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APPLICATION OF HSV COLOR ANALYSIS AND GREEN MASKING FOR UXO DETECTION IN DENSE VEGETATIONS

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Abstract

This study examined the applicability of HSV color-space analysis and green-mask segmentation for the preliminary detection of unexploded ordnance (UXO) in densely vegetated terrain using UAV-acquired imagery. The research addressed the problem of limited visibility in natural environments where vegetation frequently obscures surface objects and reduces the effectiveness of conventional optical detection. High-resolution RGB images collected by a low-altitude UAV flight were converted into the HSV domain to isolate vegetation based on hue, saturation, and value distributions. Segmentation thresholds were optimized through histogram-based calibration and iterative refinement. The analysis revealed that vegetation covered approximately 70–74% of the test area, resulting in complex contour patterns and underscoring the need for color-space preprocessing in cluttered environments. Importantly, UXO models were consistently excluded from the green mask, indicating that the segmentation method successfully differentiated non-vegetative objects from natural background elements. These findings demonstrated that HSV-based vegetation extraction enhanced object visibility and provided a reliable foundation for subsequent UXO recognition. The study concluded that integrating HSV segmentation with UAV imagery improves early-stage UXO detection and should be further expanded through multimodal sensing and machine-learning approaches.

Keywords: *UXO, HSV Analysis, Green Mask, Vegetation Detection, Contours, Drone Imagery*

INTRODUCTION

Humanitarian mine clearance represents a critical component of post-conflict recovery, as unexploded ordnance (UXO) and landmines continue to endanger civilian populations, limit agricultural productivity, and impede infrastructure development in numerous regions worldwide. Although substantial progress has been achieved, mine action operations remain labor-intensive, time-consuming, and often hazardous due to difficult terrain, dense vegetation, and limited visibility. In recent years, unmanned aerial vehicles (UAVs) equipped with high-resolution optical and thermal sensors have emerged as a valuable tool for rapid, safe, and cost-effective reconnaissance of potentially contaminated areas (Bajić 2020; Vivoli, Bertini, and Capineri 2024). UAV imagery enables large-scale data acquisition without direct exposure of personnel to risk and provides a foundation for automated detection systems supported by advanced image-processing techniques.

A growing body of research has explored the use of artificial intelligence, thermal imaging, and photogrammetric analysis for mine and UXO detection (Zhang et al. 2022; Blagojević et al. 2025). However, the challenge of detecting objects obscured by dense or heterogeneous vegetation remains unresolved. Vegetation often conceals surface objects, alters spectral characteristics, and produces shadows and chromatic noise that reduce algorithmic reliability (Shi, Fang, and Zhao 2023). Despite the demonstrated robustness of the HSV (Hue, Saturation, Value) color model for vegetation segmentation in UAV imagery (Balasubramanian and Ganesan 2019), its application specifically to UXO detection has been scarcely examined. Existing studies rarely evaluate how the removal or attenuation of vegetation layers affects the visibility, contour structure, or geometric prominence of UXO-like objects embedded in complex natural environments. This represents a critical research gap, given that vegetation remains one of the most persistent and operationally limiting factors in mine-action workflows.

This study addresses this gap by evaluating the effectiveness of HSV-based segmentation for isolating vegetation in optical UAV images and assessing its contribution to the improved visibility of small UXO models in realistic field conditions. The primary objective of the study is to determine whether vegetation extraction can enhance object prominence, reduce visual clutter, and serve as a reliable preprocessing stage for subsequent anomaly-detection or machine-learning workflows. Accordingly, the central research question is: *To what extent does HSV-based vegetation segmentation improve the detectability of UXO-like objects in densely vegetated terrain?* The working hypothesis is that *removing vegetation-dominant regions through HSV masking increases the visibility and geometric distinctiveness of surface anomalies associated with UXO models, thereby improving detection potential.*

The broader significance of this research lies in supporting safer and more efficient mine-action operations by improving early identification of suspicious objects in complex natural environments. In addition to evaluating segmentation performance, the study contributes a methodological framework that integrates vegetation coverage metrics, contour-density analysis, and HSV-based masking into UAV-supported reconnaissance. This framework provides practitioners with a reproducible, sensor-agnostic approach that can be extended to various operational scenarios, including search-and-rescue (SAR), environmental monitoring, and infrastructure assessment (Blagojević et al. 2022).

LITERATURE REVIEW

Research on UXO and landmine detection has evolved significantly over the past two decades, driven by advances in remote sensing, unmanned aerial systems (UAS), and artificial intelligence. Early studies primarily focused on identifying visual contrast cues and surface anomalies using conventional optical imagery. Coath and Richardson (2000) demonstrated that local contrast enhancement could improve the detectability of scatterable landmines, highlighting the importance of spectral and textural irregularities in cluttered natural scenes. However, traditional optical approaches suffered from high susceptibility to illumination changes, shadows, and partial occlusion, limiting their operational value in vegetated or structurally complex environments.

With the increasing availability of UAV platforms, researchers have expanded the scope of detection techniques. The use of high-resolution RGB sensors mounted on UAVs has proven particularly promising due to their ability to capture detailed spatial information at low cost and with minimal risk to personnel. Vivoli et al. (2024) developed a deep-learning-based real-time detection system for surface UXO using UAV imagery, demonstrating substantial improvements in recognition accuracy under favorable visibility conditions. Building on this progress, Also, Zhang et al. (2022) introduced the ECViST architecture, which integrates edge computing with a Swin Transformer–YOLOv5 hybrid model to enable efficient and scalable airborne monitoring of suspected minefields. Further Blagojević et al. (2022) highlighted the contribution of UAV platforms in improving landmine field detection procedures, emphasizing systematic flight planning, optimized sensor deployment, and enhanced spatial coverage as key factors in improving operational efficiency.

Thermal imaging has also emerged as an important complementary modality. Bajic and Potocnik (2023) showed that UAV-mounted thermal cameras, combined with convolutional neural networks, could reliably detect heat anomalies associated with UXO and explosive materials. Earlier operational reports by Bajic (2020) documented the practical value of thermal infrared imaging in supporting reconnaissance missions and validating standard operating procedures in contaminated areas. Expanding on this approach, Blagojević et al. (2024) demonstrated that the integration of thermal anomaly detection into UAV-based monitoring frameworks can significantly improve UXO identification in dense vegetation and cluttered environments, highlighting the synergy between RGB imagery, thermal data, and UAV operational strategies.

In aquatic environments, Zhang and Li (2022) adapted the YOLOv5 algorithm for underwater mine detection, providing an example of the versatility of deep-learning frameworks across diverse sensing domains. Parallel to algorithmic advances, researchers have investigated new forms of human–machine interaction for demining. Qabas et al. (2022) proposed an augmented-reality UXO classification tool designed to assist deminers by visualizing detection cues in real time. Dodić and Čungurski (2023) further explored the potential of AI-assisted visualization systems to enhance situational awareness and speed up decision-making processes in field operations. These contributions illustrate a gradual shift toward integrated, user-centered technological ecosystems in mine-action activities.

Although RGB and thermal imagery dominate the literature, several studies have emphasized the importance of robust color-space transformation for handling environmental variability. The HSV model, in particular, has been widely used for object segmentation in UAV applications due to its ability to separate chromatic information from illumination intensity. Shi

(2023) employed HSV-based techniques to detect shadows in multispectral UAV imagery, demonstrating improved stability under variable lighting. Balasubramanian and Ganesan (2019) utilized LAB–HSV combinations for obstacle detection in aerial navigation, while Liu et al. (2022) applied HSV-based compensation to remove shadows and enhance texture consistency. These studies collectively underscore the advantages of HSV segmentation in handling heterogeneous outdoor environments.

Despite its proven strengths, HSV segmentation has seen limited application in UXO detection. Most existing UXO studies rely on either (1) deep-learning models applied directly to RGB or thermal imagery, or (2) manual or semi-automated visual inspection. Few works integrate color-space preprocessing as a systematic step within the detection pipeline. Moreover, while deep-learning models such as YOLO show excellent performance on clean and unobstructed training samples, their reliability decreases sharply in heavily vegetated scenes due to occlusions, spectral ambiguity, and insufficient training examples representing natural clutter.

This gap is particularly relevant because vegetation is one of the most persistent obstacles in mine-action operations. Dense vegetation not only conceals UXO but also modifies scene morphology, producing numerous small contours and chromatic fluctuations that obscure object boundaries. Although HSV is frequently used in agriculture and environmental remote sensing to identify vegetation, it has not been systematically evaluated as a preprocessing tool specifically for UXO visibility enhancement.

The present study contributes to the literature by integrating HSV-based vegetation segmentation into a UAV-based UXO detection framework and empirically testing its performance under realistic field conditions. Unlike previous works that rely exclusively on machine learning or thermal imaging, this research examines the value of color-space transformation itself as a method for improving object prominence, reducing visual clutter, and supporting downstream anomaly recognition. Furthermore, the study bridges a methodological gap by linking vegetation coverage metrics, contour analysis, and segmentation efficiency to UXO detectability in complex environments. By combining RGB, HSV, and thermal data within UAV operational frameworks, this research demonstrates the synergistic potential of multimodal sensing for enhancing field detection reliability and operational safety (Blagojević et al., 2022; Blagojević et al., 2024).

METHODOLOGY

The experimental methodology was designed to evaluate the effectiveness of UAV-based aerial imaging combined with advanced image processing techniques for vegetation detection and preliminary unexploded ordnance (UXO) assessment (Fig. 1). The study was conducted over a densely vegetated test area of approximately 2000 m², chosen to replicate realistic environmental conditions frequently encountered in post-conflict or ecologically complex regions. The UAV survey was performed at a consistent flight altitude of 12 meters under stable weather conditions, minimizing the influence of wind, atmospheric distortion, and illumination variability on image quality.

A DJI Matrice 300 RTK (M300 RTK) drone, equipped with a DJI Zenmuse P1 high-resolution RGB camera, was used for image acquisition (DJI 2023). The DJI Zenmuse P1 features a full-frame 45 MP sensor, a global mechanical shutter, and supports multiple fixed focal length lenses, enabling high-precision photogrammetric mapping and detailed capture of surface features. The M300 RTK's integrated real-time kinematic (RTK) positioning system provides centimeter-level accuracy, ensuring georeferenced imagery suitable for quantitative analysis and reliable orthomosaic generation. The UAV followed a pre-programmed grid flight path with 70–80% forward and side overlap, covering the entire study area systematically. Approximately 1200 images were acquired, forming a comprehensive dataset for both qualitative and quantitative evaluation of vegetated terrain and simulated UXO objects.

To simulate realistic field conditions for UXO detection, eight inert UXO models were strategically placed within the vegetated area. These models were partially concealed by natural foliage, including grass, shrubs, and low-lying plants, introducing varying levels of occlusion. This setup allowed the methodology to assess the efficiency of vegetation segmentation while testing the potential for UAV-assisted recognition of partially visible objects, providing insights relevant to humanitarian demining, search-and-rescue operations, and security-oriented reconnaissance missions.

IMAGE PROCESSING AND HSV-BASED MASKING

A custom Python script was developed to process the acquired imagery and perform vegetation segmentation. The methodology leverages several Python libraries: OpenCV (cv2) for image loading, manipulation, color space conversion, masking, and contour detection; NumPy for efficient numerical computations; Matplotlib for visualization; and os and glob for file handling and batch processing. This framework ensures reproducibility, scalability, and adaptability across different datasets and operational scenarios. The workflow begins with RGB-to-HSV color space conversion, which separates chromatic information (hue) from brightness (value) and color intensity (saturation). This separation enhances robustness to illumination changes, shadows, and variable environmental conditions. Within the HSV space, initial hue ranges corresponding to typical green vegetation were defined and dynamically optimized through histogram analysis and calibration on representative sample images. This adaptive procedure ensures consistent detection across images captured at different times of day or under varying weather conditions.

The HSV-based segmentation produces binary vegetation masks, where pixels representing vegetated areas are assigned a value of 1, and non-vegetated pixels are set to 0. These masks isolate regions of interest and suppress irrelevant background, enabling efficient and focused analysis. Small artifacts and noise are removed using morphological operations such as dilation and erosion, and overlapping vegetation regions are merged to accurately represent spatial extent. Contours are extracted from these masks, providing precise delineation of vegetated areas and forming the basis for quantitative analysis.

Visual outputs include the original images overlaid with vegetation contours, binary masks, and negative images highlighting non-vegetated regions. Histograms of HSV values are generated to document the distribution of chromatic and brightness information across the dataset. Quantitative metrics such as vegetation coverage percentage, spatial distribution, and density are calculated and logged for each image. This structured approach allows longitudinal monitoring, spatial comparison, and integration with additional data layers, such as thermal or multispectral imagery, enhancing analytical versatility.

The workflow outlines the sequential steps from UAV flight planning to data analysis, ensuring systematic and reproducible processing of aerial imagery. It integrates image acquisition, HSV-based vegetation segmentation, contour extraction, and quantitative analysis to generate reliable and high-resolution spatial information.

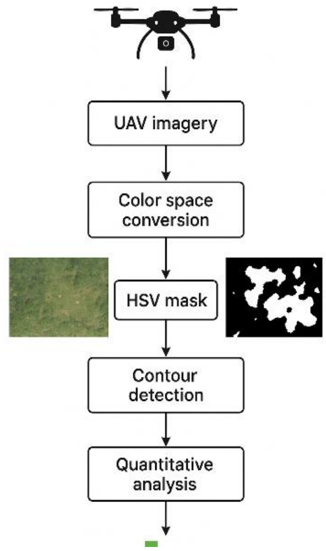

Figure 1: Workflow of Methodology (Source: Authors' depiction)

A schematic overview of the methodology, summarizing the workflow from UAV flight planning and aerial data acquisition, through HSV-based image segmentation, to quantitative analysis and validation has been presented in Fig.1. The workflow is sequential and repeatable, encompassing seven key stages: (1) UAV flight planning with optimized altitude, speed, and overlap; (2) aerial data acquisition with high-resolution imaging; (3) pre-processing including alignment, distortion correction, and normalization; (4) HSV-based masking and vegetation segmentation; (5) contour extraction and morphological optimization; (6) quantitative analysis of vegetation coverage and spatial metrics; and validation as through manual inspection and cross-comparison of overlapping segments as a final step.

The integration of UAV technology with HSV-based image processing enhances the detection of partially concealed UXO by isolating vegetated areas and reducing visual clutter. Combined with contour detection, edge enhancement, and adaptive morphological filtering, this methodology improves the reliability of automated detection systems while providing high-resolution spatial data for environmental monitoring and operational planning. Key UAV flight parameters, such as sensor orientation, speed, and overlap, directly influence the spatial resolution, coverage uniformity, and photogrammetric reconstruction quality, which are critical for subsequent image analysis.

To ensure reliability and scientific rigor, a carefully selected subset of UAV-acquired images was manually validated against the original high-resolution RGB data. This validation process involved a comprehensive assessment of multiple performance metrics, including classification accuracy, false positive and false negative rates, and spatial consistency of detected features. By systematically comparing segmented masks with ground-truth imagery, the study quantified the precision and robustness of the HSV-based vegetation segmentation approach under realistic field conditions. Additionally, repeated UAV flights conducted under comparable environmental and atmospheric conditions confirmed the reproducibility and stability of the workflow, highlighting its operational reliability for field deployment. Dynamic calibration of HSV thresholds was implemented as an adaptive mechanism to account for variability in lighting conditions, seasonal phenology of vegetation, and heterogeneous environmental contexts, ensuring that segmentation performance remained consistent across diverse scenarios. This methodological framework not only enhances the reliability of UAV-assisted vegetation mapping and UXO reconnaissance but also establishes a reproducible and scalable approach that can be extended to a variety of applications, including environmental monitoring, ecological assessments, agricultural mapping, and security or defense-related operations. The combination of high-resolution aerial data, adaptive color-space analysis, and rigorous validation procedures provides a robust, flexible, and scientifically defensible foundation for future UAV-based remote sensing initiatives.

RESULTS AND DISCUSSION

During the analytical procedure, a total of 250 UAV-acquired images were processed, with each UXO model (Fig. 2) recorded in five repeated acquisition cycles to account for variability in illumination, viewing angle, and background complexity. From this dataset, 40 images contained clearly visible UXO objects, providing a robust basis for HSV color-space analysis, segmentation, and subsequent contour extraction. Histogram evaluation of HSV components revealed characteristic distributions: Hue (H) predominantly ranged between 35–85°, corresponding to green vegetation and camouflage tones; Saturation (S) values were concentrated in the upper dynamic range (150–255), indicating highly chromatically stable surfaces; and Value (V) spanned mid-range brightness (100–182), reflecting moderate and uniform illumination (Fig. 3).

Figure 2: The Results of the Masking Technique UXO Image (Source: Authors' depiction)

Threshold parameters for segmentation were iteratively optimized using histogram analysis, visual inspection, and contextual evaluation of the scene, ensuring that vegetation was accurately isolated while minimizing misclassification of non-vegetated areas and UXO objects. This preprocessing step established a reproducible foundation for subsequent quantitative analysis and operational interpretation.

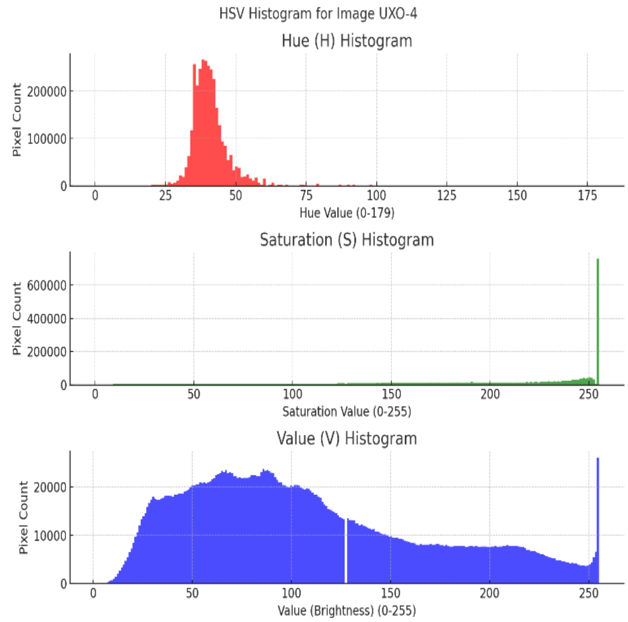

Figure 3: HSV Hystograms of UXO (Source: Authors' depiction)

Quantitative assessment of vegetation coverage across the full dataset revealed an average coverage of 71.2% with a standard deviation of 2.1%, indicating consistently dense vegetation throughout the surveyed area. Contour analysis demonstrated a highly skewed distribution: the majority of detected contours were small, with areas below 50,000 pixels, while a small number of large contours exceeded 2.8–3.0 million pixels, representing dominant vegetation masses. Across all images, the average contour count was 615, with a standard deviation of 340, reflecting variability in vegetation structure ranging from fine, high-frequency grass textures to coarser shrubs and low-lying plants. These metrics confirm the robustness of HSV-based segmentation in capturing both fine-scale and large-scale vegetation features while preserving UXO object visibility.

(a) (b)

Figure 4: Vegetation Coverage Contour analysis, a) without UXO present b) with UXO present (Source: Authors' depiction)

Table 1: Vegetation Coverage, Contour Density, and Segmentation Efficiency for figures 4a and 4b (Source: Authors' depiction)

Parameter	Image 4a	Image 4b	Interpretation
Vegetation Coverage (%)	78%	54%	4a shows significantly denser vegetation, increasing occlusion risk.
Number of Extracted Contours	1240	685	High contour count in 4a indicates visual clutter; reduced contours in 4b improve object isolation.
Contour Density (contours/m²)	High	Moderate	Dense vegetation in 4a creates structural noise; 4b provides cleaner segmentation.
HSV Segmentation Efficiency (%)	61%	82%	Segmentation in 4b is more stable due to lower chromatic interference from vegetation.
Shadow/Sunlight Interference	Pronounced	Low	4a has strong shadows impacting threshold stability; 4b is less sensitive to illumination.
Visible Potential Anomalies (UXO Indicators)	Low visibility	Moderate to high	UXO-like shapes are partially masked in 4a; more distinguishable in 4b due to a clearer background.
False-Positive Probability	High	Moderate	Excess vegetation in 4a increases misclassification risk.
Operational Detection Value	Limited	High	4b provides more reliable visual cues for UAV-supported UXO reconnaissance.

Comparative analysis of representative images, Fig. 4a (without UXO) and Fig. 4b (with UXO), highlights structural differences influencing segmentation outcomes. Fig. 4a contains 1121 contours, corresponding to fragmented grass microstructures, whereas Fig. 4b contains only 220 contours due to coarser vegetation elements. Dominant contours in both images exceed 2.8–3.0 million pixels and were excluded through area-based filtering to focus on mid-size and small contours, which are more likely to contain UXO signatures. In Fig. 4b, the UXO object is correctly excluded from the green mask, validating threshold calibration and confirming accurate differentiation between vegetation and objects of interest. Centroid analysis indicates heterogeneous distribution of green regions: dispersed in Fig. 4a, and clustered around large vegetation patches in Fig. 4b, reflecting increased occlusion potential.

Removal of green background elements enhanced the signal-to-noise ratio, improving both computational and visual detectability of UXO. Spatial descriptors derived from contour geometry and centroid positions can support more advanced object-recognition algorithms, including anomaly detection and 3D reconstruction. Iterative threshold optimization ensured adaptability to varying illumination conditions, vegetation density, and seasonal changes.

Operationally, variations in vegetation type, density, and structural complexity have significant implications for UAV mission planning, sensor configuration, and overall data acquisition strategies. Areas dominated by fine, low-lying vegetation require high-resolution imagery, increased flight altitude control, and greater image overlap to ensure sufficient coverage for accurate segmentation and anomaly detection. In contrast, coarser or multilayered vegetation, such as shrubs or mixed forest, introduces challenges related to occlusion and partial object concealment, necessitating the use of adaptive contour filtering, dynamic thresholding, and potential multi-angle image acquisition to mitigate blind spots. These vegetation-dependent considerations influence decisions regarding flight path design, sensor selection—including RGB, multispectral, and thermal cameras—and UAV speed and stability parameters, all of which directly affect the quality and reliability of the captured data. By systematically accounting for these variables, the proposed methodology enables the identification and prioritization of high-risk or high-interest areas for targeted inspection, while simultaneously minimizing operator exposure to hazardous terrain and unsafe conditions. The integration of adaptive UAV operational planning with HSV-based image processing and vegetation segmentation not only improves detection efficiency and accuracy but also provides a framework for scalable deployment in diverse environments. This approach ensures that UAV missions are both safe and effective, supporting a range of applications from UXO reconnaissance to environmental monitoring, ecological surveys, and security operations.

Despite methodological advances, several limitations remain. Dense canopy, shadows, variable terrain, and adverse weather can reduce segmentation and detection accuracy. UAV payload and flight-time limitations restrict sensor choice and survey coverage. HSV-based segmentation mitigates illumination variability but cannot fully resolve occlusion. AI-based detection algorithms, including YOLO, may produce false positives or fail in unfamiliar environments, and multisensor integration requires complex data fusion and substantial computational resources. Field validation is often constrained by safety, access, and logistics, highlighting the importance of adaptive algorithms, calibration, and comprehensive testing.

The integrated UAV and HSV-based segmentation workflow on this way, provides a robust, reproducible, and operationally relevant methodology for vegetation mapping and preliminary UXO detection. By combining quantitative analysis, spatially resolved contours, and comparative evaluation of vegetation structures, this approach enhances the detectability of partially concealed UXO objects, informs mission planning, and supports safer, more efficient operations in complex field environments.

CONCLUSION

This study has demonstrated that the use of UAV platforms in combination with advanced image processing techniques, particularly HSV color analysis and green vegetation segmentation, represents an effective yet challenging approach for the preliminary detection of unexploded ordnance (UXO) in areas with dense vegetation. The employment of UAV systems enabled the collection of high-frequency visual data at low altitudes, achieving the spatial resolution necessary to capture fine visual details that conventional satellite imagery or ground inspections cannot provide at the same level. This capability of UAVs to rapidly, safely, and systematically cover large areas is a critical advantage in the context of humanitarian mine clearance.

The results indicate that HSV segmentation effectively isolates vegetative structures and allows the creation of masks that define zones of potential visual overlap between natural elements and objects that may represent UXO. However, the analysis also revealed clear limitations. High vegetation homogeneity, color similarity between rocks, soil, and camouflaged UXO objects, as well as shadows, reflections, and lighting variations, lead to histogram overlaps. Consequently, color-based segmentation methods alone, even when carefully calibrated, cannot ensure reliable classification in complex environments.

In light of these results, it becomes evident that the greatest potential lies in a combined approach, where UAV systems evolve from platforms solely for RGB image acquisition into multisensor systems integrated with thermal, multispectral, and advanced analytical methods. The integration of thermal cameras enables the detection of anomalies that are not visible in the conventional spectrum—such as heat retained in metal components, soil structure changes, or thermal inertia of surface layers. When combined with HSV and histogram analyses, these data significantly increase the probability of accurate target identification and reduce false positives.

Algorithmic processing results suggest that further progress requires the implementation of machine learning and deep convolutional network models capable of learning complex patterns of vegetation, terrain geometry, and anomalies from large UAV datasets. Such models would allow automated, adaptive, and context-aware object detection, transforming UAV platforms into autonomous early-risk identification systems.

From an operational perspective, the findings of this study demonstrate that vegetation structure is not merely a visual obstruction but a decisive factor that shapes detection strategy, UAV flight planning, sensor selection, and risk assessment. The integration of vegetation metrics, contour density analysis, and multispectral segmentation into pre-mission planning can assist operators in prioritizing critical areas, optimizing flight altitude and camera orientation, and minimizing exposure to hazardous zones. This greatly enhances the practical value of UAV-assisted reconnaissance and supports safer field operations.

Moreover, the methodological framework presented here has broader applicability beyond UXO detection. The combination of UAV imaging, HSV-based segmentation, and anomaly-focused analysis can be extended to various civilian and security domains. These include search-and-rescue (SAR) missions in forested environments, environmental monitoring of degraded landscapes, inspection of critical infrastructure hidden by vegetation, detection of illegal waste disposal sites, and reconnaissance in post-conflict regions where terrain is difficult to access. The versatility of the proposed approach reinforces its relevance and positions it as a flexible tool with multisector potential.

Finally, this study confirms that UAV-based image processing methods hold significant promise for enhancing humanitarian mine-action operations, but their full effectiveness depends on integrating multisensor technologies, data fusion techniques, and adaptive algorithms. Future research should focus on developing standardized UAV-based detection protocols, expanding annotated datasets for machine-learning training, and validating multimodal detection systems under diverse environmental and seasonal conditions. By moving toward highly automated, multimodal UAV architectures designed specifically for complex terrain, it is possible to significantly improve the precision, reliability, and operational efficiency of UXO detection workflows. The results of this research provide a solid foundation for these developments and emphasize the strategic importance of continued innovation in UAV-enabled humanitarian demining technologies.

CRediT AUTHOR STATEMENT

Dejan Blagojevic: Conceptualization; Supervision; Methodology; Writing – Original Draft; Writing – Review & Editing. **Bojan Glamoclija:** Investigation; Formal Analysis; Data Curation; Writing – Original Draft; Writing – Review & Editing. **Jelena Krsitc:** Investigation; Formal Analysis; Data Curation; Writing – Original Draft; Writing – Review & Editing.

All authors have read and agreed to the published version of the article.

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