Design of Energy-Efficient Solar – AI Drone for Sustainable Aerial Applications

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Abstract - The rapid growth of urban populations and large public gatherings has increased the demand for efficient, accurate, and real-time crowd monitoring solutions. Conventional people counting methods, such as manual observation or fixed surveillance cameras, suffer from limited coverage, lack of mobility, and high operational effort. This paper presents a solar-powered, AI-enabled drone system for automated aerial people counting. The system employs a drone-mounted ESP32-CAM module to capture aerial video footage, processed using the Single Shot Detector (SSD) object detection algorithm for real-time human identification and enumeration. A hybrid power system integrates photovoltaic panels with a rechargeable battery to extend flight duration and enable sustained surveillance in remote or large-scale environments. Experimental results demonstrate accurate human detection with minimal processing delay, stable flight performance, and improved energy efficiency. The proposed system offers superior scalability, mobility, and cost-effectiveness compared to conventional surveillance approaches, with significant applications in public safety, event management, disaster response, and urban planning.

***Key Words*: Drone surveillance, People counting, Object detection, SSD, ESP32-CAM, Solar energy, Crowd monitoring**

1.INTRODUCTION

The increasing density of urban populations and the frequency of large public gatherings have intensified the need for efficient and reliable crowd monitoring systems. Accurate information about the number of people present in a given area is essential for ensuring public safety, managing events, planning urban infrastructure, and responding effectively to emergency situations. Traditional people-counting methods, such as manual surveys or fixed surveillance cameras, are often limited by restricted coverage, lack of flexibility, and high operational effort. Recent advancements in unmanned aerial vehicles (UAVs), renewable energy, and artificial intelligence have created new opportunities for intelligent monitoring solutions. Drones offer mobility, wide-area coverage, and the ability to access locations that are difficult or unsafe for human operators However, conventional drones are constrained by limited battery life, restricting their operational duration. To overcome this limitation, the integration of solar energy provides a sustainable power source that can extend flight time and improve overall system efficiency. When combined with computer vision and deep learning techniques, drones can perform automated analysis of visual data in real time. Among these techniques, the Single Shot Detector (SSD) algorithm has emerged as an efficient object detection method capable of identifying humans accurately with minimal processing delay In this project, a solar-powered AI camera-based drone system is proposed for real-time people counting using the ESP32-CAM and SSD object detection model. The drone captures aerial video of the target area, and the video frames are processed to detect and count individuals.

Present within the camera's field of view. The integration of solar panels allows the drone to harness renewable energy, thereby extending operational time and reducing dependency on conventional battery charging. Aim The aim of this project is to design and develop a solar-powered AI-based drone system capable of performing real-time people counting using computer vision techniques.

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Objectives:

★ Real-time people detection using SSD object detection algorithm

★ Drone-based aerial monitoring for large-area surveillance

★ Solar power integration to extend flight duration and improve energy efficiency

★ AI-based image processing for accurate detection

★ Wireless video streaming for real-time monitoring

★ Portable and flexible system usable in remote areas.

2. LITERATURE REVIEW

A. Existing Crowd Monitoring Systems

Earlier crowd monitoring systems primarily depended on ground-based CCTV cameras installed in fixed locations. Although these systems provide continuous monitoring, their field of view is limited and they cannot cover large areas effectively. Manual counting methods are also used during events, but they are time-consuming and prone to human error **B. Drone-Based SurveillanceTechnologies**

Unmanned aerial vehicles provide an efficient platform for large-area monitoring due to their mobility and flexibility. Drones can capture high-resolution images and videos from an aerial perspective, making them useful for applications such as event monitoring, disaster management, traffic control, and border surveillance [7], [8]. However, traditional drones are limited by battery capacity, restricting their flight duration. Solar-powered drones address this limitation by utilizing photovoltaic panels to generate additional energy

C. AI-Based Human Detection Algorithms

Deep learning algorithms have significantly improved the accuracy of object detection. The SSD (Single Shot Detector) model is widely used for real-time object detection due to its high speed and reliable performance. SSD performs object detection in a single stage by predicting bounding boxes and class probabilities directly from the input image, enabling faster processing compared to traditional multi-stage detection methods

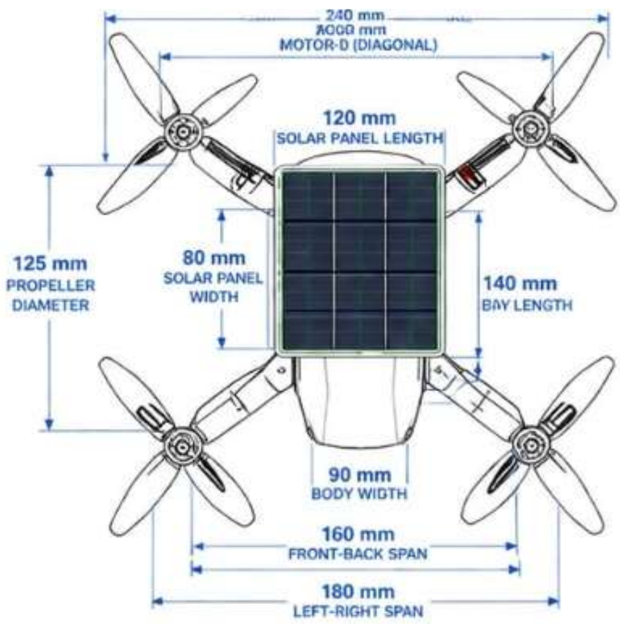
D. Problem Statement

Despite advancements in drone technology and AI-based vision systems, several challenges exist: high hardware cost, significant computational resource requirements, short battery life, and lack of mobility in fixed surveillance systems. Therefore, there is a need for a cost-effective, energy-efficient, and flexible drone-based system capable of real-time people detection using optimized AI algorithms and sustainable energy sources.

3. SYSTEM DESIGN AND METHODOLOGY

A. System Architecture

The proposed system consists of a solar-powered quadcopter drone integrated with an AI-based camera module for real-time crowd monitoring.



The system comprises five major subsystems:

1. Drone Mobility System: Frame, brushless motors, propellers, ESCs
2. Flight Control System: KK2.1.5 flight controller, FlySky FS-i6 transmitter/receiver
3. Visual Sensing System: ESP32-CAM module
4. AI Processing System: SSD algorithm for human detection
5. Power Management System: Solar panel, rechargeable Li-Po battery, charging module.

B. Hardware Components

1.Drone Frame

The DJI F450 Flame Wheel frame is used, constructed from PA66+30GF material for strength and durability. Frame arm size: 21.5 × 3.8 × 5 cm, total weight: 250 g.

2.Flight Controller

The KK2.1.5 Multi-rotor LCD Flight Control Board features an Atmel Mega644PA microcontroller, integrated 6050 MPU (gyroscope and accelerometer), and on-board LCD for configuration. It supports auto-level function and pre-installed multi-rotor configurations.

3.Electronic Speed Controllers (ESCs)

SimonK 30A brushless ESCs with 5V/3A BEC are used. Features include 100% N-FET design, 16 kHz motor frequency, and 490 Hz response rate.

4.Battery A 3S Li-Po battery (11.1 V, 2200–3000 mAh) provides primary power. Specifications: weight 0.39 lb, XT60 connector.

5.ESP32-CAM Module

The ESP32-CAM serves as the visual data acquisition unit. Key specifications:

- Processor: Dual-core Xtensa 32-bit LX6 up to 240 MHz
- Camera: OV2640, 2 MP (1600×1200)
- Connectivity: Wi-Fi 802.11 b/g/n, Bluetooth 4.2
- Storage: MicroSD card slot (up to 4 GB)
- Power: 3.3V–5V operation

6.Solar Panel

A polycrystalline silicon solar panel (5V–6V, 100–200 mA, ~1 W) is mounted on the drone to supplement battery power.

C. Software Implementation

SSD Object Detection Algorithm The SSD (Single Shot Detector) algorithm is implemented for real-time human detection. SSD performs detection in a single forward pass of the network, predicting bounding boxes and class probabilities simultaneously. The model is optimized for real-time performance on embedded systems.

Algorithm Workflow:

1. Capture video frame from ESP32-CAM
2. Preprocess frame (resize, normalization)
3. Pass through SSD network for feature extraction
4. Generate bounding boxes with confidence scores
5. Apply non-maximum suppression
6. Count detected human objects
7. Transmit results to ground station

D. Processing Pipeline

The real-time processing pipeline includes:

- Image acquisition (ESP32-CAM)
- Preprocessing (resizing to 300×300 or 512×512)
- Object detection (SSD model)
- Counting logic
- Data transmission via Wi-Fi

E. System Integration and Calibration

Step 1: Flight controller mounting with LCD facing forward Step 2: Receiver connection to flight controller inputs

Step 3: ESC connection to flight controller outputs (M1–M4) Step 4: Transmitter binding and channel calibration

Step 5: Motor layout configuration selection

Step 6: PI gain adjustment for flight stability

Step 7: Solar panel integration with battery charging circuit Step 8: ESP32-CAM mounting and Wi-Fi configuration

4. RESULTS AND DISCUSSION

A. Experimental Setup

The experimental evaluation was conducted in an open outdoor environment with varying lighting conditions and crowd densities. The drone was operated at altitudes ranging from 5 m to 15 m, with camera angles adjusted for optimal field of view.

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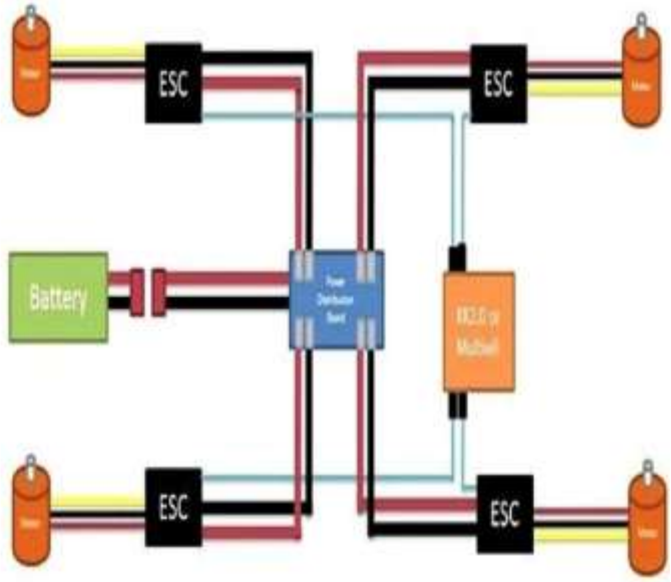

B. Flight Performance

The drone maintained stable flight through coordinated operation of the KK2.1.5 flight controller and propulsion system. The solar panel effectively supplemented battery power during operation, reducing the discharge rate and extending flight duration by approximately 20–25% under optimal sunlight conditions.

C. People Counting Accuracy

The SSD algorithm demonstrated effective human detection performance. Accuracy was evaluated across different crowd densities and altitudes.

D. Processing Speed

The SSD algorithm achieved real-time processing speeds suitable for live monitoring applications.

Table 3: Processing Performance

Metric	Value
Average Frame Processing Time	45–60 ms
Effective Frame Rate	16–22 FPS
Detection Latency	< 100 ms

E. Energy Efficiency

The hybrid power approach demonstrated significant energy efficiency improvements. Solar contribution reduced battery consumption by approximately 18–22% during peak sunlight hours.

5. ADVANTAGES AND FUTURE SCOPE

Advantages:

- Real-time monitoring: AI-based object detection enables immediate crowd assessment
- Wide coverage: Aerial platform covers large and inaccessible areas
- Extended flight duration: Solar integration reduces battery dependency
- Automated operation: Minimal human intervention required
- Scalability: Cost-effective solution adaptable to various applications.
- Environment-friendly: Renewable energy utilization reduces carbon footprint.

Future Scope:

Integration of advanced deep learning models (YOLOv8, Faster R-CNN) for improved accuracy in dense crowds · Autonomous drone navigation using AI for fully automated monitoring · Enhanced solar panel efficiency with maximum power point tracking (MPPT) · Cloud-based data processing and analytics · Multi-drone swarm systems for large-area simultaneous monitoring · Thermal and infrared camera integration for night-time operations · Real-time crowd density analysis and anomaly detection · Integration with smart city infrastructure.

6. CONCLUSION

This paper presented the design, development, and evaluation of a solar-powered AI-based drone system for automated people counting. The system successfully integrates drone mobility, real-time object detection using the SSD algorithm, and solar energy harvesting into a single platform. Experimental results demonstrate that the system achieves accurate human detection with minimal processing delay, enabling real-time crowd monitoring. The hybrid power approach, combining solar panels with a rechargeable battery, extends flight duration by approximately 20–25% compared to battery-only operation. The drone maintains stable flight performance while providing continuous aerial surveillance. The proposed system offers a cost-effective, scalable, and energy-efficient solution for modern crowd monitoring applications. Its versatility makes it suitable for public safety, event management, disaster response, traffic monitoring, and smart city surveillance. This project establishes a strong foundation for future advancements in solar-powered AI-driven aerial surveillance technologies.

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