systems. The key components of our system include data and image processing using advanced algorithms to process incoming video data in real-time. It leverages Artificial Intelligence (AI) powered models developed from scratch, including object detection[18-19], target classification, and tracking algorithms. These advanced AI models enable precise identification and accurate classification of small drones. The object detection model was trained on a customized dataset that was constructed by the work team and will be made available in the future. Our solution includes a multi-layered dashboard that presents the processed data in a user-friendly manner. The dashboard provides real-time visualizations, including maps and live video feeds, to enhance situational awareness and facilitate quick decision-making preventing wrong decisions in UAV detection and combatting.

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To evaluate the effectiveness of our multi-layered solution, we deployed it in a no-fly zone. The system successfully identified and tracked small drones in near real-time. The multi-layered dashboard provided operators with a comprehensive view of the monitored area and enabled them to respond promptly to potential drone threats. The evaluation results demonstrate that our solution offers an intuitive user interface, effectively processes video data, and exhibits significant potential in enhancing monitoring capabilities and responding to drone threats efficiently.

The paper is organised as follows; Section 2 presents the components of the proposed C4 software system. Section 3, details the development steps and architecture. Then deployment of the complete monitoring system is described in Section 4. Finally, in Section 5 summarisation of the main features of the developed system and emphasize its ability to be deployed in a real environment against suspect drones is done.

2. METHODOLOGY

An AI-powered Data Analysis and Management Software (DAMS) is proposed that can support the deployment of an Air-defence system to secure a no-fly zone, a restricted area, or a critical civil infrastructure from drone threats. DAMS combine data from the various used sensors and controls the hardware modules along with the user rights. It leverages a modified version of the YOLOv5 model to provide the required functionalities of an anti-drone system.

The proposed solution integrates the following elements to facilitate command and control operations during the fight against malicious drones. (1) The command component refers to the administration authority. It involves the planning, coordination, and execution of operations, as well as the access right allocation. (2) The control component focuses on monitoring and adjusting ongoing operations to ensure they align with the desired objectives and plans set by the command. (3) The communications component deals with the transmission and exchange of information between different entities. This includes data transmission and other means of conveying critical information in real time. (4) The computer component involves the use of technology and computing systems to support command, control, and communications functions. Computers are used for data processing, information storage, decision support, and other tasks related to the management of operations. Together, the C4 system aims to enhance situational awareness, streamline decision-making processes, enable effective communication, and improve overall operational efficiency. It plays a crucial role in C-UAV operations by providing the tools and infrastructure needed to exercise command and control. It is designed to support Counter-UAV systems to detect, identify, track, and neutralize drone threats.

As shown in Fig. 1, this paper presents a layered software architecture of the video data analysis dashboard with two tiers to support the operation of the anti-drone monitoring system. On one hand, the analyst tier is responsible for analyzing and processing data. This is where the data is transformed, cleaned, and processed before being sent to the management and visualisation tier to be presented to the user. The analyst tier is also responsible for integrating data from various sensors. In addition, he provides the data and analytical models that support the decision-making process of the sky monitoring system. The management and visualization tier, on the other hand, is responsible for displaying the data and managing the system functionalities. This tier typically includes the user interface, as well as the components and logic that control access to the system's data and functionalities. It also includes the layer that manages the data, security, and authorization of the application. The visualization tier is the part of the system that provides the interface to the user, through a desktop application, allowing the user to interact with the system and view the data. This tier can also include reporting, screens, and other tools for visualizing and analyzing the data.

In the following paragraphs; we detail the layers of the proposed software solution.

2.1 Presentation Layer

It is the layer responsible for the user interface and the way the data is presented. The main function of this layer is to present the data and functionality of the system in a clear, intuitive, and user-friendly way. This layer interacts with users through screens, forms, menus, reports, etc. It defines the application's overall look and presentation to the end-users.

2.2 Interaction Layer

The interaction layer serves as a gateway to various functions about notifications, status updates, actions, and events, granting users seamless access and control over these essential elements:

- Sound Alarm, which activates the sound alert at interesting events, such as the detection of an unwanted drone.
- Visual Alarm, which prepares and presents insights into the detected target to the system operator via the graphical user interfaces in the presentation layer.
- Neutralization, which makes decisions in response to events of interest to neutralize unwanted targets, such as jamming the frequencies of small drones.

These classes work together to provide comprehensive and integrated support for detecting and responding to events of interest in the protected area.

2.3 Application Layer

It handles the main programs of the architecture. It includes the code definitions and most basic functions. This layer receives insights from the communication layer and sends them to the interaction layer to be displayed, after being computed. It also sends orders from the interaction layer to the communication layer to control devices of the anti-drone system.

2.4 Data Management Layer

This layer is responsible for managing data access, storage, and retrieval. In the analyst tier, the data layer is responsible for handling the connection to various data sources, including cameras and other devices, to retrieve and process data. This

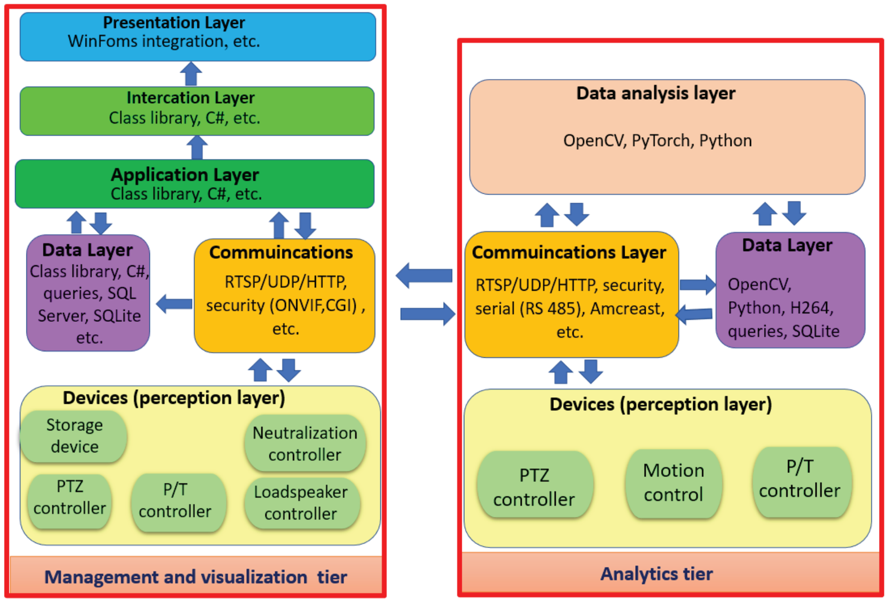


Figure 1. Design of the proposed layered dashboard architecture: (a) Management component tier, and (b) Analytics component tier.

layer may indeed include loading camera settings such as ID, name, login, password, IP address, and type, as well as device settings and video stream configurations.

In the management and visualization tier, on the other hand, the data layer has the responsibility of storing various types of data that are required for the software application to operate effectively, including but not limited to user data, drone data, camera data, device data, and reports.

2.5 Communication Layer

It is shared between the left and right tiers using RTSP, UDP, HTTP, and RS485 protocols. For the left tier, the communications layer sends information (insights, device configuration, etc.) to the data layer to be stored and to the application layer to be exploited. Also, it receives raw video and sends controls to the device layer. For the right tier, the communications layer receives raw video via RTSP and forwards it to the data analysis layer.

2.6 Data Analysis Layer

It only belongs to the analyst tier. The gathered data from the communications layer are forwarded to the data analysis layer to conduct the processing. This layer can extract low-level information using data processing algorithms. It enables event detection, such as the presence of nefarious flying drones in the protected area. The data processing in this layer can be recognized as a combination of the following four main DL-powered tasks that will be explained in subsection 3.3: detection, super-resolution (SR), identification (classification), and tracking.

2.7 Device Layer

The devices layer is responsible for managing the hardware components of the system, such as cameras and jamming devices. It collects data from the devices and receives commands from the communication layer to control the position of the cameras and jamming devices. The devices layer also includes modules to manage the life cycle of these components:

- PTZ (pan-tilt-zoom) controller for cameras,
- Loudspeaker controller for speaker systems,
- P/T (pan-tilt) controller manages the life cycle of the moving jammer positioner.
- Neutralization Controller for countermeasure component.
- The storage controller manages the storage medium.
- These modules ensure that the hardware components of the system are functioning properly and effectively.

3. DEVELOPMENT OF THE LAYERED DASHBOARD ARCHITECTURE

3.1 Receiver: Management and Visualization Tier

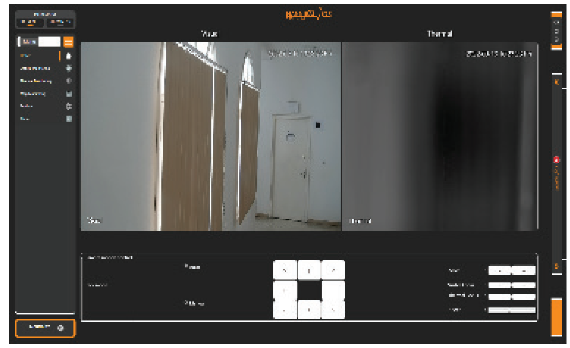
Creating efficient and user-friendly user interfaces (UIs) for the proposed dashboard entails meticulous attention to a range of crucial prerequisites. These include but are not limited to usability, functionality, accessibility, responsiveness, consistency, security, and branding. Our team has developed a Monitor console station that excels in video data management, analysis, and visualization. By taking these requirements into account, you can craft UIs that effortlessly meet the demands of video data management, analysis, and visualization while ensuring effectiveness and efficiency.

Authentication is the security process that allows users to verify their identities to gain access to their accounts on a website or software. It includes the software name and logo then comes username and password text zones for login, in case of a forgotten password there is a "password recovery" field.

3.1.1 User Settings Section

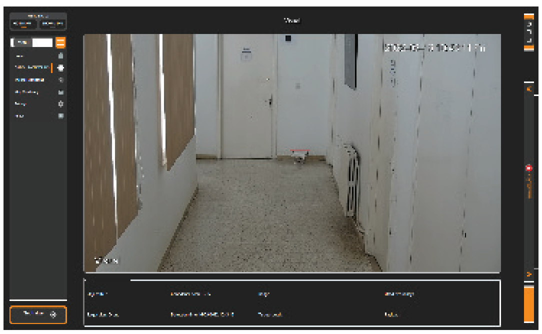
Users can personalize and change their account settings, such as contact information, passwords, notifications, and privacy preferences, on the users settings page of the proposed

(a)



(b)

Figure 2. User settings and home pages of the proposed dashboard, (a) User settings page; and (b) Home page.



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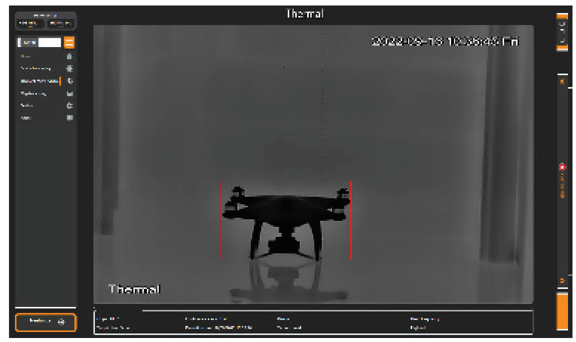

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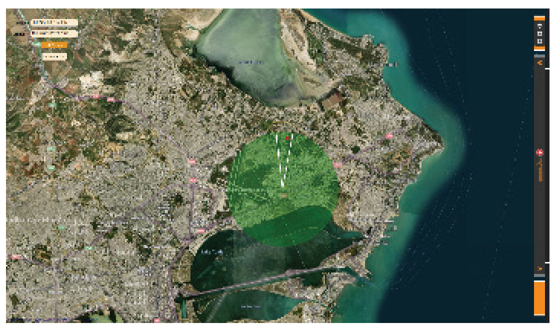

(c)

Figure 3. Monitoring screens of the proposed dashboard, (a) Visual monitoring screen; (b) Thermal monitoring screen; and (c) Map data monitoring screen.

video data analytics dashboard for the anti-drone system. Additionally, it enables users to create unique roles and permissions for other people as well as control their access to the system. Giving users control over their user system is the goal of the Users Settings page.

Figure 2(a) displays how users can manage their information, On the left side Data Grid View shows all users dealing with user type. By clicking on the Data Grid View column, users' information will be shown on the right side and ready to be updated or deleted.

3.1.2 Home Page

After Authentication, the user is redirected to a home page (given in Fig. 2(b)) in which he finds a simple menu to navigate throw different software windows. Moreover, there are visible and thermal flow displays. Furthermore, on the left bottom, there is a group box in which the user has to select between automatic or manual mode (i.e. by navigation buttons), On the other side he finds a jamming group box that lets him choose the way of neutralization.

3.1.3 Visual Monitoring Display

This window enables optical data monitoring providing information about detected drones. As shown in Fig. 3(a), the corresponding screen allows users to monitor drones using the optical flow. Moreover, its left bottom group box shows details such as ID, class, range, payload, detection time, etc.

3.1.4 Thermal Monitoring Display

Modern thermal imaging technology is used by our sophisticated anti-drone system to identify the distinct heat signature that small drones emit and separate it from other airborne objects (Fig. 3(b)). Our solution dramatically improves tiny drone detection accuracy and effectiveness by smoothly integrating this technology. As a result, it is a crucial asset for protecting restricted airspace and maintaining the highest level of safety.

3.1.5 Map Monitoring Display

Users can access the Map-Monitoring window from the top menu in the sequence shown in Fig. 3(c). G Maps are used

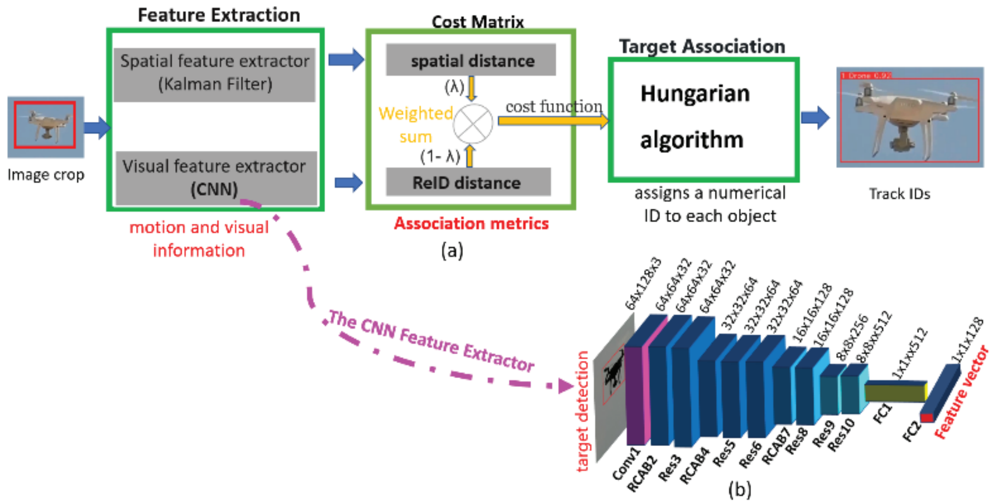

Figure 4. (a) An illustration of the proposed multi-object tracking algorithm, and (b) The visual feature extractor.

to track the drones[18]. The user can set his current position in two text boxes in this window, and there is also an option to personalise the detected drone icon. A map with a green circle around his position and two adjustable crossed lines (field of view) to indicate camera range and direction can be found on the left side.

3.2 Sender: Analytics Component

The analytics component in the video data dashboard is responsible for processing and analyzing the data gathered by the anti-drone system. It typically includes the following Deep learning algorithms:

3.2.1 Deep Detection Model

As flying small UAVs have small sizes and few pixel features, the detection model has to acquire a strong ability to deal with small objects. In the original YOLOv5 architecture[21–23], the feature map of the vast scale of the convolutional network structure is too small to meet the requirements of subsequent detection and regression.

To solve this problem, we have applied the following three modifications and improvements to release 6.1 of the original YOLOv5 model to develop a deep detection model able to detect small drones[24-25].

We added three Residual Channel Attention Blocks (RCAB) in the backbone network. Stating that block can help the network find a region of interest in images that have large region coverage. Thus, inspired by the "attention mechanism" of human vision, we use feature extraction by the RCAB layer to extract the most useful information from small objects.

In the Neck and prediction parts of the proposed detection model, a fourth scale with seven layers is added to the three scales feature maps, already existing in the standard version of the YOLOv5 model. The added part helps capture more texture and contour information of small objects.

Feature maps from the backbone network are brought into the added fourth scale to reduce feature information loss of small UAVs. The connection is added to bring the feature information from the backbone network into the added fourth scale of the neck network.

3.2.2 Deep Super Resolution Model: Lensful Imaging

We propose a super-resolution model to display more details about the target. Our improvement of the quality of the image consists in using a Single Image Super Resolution (SISR)[26]. This method consists of converting a Low Resolution (LR) image to its High Resolution (HR) equivalent, which helps in real-time identification tasks. Convolutional Neural Networks (CNNs) with Residual Blocks (RBi) provide efficient SR results with less computation time.

3.2.3 Imaging Deep Tracking Model

For higher accuracy and robustness of tracking in complex scenes, such as the interaction between targets and occlusion and their different shapes and view appearances[27], we improved the data association assignment by upgrading the extraction of target appearance information [28].

An illustration of the proposed tracking algorithm is summarised by the following framework and illustrated in Fig. 4. In Fig. 4(a), we provide the overall architecture of the algorithm, and we detail the deep appearance feature network in Fig. 4(b). The algorithm steps are: (1) Input an image crop; (2) Extract all object features; (3) Measure the distance between all detections and tracklets; (4) Associate detection and tracklets (5) Tracking by data assignment. The CNN feature extractor is redesigned and trained, to improve mini-UAV reidentification in the appearance feature phase of the proposed tracking algorithm.

3.2.4 Motion Control Model

PID controllers have been exploited in various industrial systems mainly based on offline tuning which results in unstable tracking[29-30]. In this work, we propose a Neural Networks (NN) based PID controller as described in Figure 5. The errors of tracking are reduced due to the continuous adjustments of the PID parameters. The proposed Deep Neural Network (DNN) consists of three layers. The sigmoid function is used as an activation function. The adequate PID gains are estimated by the NN to ameliorate the stability of the Pan-Tilt-Zoom (PTZ) platform and the P/T positioner. The controller gains are adjusted online which minimizes the tracking error.

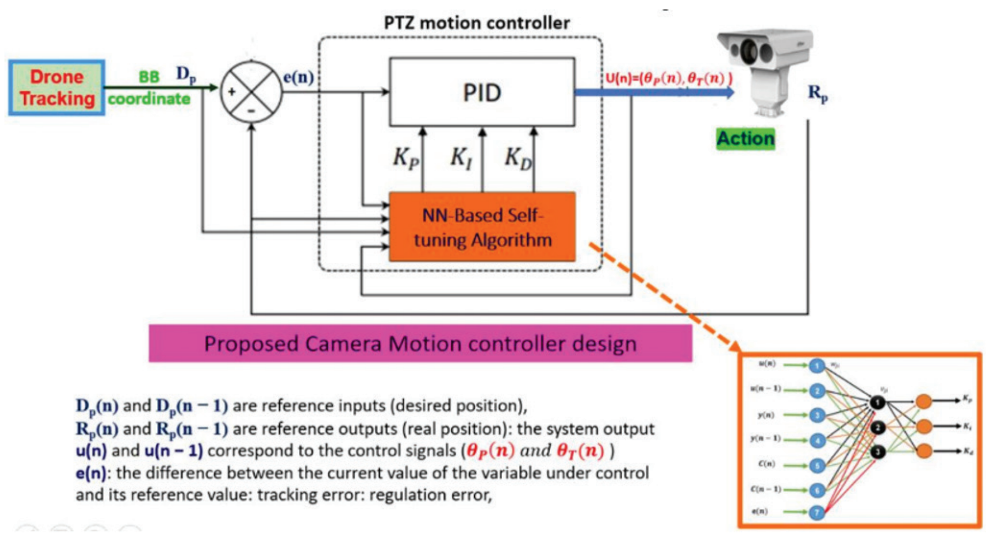

Figure 5. Intelligent motion control.

The azimuth and pitch axes of the PTZ platform[31] are adjusted by the target's angular speed by the cameras as they follow a target. For the PTZ platform and P/T positioner, we have proposed a motion control model based on angular speed to improve system performance and get rid of overshooting, lag, and vibration. The model uses a PID control technique to modify the angular speed of the pan-tilt platform based on feedback from the distance between the tracked object in the image and the center of the frame. The outcome is a Motion-Intelligence-Based Control Algorithm for Object Tracking that automatically manages the pan-tilt movements of both the camera[32] and the jammer[33].

3.2.4 *Dataset Construction*

Utilising unique datasets of air images gathered and created by the study team, the proposed deep models—namely, the deep detection model, deep SR model, and deep tracking model—were trained, validated, and put to the test. These datasets were recorded with a Dahua multisensor Network PTZ camera[32] at various times, with various levels of brightness, and in various intricate situations.

The group produced the following five datasets: the Mini/Micro UAVs Co-registered dataset consisting of 736 pairs of optical images, used to train the SR model; the Mini-UAV Visual dataset consisting of 20,000 images with 30,000 instances and 4 classes, used to train the visual Mini-UAV detection model; the Mini-UAV Thermal dataset consisting of 5,000 images with 5,200 instances and one class, used to train the Thermal Mini-UAV detection model; and the Mini-UAV ReID dataset consisting of 30,000.

4 DEPLOYMENT AND DISCUSSION

We have chosen a study location for the anti-drone system's deployment of the video data analytics dashboard as well as for continuing upkeep and support. It is the no-fly zone of Tunisia's Gafsa Governorate's Gafsa-Ksar International Airport. We have flown our mini-UAVs to test the full monitoring system. The proposed technique was successful in detecting, classifying, and tracking tiny drones flying over the Orbata mountain, which is located east of the city of Gafsa, between El Ksar and Sened. This area has experienced several terrorist actions, primarily attacks using Improvised Explosive Devices (IEDs) and the use of commercial drones to track troop movements.

5. CONCLUSIONS

The developed C4 dashboard is a video data analytics tool that provides a comprehensive solution for analyzing and visualizing video data collected by anti-drone systems. It enables users to make informed decisions and improve the overall effectiveness of their anti-drone measures. The proposed dashboard is highly scalable due to the modern software engineering techniques and tools used during its development. It can handle large amounts of video data collected by anti-drone systems without compromising its performance. The dashboard's scalability ensures that it can be used in various scenarios. It provides users with valuable insights to improve the effectiveness of their anti-drone measures. The inference results have already demonstrated good measure performance in challenging conditions, including complex backgrounds and varying illumination. Furthermore, the results of testing and evaluation, over the Orbata mountain, show that the dashboard met all of the functional and performance requirements, further demonstrating its potential as a valuable tool for anti-drone systems. The C4 dashboard seamlessly integrates with optical and thermal imaging sensors, showcasing its adaptability within such systems. Future advancements target the expansion of its capabilities to encompass additional monitoring devices, such as RADAR and RF scanning technologies for decision-making.

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In the current study he presented the methodology, conducted experiments, designed the dashboard, and wrote the paper.

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