

Fireguard: A Real-Time Wildfire Monitoring and Risk Assessment System Using Unmanned Aerial Systems and Multi-Sensor Fusion

Gerhard Kemper¹, Hannah Kemper¹

¹ GGS GmbH Speyer, Germany

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Abstract

Disaster Risk Management benefits from innovative techniques including AI and Multi Sensor Fusion. The Fireguard Approach uses such technologies to improve the Wildfire Management works in Saxony, Eastern Germany by supporting standing efforts in Early Warning, Disaster Response and Monitoring. Unmanned Aerial Systems (UAS) play a vital role in providing real-time information via a 5G network to a central information management system that delivers geospatial information to response teams. This study highlights the potential of combining UAS, AI, geospatial solutions and existing data for real-time wildfire monitoring and risk assessment systems. The preliminary study successfully shows the potential of the provided solution to enhance Wildfire early detection, response and monitoring to address immediate and long-term needs of response teams.

1. Introduction

Climate change, resulting in increasing temperatures, decreasing rainfalls, and economy-driven forest management contribute to rising wildfire risks across Europe (Preinfalk et al., 2024). Despite its rather humid climate Germany is threatened by high wildfire risks (EFFIS, 2024). Current management practices are focused on emergency response mechanisms after sighting of fires, though there were rather few innovations tested in the recent years to improve the current processes. Implementations of real-time monitoring using aerial imagery would not have been successful due to the limited mobile data network capacity in the rural affected areas, as the data transfer was too slow to provide any advantages to the given system. Once the German Ministry of Traffic and Data Infrastructure launched a research program to enhance the use of 5G mobile networks to test modern and advanced technologies, the opportunity to test a novel system was used (Kanand, T. et al., 2021, El Emam et al., 2020). Novel data management workflows operating in real-time for improved wildfire management and response were developed and tested in one project site. Special focus is placed on the AI based capture of images with specific camera and gimbal technology on fire observation towers. Crisis Management is shown by using support of the fire brigades using Unmanned Aerial Systems (UAS) with streaming camera technology and AI to assist in risky situations (Khan et al., 2022; Merino et al., 2012; Peruzzi et al., 2023). Collecting information e.g. with aerial images and preparing a GIS Database build the Crisis Preparedness foundation (Abujayyab et al., 2022). This paper shows the combination of fixed Multispectral Sensors, autonomous UAS missions and online geospatial data handling for the detection of wildfires. The use of a central crisis management server and the data handling with user interface combine all developments, platforms and sensors. The Forest Guardian Project combines several research institutes, state organizations and small/medium enterprises (SME) for providing various technologies to monitor forest health and forest fires. The main aspect was to set up a technology for wildfire monitoring using fixed observation points and autonomous UAS to finally localize the hot spots. The project site was in Saxony, Eastern Germany (see Fig. 1) where wildfires are a serious issue due to the flat terrain and low rainfalls. In the last decade, droughts have become quite common; an effect being discussed as a first result of global

warming. More than 50% of the project area is covered with pine and oak trees on sandy soils, a very vulnerable ecosystem for wildfires. The European Forest Fire Information System (EFFIS) (Heyns et al., 2021) classifies the wildfire risk in this area as high, the economic-ecological vulnerability as medium to high and the danger by thermal anomalies as very high. A few towers enable human observers to monitor for smoke in the region during such dry periods.

2. Theory



Figure 1. Project area Fireguard Project, Saxony Germany

Disaster Risk Management (Altan & Kemper, 2016) can be conceptualized as a cycle of ongoing activities. After the hit of a crisis the Disaster Response phase will be used for lifesaving operations and the minimization of immediate impacts followed by a Disaster Recovery phase that investigates restoring activities and services. Disaster Prevention focuses on the minimization of impacts, meanwhile Preparedness incorporates activities that focus on the management of an upcoming crisis (Krsnik et al., 2024). In the case of a wildfire the Disaster response lies in the hand of the local firefighting authority, meanwhile recovery measures concern the reforestation of affected areas by volunteers or forestry agencies (Grari et al., 2022). Disaster prevention instead would look into the fuel reduction within the forest, the cutting of affected trees and the planting of drought resistant species. Disaster Preparedness measures could include the gear preparation of the firefighters,

depositing water tanks across the site or the alerting of the local population.

2.1 State of the Art in Disaster Risk Management

The local management of wildfires at the project is set up in a rather traditional way. Monitoring is primarily limited to critical weather periods. The observation is managed by human observers on elevated points or observation poles for detection of smoke columns (Heyns et al., 2021). In wider areas, so called "fire-flights" are undertaken using small airplanes e.g. Cessna 172 or similar to search for such smoke columns. Very often private hobby pilots provide this type of labour and report findings to fire stations. That is in most cases based on private initiative and rarely integrated in a systematic monitoring system. The use of satellite images is used only for monitoring bigger fire events but rarely for the finding of upcoming wildfires. This is related to the temporal and spatial resolution of satellite imagery. A necessity for more innovative technology has been identified leading to some fire-fighting stations implementing first trials of using UAS. These were mostly used for running inspection flights after getting an alarm notice from elevated points, however, the systematic integration is something that is still outstanding. Very often the alarming system is individually managed, manually processed, quite cost-intensive and not automated.

3. Fireguard Approach

The Fireguard Approach follows the Disaster Management Cycle (Fig. 2) providing technical inputs into different sections (Mohapatra & Trinh, 2022; Qiao et al., 2024; Suarez et al., 2024). The Monitoring of the project area is conceptualized as an ongoing activity, meanwhile the response mechanisms and preparedness phase align with the disaster risk management cycle.

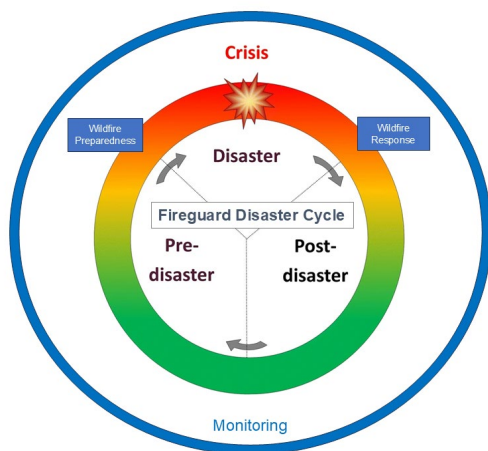


Figure 2. Disaster Management Cycle (adapted from Le Cozannet et al., 2020)

3.1 Wildfire Preparedness

For the Wildfire Preparedness Section (Fig.3) within the Fireguard project the leverage of existing datasets is crucial. Geospatial data such as topography, land use, forestry maps or terrain and surface models are used for a pre-feasibility study and overall orientation (Cetin et al., 2023; Ciesielski et al., 2022). Using infrastructural maps of supply systems such as water, electricity and gas, routes, and urban settlements is key

for awareness and to streamline operations in the response phase. Furthermore, additional data was collected to complement the environmental study. In this phase an aerial mission with a 5-band system was used to create a 3D surface model of ultra-high precision. A forest health status and the status of bark beetle infection was done, and an inventory of the fire watch towers, and water tap stations was collected. Within the analysis part of the preparedness works, risk assessment for humans, infrastructure and environment was done. The Accessibility of the area for fire brigades and the calculation of evacuation routes was realized. Communication paths were tested including also the visibility of the fire towers to understand the coverage of the project site. Sites for possible ground-based sensors were identified. Further needs were identified, including additional observation locations, the lack of ancillary data, the setup of a communication infrastructure and the need for improved data management.

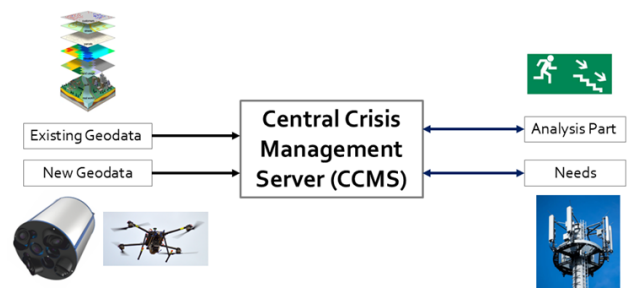


Figure 3. Wildfire Preparedness Concept featuring a Central Crisis Management Server (CCMS)

A complete update of the area was made by an aerial survey in 2022 using an oblique camera setup and a 5-band nadir observation (RGB, Near Infrared (NIR) and Red Edge). 4.3 Terapixels of image data were captured with an aerial mission using the OIS.5B sensor of GGS company and the data finally processed with Photomesh of Skyline Software. The data resulted in a 3D reconstruction with a Ground Sampling Distance (GSD) of 5 cm of the overall area (Fig. 4).

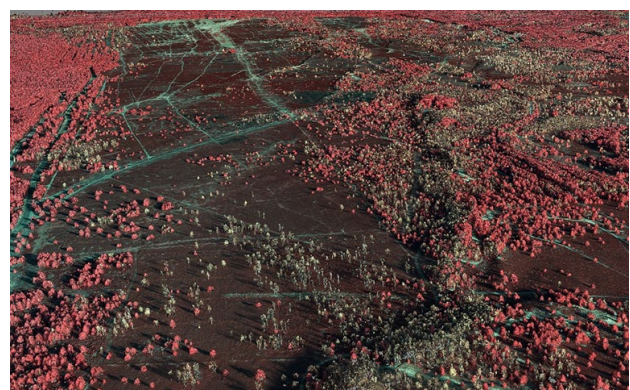


Figure 4. Digital twin in CIR bands as part of the project area

Overlaid with existing vector data (Fig. 5 & 6), the Orthophoto enables a far better way to plan access for the fire brigade into the forest area. Vector data of technical infrastructure such as water taps, pumps and other strategic systems are made available. Besides that, detections of smoke columns may be better linked to the real-world situation (Wang et al., 2022).



Figure 5. Identified accessible ways



Figure 6. Simulation of wildfires with the digital twin in Terra Explorer

As part of the data collection, the operability of UAS were tested within the project site. Smaller test-plots inside were created and small fires were lit under authorization. With acknowledgement of the Forest-Ranger an area with Heather-Vegetation that must be treated was selected. Beforehand, a detailed mapping with five Bands and a LiDAR Survey took place to get a detailed Model with < 1 cm GSD and a point cloud of 1000 p/m².



Image 7. Very dense Point-cloud generated with DJI Matrice 350 and L2 LiDAR of the test-plot

3.2 Wildfire Monitoring

Wildfire monitoring (Fig. 8) is based on forecast and observation technologies. The installation of high-grade Camera Technology placed in a gimbal on top of fire watch towers replace human observation and enable all year monitoring. In critical periods, especially in dry and hot seasons, the fresh rate of the camera system may be enhanced for better observation and detection. This way, forecast and control of the camera gimbals can be handled automatically by the CCMS.

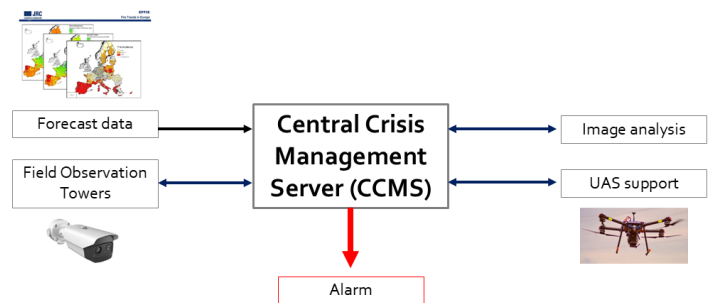


Figure 8. Monitoring concept

In most European countries, a wildfire warning forecast is implemented. A European wide modelling, as performed with EFFIS, takes weather parameters, history and soil parameters into account. Some models also make use of land-use data and forest inventory as far as available. This kind of monitoring also takes thunderstorms or other critical events into account. Nationwide there is the DWD (Deutscher Wetterdienst) and the countries that provide wildfire risk maps on their website.

In the project area, the existing three fire-observation towers are occupied by personnel in case of risk-level 3 and 4. At a risk level of 5, that represents an extreme high risk for wildfires, the towers are 24/7 occupied.

In the project, these forecasts were used to validate ground sensors that register soil temperature, soil-humidity and terrain climate parameters. That way a more detailed and guided alarm scenario has been applied and managed in the CCMS. One reason was to set up a higher frequency to the cameras and gimbals described in the following paragraphs.

In this flat landscape the localization of fires and their smoke column is difficult. The determination of the direction is semi-accurate, while the estimation of distance is problematic. This also results in problematic guidance of the firefighting teams. The observation from different points may improve the localization, but the coordination is not well managed, and a central management centre is lacking. Besides that, a great critical issue remains navigating fire control with reference to location factors: different villages only having voluntary fire departments, the private coal mining company LEAG AG in Nochten, and the military training area of the German Armed Forces with a size of 175 km².

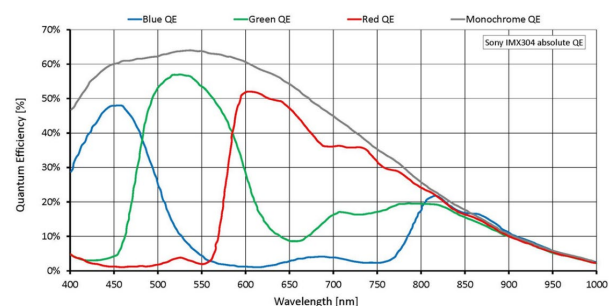


Figure 9. Wavelengths of the Fireguard Cameras

Online monitoring of the landscape is the key to detect wildfires (Lehnert et al., 2024). The three Fire Observation towers have been equipped with an innovative set of cameras. While on Tower Podrosche a single camera has been installed (Fig. 9 & 10), on Tower Rietschen and Brand four cameras were inserted into a gimbal and installed on the roof of the Towers. Industrial cameras with a complementary metal-oxide-semiconductor

(CMOS) Sensor and 12 MP were selected for RGB with Bayer Pattern, achromatic as a pure black and white Camera and NIR on an achromatic with a Block-Filter < 800 nm. The cameras were mounted in portrait format to have a bigger vertical coverage while the gimbal will provide the horizontal movement. A long focal length of 75 mm was chosen to achieve a high resolution also on remote detections. Additional to these three cameras, a thermal camera with a 60 mm lens and a resolution of 640*512 pixels was integrated. The field of view of the cameras is 10.8° and horizontally 7.9 degree. This results in a GSD of 20 cm at a distance of 4350 m which represents an extremely high resolution. All cameras were synchronized, and the control of the cameras was done through an in-house developed software tool. In combination with a stepper motor controller, the images were taken with a 50% overlap. The gimbal enables a full 360-degree rotation. The speed and the step width can be controlled externally via 5G, as well as the frame rate of the cameras or a specific observation heading. This enables event-based control of the observation to enhance the monitoring quality in case of a fire detection.

The image data were in real-time be compressed to JXL format and sent via 5G to the CCMS. The RGB Images were used in the first place to detect smoke columns. The Achromatic Images supported a better image capturing during bad light conditions while the NIR delivered data with high contrast even in slight foggy situations. The Thermal camera was mainly intended to capture data in the nighttime without any daylight.

The control of the cameras, data management and control of the gimbal was managed with an onboard PC inside the gimbal. This gimbal also has a 5G modem with antennas to stream the data to the server. All had to be made waterproof and wind resistant. The harsh conditions on top of the towers as well as the installation were rather challenging. Some poles had to be constructed to manage a proper installation.



Figure 10. Fireguard360 Camera gimbal on the Tower Podrosche left and the tower itself

To analyse the images, that were transmitted every two seconds from all cameras to the CCMS, which resulted in nine independent but synchronized camera shots. In case of detection, the frame rate can be increased automatically. The CCMS sends such a request to the gimbals and camera controllers.

A pre-trained AI model (Skinner et al., 2022) was used and refined with a set of generated smoke data to get a first detection level. With the help of real data that was created by a controlled wildfire of the fire brigade and forest rangers, as well as tests with smoke bombs, the reliability of the model reached almost 99% of the real smokes with about 10% false positive detections.



Figure 11. AI based detection of a smoke bomb test from Firewatchtower Rietschen

Mainly the RGB images have been evaluated, and the combination of the cameras gives the incentive that a reduction of the false positive detections can be reduced. Monitoring for real fires during the year 2024, all the real wildfires have been detected which means almost 100% detection rate.



Figure 12. The AI module detects with high reliability the real fires as seen on the image from the 13th of May last year seen from Tower Brand.

Even the detection of smoke bombs, used during several tests, were tested successfully despite having a whiter colour. The analytics of the AC Images, so far tested, give similar results with a slightly lower detection rate during daytime but a better result in darker conditions. The NIR images have a higher contrast but can be affected by slight fog or smoke. As a result, these images detect remote strong smoke better than RGB but are less precise during the detection in close range areas and less intensive smoke columns. Analytics on the thermal data have not yet been tested - but smoke and fire is visible also during daytime on such data.

The data was also visualized on the CCMS using Graphana and Node red interfaces (Fig. 13-16). That way, the view of the cameras related to the tower and gimbal heading can be monitored. Also, a panoramic view can be enabled to receive a 360-degree image per camera and tower in almost real time.

Very important is the calibration of the gimbal. First, it needs to be perfectly levelled so that all views show a similar horizon line with exception of small terrain changes in this dominantly flat project area. The second step of the calibration is the heading adjustment by landmarks measured on the aerial images and maps related to the gimbal coordinates. The coordinates have been surveyed using a global navigation satellite system (GNSS) receiver from RTG.

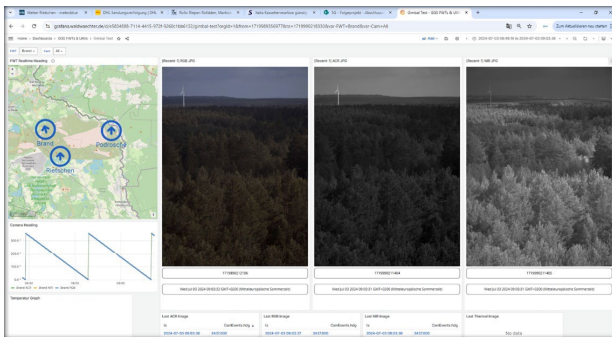


Figure 13. Developer Interface on the CCMS

If a detection was registered on the CCMS, it is important to calculate the location. In a first approach, it is done on the data of a single tower by using the bounding box, the estimated centre of the source (typically on the lower corner) and the heading information of the gimbal. Depending on the position of the bounding box in the image respectively the Y-coordinate of the lower bounding line, also a distance estimation can take place. This works well at close detection and is just a core estimate on remote detections.

That way the combination of observations of two or all three towers take place to triangulate the location. This is done in combination using Leaflets in a Geodata-Server. In the last fire test, the smoke was visible from Tower Rietschen and Brand, unfortunately the location was aligned between the two views. In that case the use of a Heatmap based on the bounding box interpretation was used to highlight the most likely source that helps to prepare the next steps e.g. a UAS inspection.

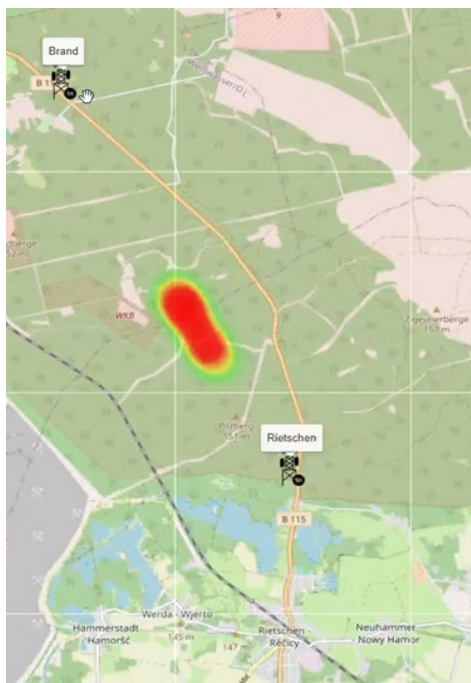


Image 14. Hotspot determination using a heatmap.

Nevertheless, this underlines the importance of a third observation. Reviewing the images through manual verification as seen in Figure 15 can support the location. Using the estimated source in the bounding box in combination with the heading of the camera gives a much clearer localisation of the wildfire.



Figure 15. Triangulation to determining the fire hotspot

If the camera gimbals have detected smoke or any kind of anomaly, a flightpath is generated and uploaded via 5G to a UAS. It is a novel approach to define a target coordinate out of the AI detection and generate a flightpath for a UAS via Internet/5G. Depending on the location of the heatmap, the flight path can be a circle or a line. Besides, also the gimbal on the drone can be made smart - that means the observation direction left-right, forward-backward can be generated besides the flightpath. The idea behind this feature is a semi-automated start of the UAS and an autonomous mission also beyond visual line of sight (BVLOS) via Internet connection. With usual Mission Plans this is not possible.

The UAS, typically a vertical take-off and landing (VTOL) or Multicopter, carries a thermal and RGB camera and should more precisely find the fire location to document what is burning and if immediate access of the fire brigade is needed. The UAS should also update the environment to detect other dangerous risks for the fire fighters e.g. vehicles.

The UAS is carrying a high-resolution thermal camera with a combined high resolution RGB camera. This camera setup is mounted in a gimbal that enables the cameras scanning the landscape left and right while flying a mission line to search more efficiently the fire. An onboard PC makes an AI based evaluation of the findings and calculates the position based on UAS GNSS Position, flight altitude, attitude of the gimbal and position of the bounding box in the image. For a better evaluation the data are streamed as a video stream via 5G to the CCMS.

Especially in the military training area, this information is important beforehand to manage safe access to the area. But also, to get information about the actual access to this place is of high importance.



Image 16. AI based analytics of smoke and fire

Different AI models have been trained to check the most performant version in relation to the hardware including Jetson Nano, Latte Panda Sigma etc. A big dataset was captured with different UAS during the test fires, including fire in bowls or the smoke bombs (Casas et al., 2023). Still the AI has to be further optimized and the research on the localization and real time-display on the CCMS is ongoing.

3.3 Wildfire Response

The firefighting management (Fig. 17) depends on the real time GIS system and has the urge of up-to-date information. The information management must be fast to ensure that the teams heading to the forest fire know the size and how to combat the flames. Upon this the teams decided whether they need further support or consider the wind direction to take preventive measures. When firefighters are on-site, the UAS is responsible for a real time monitoring of the fire to assure that the chosen technique is appropriate and to decide on further processes. The control of the wind direction can give important information about people being exposed to smoke, These people should be alerted to close their windows for a certain time and get informed when the air quality improves again. Furthermore, it is necessary to guarantee human safety on-site, so the possibility of people entering the danger zone should be seen by the drone.

The procedure is as follows:

1. Thermal camera detects anomalies in the covered area. Possible forest fires are detected, and this information is given to the UAS
2. UAS leaves firefighter station and heads to the detected area
3. Parameters are detected; pictures and videos are sent in real-time to the firefighter station (5G needed)
4. Decision if firefighters act

In case immediate action is required: firefighters head to affected area (with use of the rescues plans and the information given by the UAS) and extinguish the fire in an initial phase. In case no action is required: UAS returns to starting position, ready for the next discovery mission and waiting for thermal information. The fire fighters can make use of additional linked devices such as GPS and cameras to stream the data of the trucks while ap-approaching the area. This can help to get additional warnings and actions started on the fly. It is also important to connect the various firefight stations to have the fastest possible access and may be from different start and routing points to optimize the defence of the wildfires.

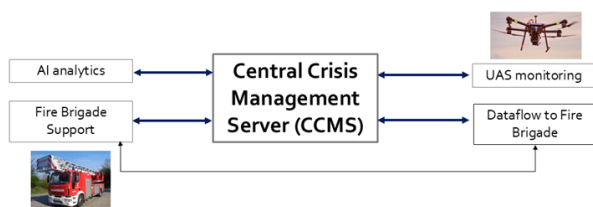


Figure 17. Disaster Response Concept

An important part of the firefight is the real time information that is coming from the towers and the UAS via the CCMS. Once the fire location is precisely determined and the information about size, type of fire and the environment is available, the fire brigade drives into the area. The CCMS updates with additional information and pre-define the needs for additional neighboured brigades. The coordination of the routes (Fig.18) is related to the accessibility of the paths depending on the vehicle (two or four-wheel drive) in the geodata server. Each vehicle has access to the CCMS and gets updates on time. The navigation follows the best available dataset, orthophoto with overlaid vector data with information about the accessibility. This is a very difficult task in a remote forest area with training facilities.

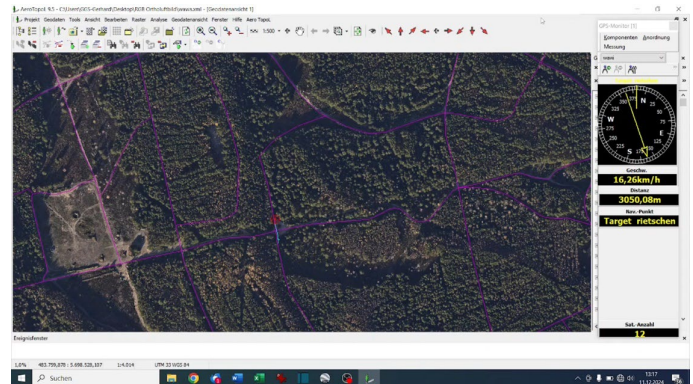


Figure 18. First approach for a navigation solution inside the forest and training area

The navigation is tracked by the CCMS in such a way that other vehicles can be monitored and the information provided to other brigades. In that way, there is better information which brigade arrives from which direction.

In case of a fire, the towers monitor the location and environment more frequently and provide new images in real-time (Fig.19). This can be done also with the user interface on the CCMS as shown before. The UAS data is also accessible, and the fire brigade can send commands to the CCMS to move the UAS into different perspectives if needed.

The UAS, once it has reached and perfectly located the fire nest, will operate in the area until the battery-capacity requires a RTH (return to home). There are different mission scenarios that are applied to the UAS to monitor the fire area. One is to measure the area that is under fire in size and structure. This is important for the fire-fighters. Furthermore, parameters such as wind direction and wind speed, movement of the smoke column and a forecast of the fire travel in this area. It is important for the fighters from which side to approach the fire-nests.

Very important is also to detect all fire nests that are sometimes hidden under trees and bushes. For that especially the Thermal camera is used to get clear information about the spatial distribution of these hotspots.

Based on training data an additional AI for fire monitoring has been developed. It is running on the CCMS and gives an analysis of fire, smoke, vehicles and persons in this area.



Figure 19. AI based assistance for the fire brigade to monitor and assist in the defence

A challenge was the combined video stream from the UAS via 5G to the server. The data handling of the thermal and RGB Image in the onboard computers needed several developments on the Jetson Nano and the Latte Panda.

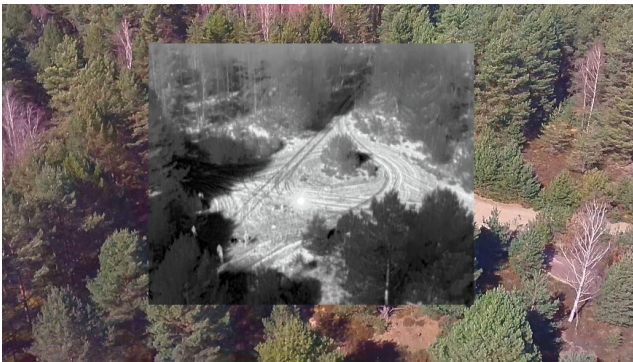


Figure 20. Thermal B&W overlay on the RGB Image.

In the Figure 20 above the hot spot of the fire bowl is visible. An additional function has been implemented to automatically place a cursor on the hotspot and measure the temperature. That is something very important to detect fire nests and check if the defence was overall successful. The implementation of this measurement is pixel-based histogram analytics with recalculation of the single 16 bit-values to real temperatures. Even though this is not a thermal emission that was perfectly calculated, the anomaly is the most important at this point (Allen et al., 2016).

4. Conclusion & Discussion

Wildfires are a serious and increasing issue in Europe. Modern communication infrastructure such as 5G mobile networks can assist in wireless data handling for rapid response to the firefighting teams. A proper setup of geospatial data capturing, a CCMS to combine all data sources and AI analytics help in early defence of wildfires before a bigger disaster arises. The combination of different technologies is one of the fundamental tasks that make this system successful.

Not all aspects could be tested to demonstrate the operability. One big issue is the availability of a proper wireless network inside the forest. Most operational is the setup of gimbals with multispectral camera technology on observation towers. They built the key for the early wildfire detection. The AI on the camera data works nearly perfectly and the number of false positive detection is small.

The use of UAS for the proper localization of the wildfire and the type and dimensions was tested on artificial fires and smoke-bombs, but the autonomous flights were only tested with backup of a drone-pilot. There are still administrative regulations for BVLOS missions.

The use for the fire-brigades was only tested in a simulation, but not in a real-world scenario. This was due to the short project period that did not allow for a real-life test.

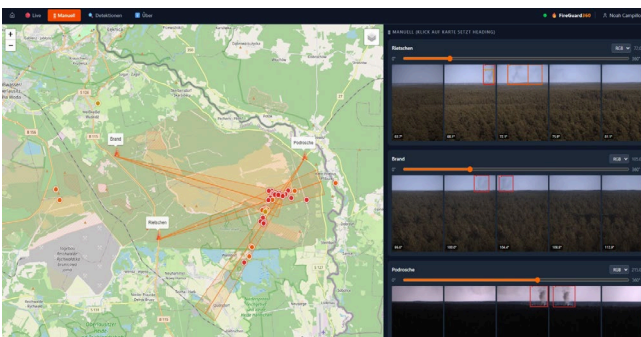


Figure 21: The new Fireguard360 UI of the meanwhile operational system in Saxonia/Germany

As a result, the achievements led to an ongoing installation of the camera gimbals for monitoring this area and became operational in 2026 (Fig. 21). A new GUI was installed to support the fire brigade for the season in this year including new background maps and coordinate support for what3words.

A new project is to develop gimbals for mountainous areas. The benefit can be that when using a digital terrain model (DTM), a single camera can localise the fire on the slopes. But a proper calibration of a two-axis gimbal is essential, and the idea is to use such a system with an autonomous power supply using a mobile mast and solar-panels. Such a setup can reach areas that do not have any observation technology yet. The lack of the availability of a proper communication technology might result in onboard evaluations and transmission of the results alone, in a worst case with Lora Wan technology.

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References

- Abujayyab, S. K., Kassem, M. M., Khan, A. A., Wazirali, R., Coşkun, M., Taşoğlu, E., ... & Toprak, F. (2022). Wildfire susceptibility mapping using five boosting machine learning algorithms: The case study of the Mediterranean region of Turkey. *Advances in Civil Engineering*, 2022(1), 3959150.
- Allen, C., Tsou, M.-H., Aslam, A., Nagel, A., Gawron, J.-M. 2016. Applying GIS and Machine Learning Methods to Twitter Data for Multiscale Surveillance of Influenza. *PloS one* 11 (7), e0157734.
- Altan, O., Kemper, G. (2016): "Innovative airborne sensors for Disaster management." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 41 (2016): 11-16.
- Casas, E., Ramos, L., Bendek, E., & Rivas-Echeverría, F. (2023). Assessing the effectiveness of YOLO architectures for smoke and wildfire detection. *IEEE Access*, 11, 96554-96583.
- Cetin, M., Isik Pekkan, Ö., Ozenen Kavlak, M., Atmaca, I., Nasery, S., Derakhshandeh, M., & Cabuk, S. N. (2023). GIS-based forest fire risk determination for Milas district, Turkey. *Natural Hazards*, 119(3), 2299-2320.
- Ciesielski, M., Balazy, R., Borkowski, B., Szczesny, W., Zasada, M., Kaczmarowski, J., ... & Milanovic, S. (2022). Contribution of anthropogenic, vegetation, and topographic features to forest fire occurrence in Poland. *iForest- Biogeosciences and Forestry*, 15(4), 307.
- EFFIS Wildfire Risk Viewer 2024
- El Emam, K., Mosquera, L., & Hoptroff, R. (2020). Practical synthetic data generation: balancing privacy and the broad availability of data. O'Reilly Media.
- Grari, M., Idrissi, I., Boukabous, M., Moussaoui, O., Azizi, M., & Moussaoui, M. (2022). Early wildfire detection using

- machine learning model deployed in the fog/edge layers of IoT. *Indones. J. Electr. Eng. Comput. Sci.*, 27(2), 1062-1073.
- Heyns, A. M., du Plessis, W., Curtin, K. M., Kosch, M., & Hough, G. (2021). Analysis and exploitation of landforms for improved optimisation of camera-based wildfire detection systems. *Fire Technology*, 57(5), 2269-2303.
- Kanand.T., Kemper. G., König. R., Kemper. H. (2020): Wildfire Detection and Disaster Monitoring Systems using UAS and Sensor Fusion Technologies. ISPRS
- Khan, A., Hassan, B., Khan, S., Ahmed, R., & Abuassba, A. (2022). DeepFire: A novel dataset and deep transfer learning benchmark for forest fire detection. *Mobile Information Systems*, 2022(1), 5358359.
- Krsnik, G., Olivé, E. B., Nicolau, M. P., Larrañaga, A., Terés, J. Á., Garcia-Gonzalo, J., & Olabarria, J. R. G. (2024). Spatial multi-criteria analysis for prioritising forest management zones to prevent large forest fires in Catalonia (NE Spain). *Environmental Challenges*, 15, 100959.
- Le Cozannet, G., Kervyn, M., Russo, S., Ifejika Speranza, C., Ferrier, P., Foumelis, M., Lopez, T., Modaressi, H. (2020): Space-based Earth Observations for Disaster Risk Management. *Survey in Geophysics*. 41:1209-1235.
- Lehnert, A. et al. 2024: Xp1Ainable: Explainable AI Smoke Detection at the Edge, *Big Data Cogn. Comput.* 2024, 8, 50. <https://doi.org/10.3390/bdcc8050050>
- Merino, L. et al.(2012) "Unmanned aerial vehicles for forest fire monitoring and management," *Remote Sensing*, vol. 4, no. 5, pp. 1422–1444
- Mohapatra, A., & Trinh, T. (2022). Early wildfire detection technologies in practice—a review. *Sustainability*, 14(19), 12270.
- Peruzzi, G., Pozzebon, A., & Van Der Meer, M. (2023). Fight fire with fire: Detecting forest fires with embedded machine learning models dealing with audio and images on low power iot devices. *Sensors*, 23(2), 783.
- Preinfalk, E., Handmer, J. (2024): Fueling the fires - An exploration of the driver and the scope for management of European wildfire risk under the Shared Socioeconomic Pathways. *Climate Risk Management*. 45, 100638.
- Qiao, L., Li, S., Zhang, Y., & Yan, J. (2024). Early wildfire detection and distance estimation using aerial visible-infrared images. *IEEE Transactions on Industrial Electronics*.
- Skinner, R., Luther, M., Hertelendy, A. J., Khorram-Manesh, A., Sørensen, J., Goniewicz, K., & Ransie, J. (2022). A literature review on the impact of wildfires on emergency departments: enhancing disaster preparedness. *Prehospital and disaster medicine*, 37(5), 657-664.
- Suarez, D., Gomez, C., Medaglia, A. L., Akhavan-Tabatabaei, R., & Grajales, S. (2024). Integrated decision support for disaster risk management: Aiding preparedness and response decisions in wildfire management. *Information Systems Research*, 35(2), 609-628.
- Wang, Z., Wu, L., Li, T., & Shi, P. (2022). A smoke detection model based on improved YOLOv5. *Mathematics*, 10(7), 1190.