DEVELOPMENT OF UAVs/DRONES EQUIPPED WITH THERMAL SENSORS FOR THE SEARCH OF INDIVIDUALS LOST UNDER RUBBLE DUE TO EARTHQUAKE COLLAPSES OR ANY EVENTUALITY REQUIRING SUCH CAPABILITIES

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Abstract

The development of UAVs (Unmanned Aerial Vehicles) or drones equipped with thermal sensors is a significant advancement in search and rescue operations, particularly for locating individuals trapped under rubble due to natural disasters like earthquakes. This innovation addresses the urgent need for rapid and efficient responses in disaster scenarios, where limited visibility and accessibility pose significant challenges.

UAVs can fly over affected areas, providing real-time data to rescue teams. Thermal sensors are crucial as they detect the heat emitted by human bodies, enabling the identification of trapped individuals even in low visibility conditions. This technology is particularly effective for locating injured or unconscious individuals, enhancing the accuracy and speed of rescue operations, and increasing survival chances.

The development process involves overcoming technical challenges such as miniaturizing thermal sensors to fit UAVs, developing algorithms for image processing, and ensuring robust communication systems for real-time data transmission. Additionally, solutions for dust accumulation, which impacts sensor visibility and UAV electronics, are explored. These include automatic cleaning systems using methods like vibration or compressed air and advanced thermal sensor designs to resist dust.

UAVs offer additional benefits like mapping affected areas, assessing structural damage, and delivering essential supplies to trapped individuals. Specialized drones equipped with robotic arms can also assist in debris removal, working in coordination with ground rescue teams. This integration improves the overall efficiency and effectiveness of rescue operations.

Supply drones play a vital role in delivering water, food, medical supplies, and other essentials to trapped or isolated individuals, even in inaccessible areas. This immediate assistance provides material aid and conveys hope to survivors, emphasizing the crucial role of drones in disaster response and recovery.

Keywords: UAVs/Drones, thermal sensors, search-and-rescue, earthquakes.

1. Importance of innovative technologies in disasters management

Natural disasters such as earthquakes, hurricanes, floods, and landslides have devastating effects all over the world, leading to extensive damage and loss of life. The unpredictability and severity of these events necessitate the continuous improvement of disaster management strategies. Traditional search-and-rescue (SAR) operations often face significant challenges, including limited accessibility, high risk, slow response times, and more. In those scenarios, innovative technologies can play a crucial role in enhancing the efficiency and safety of SAR operations.

Our proposal includes the use of Unmanned Aerial Vehicles (UAVs) or drones for disaster management. Drones can be deployed rapidly and reach the affected areas faster than any other traditional means of rescue. This technology is also capable of navigating through rubble, collapsed structures and other challenging terrains while using lanterns and thermal sensors to help find people; a task that will be extremely dangerous for human rescuers. We propose thermal sensors because they can detect the heat generated by human bodies. If they are fast enough, they can see through the camera sensor the thermal footprint of this heat even if the person has already changed place or position, meaning it is no longer there. This capability allows UAVs to identify heat signatures from individuals trapped under rubble or in other obstructed environments. Unlike traditional visual methods, thermal imaging is effective even in low visibility conditions, such as night or through dense debris.

The recent growth in the use of Artificial Intelligence (AI) also provides a useful feature that significantly enhances the capabilities of thermal sensors on drones for detecting people in harsh conditions. AI algorithms, particularly those involving machine learning and deep learning, can process the thermal images captured by the sensors more accurately and efficiently than traditional methods. By training these algorithms on vast datasets of thermal images, they can learn to recognize the unique heat signatures of human bodies even in challenging environments, such as through dense debris, heavy foliage, or in adverse weather conditions.

One of the key benefits of AI in this context is its ability to filter out noise and irrelevant data from the thermal images. In disaster scenarios, thermal sensors often pick up numerous heat sources, such as fires, animals, or machinery, which can complicate the identification process. AI algorithms can be trained to distinguish between human heat signatures and other heat sources, thereby reducing false positives and improving the accuracy of detections. Moreover, AI can enable real-time processing of thermal images, allowing for immediate analysis and decision-making. This is crucial in search and rescue operations, where time is of the essence. AI-powered systems can quickly analyze incoming data, identify potential human presences, and alert rescue teams to their exact locations. This rapid processing capability not only speeds up the search process but also allows for better coordination and deployment of resources.

AI also facilitates the development of predictive models that can anticipate the movements and locations of trapped individuals based on the analysis of previous disaster data. These models can help prioritize search areas and optimize the flight paths of drones, ensuring that the most critical regions are surveyed first. Additionally, AI can assist in mapping and reconstructing the disaster site, providing a detailed overview of the affected area and identifying potential hazards for rescue teams.

2. Technological overview of UAV

2.1 History and evolution

The first time the idea of creating unmanned aircraft vehicles arose can be traced back to the First World War, when Britain's Aerial Target emerged in March 1917. The following year, in October 1918, the Kettering Bug would be tested in the United States, an aerial torpedo. Both demonstrated potential during flight tests, but neither was deployed operationally during the war [1]. In the mid-1930s, radio-controlled model airplanes were used by the U.S. Army Air Corps to develop aerial targets for anti-aircraft training. A few years before the Second World War began, in 1935, the Radioplane Co. in California, founded by former movie star and modeler Reginald Denny, produced several versions of the Radioplane OQ-2A [2]. The successful OQ-2A model led to contracts for nearly 1,000 targets in 1943, making it the first mass-produced UAV or drone in the United States [3].

In the early 1960, during the Cold War, the D-21 drone program addressed the need for deep penetration imagery without risking pilots, pushed technological boundaries, and maintained strict secrecy [4]. At the same time, the Ryan 147 UAV was crucial during the War in Southeast Asia, leading to the development of modern UCAVs (Unmanned Combat Aerial Vehicles). The Ryan 147 evolved to the BGM-34A, but it was later canceled and all the Air Force UAV programs were paused for over a decade [5]. Nevertheless, these early UAVs were primarily used by the military and had limited application in civilian domains such as SAR missions due to their size, cost, and operational complexity. Advances in miniaturization, GPS technology, and battery life during the following years made UAVs more accessible for civilian use.

Among the first companies to venture into the production of commercial drones stand out: AeroVironment, pioneering American company in the development of small Unmanned Aerial Systems (sUAS) for commercial and military applications; Dà-Jiāng Innovations (DJI), revolutionary Chinese company in the commercial drone market with the introduction of easy-to-use and high-performance multitask quadcopters; and Parrot, an innovative French company that introduce the AR Drone, capable of being controlled by mobile devices. In the last decade, drones have evolved and become important instruments in the aftermath of natural disasters. In 2017, after Hurricane Harvey, eased Federal Aviation Administration (FAA) restrictions enabled drones to quickly assess damages, expediting insurance claims and inspection [6]. Two years later, in 2019, drones aided post-Typhoon Hagibis relief efforts by capturing images of inaccessible areas and delivering relief supplies in Tokyo [7]. The next year, in 2020, GeoAcuity provided drone-based imagery of California fires, aiding coordination among firefighters and disaster prevention agencies [8].

2.2 Types of UAVs

According to Lyu, Zhao, Huang & Huang (2023) UAVs are generally classified into fixed-wing, multirotor, and unmanned helicopter types [9]. We can also find hybrid UAVs, which combine fixed-wing and multirotor designs. Selecting the UAV type is based on mission requirements and specific design characteristics. The most important characteristics of each one will be briefly explained below, while the advantages and disadvantages of each of the types of UAV mentioned below are compiled from the work of Ajith & Jolly (2021) [10].

2.2.1 Unmanned Helicopter

Unmanned helicopters have a main motor with a large propeller for lift and movement, and a tail motor for torque balance [11]. They are agile and suited for complex environments, but have a complex main rotor structure, leading to high maintenance costs. They excel in surveillance and tracking missions.

2.2.2 Multirotor UAV

Multirotor UAVs, the most common type, use motors and propellers for lift and can be classified by the number of rotors: octocopters, hexacopters, quadcopters, and tricopters [12]. They feature a simple structure, good maneuverability, Vertical Take-off and Landing (VTOL) capability, and are suitable for indoor and outdoor use. However, they have poor endurance due to high electricity consumption.

2.2.3 Fixed-Wing UAV

Fixed-wing UAVs, like commercial airplanes, generate lift via pressure differences between their surfaces and achieve thrust, typically from a tail-mounted engine. They use elevators, ailerons, and rudders for pitch, roll, and yaw movements [13]. Ideal for surveillance and large-scale searches, they are energy efficient but require high speeds, limiting their maneuverability.

2.2.4 Hybrid UAV

Hybrid UAVs combine multirotor and fixed-wing advantages, achieving VTOL and long-range capabilities [14]. However, multiple motors and propellers add weight and wind resistance, complicating control system design. They are ideal as communication relay stations, providing network connectivity and disaster relief support.

2.3 Key Components

The components of a UAV can be classified according to several factors, however, it has been decided to use one of the most general classifications: software and hardware. The hardware is all the tangible or physical parts of the UAV, while the software is the non-physical instructions and programs that control the UAV's operation. Below, the elements of the UAV that fall into each of the components are specifically presented.

2.3.1 Hardware

Here is included the airframe and the wings, in case of a fixed-wing or hybrid design, of the UAV. It also includes the means of propulsion which are, depending on the case: electric, combustion or jet motors, servos or blades. According to the mission we will also find all the sensors within the hardware, e.g., Inertial Measurement Unit (IMU), barometers, magnetometers, thermometers, thermal sensors, to name a few. The flight controller and transmitters and receivers are also hardware fundamentals for managing flight dynamics and stability and ensure communication between the UAV and the ground control station. The powering system of the UAV, in most of the cases composed by batteries, is part of the hardware too. Finally, more specialized drones have additional hardware such as cameras, antennas, or displays.

2.3.2 Software

The software includes the Flight Controller (FC) Firmware, which manages flight dynamics, stability and navigation. Some examples of the FC Firmware includes: Ardupilot, Betaflight, INav and PX4. The telemetry software is also included here and is responsible for transmitting data between the UAV and the ground control station. It is also important to mention the Ground Control Station (GCS) software, which interfaces with the UAV, providing a platform for mission planning and real-time monitoring. Some of the most remarkable GCS software are Mission Planner and QGroundControl. In some cases, when the drone is partially or completely autonomous, an Autonomous Navigation Software is required. This tool enables the UAV to follow pre-set routes or react to environmental conditions without human intervention.

3. Thermal Imaging Technology

3.1 Basics of Thermal Imaging

Thermal imaging technology works by detecting infrared radiation (heat) emitted by objects. Unlike visible light, infrared radiation is not visible to the naked eye but can be captured and visualized using thermal sensors. These sensors convert the heat energy into an electronic signal, which is then processed to create a thermal image or heat map. Different temperatures are represented by different colors or shades in the thermal image, allowing for the identification of heat sources, such as human bodies, even in low visibility conditions.

3.2 Types of Thermal Sensors

Thermal sensors can be categorized into two main types: cooled and uncooled.

- **Cooled Thermal Sensors:** These sensors contain cryogenically cooled infrared detectors that provide high sensitivity and resolution. They are capable of detecting minute temperature differences and are typically used in applications requiring high precision, such as military surveillance and scientific research. However, they are more expensive and require more maintenance due to the cooling system.

- **Uncooled Thermal Sensors:** These sensors operate at ambient temperatures and do not require cooling. They are more common in commercial applications due to their lower cost and ease of use. While they may not offer the same level of sensitivity as cooled sensors, advancements in technology have significantly improved their performance, making them suitable for most search and rescue operations.

3.3 Applications

Thermal imaging technology has a wide range of applications beyond search and rescue, including:

- **Medical Diagnostics:** Used in detecting inflammation, circulatory issues, and other medical conditions.

- **Building Inspections:** Identifying heat leaks, moisture intrusion, and electrical faults.

- **Industrial Monitoring:** Monitoring machinery and equipment for overheating or other thermal anomalies.

- **Environmental Studies:** Tracking wildlife, monitoring vegetation health, and studying climate change.

4. Integration of Thermal Sensors with UAVs

4.1 Technical Integration

Integrating thermal sensors with UAVs involves several technical steps to ensure optimal performance. This includes mounting the sensor securely on the UAV, ensuring proper calibration of the sensor, and establishing a reliable data link between the sensor and the UAV's control system. The integration process also involves configuring the sensor to operate in sync with the UAV's navigation and communication systems, allowing for real-time data transmission and processing.

- **Mounting and Stabilization:** Thermal cameras need to be securely mounted on the UAV to minimize vibrations and movement, which can distort the imagery. The use of gimbals, which are stabilization devices, is crucial. Gimbals compensate for the UAV's movements and ensure that the thermal camera remains steady and focused on the target area.

- **Communication Systems:** A reliable communication system is essential for transmitting thermal images from the UAV to the ground control station in real-time. This involves using high-frequency radio transmitters or dedicated data links. The communication system must be robust enough to handle high data transfer rates and resistant to interference, ensuring continuous and clear image transmission.

- **Image Processing and Software Integration:** The thermal images captured by the sensors need to be processed and analyzed using specialized software. This software should be capable of detecting heat signatures and distinguishing between different types of objects. Integration with AI and machine learning algorithms can enhance the capability of thermal sensors by improving object detection and reducing false positives.

4.2 Challenges and Solutions

- **Environmental challenges:** Thermal sensors can be affected by various environmental factors such as temperature extremes, humidity, and precipitation. Protective housings for thermal cameras can mitigate some of these effects, and advanced calibration techniques can help maintain accuracy in varying environmental conditions.

- **Power Management:** One of the significant challenges in integrating thermal sensors with UAVs is power management. Thermal cameras, especially high-resolution ones, consume a considerable amount of power. Ensuring that the UAV has sufficient power to operate both the thermal camera and itself is crucial. Solutions include using high-capacity batteries and optimizing the power usage of the UAV's systems.

- **Data Management:** Managing the large amounts of data generated by thermal sensors can be challenging. Efficient data storage solutions are needed to store and retrieve thermal images quickly. Cloud storage and advanced data compression techniques can help manage this data effectively.

4.3 Power and Data Management

- **Battery Technology:** Advancements in battery technology are critical for the successful integration of thermal sensors with UAVs. High-density batteries that provide longer flight times without significantly increasing the UAV's weight are essential. Battery management systems (BMS) can monitor and optimize battery performance, ensuring that the UAV can operate for extended periods with a thermal sensor.

- **Data Transmission and Storage:** Efficient data transmission systems ensure that the thermal images are sent to the ground control station without delay. This includes using high-speed data links and ensuring minimal latency. For data storage, both onboard storage solutions and cloud-based systems can be used. Onboard storage should be fast and reliable, with solid-state drives (SSDs) being a preferred choice due to their speed and durability.

- **Redundancy and Reliability:** Redundancy in both power and data systems increases the reliability of UAVs equipped with thermal sensors. This includes having backup batteries and data links to ensure continuous operation even in case of a failure. Ensuring redundancy helps in maintaining the operational effectiveness of the UAV during critical search and rescue missions.

5. Search and Rescue Operations

5.1 Methodology

The methodology for utilizing UAVs equipped with thermal sensors in search and rescue operations involves several steps:

- **Deployment:** UAVs are deployed to the disaster site, where they are programmed to follow specific flight paths to cover the affected area thoroughly.
- **Data Collection:** As the UAVs fly over the area, the thermal sensors capture heat signatures from potential survivors trapped under rubble or debris.
- **Data Analysis:** The thermal images are processed in real-time to identify human heat signatures. AI algorithms can be employed to enhance detection accuracy.
- **Reporting:** Identified locations of survivors are marked and communicated to ground rescue teams, along with thermal images and precise coordinates.

5.2 Study Cases

Several case studies highlight the effectiveness of UAVs with thermal sensors in search and rescue operations:

5.2.1 Mexico Earthquake (1985)

The 1985 Mexico City earthquake was one of the most catastrophic events in the history of the region, causing extensive damage and resulting in a significant loss of life. Although UAV and thermal sensor technology was not available at that time, the disaster highlighted the potential impact such technology could have in future rescue operations. The earthquake led to the collapse of numerous buildings, trapping thousands under debris. The subsequent rescue efforts were hampered by the lack of real-time information and the difficulty in accessing affected areas.

In retrospective analysis, experts have emphasized how modern UAVs equipped with thermal sensors could have transformed the rescue operations during the 1985 earthquake. Thermal imaging could have provided real-time data on the location of survivors, allowing for more efficient and targeted rescue efforts. The ability to quickly identify heat signatures through rubble would have significantly reduced the time needed to locate and extract trapped individuals. Additionally, UAVs could have assisted in mapping the disaster area, assessing structural damage, and identifying safe access routes for rescue teams.

5.2.2 Haiti Earthquake (2010)

UAVs equipped with thermal sensors were deployed to locate survivors trapped under collapsed buildings. The technology helped in quickly identifying heat signatures, significantly aiding rescue efforts. In January 2010, a devastating earthquake struck Haiti, causing widespread destruction and leaving thousands trapped under rubble. In response, UAVs equipped with thermal sensors were deployed to locate survivors. These UAVs provided real-time thermal imaging, which was instrumental in identifying heat signatures of trapped individuals. The technology significantly enhanced the efficiency of rescue operations, allowing teams to focus their efforts on areas where survivors were detected. This rapid identification and response were crucial in the critical hours following the disaster, ultimately saving many lives.

5.2.3 Nepal Earthquake (2015)

Similar UAV deployments in the aftermath of the Nepal earthquake provided critical data that facilitated the rescue of numerous individuals. The Nepal earthquake in April 2015 presented a similar scenario, where UAVs with thermal sensors played a pivotal role in search and rescue missions. The rugged terrain and extensive damage made it difficult for ground teams to navigate and locate survivors. UAVs were able to fly over inaccessible areas and provide thermal imaging data that highlighted the presence of heat signatures, indicating possible survivors. This technology not only improved the speed of search operations but also minimized the risks to rescue personnel by identifying safe routes and hazards.

5.2.4 Injuries, Missing and Dead People

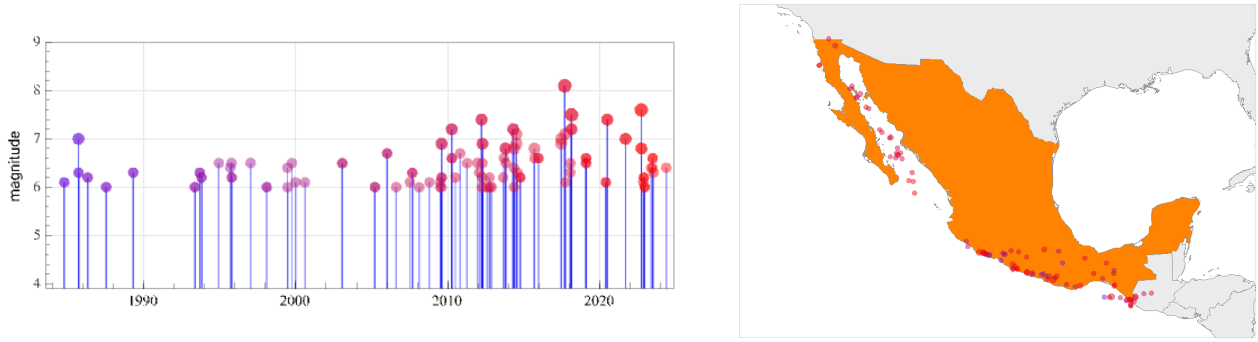
Using various databases and mainly focusing on the NCEI/WDS Global Historical Tsunami

Database, and the Significant Earthquake Database, and reducing the scope of those databases only from years 1984-2024, it was possible to do a good estimation on the accountability of injuries, missing and dead people due to natural disasters, focusing only on earthquakes and tsunamis, as the following table shows.

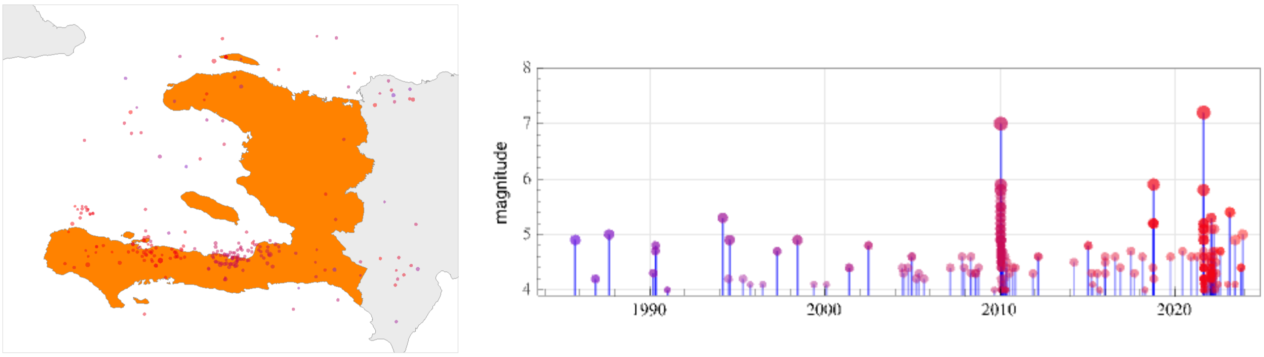
Category	Earthquakes	Tsunamis	Total[1] Earthquakes	Total Tsunamis
Injuries	1,627,271	64,953	1,911,868	1,172,043
Missing	2,832	800	2,933	2,140
Deaths	789,484	256,749	1,040,822	808,947

Table 1. *Important data collected from 1984 to 2024 using NCEI/WDS databases.*

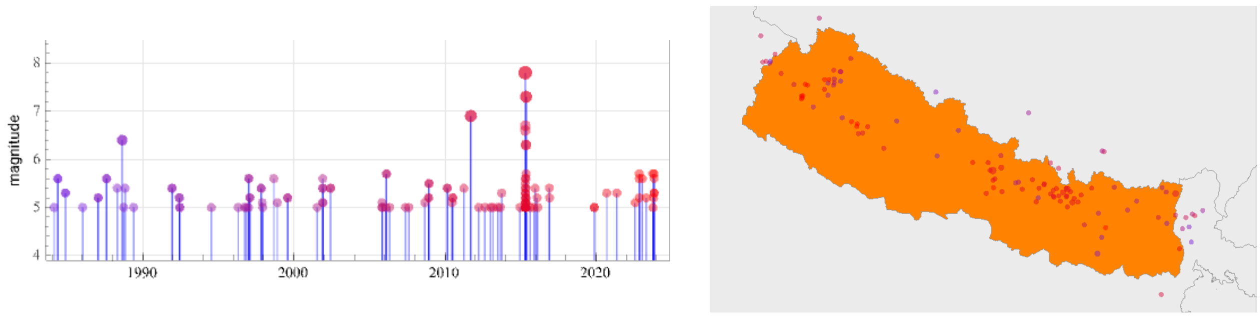
Due to the essential information categorized in Table 1, a more in depth study was done in order to find out which are the most seismic places on earth, not just to rank them, but to use them as a guideline on the efforts to apply this conceptual project into real life. That can be crucial for many of the following countries.



(a) Mexico

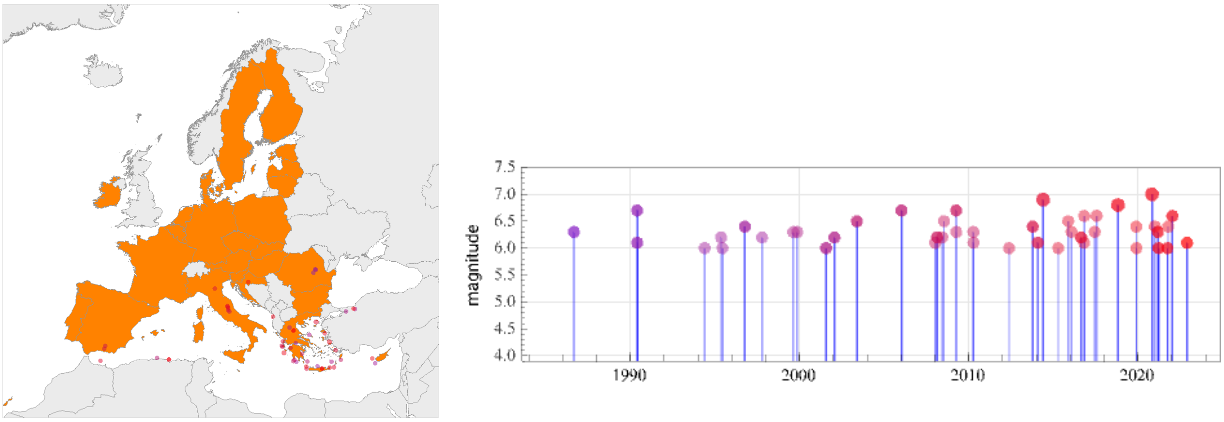


(b) Haiti

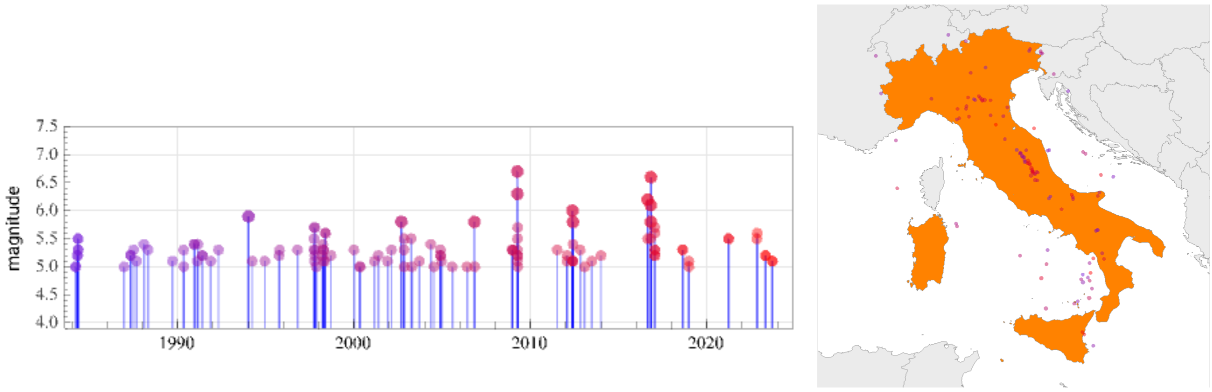


(c) Nepal

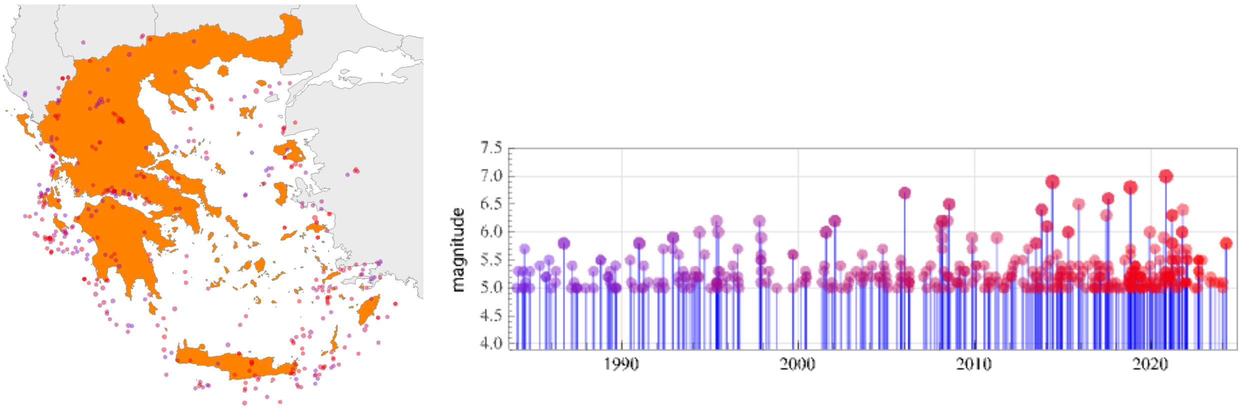
[1] Total column refers to the actual sum of affected people of that specific original natural disaster and the secondary effects it produced.



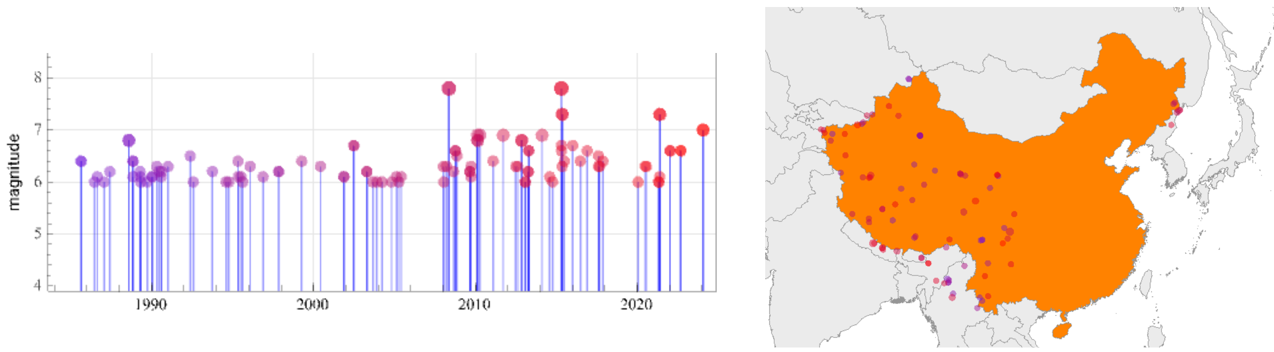
(d) European Union



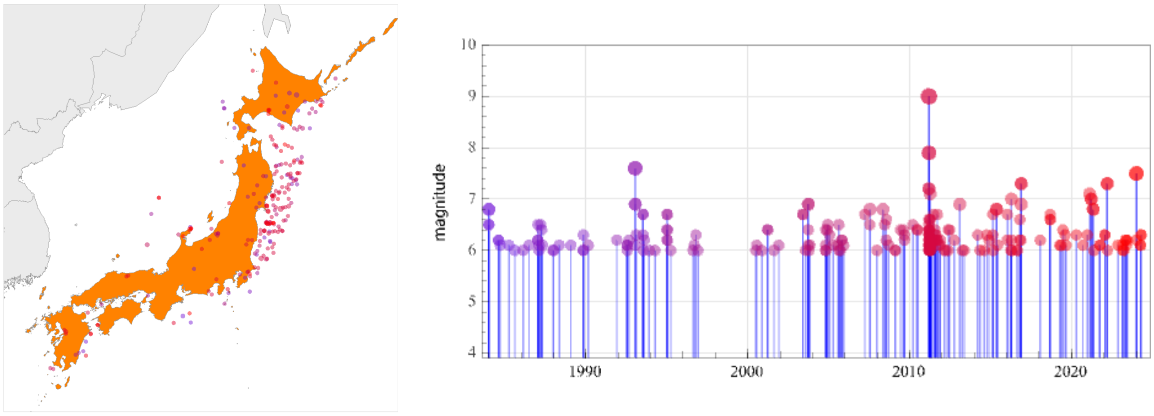
(e) Italy



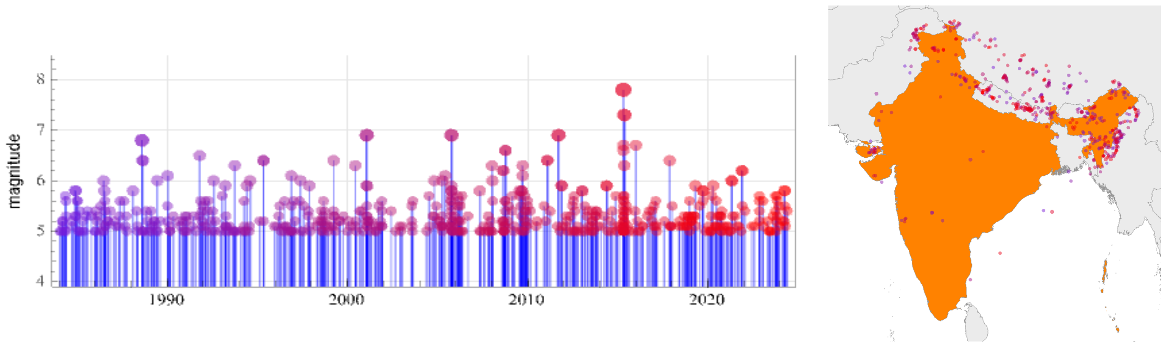
(f) Greece



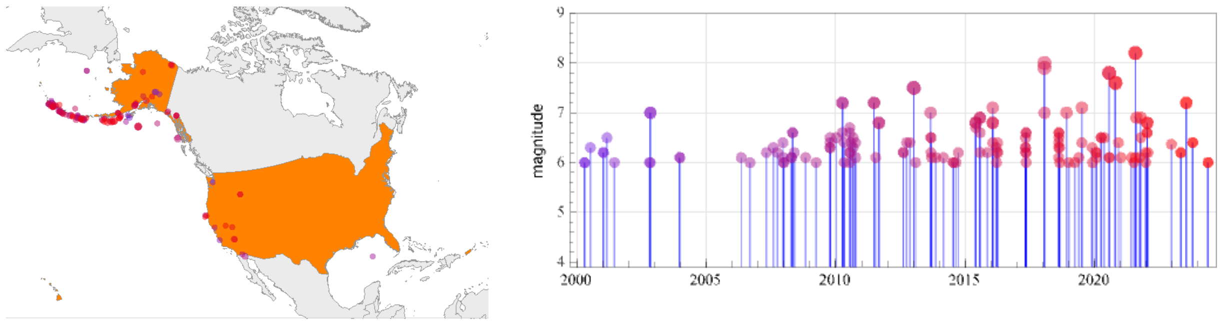
(g) China



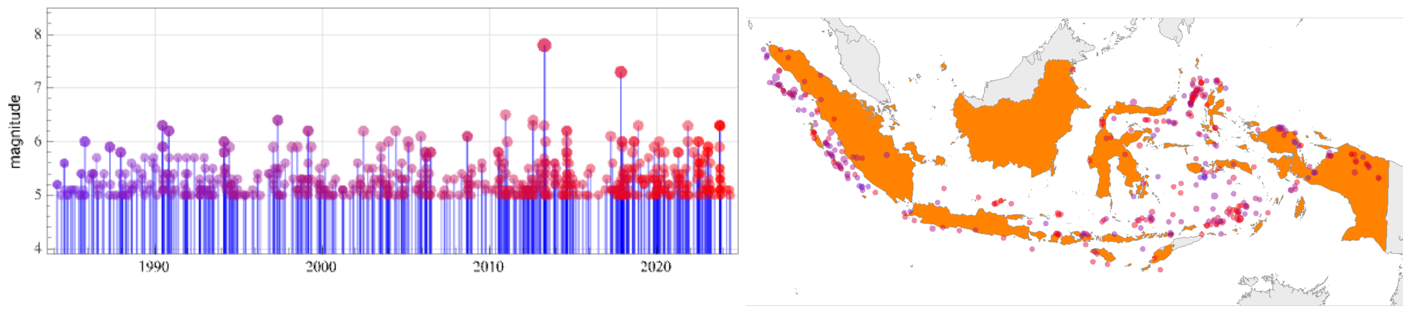
(h) Japan



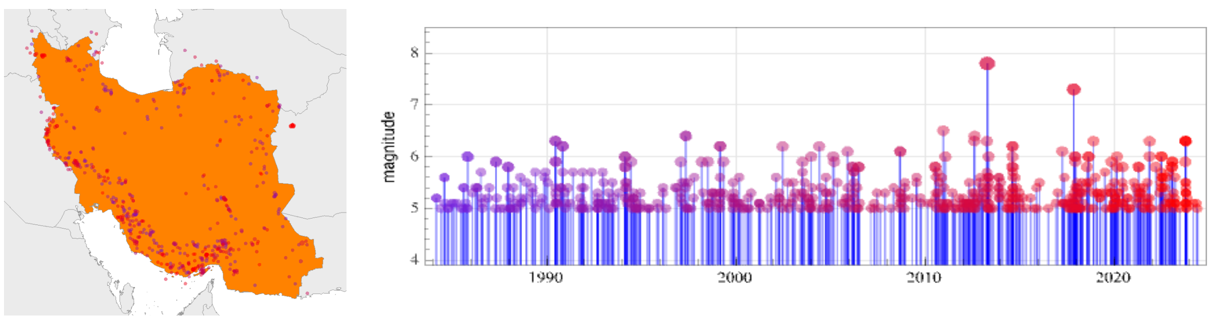
(i) India



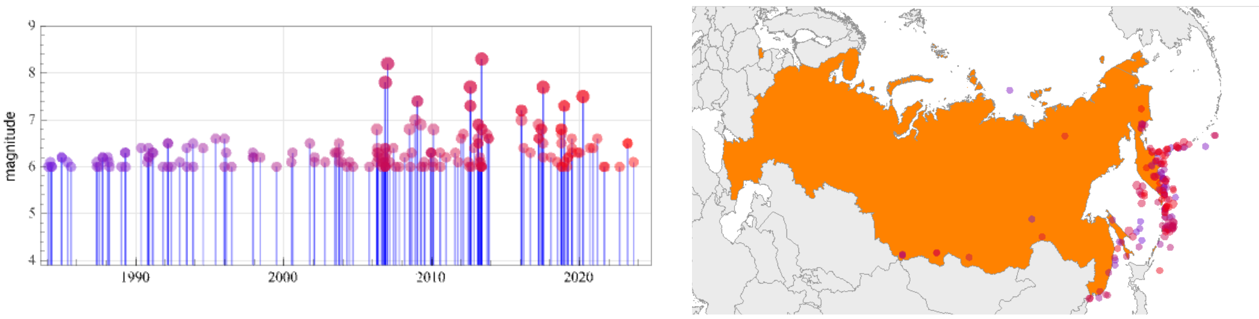
(j) United States



(k) Indonesia



(l) Iran

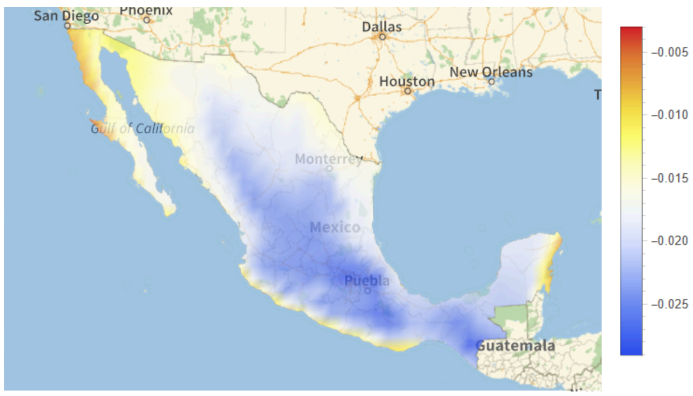


(m) Russia

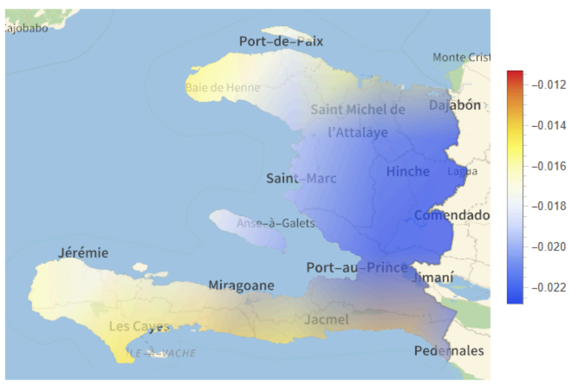
Figure 1 - Maps with graphics for different countries and their earthquakes in the last 40 years.

A gravity anomaly is a tool used to study subsurface geology by showing how local gravity varies from the global average. Models can calculate gravity changes on a large scale worldwide, noting that gravity near the equator and poles deviates more due to Earth's shape. Mountains also cause anomalies, disrupting the smooth gradient of gravity values.

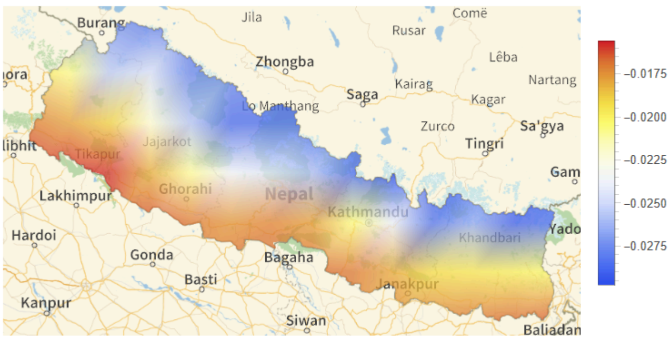
For instance, in North America, there is a general trend of gravity anomalies shifting from positive in the north to negative in the south, with the Rocky Mountains causing additional local variations due to their elevation. Applying this to the countries presented earlier in Figure 1 the following can be seen as a result.



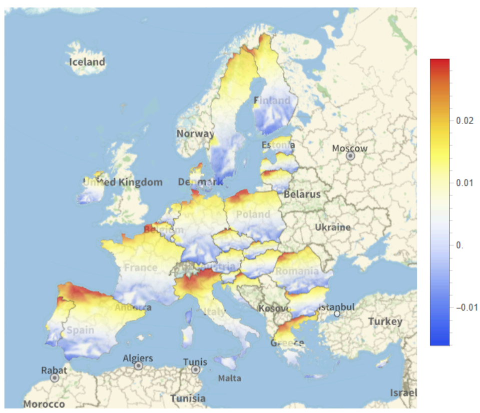
(a) Mexico



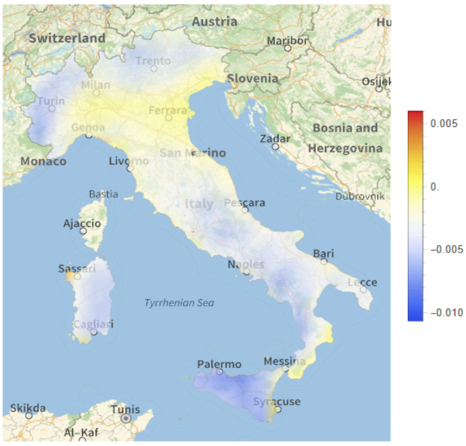
(b) Haiti



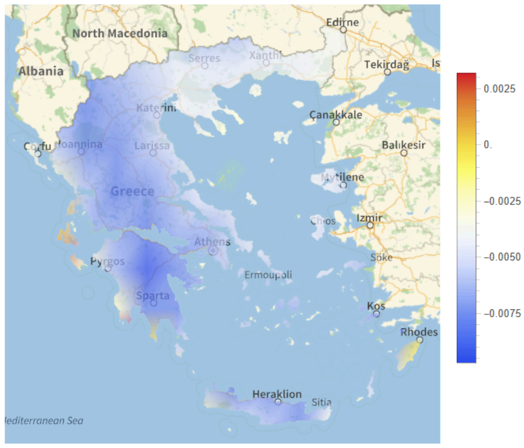
(c) Nepal



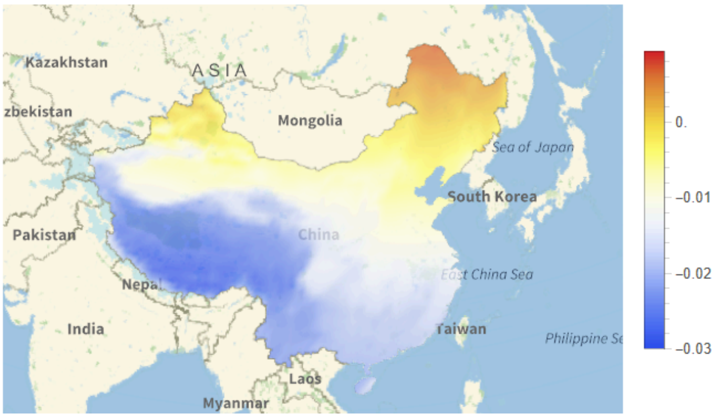
(d) European Union



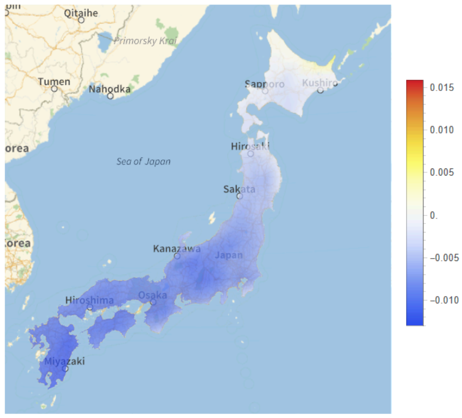
(e) Italy



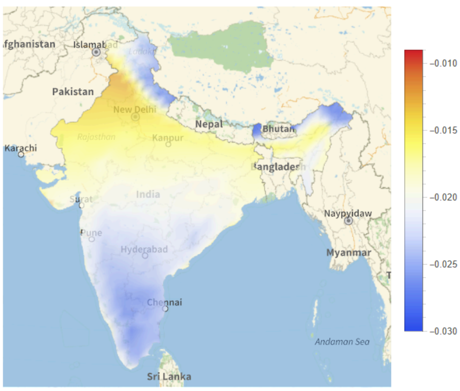
(f) Greece



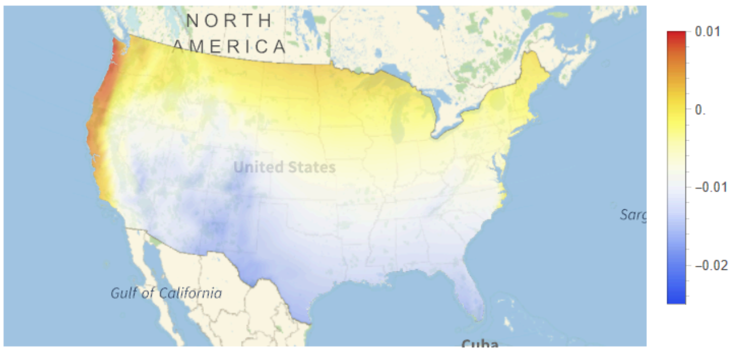
(g) China



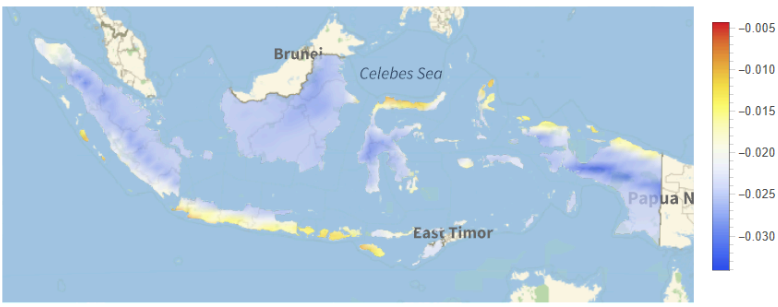
(h) Japan



(i) India



(j) United States



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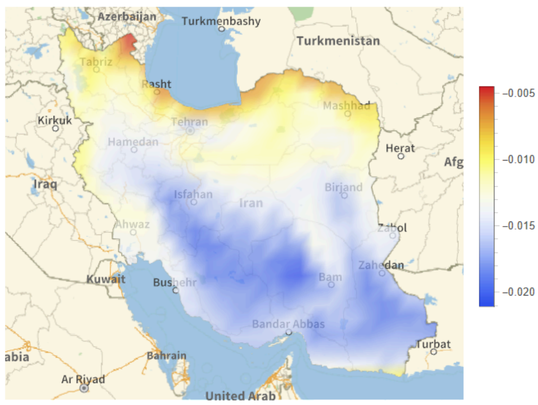
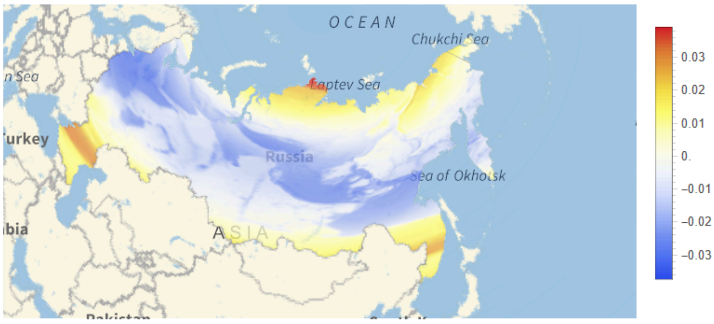


(l) Iran



(m) Russia

Figure 2 - Maps with thermal interface where there are gravity anomalies for the different countries.

All the presented countries result of special interest for this paper, mainly because they have got a huge impact when referring to earthquakes, or because of their territorial extension. In most of them, all earthquakes with magnitude less than 4 were excluded, except for the case of Haiti, because of the relevance it had in 2010 and 2022. As for the other countries, almost all of them had been graph only with earthquakes with magnitude of 5 as a minimum to be considered and some of 6, when they have higher magnitude for a wide variety of their seismic activity.

5.3 Coordination with Ground Teams

Effective coordination between UAV operators and ground rescue teams is crucial for successful search and rescue operations. This involves establishing clear communication channels and protocols for data sharing. Ground teams must be trained to interpret thermal images and act on the information provided by UAVs. Regular drills and joint training exercises can enhance the synergy between UAV operators and rescue personnel, ensuring a prompt and efficient response in real disaster situations.

6. Advantages of Using UAVs in Rescue Missions

6.1 Speed and Efficiency

Considering that the time after the natural disaster has passed is vital to saving people's lives, the priority is to find a means that can act quickly and efficiently. According to Khan Mod, Hoang, Nguyen et al. (2022) “[...] drones have significant benefits in terms of time as well as resources. [15]” Other authors who agree with this idea are Apvrille, Tanzi and Dugelay (2014) emphasizing that “drones have an impressive high potential to offer fast and efficient responses in rescue conditions, even if some difficulties must be tackled. [16]” Although the survival time of a person under the rubble varies greatly and depends on the conditions under which the person is found and the weather conditions, experts estimate that this time generally does not go beyond 7 days [17].

Karaca and his team (2018) carried out an experiment where a very interesting comparison is made between the use of traditional search means and the use of UAVs in search and rescue missions for people in the mountains. Drone systems are capable of reaching a target 6.43 faster than conventional search equipment and not only that, but they were also able to register 2.58 times more area than the latter, having an astonishing number of 32,979.9 m^2 as median area searched per minute [18]. Another intriguing study was conducted by Doherty and Rudol (2008) in which they present an algorithm capable of detecting humans lying on the ground using thermal and color video source from a UAV [19]. The results were positive, detecting all eleven bodies in the area, despite some false positives due to a lenient classifier. Geolocation accuracy was within a 3-meter radius, though errors arose from GPS inaccuracies and other factors.

These two cases are just two examples of many experiments that have been carried out to test the performance of UAVs in SAR missions. Based on what's seen above, it is reaffirmed that the use of drones would really bring more efficient and faster results than traditional search and rescue methods.

6.2 Accessibility

After large earthquakes it is common to find collapsed buildings and as a consequence people are trapped under the rubble of the buildings. In order to find the victims of a collapse, an instrument is necessarily capable of accessing areas that are very difficult to approach due to the amount of debris that makes it impossible for rescue teams to pass. According to Karamau et al. (2018) “UAVs can easily and quickly access inaccessible environments. [20]” The United States National Search and Rescue Committee (NSRAC) in its *Unmanned Aerial System Search and Rescue Addendum* (2016) *(*reaffirms that “UAS are frequently employed in search areas which are inaccessible to ground parties and manned aircraft. [21]” Drones must search for and document survivable void spaces, like stairwells or areas beneath beams, where people may survive for days. Larger voids (at least 3 or 4 feet high) increase survival chances, while smaller ones (less than 3 feet high) are more dangerous due to limited space and higher risk of debris movement or structural collapse.

Candigliota and Immordino (2012) conducted a study in Bondeno, Ferrara in which they confirmed Low Altitude Remote Sensing’s effectiveness of monitoring earthquake-damaged historical buildings using drones. One of the most remarkable conclusions of its works is that UAVs remote sensing is a low-cost technology for inaccessible or damaged areas, ideal when traditional satellite and airborne platforms are impractical or inconvenient [22]. In the same way, Albeiano, Gheisari and Franz conducted a systematic review of literature regarding UAV applications in Architecture, Engineering and Construction (AEC) industry. According to the data collected in the category of Post-Disaster Assessment, 100% of the drones that have been used for this task were chosen due to the danger that these activities represent for humans [23].

It is more than evident that the use of UAVs is more than necessary when it comes to accessing places that, after a catastrophe such as a landslide after an earthquake, are totally inaccessible to rescue brigades. It is not only about saving lives, but it is also a matter of not risking more lives in tasks that can be extremely dangerous due to the conditions that arise.

6.3 Cost-Effectiveness

After a major natural disaster, authorities must invest all available resources to safeguard the well-being of the population, regardless of the cost. However, having an effective and low-cost option will always be a priority for rescue forces. Ahlskog (2023) assures that drones “provide a swift, cost-effective method to collect aerial data, aiding efficient ground surveys and significantly improving the chances of promptly finding missing individuals. [24]” According to Alsamhi et al. (2022) “UAVs are distinguished from conventional vehicles by their cost-effectiveness, ease of use and maintenance, affordability, market availability, and ease and speed of entry to disaster areas.”

It is actually very difficult to find exact information on what the cost of a search and rescue mission is after a natural disaster. However, based on the approaches that have been made in other works related to the topic, such as *Comparative Review on the Cost-Effectiveness Analysis of Relief Teams Deployment to Sudden-Onset Disasters* and *Search without rescue? Evaluating the international search and rescue response to earthquake disasters,* it can be affirmed that it is not an economical task for governments reaching the astronomical figure of up to almost 1 million dollars for the team deployment.

According to Jouav, a Chinese company specializing in UAV technology, The price of search and rescue drones varies widely, from several hundred to tens of thousands of dollars, based on their size, features, and specifications. Basic models are available for $500-$1,500, mid-tier options for $1,500-$5,000, and high-end or custom drones for $5,000-$30,000 or more. Additional costs can include accessories, maintenance, and training.

7. Challenges and Limitations

Despite the significant advancements in UAV and thermal sensor technologies, several challenges and limitations still need to be addressed to maximize their effectiveness in search and rescue operations. These challenges can be broadly categorized into technical limitations, environmental factors, and regulatory issues.

Addressing these challenges and limitations is essential for optimizing the deployment and effectiveness of UAVs equipped with thermal sensors in search and rescue operations. Continued advancements in technology, coupled with the development of robust regulatory frameworks, will be crucial in overcoming these obstacles and ensuring the successful integration of UAVs into disaster management strategies. By tackling these issues, UAVs can play an increasingly vital role in saving lives and enhancing the efficiency of search and rescue missions in the face of natural disasters and other emergencies.

7.1 Technical Limitations

7.1.1 Battery Life and Endurance

One of the primary technical limitations of UAVs is their battery life and endurance. Most commercial UAVs have limited flight times, often ranging from 20 to 60 minutes, which can constrain their operational capabilities during prolonged search and rescue missions. Continuous advancements in battery technology and energy management systems are essential to extend the operational duration of UAVs.

7.1.2 Payload Capacity

The payload capacity of UAVs is another critical limitation. Thermal sensors and other essential equipment add to the weight, impacting the drone's flight performance and endurance. Developing lightweight yet powerful sensors and optimizing the design of UAVs to balance payload capacity and flight efficiency are necessary steps to overcome this challenge.

7.1.3 Sensor Accuracy and Resolution

The accuracy and resolution of thermal sensors can be affected by various factors, such as sensor quality, calibration, and data processing algorithms. High-resolution sensors can provide more detailed thermal images, but may require more processing power and data storage. Ensuring that sensors are accurately calibrated and developing efficient algorithms for processing thermal data are crucial for reliable human detection.

A common misconception perpetuated by movies and popular media is that thermal sensors can easily detect people through solid surfaces such as walls, floors, and large debris. This portrayal is misleading and does not accurately reflect the capabilities of current thermal imaging technology. In reality, thermal sensors detect infrared radiation, or heat, emitted by objects and people, but they cannot see through solid objects. While thermal imaging can detect heat signatures on the surface of objects, it cannot penetrate materials like concrete, metal, or thick debris. This limitation is crucial to understand, as relying on the unrealistic capabilities shown in films could lead to misguided expectations and ineffective search and rescue strategies. Therefore, it is essential for both rescue teams and the public to have a realistic understanding of what thermal sensors can and cannot do, ensuring that these technologies are used effectively and appropriately in real-world scenarios.

7.1.4 Data Processing and Transmission

Real-time data processing and transmission are vital for effective search and rescue operations. UAVs must be equipped with robust onboard processors to handle the large amounts of data generated by thermal sensors. Additionally, reliable communication links are required to transmit data to ground teams in real-time. Overcoming latency issues and ensuring uninterrupted data transmission, especially in remote or disaster-stricken areas, remain significant challenges.

7.2 Environmental Factors

7.2.1 Adverse Weather Conditions

Adverse weather conditions, such as heavy rain, strong winds, snow, and extreme temperatures, can significantly impact the performance of UAVs and thermal sensors. These conditions can affect flight stability, sensor accuracy, and data transmission capabilities. Designing UAVs and sensors that are resilient to harsh weather conditions is crucial for maintaining operational effectiveness.

7.2.2 Obstructed Environments

In disaster scenarios, UAVs often need to navigate through obstructed environments filled with debris, dust, smoke, and other visual obstructions. These obstacles can hinder the visibility and accuracy of thermal sensors. Incorporating advanced navigation systems and obstacle detection technologies, such as LiDAR and sonar, can help UAVs maneuver through challenging environments safely.

7.2.3 Dust and Debris

Dust and debris can accumulate on the sensors and cameras of UAVs, reducing their effectiveness and accuracy. Implementing automatic cleaning systems, such as vibration mechanisms or compressed air blowers, can help maintain sensor visibility. Additionally, designing sensors with dust-resistant features can enhance their durability and performance in debris-filled environments.

7.2.4 Limited Visibility

Thermal sensors can be influenced by limited visibility conditions, such as darkness or dense smoke. While thermal imaging can detect heat signatures through some obstructions, extreme conditions may still pose challenges. Enhancing sensor sensitivity and integrating additional imaging technologies, such as infrared lights or multispectral cameras, can improve detection capabilities in low-visibility environments.

7.3 Regulatory Issues

7.3.1 Airspace Regulations

The operation of UAVs is subject to various airspace regulations that can vary significantly between countries and regions. These regulations often include restrictions on flight altitudes, no-fly zones, and requirements for obtaining special permits for UAV operations. Navigating these regulatory landscapes can be complex and time-consuming, potentially delaying critical search and rescue missions.

7.3.2 Certification and Training Concerns

Operating UAVs for search and rescue missions typically requires specialized training and certification for pilots and operators. Regulatory bodies may mandate specific training programs and certification processes to ensure the safe and effective use of UAVs. Establishing standardized training protocols and certification requirements can help streamline the deployment of UAVs in emergency situations.

7.3.3 Privacy and Security Requirements

The use of UAVs equipped with advanced sensors raises privacy and security concerns. Thermal imaging can inadvertently capture sensitive or private information, leading to potential legal and ethical issues. Ensuring that UAV operations comply with privacy laws and implementing robust data protection measures are essential to address these concerns.

8. Conclusion and Future Works

The development of Unmanned Aerial Vehicles (UAVs) equipped with thermal sensors marks a significant advancement in search and rescue (SAR) operations. This innovative technology greatly enhances the ability to locate individuals lost under rubble during earthquakes and other emergencies. Key aspects include the technological foundation of UAVs, the application of thermal imaging technology augmented with artificial intelligence (AI), the integration of sensors and cameras, practical applications in SAR missions, and the benefits and challenges associated with UAVs use.

The evolution of UAVs from military tools to versatile devices for civilian use, particularly in SAR operations, has made them indispensable in disaster response. Thermal imaging technology is crucial for detecting body heat, allowing UAVs to locate survivors where visual identification is challenging. Integrating thermal sensors with UAVs significantly improves the effectiveness of SAR missions.

Research consistently demonstrates UAVs' ability to provide rapid, efficient, and safe assessments of disaster sites. UAVs can cover large areas, access hard-to-reach locations, and being a relatively low-cost option for rescue teams. Despite challenges such as battery life, payload capacity, environmental factors, and regulatory issues, the impact of UAV technology on future SAR operations is profound. The continued integration of advanced technologies like AI will further enhance UAV capabilities, enabling UAVs to autonomously navigate complex environments, analyze data in real-time, and make intelligent decisions during SAR missions. This makes them even more effective in saving lives during emergencies.

The 1985 Mexico City earthquake, and many other natural disasters, serve as a poignant reminder of the potential impact of advanced SAR technologies. Although UAV and thermal sensors' technology were not available at the time, that specific disaster underscored the urgent need for such innovations. If equipped with current UAV technology, rescue teams could have benefited from rapid aerial assessments and real-time thermal imaging to local survivors more efficiently. The figures and research presented in this paper demonstrate that UAVs can provide rapid, efficient and safe assessments of disaster sites, covering large areas and accessing hard-to-reach locations. This makes the current best option for the job.

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10. Copyright Statement

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