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Smart Helmet: combining sensors, AI, Augmented Reality and personal protection to enhance first responders' situational awareness

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Abstract—Augmented reality can enhance first responders' (FR) situational awareness, displaying data about the environment, location, team status, objectives and more. However, augmented reality headsets are not well-suited to operational use, as they are incompatible with personal protective equipment and lack adequate power autonomy. This paper presents the Smart Helmet, a protective helmet featuring an infrared camera, a power source, a processing hub, and a near-eye augmented reality display. The processing hub runs infrared image enhancement, object recognition Artificial Intelligence (AI) algorithms, and the augmented reality interface, which can be connected to, and display information from, other components. The Smart Helmet is modular, therefore individual parts can be selected according to mission needs, including the helmet structure, processing device, additional sensors, and other connected information sources. The whole system is self-reliant, independent from external connectivity. The Smart Helmet has been tested in three field trials by first responders of diverse sectors.

First responders (FRs) are often called to operate in dangerous conditions and environments. In such conditions, situational awareness (SA)[1], that is, their knowledge and perception of a changing environment, is a core concept that serves both to keep FRs safe and to increase their efficiency. Recent advances in eXtended Reality (XR, an umbrella term that includes augmented, virtual, and mixed reality) can drastically improve FR SA, presenting information about location, teammates' status, information from the command centre, or virtual annotations on danger zones, and other important items[2,3].

However, modern XR headsets are not appropriate for operational use, for two main reasons: a) they are not compatible with FRs' personal protective equipment (PPE), in particular head protection; and b) their operational parameters, such as battery life and safe temperature range, impose severe limits on relevant use-case scenarios. Therefore, to this day, XR aid in response missions has been mostly limited to proof-of-concept demonstrations.

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In this paper, we present a "Smart Helmet" system that combines an Augmented Reality (AR) interface with a helmet that meets the operational requirements of FRs. Its purpose is to increase their safety and efficiency, reducing the danger and loss of life for both FRs and affected civilians.

OBJECTIVES

The Smart Helmet system is being developed in the context of the European Project RESCUER[4], which aims to identify and address the challenges of FRs facing operations in adverse conditions or hostile environments through cutting-edge technologies. The final outcome of the project will be a prototype of a complete toolkit that accomplishes four main objectives: sense augmentation, precise self-positioning, cognitive support and feedback, and robust ad-hoc intra-team communications. The proposed toolkit benefits from AI technologies on the edge, focusing on lightweight, non-obtrusive, natural interaction with sensors and AR interfaces. From these tools, this paper will cover in detail the infrared image acquisition and subsequent object detection and visualization, which form an integral part of the Smart Helmet. Other tools and functionalities which are supported and compatible with the helmet and its AR interfaces are only mentioned in passing, as their detailed description lies outside the scope of this work.

The Smart Helmet system tends to achieve several of the proposed goals by giving specific target use cases that are defined together with FRs' contributions. Regarding this context, the helmet system aims to accomplish the following objectives:

- *Modular intra-communicative architecture*— System able to support an extensive quantity of tools with high rates of communication to share information between themselves and other FRs' systems.
- *Visual sense augmentation*— Enhancement of visual abilities under adverse conditions defined as low light, smoke, and complete darkness, involving AI-based algorithms.
- *Compatibility with FRs' operations*—Considering limitations of FRs actions and PEE within the development of the whole system in terms of size, feasibility to be carried or wore, and functionality in adverse conditions.
- *Smart information visualization*—Presenting relevant information on multi-sense AR interfaces taking into account the FR's preferences and cognitive effort.

GENERAL ARCHITECTURE

The Smart Helmet system is based on a highly modular architecture that enables the interconnection between various operational modules with the objective of retrieving, processing, and displaying relevant information to the FRs. In Figure 1, an overview of the main architecture is represented. There are 3 main components that shape its architecture: the infrared (IR) camera, the processing unit, and the AR interface.

The first one is the IR camera that acquires and processes thermal information about the environment. The camera is connected by cable to the second component, the processing unit, which received the processed video stream.

The processing unit hosts software that processes data from the IR camera, as well as other connected sensors, and outputs high-level information that is useful to the user. In addition, it contains the orchestrator of all of them: the Message Queuing Telemetry Transport (MQTT) broker. MQTT is a lightweight messaging protocol commonly used in Internet of Things (IoT) applications[5]. The protocol uses a publish-subscribe model, where publishers send messages to a topic on a broker, and subscribers receive messages from selected topics. The broker is in charge of managing a message repository from all available tools working on the FR's processing unit or any other FR's processing unit coming from the Data Sharing Orchestrator (DSO). Wireless connections are enabled through a gateway unit, which generates a personal WiFi network to which the processing unit and other tools are connected.

The AR Interface displays useful information to the FR that has been previously processed and has been shared with the DSO so the visualization module is able to retrieve it and preprocessed it to be properly shown.

HELMET MOUNT

Every component of the system design is based on compatibility with an operational helmet. A wide variety of commercial helmets are compatible with the system, as the mount can be easily adapted according to the needs of the FR organizations. There are two helmets that were considered for this implementation: the MSA F2 X-TREM Forest Fire[6] by Marine Safety Europe and the Safety Helmet Vertex[7] by Petzl. The first is the most used by rescue teams. The second was a suggestion of the Hellenic Rescue Team[8]. The evaluation of both helmets with the Smart Helmet component attached in the field was positive; therefore, the strap was designed to fit both of them. The final product looks as seen in Figure 2. The components shown there have been

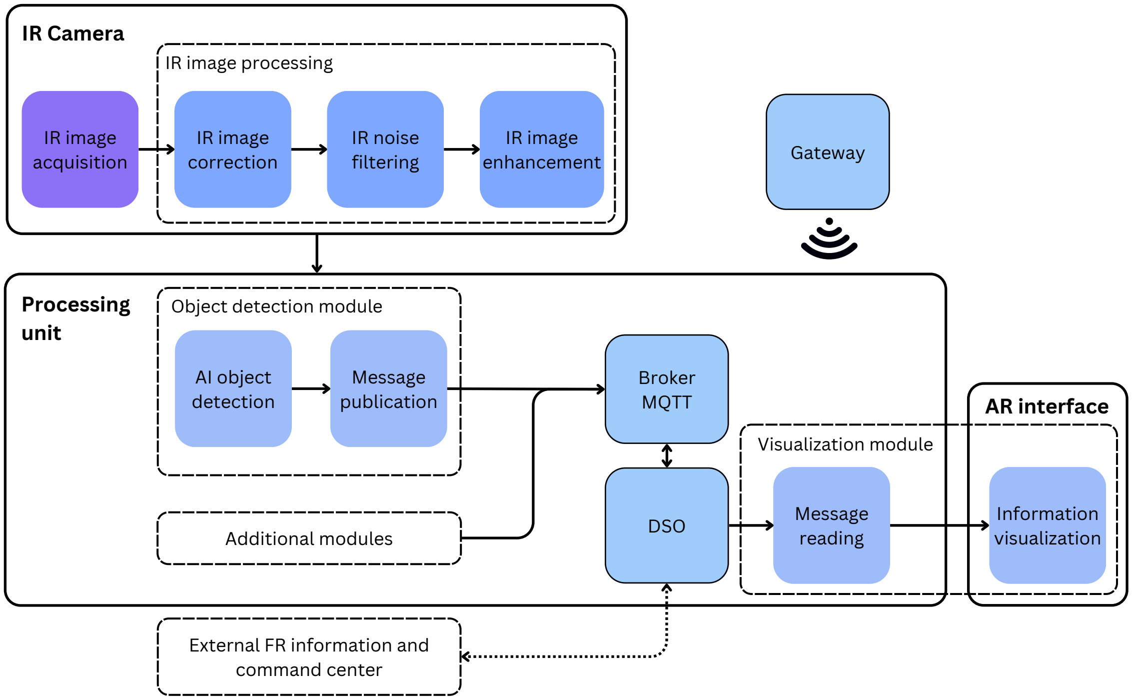

FIGURE 1. General architecture of the Smart Helmet. It is mainly divided into three devices interconnected between them, which are the IR camera, the processing unit, and the AR interface. Each of these components present inside the main operational modules that participate in the Smart helmet functions.

tested to be operative in the temperature range of -40ºC to 50ºC and they are described in detail in the following subsections.

Head Up Display (HUD)

The Head-Up Display (HUD) is a device which aims to display AR visuals on one eye of the FR. It consists of a micro-controller, a Field Programmable Gate Array (FPGA), a micro OLED display, a digital accelerometer, a digital compass, and a free-form prism with 39° diagonal Field of View (FOV). The micro-controller controls the brightness and the orientation of the micro OLED display. Also, the micro-controller calculates the orientation of the system by getting data from the digital accelerometer and the digital compass. The micro-display is perpendicular to the FOV plane of the FR. Using the prism, the FOV of the micro-display is fused by the FOV of the FR, so the FR is able to see through the HUD without losing the view of the real world. The FPGA gets the video signal from an external device and displays it on the micro-display. The HUD is mounted on a 5 degree-of-freedom mount that can be adjusted according to the user's ergonomics. This mount is also mounted on the front side of the strap attached to the helmet.

Helmet Mounted Camera (HMC)

The Helmet Mounted Camera (HMC) is an on-field thermal camera that enables sight in darkness or smoke scenarios. It consists of an FPGA with a microcontroller and an uncooled long-wavelength infrared (LWIR) microbolometer with 8-14um wavelength and with 640x480 resolution. The first two are responsible for reading the LWIR microbolometer and producing the final thermal image, using digital image processing algorithms.

Smart Battery Pack (SBP)

The Smart Battery Pack (SBP) provides both battery and processing power to the helmet components. It is lightweight, energy-efficient, and integrated into the FR protective gear, providing an efficient processing platform with the ability to create rendered camera images and auxiliary sensory information, resulting in an AR processing unit. It also provides connectivity with other FR, receives video and fuses this video with the sensed data into a video output stream. The SBP supports wireless (WiFi and Bluetooth) and wired

FIGURE 2. Complete Smart Helmet system side and front view and naming of every component attached to the helmet.

(USB2.0) connectivity in the physical layer and MQTT in the application layer. The Operating System (OS) which the SBP is running is Linux based.

At this stage of development, a trade-off between processing capacity and the weight added to the FR is needed. In these cases, a laptop has been used to provide spare processing power to the system. Two models have been used: Alienware x15 R2 Gaming Laptop and Razer Blade 14" 3080-TI, adding 2.27 kg and 1.78 kg, respectively, to the FR backpack. The specifications regarding temperature range for the CPUs is estimated to cover from -20ºC up to 95ºC. Although this option does not provide the desired robustness and comfort to the FR, it is convenient for demanding processing during the first demos.

IR CAMERA PROCESSING MODULE

The thermal image generated by the HMC microbolometers suffers from imperfect calibration, noise, and blur, all of which can degrade its usefulness to the FR and degrade the quality of object detection performed by the AI algorithm. To optimize quality, the image has to go through 3 steps before showing the image on the HUD: IR image correction, IR noise filtering and IR image enhancement. An example of the processing applied to the raw image capture can be seen in Figure 3.

IR image correction

The first step is to make sure that the camera is working properly, making a calibration to guarantee that every pixel of the sensor responds correctly to the input it receives. There are several things done during this calibration: ensure that every pixel produce the same response when exposed to the same amount of radiation and verify that the value of the pixel changes according to the sensor temperature or the scene temperature.

IR noise filtering

The second step is the equivalent of removing the static from a television image by processing the received image. Both temporal and spatial filters are applied. For temporal noise removal, each incoming frame is stored in memory and then is read during the arrival of the next one. These two frames get averaged, thus reducing noise, since noise's average value in time is zero. The spatial filter, used for dead pixel correcting, is only applied per user request, and is implemented through a specific multiplication kernel that scans the picture for abrupt, thus noisy, changes and mitigates them. The product of the above two filters is a smoother image.

IR image enhancement

The objective of the final step is to make sure that the results are clearer for the end user to interpret by enhancing important details. In order to achieve this,

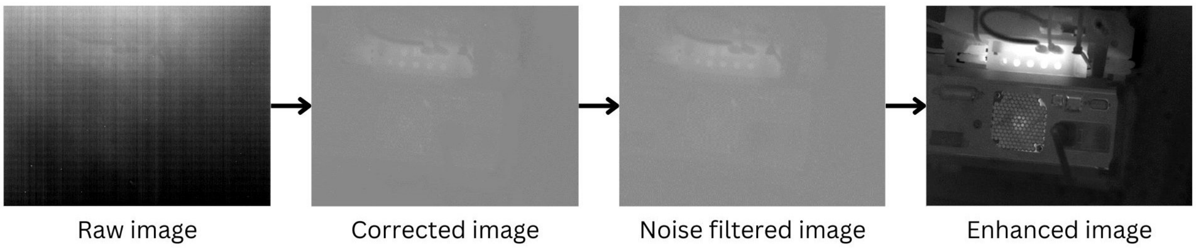

FIGURE 3. Example of the IR camera processing steps from the raw image captured by the sensor to the final enhanced image delivered by the camera.

we identify and remark edges in the image that can be used to highlight the details, also perform a histogram equalization, and dynamically adjust the range of the temperatures shown for scenes with wide temperature difference.

OBJECT DETECTION MODULE

Object detection applications are designed to focus on objects of interest to be detected. For the FR use-case and based on the camera used, the effort has been focused on both person detection in thermal imaging and hot areas detection with respect to the background of the image. The second can provide additional information about objects or areas with high temperatures that may pose some risk or interest in the detection.

For the first analysis, i.e. person detection, processing speed is one of the main goals; therefore, it was decided to employ optimized AI solutions for object detection. In this case, YOLOv8 object detector has been selected as baseline[9], which is the state-of-the-art solution in terms of processing speed and detection accuracy[10]. The network had to be retrained on a dataset of persons annotated in thermal images. For this purpose, a specific dataset was used, Teledyne FLIR Thermal dataset[11], which provides examples with 15 annotated types of objects, being "person" the one we used.

Network training was carried out using the default training parameters and taking as initialization the pre-trained weights in the COCO dataset[12]. This technique known as transfer learning will help to learn faster the representation of persons in thermal images. The network was trained with 200 epochs, obtaining the best results at epoch 168 with a precision of 0.86, recall of 0.78 and mAP50 of 0.87 for the test subset of the dataset used.

The second detection block is focused on hot zones detection and, in order to speed up the operations, a computer vision analysis was employed. First, the input image is binarized, setting a threshold that will assume values higher than 0.7 as areas of interest because they have higher temperatures. Next, dilation operations are applied to better define the areas and fill in the gaps. These areas are segmented by extracting their shape and the bounding box that contains them. To filter regions, those that are smaller than 10% of the total pixels in the image and where the average intensity value of the pixels outside the regions of interest with respect to the average intensity value of the region of interest is less than 50%, are removed.

For both approaches, the input to the algorithm is the video frames retrieved by the IR camera that the processing unit receives. The output is homogenised as a message that is sent to the broker containing per each detection the following items:

- *Coordinates of the bounding box*— formatted as coordinates of the centre point of the box in pixels, together with its width and height.
- *Label of the detection*— the object or entity detected, which are "person" and "warm".
- *Confidence*— a value ranging between 0 to 1 representing the probability of the detection according to the algorithm.

SMART VISUALIZATION MODULE

The Smart Visualization Module (SMV) has been built to unify all the new information from the different devices in an intuitive and not overloaded visual interface. To do so, the interface has been segmented so that the amount of information can be modified by the command centre depending on the scenario, prioritizing which information is shown.

There are different types of information displayed on the device. The first one is information about the status of FR/devices, including their ID and position, bio-signals information from the FR, and feedback from devices that are constant sources of data. For exam-

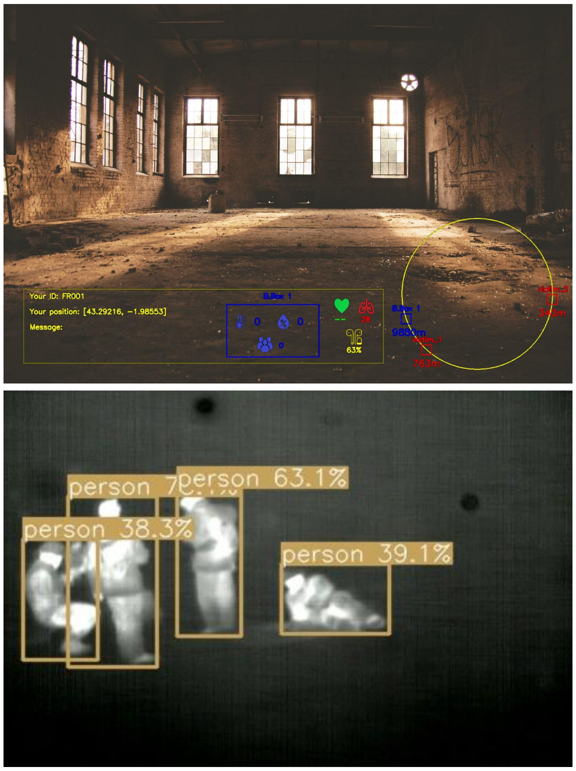

FIGURE 4. Examples of the smart visualization displayed on HUD. The upper part represents the visualization of the combined information on top of reality. The lower part shows the visualization of the thermal video stream with an object detection algorithm running on top, where 4 people are detected.

ple, devices that provide information about the environment around them, such as temperature, humidity, etc. In Figure 4, all of this information is shown inside the yellow rectangle, the environmental information can be seen inside the blue square, and next to the heart and lungs icons for the bio-signals.

In addition, information about location of either people, objects of interest, or hazards is also included. Information about other locations of interest is provided by the command centre, such as other FR, victims located, or extraction points. The way the information is displayed resembles the way modern First Person Shooter (FPS) video games provide information to the player about the location of the current objective: a radar, shown in Figure 4 as the yellow circle. According to this representation, the position of the FR is the centre of the circle. Based on that, they can intuitively know the direction where the entities displayed on the radar are. On top of that, the identifiers of the objective and the distance to this object are constantly drawn next to the square representing the object.

Finally, the thermal video stream with the detected persons and hot areas bounding boxes, together with their labels and confidences, is presented in the HUD. An example can be seen in Figure 4.

TESTING IN REALISTIC SCENARIOS

For technical developers and researchers who implement the Smart Helmet, as well as for end users who benefit from the toolkit, it is key to perform testing actions in realistic scenarios in which FRs provide feedback on the tools. This is why three events were held for this purpose in Weeze (Germany), Navacerrada (Spain), and Modane (France), in November 2022, January, and March 2023, respectively. See some tests in Figure 5.

In all field trials conducted, the scenarios were defined to try to exploit the Smart Helmet capabilities at the hands of the FRs. The setup evaluated consisted of the Smart Helmet system with the thermal camera and the video stream visualization on the HUD. The main use case defined for the tests was finding victims in low-visibility conditions: a room with low light, smoke, and complete darkness. Between one event and the next, there was room for improvement regarding the drawbacks of the tools, which were mainly connectivity and robustness. Additionally, in Modane, all Smart Helmet subsystems were available for testing, including SVM and object detection algorithms.

FIGURE 5. Tests in realistic scenarios. On the left image, a FR is evaluating the system in Navacerrada pilot outdoors surrounded by snow. On the right side, the system is tested inside a fire simulator in Modane.

Afterwards, the FRs fill out a questionnaire to report their feedback. These are made up of 30 questions including multiple choice and free text answers divided into functional evaluation of the tool, evaluation of the test scenario and real applications, technical compatibility, and other general user information. These forms are analyzed and anonymized to obtain the most relevant information.

Until now, the feedback from the first two pilots, that is, Weeze and Navacerrada, is available for a total of 12 and 9 FRs, respectively. Some of the main questions regarding usability and performance of the tool are shown in Table 1.

In the two months between the two pilots, user feedback was taken into account and several improvements and fixes were performed, resulting in improved performance and usability. This is reflected in the overall increase of FRs' satisfaction: the general performance of the tool 66.6% FRs stated that it was good or very good in Weeze, and it increased up to 88.9% for Navacerrada, without any negative feedback in both cases; and all related questions in the FR questionnaire also improved their average rating.

User feedback has been of significant help in designing a mission-relevant system and associated tools. This is also reflected in the rapid increase in user acceptance during each subsequent field. For example, regarding the reliability of the system, only 25% of them agreed or strongly agreed that the tool would make their work safer in Weeze, which increased to 66.6% in Navacerrada. Most of the FRs stated that the helmet is useful to enhance their orientation capabilities in low-visibility environments, decrease the search time of victims, and consequently the exposure to risks. The main drawback pointed out was the compatibility with their PEE, which is sufficient for scenarios such as earthquake disasters but difficult to integrate with a complete firefighter suit.

TABLE 1. Answer statistics of 5 of the most representative questions for the evaluation of the tool, including results for both pilots, Weeze and Navacerrada. SD: strongly disagree, D: disagree, N: neutral, A: agree and SA: strongly agree, VB: very bad, B: bad, G: good and VG: very good.

	General performance				
	VB	B	N	G	VG
Weeze	0%	0%	33.3%	58.3%	8.3%
Navacerrada	0%	0%	11.1%	55.6%	33.3%

	The tool would make my job safer				
	SD	D	N	A	SA
Weeze	8.3%	8.3%	58.3%	16.7%	8.3%
Navacerrada	11.1%	0%	22.2%	33.3%	33.3%

	The tool would make my job efficient				
	SD	D	N	A	SA
Weeze	8.3%	8.3%	16.7%	41.7%	25%
Navacerrada	11.1%	0%	11.1%	44.4%	33.3%

	The tool provided/visualized relevant information for me				
	SD	D	N	A	SA
Weeze	8.3%	8.3%	50%	33.4%	0%
Navacerrada	11.1%	0%	11.1%	44.5%	33.3%

	Robustness	
	Not enough	Adequate
Weeze	33.3%	66.7%
Navacerrada	25%	75%

CONCLUSION

The Smart Helmet system has the potential to revolutionize rescue scenarios and improve the safety and effectiveness of FRs. The system managed to be compatible with FRs' manoeuvres and operational helmet, has a modular design of inner highly communicative tools, and is robust against low light, smoke, and complete darkness, enhancing the responders' visual capabilities with AI-based algorithms. The visualization of information as an eye-mounted display of augmented reality enables a complete hand-free toolkit that can be exploited for the responder's benefit.

Regarding hardware, future improvements can include increased battery life and processing power. A major concern is overheating, which can lead to reduced performance or outright failure of the system. Heat dissipation can be hampered by FRs' clothing and protective equipment, as well as operation in hot environments, including near fires. Future work will explore methods to address this, which may be achieved both by more efficient cooling and more economical processing.

On the part of the AR interfaces, an adaptive approach will be adopted in the future, which will aim to reduce information overload that might distract the user. This will be pursued using the guidance and feedback of the FRs. Object detection can also be enhanced to include additional classes that might be relevant in disaster situations, again as advised by FRs.

Rigorous testing is also needed to ensure that the system complies with the highest safety standards and can withstand harsh environmental conditions. Despite these challenges, FRs appreciate the advances made in this technology and the potential benefits it can bring to their work, including saving more lives and reducing the risk of injury. Additional feedback from FRs will help to improve the functionality of the system, making it more efficient and effective in their missions.

In general, the Smart Helmet system represents a significant advancement in extended reality technology and has the potential to transform the way FRs operate in hazardous environments.

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