ISSN: 3143-8458

Wissen PUBLICATION GROUP

Journal of
Artificial Intelligence and Data Analytics

Research Article

Volume: 1 | Issue: 3 | November 2026 | Pages 01-05

Geospatial Wildfire Mapping Using a DEM-Ray Intersection Method

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Submitted: 20 October 2026 **Accepted:** 27 October 2026 **Published:** 03 November 2026

Citation: Liuska, M., Saukko, O., Hartikainen, M., Alekseev, S., Kippola, T., et al. (2026). Geospatial Wildfire Mapping Using a DEM-Ray Intersection Method. Journal of Artificial Intelligence and Data Analytics, 1(3), 01-05. DOI: doi.org/10.67927/JAIDataAnalytics/2026(1)114.

Abstract

Wildfires are increasing in frequency and impact, and responders need timely information on fire fronts, spot fires, and residual burning areas during suppression and damping-down operations. Thermal cameras on unmanned aerial vehicles (UAVs) reveal such phenomena, but these observations must be converted into georeferenced data before they can be shared with other responders and integrated into geographic information systems (GIS). This paper presents a DEM-Ray intersection method for geolocating fire areas detected in thermal images captured by UAVs. Image coordinates associated with the fire detections are converted into viewing-direction vectors based on the camera parameters and rotated using the orientations of the UAV and gimbal. The resulting vectors, temperature values, and UAV position are transmitted to an edge system, where rays originating from the UAV are intersected with terrain represented by digital elevation model data. This produces temperature-attributed geospatial points representing the detected fire areas on the ground. The points can be visualized and further processed in GIS applications and shared with external systems using standard geospatial formats such as GeoJSON. The proposed approach can also be used to determine the geospatial coverage of each capture, which may support coverage assessment and flight planning. Developed and demonstrated within the wildfire use case of the HiCONNECTS project, the method provides a terrain-aware approach for transforming thermal-image detections into geospatial information for operational and analytical use.

Keywords: Wildfire Mapping, Geospatial positioning of wildfire, Geographic Information, Systems (GIS), DEM-Ray Intersection, Digital Elevation Model, Thermal Imaging.

Background and Objective

Wildfires create significant challenges for situational awareness and emergency response, while their frequency and impacts have increased in many regions [1]. During both active suppression and post-fire damping-down operations, responders require accurate information on the location of fire fronts, spot fires, and residual burning areas. Timely access to this information supports resource allocation and helps reduce the risk of fire spread or reignition.

Thermal imaging sensors mounted on Unmanned Aerial Vehicles (UAVs) provide an effective means for detecting fire-related phenomena over large areas. UAV-based sensing has been widely investigated for wildfire monitoring before, during, and after fire events, offering capabilities for fire detection, situational awareness, and post-fire assessment [2]. While UAV operators can readily identify fire-related phenomena in thermal imagery, sharing these observations with other responders and information systems requires the observations to be transformed into geographically referenced information that can be visualized and integrated into geographic information systems (GIS). This paper presents a DEM-Ray intersection method for geolocating fire areas detected in thermal imagery. The method utilizes the UAV's Global Navigation Satellite System (GNSS) position together with the orientation of the UAV, gimbal, and camera to calculate unit vectors from pixel coordinates associated with the detected fire areas. Rays originating from the UAV position are intersected with a Digital Elevation Model (DEM) to determine the corresponding ground locations. The method was developed and demonstrated within the wildfire use case of the HiCONNECTS project [3].

DEM-Ray Intersection Method

The proposed DEM-Ray intersection method converts pixel coordinates associated with fire areas detected in thermal imagery into geospatial positions on the terrain surface. For each detected pixel, a viewing direction is calculated based on the camera model and transformed using the known orientations of the camera, gimbal, and UAV. Starting from the UAV position, the resulting ray is projected towards the terrain until it intersects the surface represented by a Digital Elevation Model (DEM). The coordinates of the intersection point provide the geospatial location corresponding to the original pixel in the thermal image.

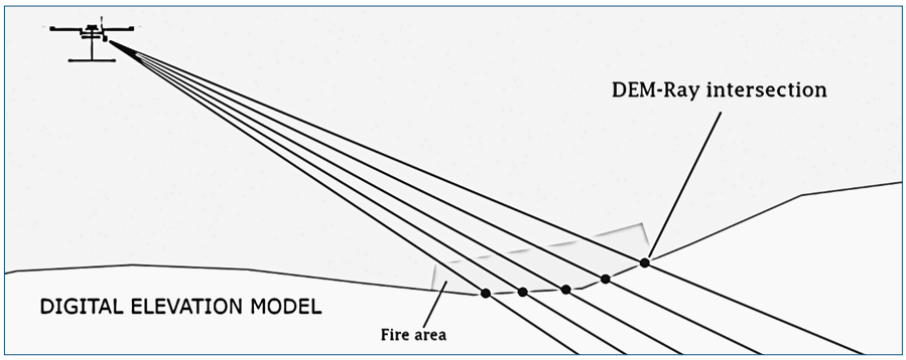


Figure 1: Principle of the Proposed DEM-Ray Intersection Method.

As illustrated in Figure 1, multiple rays originating from the UAV can intersect the terrain at different locations depending on the viewing direction and terrain elevation. When applied to all pixels belonging to a detected fire area, the method produces a set of geospatial points that represent the spatial extent of the observed fire area on the ground. These points can subsequently be stored, visualized, or further processed for operational and analytical purposes.

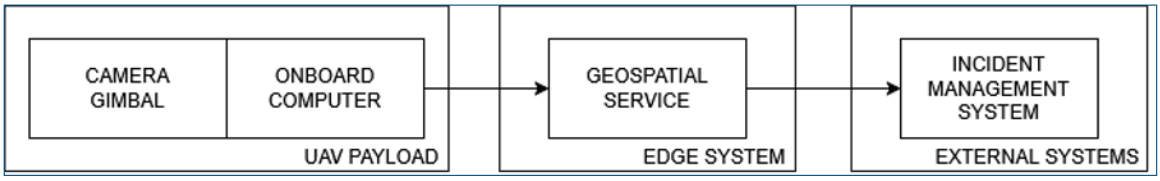


Figure 2: Architecture of the Proposed DEM-Ray Intersection Method.

Figure 2 illustrates the architecture of the proposed method and the flow of information between its components. The UAV payload is responsible for data acquisition and preprocessing, while the edge system performs the DEM-Ray intersection calculations and subsequent geospatial processing. The resulting geospatial information can then be shared with external systems for visualization and further processing.

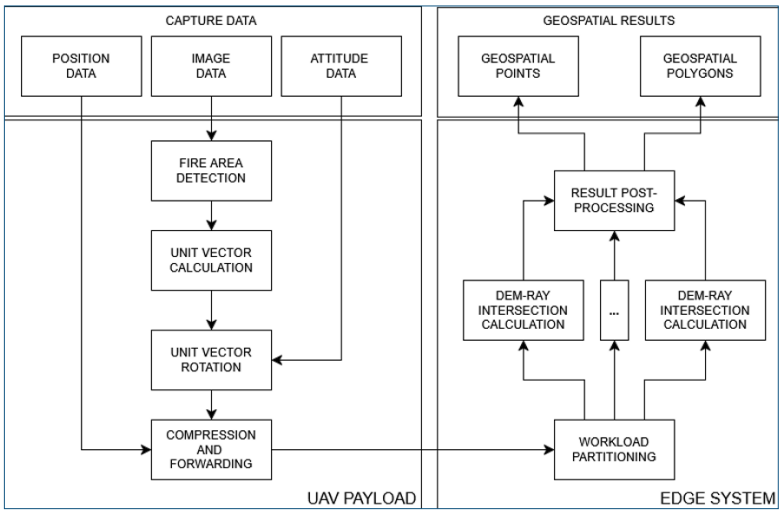


Figure 3: Overview of the Proposed DEM-Ray Intersection Workflow.

Figure 3 illustrates the processing workflow of the proposed DEM-Ray intersection method. The workflow begins with the acquisition of position, image, and attitude data on the UAV and continues through fire area detection, unit-vector generation, and data transmission to the edge system. On the edge system, the received data are partitioned into workloads for DEM-Ray intersection calculations, after which the results are post-processed and represented as geospatial points or polygons. The individual processing stages performed by the UAV payload and the edge system are described in the following subsections.

UAV's Payload

The proposed method processes image frames captured by the UAV's thermal camera on the onboard computer to detect one or more fire areas. The current implementation detects and segments fire areas from captured thermal imagery into individual detection sets by isolating candidate regions via color and thermal intensity thresholding, followed by Gaussian filtering, Canny edge detection, contour extraction, and Non-Maximum Suppression.

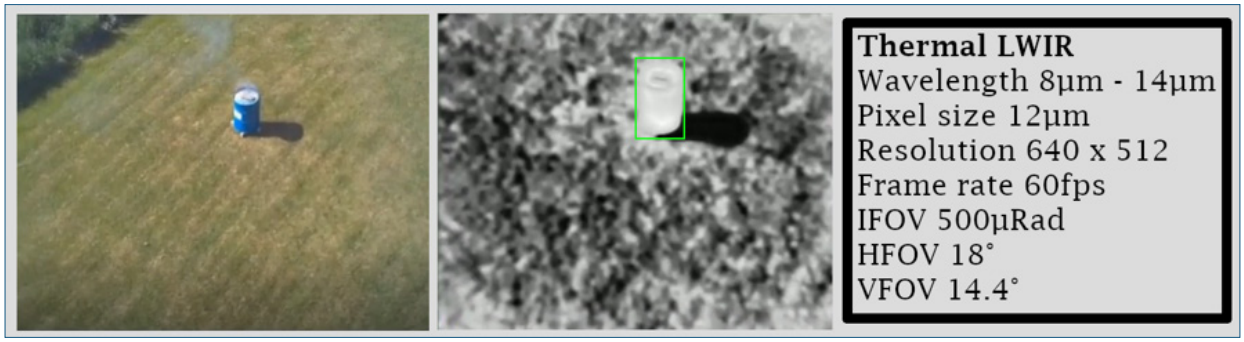


Figure 4: Detected fire area (HiCONNECTS Demonstration).

A single detection set contains the pixel coordinates and temperature values of the pixels belonging to the detected fire area. To enable geospatial positioning, the pixel coordinates are converted into unit vectors that represent the viewing direction of each target pixel in the camera coordinate system. Prior to this step, pixels are filtered based on their thermal values to reduce the number of individual vectors that need to be processed. The conversion of pixel coordinates into unit vectors is performed using a pixel-to-ray back-projection method based on the pinhole camera model [4].

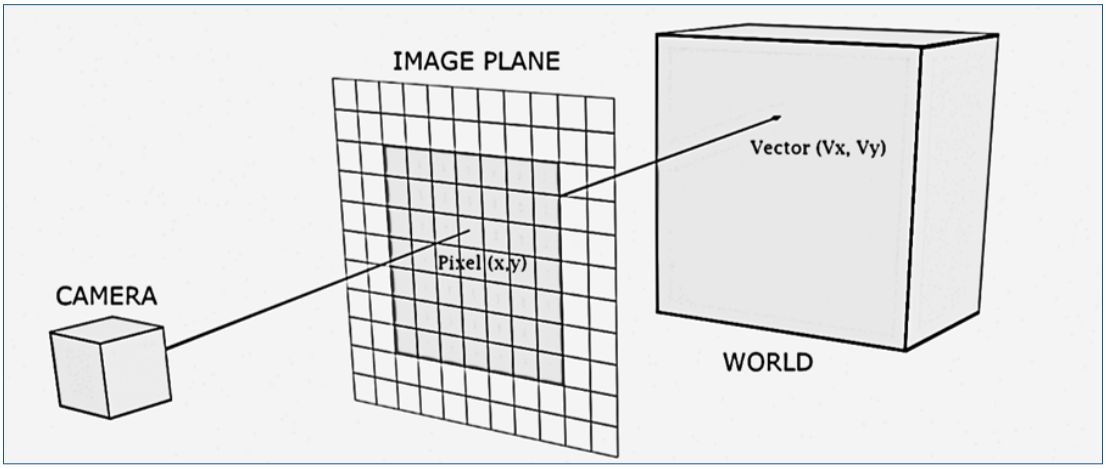


Figure 5: Visualization of the Pixel-to-Ray Back-Projection.

The calculation of unit vectors is based on the camera's intrinsic parameters, specifically the image resolution (640 × 512 pixels) and the horizontal and vertical fields of view (18° and 14.45°, respectively), obtained from the camera's technical specifications.

$$\hat{\mathbf{v}}_{\text{camera}} = \frac{1}{\sqrt{x_c^2 + y_c^2 + 1}} \begin{bmatrix} -x_c \\ 1 \\ -y_c \end{bmatrix}, \qquad \hat{\mathbf{v}}_{\text{world}} = \mathbf{R}_{\text{uav}} \mathbf{R}_{\text{gimbal}} \hat{\mathbf{v}}_{\text{camera}}$$

$$\begin{cases} c_y = \dfrac{H}{2}, \quad c_x = \dfrac{W}{2}, \\ y_c = \dfrac{v - c_y}{f_y}, \quad x_c = \dfrac{u - c_x}{f_x}, \\ f_x = \dfrac{W/2}{\tan(\theta_h/2)}, \quad f_y = \dfrac{H/2}{\tan(\theta_v/2)} \end{cases}$$

Figure 6: Equations Used for Unit Vector Calculation and Rotation.

For each pixel coordinate, a direction vector is calculated using the principal point and focal lengths. The resulting direction vector is then normalized to produce a unit vector. At this stage, the calculated unit vectors are expressed in the camera coordinate system. To enable geospatial positioning, each unit vector is rotated using attitude data describing the orientations of both the UAV and the gimbal. The rotation is performed through matrix multiplication according to the equations presented in Figure 6. The resulting detection sets containing the rotated unit vectors are compressed together with the UAV's GNSS (Global Navigation Satellite System) position. In addition, each capture includes unit vectors corresponding to the corner pixels of the image frame, which are used to define the camera's visible coverage area at the time of capture. The compressed data are then transmitted to the edge system, where the unit vectors are used for DEM-Ray intersection calculations and geospatial positioning.

Edge System

On the edge system, the data received from the UAV, consisting of unit vectors and their associated temperature values, are partitioned into separate workloads for batch processing. As the UAV position (latitude, longitude, and altitude) is included in each batch, the workloads can be processed independently, enabling parallel geospatial processing. For each received unit vector, a ray is constructed using the UAV position as the ray origin and the unit vector as the ray direction. The edge system then performs DEM-Ray intersection calculations to determine the corresponding geospatial position on the terrain surface. The DEM-Ray intersection calculations are performed using terrain data obtained from a Digital Elevation Model (DEM). The DEM dataset used in this work was provided by the National Land Survey of Finland and uses the EPSG:3067 (ETRS89 / TM35FIN) coordinate reference system [5].

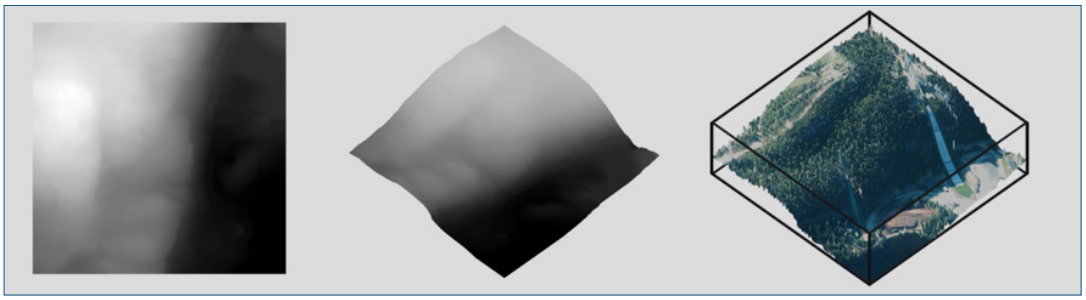


Figure 7: Visualization of DEM as Heightmap, a 3D Surface, and a Textured Terrain Model.

Figure 7 provides a visual representation of the terrain data used in the DEM-Ray intersection calculations. The ray origin is first transformed from WGS 84 coordinates into the projected Cartesian coordinate system used by the DEM datasets. Intersections between the ray and dataset bounding boxes, defined by the spatial extent and minimum and maximum elevations of each dataset, are then calculated and sorted according to their distance from the ray origin.

The intersected datasets are processed from nearest to farthest by examining the DEM cells along the ray's two-dimensional projection. At each cell, the elevation of the ray is compared with the corresponding DEM elevation. The first location where the elevation of the ray reaches or passes below the corresponding DEM elevation is identified as the terrain-intersection point. Finally, the intersection coordinates are transformed back to the WGS 84 coordinate reference system.

The DEM-Ray intersection algorithm can be summarized in five steps:

1. Convert the ray origin from WGS 84 coordinates into the projected Cartesian coordinate system used by the DEM datasets.
2. Find the intersections between the ray and the dataset bounding boxes.
3. Sort the found intersections according to their distance from the ray origin.
4. Iterate through the intersected datasets and examine the DEM cells along the two-dimensional projection of the ray. If the elevation of the ray passes below the corresponding DEM elevation, the intersection point has been found.
5. Convert the intersection point back to the WGS 84 coordinate reference system. The resulting geospatial coordinates are used as the input for the post-processing stage described in the following subsection.

Post-Processing Results

After each unit vector received from the UAV has been processed using the DEM-Ray intersection method, the result is a set of geospatial points. Each point consists of longitude, latitude, and altitude coordinates paired with the original temperature value. In the implemented system, the resulting points are stored in a geospatial database under a unique identifier corresponding to the capture. This enables the data to be queried, visualized, and further processed using methods commonly available in geospatial database systems.

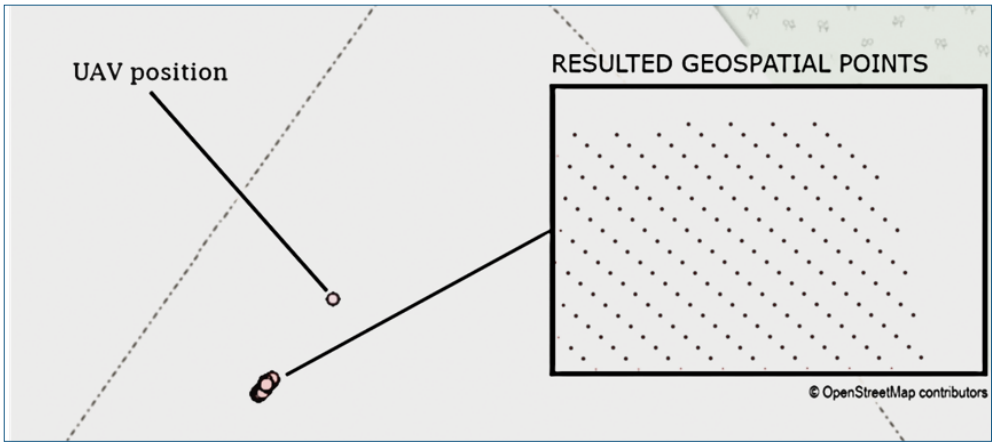


Figure 8: Visualization of Resulting Geospatial Points.

When visualized in a GIS (Geographic Information System) application, the resulting geospatial points form a representation of the detected fire area, as shown in Figure 8. Upon closer inspection, the points exhibit a staggered grid pattern originating from the pixel structure of the original image frame. The spacing between adjacent rows and columns depends on the distance between the UAV and the terrain surface as well as the intrinsic parameters of the camera. The resulting geospatial points can be distributed directly to external systems or further processed through clustering, rasterization, and polygonization to produce higher-level geospatial representations suitable for visualization and analysis. For example, the points may be clustered and converted into polygon representations of detected fire areas that can be shared using standard geospatial formats such as GeoJSON and integrated with other geospatial information systems. In addition to the fire-area points, each capture contains unit vectors corresponding to the corner pixels of the image frame. The resulting corner coordinates can be used to determine the geographical coverage area of the capture. This information may be utilized by automated systems to identify areas requiring updated observations or by UAV operators to support flight planning and coverage assessment.

Conclusions

The proposed DEM-Ray intersection method enables fire areas detected in thermal imagery to be transformed into geospatially referenced information that can be shared between operational and analytical systems. By combining UAV position and attitude information with DEM-Ray intersection calculations, the method produces geospatial points corresponding to detected fire areas. These outputs can be visualized directly in GIS applications or further processed into higher-level representations such as polygons for information sharing and analysis. The method was developed and demonstrated within the wildfire use case of the HiCONNECTS project [3]. The resulting geospatial information can support situational awareness by providing firefighters, incident-management systems, and domain experts with a common geospatial representation of detected fire areas. In addition, the information can be integrated into automated workflows and decision-support systems through standard geospatial formats.

Future work should evaluate the use of repeated UAV observations for change detection and temporal analysis of wildfire-affected areas. The effectiveness of such applications was not investigated in the present study. Future research may also examine the integration of more advanced fire-detection methods, such as those presented in, with the proposed geospatial mapping approach [6]. Although the method was developed for wildfire management, the underlying geospatial positioning approach may also be applicable in other emergency-response scenarios where image observations must be transformed into geographically referenced information. Potential applications include wilderness search-and-rescue operations, missing-person searches, and maritime target detection. These applications remain subjects for future research and validation.

Acknowledgements

This work was carried out within Task 4.2 "Public protection and disaster relief" of Work Package 4 "Public health and safety demonstrators" of the HiCONNECTS project (Heterogeneous Integration for Connectivity and Sustainability). The project has received funding from the Chips Joint Undertaking (Chips JU) under grant agreement No 101097296. The project is supported by the Chips Joint Undertaking and its members, including top-up funding by Business Finland. Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Chips Joint Undertaking. Neither the European Union nor the granting authority can be held responsible for them.

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Generative AI based on a large language model (LLM) was used during manuscript preparation to assist with language refinement, clarity, and editorial revision. The tool was not used to generate research data, perform the reported analysis, formulate scientific conclusions, or create any figures, images, or graphical content presented in the manuscript. All AI-assisted content was reviewed and, where appropriate, edited by the authors.

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