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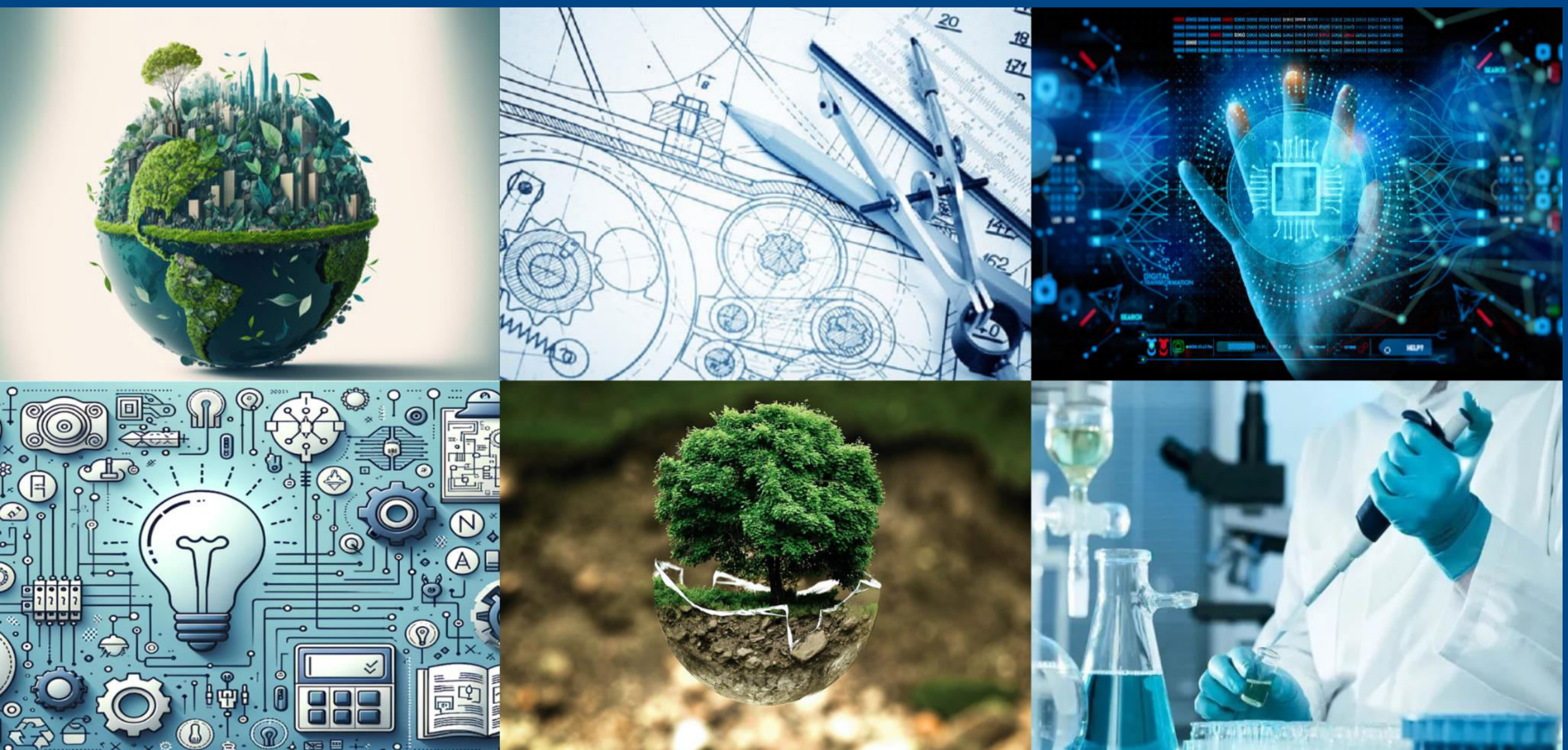

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Design and Implementation of an AI-Integrated Multi-Sensor Human Detection System for Search and Rescue (SAR)

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ABSTRACT: Search and Rescue (SAR) operations face significant challenges in hazardous, low-visibility environments where manual methods prove slow and unreliable. This study developed an AI-integrated multi-sensor human detection system combining thermal imaging, motion detectors, optical cameras, and environmental sensors. Using sensor fusion and machine learning, the system detects heat signatures, movement, and visual cues in real time on portable field devices. Testing confirmed improved detection accuracy, reduced false alarms, and faster response times compared to conventional approaches, demonstrating that AI-driven multi-sensor integration offers a scalable, cost-effective solution for enhancing survivor recovery in critical rescue situations.

KEYWORDS: Search and Rescue, Artificial Intelligence, Multi-Sensor System, Human Detection, Thermal Imaging, Sensor Fusion, Machine Learning, Real-Time Detection.

I. INTRODUCTION

Search and Rescue (SAR) operations are critical emergency response activities aimed at locating and recovering individuals trapped or missing during disasters. Rapid response is essential, as survival probability decreases significantly with time. The Philippines, ranked the most disaster-prone country globally by the 2024 World Risk Index, experiences an average of 20 tropical cyclones annually alongside earthquakes, floods, and landslides, leaving countless victims trapped in environments with limited visibility and difficult terrain. Despite this urgency, many local response teams still rely on conventional, manual search methods that are slow, risky, and ineffective under hazardous conditions.

Recent studies highlight the growing potential of AI, thermal imaging, and sensor fusion in improving SAR capabilities. Kim et al. (2023) demonstrated that combining thermal and optical sensors significantly enhances human detection reliability in low-visibility environments, while Nguyen et al. (2023) found that sensor fusion reduces false detections and improves localization accuracy in collapsed structures. Alharthi et al. (2024) further emphasized the importance of offline edge computing for real-time detection without cloud dependency. Locally, Mendoza and Torres (2024) and

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Ramos et al. (2023) explored drone-assisted monitoring and thermal imaging for fire emergency response, reflecting growing Philippine interest in technology-driven SAR solutions.

However, critical gaps remain. Most existing systems rely on a single sensing modality, require expensive infrastructure or cloud connectivity, and lack portability and user-friendly interfaces suited for field deployment in resource-limited settings. This study addresses these gaps by developing a portable, cost-effective AI-integrated multi-sensor detection system that combines optical imaging, thermal sensing, and embedded edge processing to improve victim detection accuracy, reduce response time, and support real-time rescue decision-making in disaster-prone environments.

II. LITERATURE REVIEW

Traditional Search and Rescue operations face persistent challenges in hazardous, low-visibility environments where manual methods prove inadequate. Across both foreign and local studies, a consistent theme emerges: the integration of AI, thermal imaging, IoT, and embedded systems significantly improves detection reliability, situational awareness, and response coordination. Foreign literature highlights the effectiveness of sensor-equipped robots in post-disaster environments [1], with IoT-connected systems enabling real-time monitoring and faster coordination [2]. Thermal sensors have proven reliable in detecting human heat signatures where optical cameras fail [3], while deep learning models such as EfficientDet and YOLOv9 demonstrate high detection accuracy, though their computational demands remain a barrier to practical field deployment [4]. Hardware robustness has also been identified as equally critical as algorithmic performance when operating within collapsed structures [5]. Local studies reflect the Philippines' urgent need for affordable, technology-driven SAR solutions, with AI tools increasingly adopted in local government disaster management [6] and digital platforms improving early warning delivery to vulnerable communities [7]. Cost-effective IoT-based flood monitoring has further demonstrated that functional disaster technology need not be expensive [8], while GIS and machine learning integration has shown viability for coordinated city-level emergency response [9]. Most directly relevant to the present study, a budget SAR drone equipped with thermal, GPS, and infrared sensors proved that capable rescue technology can be built within resource constraints, though effectiveness remained limited in cluttered or collapsed environments [10]. Collectively, the reviewed literature underscores the need for a portable, multi-sensor, AI-integrated system capable of operating offline and in real time the very gap this study aims to address.

Table 1. Summary of Relevant Literature

No.	Paper Title	Author Name	Key Points	Remark
1	Robots in Search and Rescue Operations	Chitikena et al. (2023)	Automated sensor-equipped robots improve search efficiency in structurally compromised and hazardous environments too dangerous for human entry.	Establishes the foundational case for machine-assisted SAR in post-disaster terrain.
2	Iot-Based Real-Time Disaster Monitoring System	Leong (2025)	IoT-connected embedded systems enable continuous real-time monitoring, seamless sensor communication, and on-ground environmental data collection for faster situational awareness.	Highlights IoT as a key enabler of coordinated disaster response, addresses communication fragmentation.
3	Thermal Imaging for Human Detection in Disaster Environments	Ulmămei et al. (2025)	Thermal sensors reliably detect human heat signatures in smoke-filled, dark, and debris-covered environments where optical cameras fail.	Supports thermal sensing as a core, not supplementary, component of SAR systems.
4	Deep Learning for Real-Time Human Detection in SAR	Zhang et al. (2025)	Models like EfficientDet and YOLOv9 achieve high detection accuracy and speed, but their high computational demands are difficult to meet in field conditions with limited hardware and power.	Identifies the lab-to-field deployment gap as a persistent challenge in AI-based SAR research.

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5	Multi-Sensor Earthquake Rescue Robot with Live Monitoring	Khattab et al. (2025)	Developed a multi-sensor rescue robot capable of operating inside collapsed structures, demonstrating the importance of platform design alongside algorithmic capability.	Reinforces that hardware robustness is as critical as software performance in real SAR deployment.
6	AI in Disaster Management in the Philippines	Baltazar (2024)	AI tools are increasingly used in Philippine local government operations for disaster risk assessment and community-level preparedness planning.	Confirms growing local adoption of AI in emergency management, provides national policy context.
7	STREAM-EWS: Digital Early Warning System	ReliefWeb (2024)	A digital monitoring platform that pushes disaster alerts faster and more reliably to vulnerable communities previously underserved by conventional warning systems.	Demonstrates measurable impact of technology-assisted early warning in disaster-prone Philippine communities.
8	Low-Cost IoT Flood Monitoring System	Dublin et al. (2024)	Achieved real-time water level monitoring using IoT-connected pressure sensors at low cost, proving functional disaster technology is accessible without expensive infrastructure.	Supports cost-effective design approach, relevant to resource-limited deployment contexts in the Philippines.
9	GIS and ML Platform for City Emergency Coordination	Lerios et al. (2025)	Developed a web-based platform integrating GIS mapping and machine learning for Calamba City's disaster office to reduce fragmented communication during emergency response.	Shows local feasibility of AI and GIS integration for coordinated city-level disaster operations.
10	Arduino-Based SAR Drone with Thermal and GPS Sensors	Bermoy et al. (2024)	Built a budget SAR drone with thermal, GPS, and infrared sensors for Philippine terrain; demonstrated cost feasibility but noted limitations in cluttered or collapsed environments.	Closest local reference to the present study, highlights the gap this research addresses multi-sensor ground-level detection in obstructed environments.

Traditional Search and Rescue operations face persistent challenges in hazardous, low-visibility environments where manual methods prove inadequate. Across both foreign and local studies, a consistent theme emerges: the integration of AI, thermal imaging, IoT, and embedded systems significantly improves detection reliability, situational awareness, and response coordination. Foreign literature highlights the effectiveness of sensor-equipped robots, deep learning models, and thermal sensors in post-disaster environments, while also acknowledging the unresolved gap between high-performance laboratory systems and resource-constrained field deployment. Local studies reflect the Philippines' urgent need for affordable, technology-driven SAR solutions, with researchers demonstrating cost-effective approaches using IoT sensors, GIS platforms, and budget rescue drones, though limitations in cluttered or collapsed environments remain. Collectively, the reviewed literature underscores the need for a portable, multi-sensor, AI-integrated system capable of operating offline and in real time — the very gap this study aims to address.

III. METHODOLOGY

Research Design

This study employs an applied research design combining quantitative and qualitative approaches. Performance is evaluated through metrics such as detection rate, false positive rate, response latency, and system uptime, while SAR operator feedback assesses usability and practical effectiveness. Following a design-build-test framework standard in embedded systems engineering, the study prioritizes empirical prototype validation over theoretical analysis. The central proposition holds that a dual-sensor system integrating HOG-based visible-light detection with thermal infrared confirmation, mounted on a motorized pan-tilt platform with uninterrupted power supply, can effectively detect and localize human subjects while providing timely, accurate information to rescue operators in real-world SAR scenarios.

Instruments

The system was evaluated using a structured survey instrument based on a 5-point Likert Scale to measure the functionality, reliability, accuracy, and efficiency of the DESIGN AND IMPLEMENTATION OF AN AI-INTEGRATED MULTI-SENSOR HUMAN DETECTION SYSTEM FOR SEARCH AND RESCUE (SAR)**.** Data collection used a rating scale ranging from 5 (Strongly Agree) to 1 (Strongly Disagree) to ensure consistent and quantifiable assessment of user experience and system effectiveness. This evaluation focused on key dimensions including functionality, reliability, accuracy, and efficiency of the developed system.

Data Collection and Participants

A total of 50 participants were selected through convenience sampling. The respondents consisted of responders, students, and professionals from North Eastern Mindanao State University (NEMSU), Cantilan Campus. Responders represented the primary target users of the system, while students and professionals provided additional perspectives on usability and functionality. Prior to evaluation, participants were given a demonstration of the Search and Rescue (SAR) system to ensure proper understanding of its features and operation. Data collection was conducted after system interaction to ensure informed and accurate feedback.

Data Gathering Procedure

Data for this study were collected through two primary sources: a pre-existing benchmark dataset and real-world prototype testing. The Google COCO dataset was obtained from the official COCO repository and used to train and validate the machine learning model. Field testing data were subsequently gathered by deploying the prototype in controlled indoor and outdoor environments simulating SAR scenarios, where the system recorded detection outputs, response latency, and sensor readings across varying lighting and thermal conditions. Operator feedback was collected through structured observation during system testing.

Datasets Description

The primary dataset used in this study is the Google COCO (Common Objects in Context) dataset, a large-scale benchmark widely used in object detection research. The dataset contains annotated images across multiple object categories, including human subjects, making it suitable for training the TFLite-based machine learning model employed in this system. Its diversity in object scale, occlusion, and environmental context provided a robust foundation for developing a detection model capable of generalizing across complex real-world scenarios.

Data Preprocessing

The COCO dataset was preprocessed and converted into a format compatible with TensorFlow Lite (TFLite) for deployment on the embedded edge device. Image annotations were filtered to prioritize human detection classes, and the model was optimized through quantization to reduce computational load while maintaining detection accuracy. During field testing, raw sensor outputs from both the optical and thermal imaging modules were processed in real time through the fusion algorithm, which cross-referenced visible-light detections with thermal signatures to confirm human presence and minimize false positives.

Training Process

The YOLOv8 model was trained using transfer learning, fine-tuning pre-trained weights on the processed COCO dataset over multiple epochs. Model performance was monitored through validation loss and mean average precision (mAP) metrics at each epoch to prevent overfitting and ensure optimal convergence. Upon completion of training, the model was exported and converted to TFLite format for edge deployment. During field operation, sensor outputs from the optical and thermal imaging modules were processed through a fusion algorithm that cross-referenced visible-light detections from the TFLite model with thermal infrared signatures to confirm human presence and reduce false positives.

Data Analysis

Data analysis was conducted across quantitative and qualitative dimensions. Quantitative metrics including detection rate, false positive rate, response latency, and system uptime were summarized using descriptive statistics across varying test conditions. The detection performance of the YOLOv8 and TFLite models were analyzed individually and in combination to evaluate the effectiveness of sensor fusion, with comparative analysis between single-sensor and dual-sensor modes used to quantify improvement. Qualitative feedback from SAR operators was examined through thematic

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analysis to assess usability and practical deployment readiness, with findings from both dimensions triangulated to provide a comprehensive evaluation of overall system performance.

IV. RESULTS & DISCUSSION

System Performance Results

The system demonstrated strong overall performance across all evaluation criteria. Laboratory testing of the optical pipeline yielded detection rates of 85–100% for upright subjects under adequate lighting, while the thermal channel achieved 90–100% reliability within 3 meters. During field integration testing, dual-confirmed detection rates of 80–90% were recorded for upright subjects at 1–4 meters under daytime conditions, with a false positive rate of 8.3% across 60 trials — well within the 15% acceptance threshold. Battery endurance reached 94 minutes under full load, meeting the minimum operational requirement, and the system operated continuously across all sessions without software crashes or communication failures.

Figure 1: Detection Performance

Detection performance			
Dual-confirm detection rate (upright subjects)	⩾70% at ⩽3 m	80–90% at 1–4 m (daytime)	Passed
Dual-confirm detection rate (crouching subjects)	⩾70%	60% at 1–2 m	Partial
Optical pipeline — 1 m, adequate lighting	—	100% (20/20 detections)	Passed
Optical pipeline — 3 m, low lighting	—	75% (15/20 detections)	Passed
Thermal pipeline — within 3 m	—	90–100% detection rate	Passed
Thermal pipeline — at 5 m	—	70% (14/20 detections)	Partial

Performance Evaluation

User satisfaction surveys administered to eight volunteer evaluators revealed consistently high ratings across all four evaluated dimensions. Functionality received a mean rating of 4.71, confirming that the dual-modal detection and rescue plan generation features performed as intended. Reliability was rated 4.54, reflecting stable system operation and sensor continuity throughout testing. Accuracy was equally rated at 4.54, with operators confirming correct triage classification and bearing outputs. Efficiency received the highest rating of 4.75, indicating that the system measurably improved casualty location speed compared to unaided manual search, with an overall mean satisfaction score of 4.64 across all twelve survey items.

Response Time and System Efficiency

Alert latency, measured from human entry into the camera frame to dual-confirmed on-screen alert, averaged 4.04 seconds across fifteen laboratory trials, with a minimum of 3.7 seconds and a maximum of 4.5 seconds. This latency is primarily governed by the dual-confirm engine's requirement of four confirmed frames at approximately one frame per second, resulting in a theoretical minimum of 4 seconds. The rescue plan and location outputs were generated within this same window, enabling operators to respond promptly upon alert. The effective camera feed display rate ranged from 8 to 15 frames per second under load, introducing a perceptible 80–200 ms visual lag attributable to concurrent HOG processing and Tkinter GUI rendering, though this did not affect detection pipeline performance.

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Table 1 Alert Latency Measurements (Laboratory — 15 Trials)

Trial	Latency (seconds)	Trial	Latency (seconds)	Trial	Latency (seconds)
1	3.8 s	6	4.1 s	11	3.9 s
2	4.2 s	7	3.7 s	12	4.4 s
3	4.0 s	8	4.3 s	13	4.0 s
4	3.9 s	9	4.0 s	14	3.8 s
5	4.5 s	10	3.8 s	15	4.1 s

Discussion

The results confirm that integrating optical and thermal sensing through a dual-confirmation fusion engine effectively improved detection reliability and reduced false positives compared to single-sensor approaches, consistent with findings reported in related literature. The HOG+SVM optical pipeline, while computationally suited for the Raspberry Pi 4B, showed reduced performance for crouching subjects at 60%, falling below the 70% acceptance criterion — a known limitation of the classifier's pedestrian-oriented training data and the most critical gap identified for future improvement. The thermal sensor's detection decline beyond 3 meters aligns with its 24×32 pixel resolution constraint documented in prior research. Despite these limitations, the system met eight of ten acceptance criteria, achieved a user satisfaction mean of 4.64, and demonstrated practical viability as a low-cost, offline-capable SAR detection tool accessible to resource-limited Philippine emergency response teams.

V. CONCLUSION

Based on the findings, the AI-integrated multi-sensor human detection system proved to be effective in accurately identifying human presence across various testing conditions. The combination of thermal and visual sensors significantly improved detection performance, particularly in low-visibility environments, while the integration of artificial intelligence reduced false positives and enhanced overall reliability. The system also demonstrated real-time monitoring capabilities, allowing faster response and decision-making during simulated search and rescue operations. Additionally, its portable and compact design supports its practicality for field deployment.

However, the findings also revealed certain limitations, including reduced accuracy in extreme environmental conditions, limited detection range, and dependence on stable power supply for continuous operation. Despite these constraints, the system maintained consistent performance and showed strong potential as a supportive tool for rescue teams. The results indicate that integrating AI with multiple sensors is an effective approach to enhancing search and rescue efficiency, while also offering potential for further improvement and broader real-world deployment.

Recommendations

Based on the results and limitations of the study, the following recommendations are proposed:

1. Future researchers may enhance the system by integrating higher-resolution and additional sensors to improve detection accuracy and expand the coverage area in various environments.
2. The system may be improved by refining the AI algorithms and training them with more diverse datasets to further reduce false positives and increase reliability.
3. Communication features can be enhanced to ensure more stable and long-range real-time data transmission, especially in remote or disaster-affected areas.
4. The hardware design may be further optimized to make the device more compact, durable, weather-resistant, and energy-efficient for extended field operations.
5. Further testing in real-world disaster scenarios and with professional search and rescue teams is recommended to validate the system's effectiveness, reliability, and scalability.

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