UNMANNED AERIAL VEHICLE DETECTION SYSTEM (UAVDES)
TÜBİTAK BİLGEM İLTAREN

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Abstract. This project addresses the growing need for portable and efficient unmanned aerial vehicle detection systems (UAVDES) in modern combat scenarios, where drones play a decisive role in operational outcomes. Motivated by insights from recent military conflicts and expert analysis, including data from the Russia-Ukraine war and the Australian Army Research Centre, the solution emphasizes portability, cost-effectiveness, and accuracy. Developed in collaboration with TÜBİTAK İLTAREN, the system integrates AI and non-AI algorithms across three modules—detection, tracking, and physical design—achieving reliable identification and tracking of drones within a 100–500 meter range. It utilizes YOLOv8s for detection, Kalman filtering for tracking, and a dual-field-of-view camera setup mounted on a portable pan-tilt mechanism, all powered by a Jetson AGX Orin and managed by a Raspberry Pi 4. The system demonstrated high detection accuracy under clear weather, effective multi-drone tracking, and robust scanning performance, while offering a compact, deployable alternative to existing fixed-platform solutions.

PROJECT DESCRIPTION

Recent international military engagements have underscored the strategic importance of drones in influencing battle outcomes and the necessity for rapid enemy drone identification. Unmanned aerial vehicle detection systems (UAVDES) are employed to detect hostile drones and alert operating personnel; however, many designs—typically equipped with pan-tilt mechanisms and cameras tailored to specific operational requirements—lack the portability required for individual soldiers. In today's volatile security environment, insights from the Australian Army Research Centre, combined with data from the Russia-Ukraine conflict (where drones have been responsible for approximately 70% of Russian casualties and up to 90% of equipment losses), further highlight the urgency of investing in advanced detection systems [1]. In response, our approach emphasizes portability and is structured into three essential modules: detection, tracking, and physical design. Success is measured by high detection accuracy under clear weather conditions, the consistent association of detected drones with the correct labels across multiple consecutive frames, and the performance of the pan-tilt mechanism within acceptable error margins to ensure efficient detection and tracking. The final product will feature an LCD user interface on the frontend and employ both AI and non-AI algorithms for detection along with Kalman filter and drone association algorithms for tracking on the backend, ensuring a comprehensive and reliable solution.

Several UAVDES solutions exist in the market. For instance, as the Retinar FAR-AD and SPYNEL provide valuable capabilities, they also exhibit significant limitations [2]. The Retinar FAR-AD, for instance, offers long-range detection and operates in challenging weather conditions but lacks visual confirmation and is vulnerable to jamming. In contrast, our system introduces novel features that overcome these drawbacks. Its dual-field-of-view design seamlessly integrates wide-angle scanning with high-resolution zoom capabilities, while AI-enhanced target verification significantly improves detection accuracy and minimizes false positives. This innovative blend not only enhances operational flexibility and precision but also offers improved portability and cost-effectiveness, marking a substantial advancement over current UAV detection and tracking solutions.

In collaboration with TÜBİTAK İLTAREN, we are developing a cost-effective, portable pan-tilt UAV detection system with a 100–500m operational range. Unlike fixed systems, our solution integrates both AI and non-AI methods to enhance processing speed and reduce false alarms.
Key Design and Performance Specifications:

- Drones must be at least 0.5m in size at 250m and 1m at 500m.
- Only drones with 4, 6, or 8 propellers are considered.
- Detection range: 100–500m; max drone speed: 100km/h.
- System supports tracking of up to 10 drones and 10 non-drone objects.
- Vertical scan: 5°–45°; horizontal scan: 0°–360° (user-defined).
- Full scan cycle completes in $\leq$ 3 seconds.
- Detected drone directions are shown on an LCD screen.
- Start, reset, and stop buttons control the scanning process.

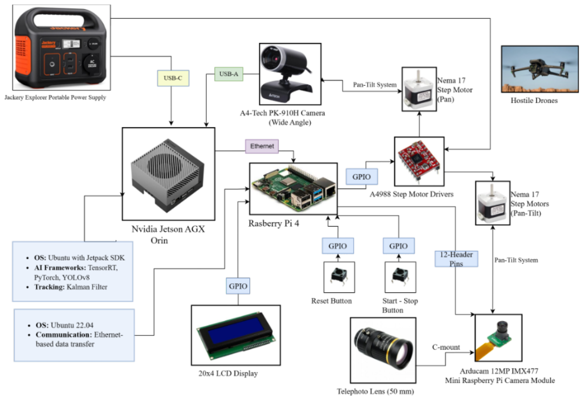

FIGURE 1. Big Picture

Figure 1 illustrates the overall system architecture and component interactions. A portable power station energizes both the NVIDIA Jetson AGX Orin and the Raspberry Pi 4, ensuring reliable operation in various field conditions. The Jetson AGX Orin executes AI-based detection using the YOLO V8s model and performs tracking with a Kalman filter combined with proprietary drone association algorithms. Concurrently, the Raspberry Pi 4 manages control tasks such as operating motors, linking a narrow-angle camera to the Jetson AGX Orin, and facilitating user interaction via a 20x4 LCD display. Multiple cameras stream video to the Jetson for real-time processing, including one equipped with a pan-tilt mechanism driven by stepper motors and motor drivers for dynamic positioning. This integrated setup delivers efficient wide-area surveillance, rapid target identification, and precise tracking in a compact, field-deployable design.

MILESTONES

The UAV Detection System (UAVDES) project progressed through four key phases, each addressing essential tasks to meet project goals.

Project Initialization. This phase laid the groundwork by defining technical and functional requirements through discussions with TÜBİTAK BİLGEM İLTAREN. Hardware and software were selected, aligning project goals with stakeholder expectations and setting the stage for future development.

UAV Detection Phase. We developed drone detection algorithms guided by a literature review and implemented them on the NVIDIA Jetson AGX Orin. Using a dataset of 30,000 images, we trained a YOLOv8s Tiny model, enhancing detection accuracy. A non-AI algorithm was also built for initial detection. A Unity-based simulation environment supported testing and optimization.

Tracking Phase. A Kalman filter-based tracking system was implemented for real-time trajectory prediction and multi-drone tracking. This integration improved system reliability and continuous monitoring capabilities.

System Design. All components were integrated for smooth operation. A custom pan-tilt mechanism was added, and multi-threaded execution enabled real-time detection, tracking, and control. Communication between Jetson AGX Orin, Raspberry Pi, cameras, and motors was optimized. Field tests confirmed system performance under real-world conditions.

DESIGN DESCRIPTION

Hardware Design. The hardware system is built around two main subsystems: a wide-angle detection unit and a narrow-angle tracking unit.Figure 2 shows the hardware design diagram.

The wide-angle detection unit features an A4Tech PK-910H webcam mounted on a single-axis rotating platform. This platform allows horizontal panning and is driven by a stepper motor. The camera is connected to a Jetson AGX Orin, which handles the initial environment scan. As the camera rotates, the Jetson processes the video feed in real time, looking for any potential targets. Once a target is spotted, its angular coordinates are calculated and forwarded to the tracking subsystem.

The narrow-angle tracking unit is centered around an Arducam 12MP IMX477 camera equipped with a 50mm telephoto lens, offering a zoomed-in view suitable for identifying small objects such as drones at a distance. This camera is mounted on a two-axis gimbal system controlled by NEMA 17 stepper motors. These motors are driven by A4988 motor drivers and are controlled by a Raspberry Pi 4, which also handles the image capture and streaming from the narrow-angle camera. The dual-axis design allows for both horizontal and vertical adjustment. Real-time angle data from motor encoders are used for coordinate transformations between the two subsystems.

For power, a Jackery Explorer portable battery pack was used, making the entire system mobile and field-deployable. A 20x4 I2C LCD display is mounted on the hardware to show system status. Physical start, stop, and reset buttons were added to allow manual control during testing phases. Every individual component, from motors to encoders and cameras, was tested manually to confirm mechanical alignment and electrical stability before full integration. This hands-on testing helped prevent hardware issues during later software integration and field trials.

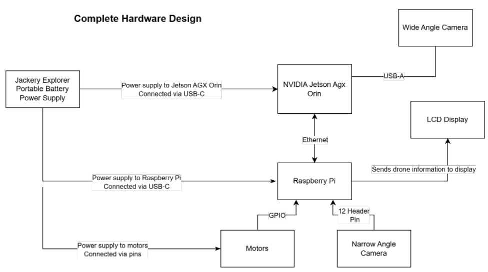

FIGURE 2. Hardware Design Diagram

Software Design. The software architecture is built around a two-stage detection pipeline, combining lightweight image processing with deep learning to balance speed and accuracy. Figure 3 shows the software design diagram.

In the first stage, the wide-angle subsystem on the Jetson AGX Orin runs a non-AI detection algorithm based on edge detection and contour analysis. This method was chosen for its speed and low resource usage, allowing the system to scan the environment efficiently. When a potential drone-like object is identified, its angular position relative to the rotating base is calculated and stored for further analysis.

The second stage uses a Kalman filter, also on the Jetson, to predict the future position of the detected object based on its motion history. This predicted position is sent to the Raspberry Pi 4, which adjusts the narrow-angle camera's orientation accordingly. Once the camera is aimed, the captured image is passed through a YOLOv8s deep learning model to verify whether the object is actually a drone. The objects, whether they are drones or not, are tracked for continuous labeling with non-AI detections.

To test this logic before deploying on real hardware, a Unity simulation was developed. The simulation allowed us to create custom drone trajectories and observe how well the Kalman filter and motor control algorithms responded in various scenarios. This helped us fine-tune parameters and debug edge cases without needing to rely on physical testing for every change. All software components were written in Python, with careful use of threading to allow the Jetson and Raspberry Pi to operate in parallel without blocking each other. This setup ensured real-time performance during both simulation and live tracking.

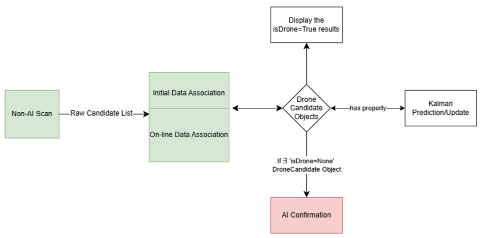

FIGURE 3. Software Design Diagram

RESULTS AND PERFORMANCE EVALUATION

Extensive testing confirmed UAVDES's effectiveness in diverse real-world conditions, meeting all design-phase success criteria. This section summarizes simulation results, experimental findings, and comparative evaluations.

Simulation Based Verification. Unity simulations modeled drone movement and camera operations for parameter tuning. UAVs sized 0.5m and 1m were detected at

250m and 500m respectively. Scanning met angle (5°–45° vertical, 360° horizontal) and timing (3 second) requirements, validating ABA-01/02 and MEI-01/02/03. As can be verified in the Figure 4.

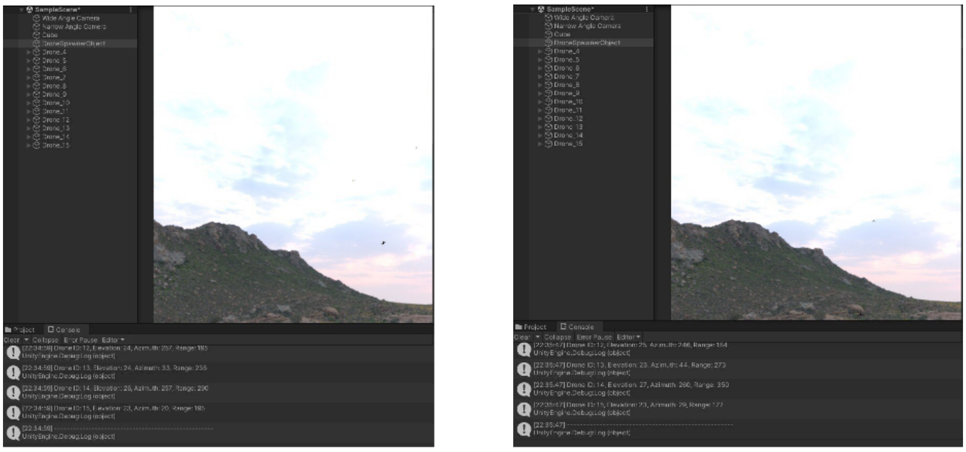

FIGURE 4. Simulation Detections at t and $t+3$ seconds

Experimental Testing Results.

Non-AI Detection. Using a wide-angle camera and Kalman filtering on Jetson AGX Orin, drones were tracked across frames with $\leq 60\%$ label consistency. Up to 10 drones and 10 other objects were tracked simultaneously, with trajectory accuracy within ±5 pixels, satisfying MSA-01 and MSA-02. Also can be seen in the Figure 5.

FIGURE 5. Non-AI Detections at t and $t+3$ seconds

AI-Based Detection. With a narrow-angle lens and YOLOv8s, drones were detected at 100–500m with 87–95% confidence and 120–140 ms processing time. Total system latency stayed below 1500 ms, meeting ABA-03 and MSA-03. Shown in the Figure 6

Mechanical System. Stepper motors (NEMA 17) controlled via Raspberry Pi showed $< \pm 10°$ error under continuous operation. Delays were under 1500 ms, and the 3D-printed structure remained functional under extended testing without overheating.

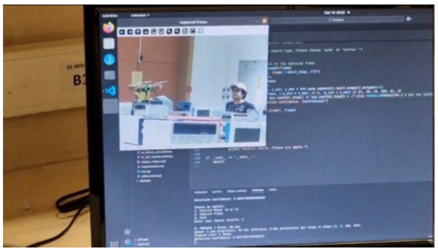 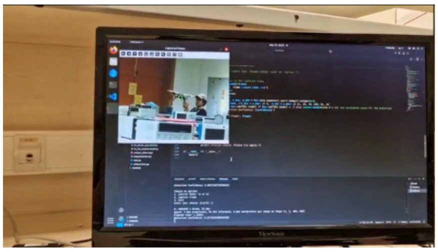

FIGURE 6. AI Detections for Different Positioning of the Drone

Comparative Evaluation. UAVDES offers a cost-effective and portable alternative to systems like Skypatriot or Aeroeye [3, 4]. While lacking radar or thermal capabilities in poor visibility, it provides AI-assisted optical confirmation, reducing false positives and enabling actionable visual validation.

CONCLUSIONS AND FUTURE DIRECTIONS

Within the scope of this project, a portable, cost-effective, and high-accuracy unmanned aerial vehicle detection system has been developed. The system utilizes both AI-based and traditional algorithms to ensure reliable drone detection and tracking across various environments. By integrating wide-angle and narrow-angle camera units, it allows for broad area scanning and high-resolution verification. The Unity-based simulation environment enabled analysis of system behavior prior to real-world testing. Field tests confirmed that the system achieved the desired levels of accuracy and responsiveness.

In the future, several enhancements could be implemented to further improve system capabilities. For instance, integrating infrared (IR) cameras may enhance performance under low visibility and nighttime conditions. Additionally, adopting more advanced versions of the YOLO model could increase AI detection accuracy. Incorporating Hall Effect sensors into the motor control system may also improve the precision of the pan-tilt mechanism. These potential upgrades would allow the system to better adapt to a wider range of operational scenarios.

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BEHIND THE SCENES