

A Novel Approach to Enhance VR User Awareness of Nearby Non-Virtual Hazards through Adaptive Visual Alerts

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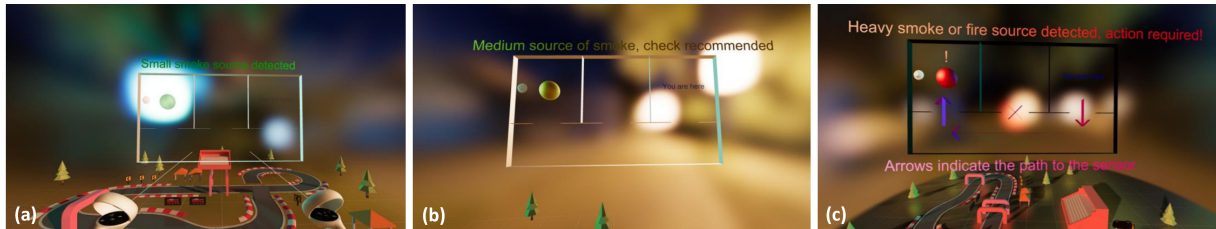


Figure 1: Screenshots from VR game with an alert prompt displayed left-to-right: (a) mild, (b) moderate and (c) critical alert.

ABSTRACT

Virtual Reality (VR), facilitated with state-of-the-art head-mounted displays (HMD), has the unique ability to provide users with immersive and interactive experiences that are otherwise unattainable in the physical world. Such devices enhance users' immersion by restricting the user's peripheral vision, thereby significantly reducing or eliminating their ability to perceive the real-world surroundings. This combination of sensory immersion and interaction fosters a deep sense of presence, making VR a powerful tool for various applications. At the same time, it can cause the users to be unresponsive or even unaware of situations taking place in their physical vicinity. Consequently, we put forth the idea of enhancing user awareness of nearby hazards without disrupting immersion. We present our initial approach to how to notify VR users about danger through adaptive visual alerts based on the intensity of the detected smoke. Moreover, we implemented our proof-of-concept app using the React JavaScript library and verified its usability with the help of well-known Nielsen's heuristics.

Index Terms: Virtual reality, smoke detection, user safety, immersive analytics, adaptive interface.

1 INTRODUCTION

Virtual Reality (VR) has the unique ability to provide users with immersive and interactive experiences that are otherwise unattainable in the physical world [20, 21] and can completely engage their users in the virtual domain [3, 8]. A vital component of this technology is the VR headset, a head-worn device designed to create an immersive environment for its users [16]. These headsets may incorporate advanced tracking technologies, including pose, gesture, head, and eye tracking, to enhance the user's sense of immersion through the perception of embodiment [2, 17]. Furthermore, commercially available VR headsets usually restrict the user's peripheral vision, thereby significantly hindering their ability to perceive real-world surroundings [1, 11]. This combination of sensory immersion and interaction fosters a deep sense of presence, making VR a powerful tool for various applications [11, 17].

However, this desired immersion in the virtual environment may also be associated with various non-virtual security issues [12]. To address these, researchers have been exploring various solutions to increase real-world awareness among VR users [5, 15]. Technology-mediated awareness systems, such as audio and haptic feedback, have been proposed to alert users to real-world boundaries and the presence of others [5]. These systems aim to provide subtle reminders of the real-world environment without impeding the immersive experience [5, 11].

The most commonly raised issues are related to bystander-VR user interactions and indicators for real-world boundaries [5, 11, 12, 15]. Regarding interactions, authors analyze various technology-mediated awareness systems introduced to increase a user's awareness of bystanders [15]. Concerning real-world boundaries, conducted experiments pertain to the use of audio and haptic signals as indicators for real-world boundaries [4].

Building on these examples, our paper explores a new approach to enhancing VR users' real-world situational awareness through adaptive visual alerts positioned within their field of view (FoV). To that end, we utilized *Functional System Analysis Technique* (FAST) and *Failure Mode and Effect Analysis* (FMEA) to analyze and reason about needed functionality [23] and potential failure modes [6] of our approach, respectively. Finally, we verified its usability with the help of well-known Nielsen's heuristics [13, 14].

2 ADAPTIVE VISUAL ALERTS FOR VR

2.1 Case Study: Smoke Detection Scenario

The main goal of safety systems is to ensure vigilance and provide prompt notifications of potential hazards situated in a given indoor environment (e.g. gas, fire or smoke detection systems). In addition, the design, specifications and maintenance of such solutions are set by relevant health and safety bodies¹ and can offer various levels of security as needed in a given use case scenario.

In our case study, we decided to focus on the example of smoke and carbon monoxide detection systems, as their failure may lead to health-threatening carbon monoxide poisoning. Furthermore, undetected or ignored leaks pose a serious threat due to carbon

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¹Health and Safety Executive: <https://www.hse.gov.uk/> [Last accessed: 20/07/2024]

monoxide being odorless², especially dangerous for a person immersed in highly engaging tasks such as VR gameplay. At the same time, alerts should correlate with detected threat levels (i.e. low, moderate, and critical), eliminating the need for users to break immersion by removing the headset to check their physical environment due to false positive detection.

Furthermore, typically, some crucial components of such systems (e.g. smoke and carbon monoxide detectors) are installed in other parts of an apartment or building (e.g. kitchen, common spaces) but non-necessarily near the VR gaming setup.

2.2 Functional System Analysis Technique (FAST)

We employed FAST to reason about the needed functionality behind our solution [23]. Such analysis was previously used in other VR research [18, 20].

The method results in the generation of the FAST diagram presented in Fig. 2. A systematic breakdown of each function given in the rightmost column of the diagram ensures the complete identification of all necessary requirements. Moreover, in this approach, we are only concerned with adaptive visual alerts. Therefore, we will refrain from analyzing appropriate reactions after the user receives the alert.

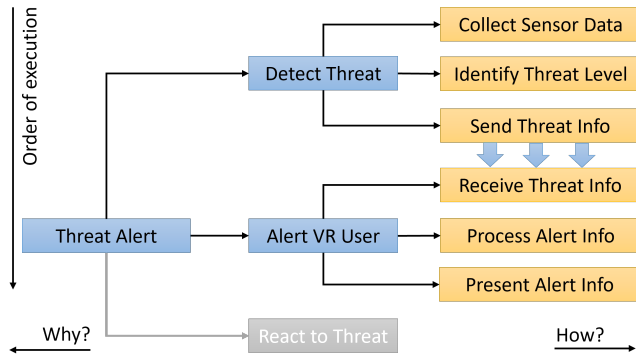


Figure 2: The FAST diagram.

The FAST diagram shows that our solution can be considered as consisting of two main components (see Fig. 2): (i) physical-module responsible for smoke and carbon dioxide detection, (ii) cyber-module module responsible for alerting the user. These are further broken down into six necessary functionalities that can all be considered critical for VR user safety. These are as follows.

[*Collect Sensor Data*]: The system needs to swiftly detect smoke and carbon dioxide levels correctly.

[*Identify Threat Level*]: The detector must effectively process sensor data to derive meaningful insights; otherwise, the data remains unusable.

[*Send Threat Info*]: Failure to broadcast information about the detected threat to the VR system would prevent its user from receiving alerts about ongoing undesired events.

[*Receive Threat Info*]: Failure of the VR system to receive information about the detected threat would prevent its user from receiving alerts about ongoing undesired events.

[*Process Threat Info*]: Failure to process information about the detected threat could cause an unintended system reaction (e.g. false-positive alarm, incorrect threat level) and mislead the VR user.

[*Present Alert Info*]: Proper alert mechanisms are necessary for notifying the VR user about the detected threat and its respective severity level.

²Carbon Monoxide Poisoning Needless Deaths Unnecessary Injury: <https://www.gov.wales/> [Last accessed: 20/07/2024]

2.3 Conceptual Design

Table 1: The morphological tabulated chart of concurrent implementation approaches with selected function carriers in orange.

Function	Solutions		
	#1	#2	#3
<i>Collect Sensor Data</i>	heat	<i>CO</i>	camera feed
<i>Identify Threat Level</i>	temperature	biomimetic gel	CV
<i>Send Threat Info</i>	wired	wireless	audio
<i>Receive Threat Info</i>	wired	wireless	microphone
<i>Process Threat Info</i>	server	onboard	cloud
<i>Present Alert Info</i>	audio	visual	tactile

For each of the functions identified with FAST analysis (see Fig. 2), we provided up to their three alternative realizations (carriers) [19, 22]. These potential solutions are presented in Tab. 1 with the selected ones gathered and color-coded (in orange) in a single column for clarity.

We can construct our solution in many ways by selecting a subset of realizations (i.e., function carriers) for all identified functionalities (i.e., functions). Moreover, we have to remember that smoke detectors are typically closed systems that can offer redundancies. For instance, the smoke alarm can have the form of a loud audio signal and simultaneous broadcast threat detection to appropriate services (e.g. fire department, building security, etc.)

The selected solution consists of an off-the-shelf, cost-effective *CO* detector utilizing biomimetic gel that changes color in contact with carbon monoxide that wirelessly communicates monoxide detection. The broadcasted threat information is then picked up by a VR system. The headset processes this data and displays it visually, potentially superimposing in the VR user's FoV a floor map with the denoted point of hazard detection (see Fig. 1). The display indicates the level of smoke detected by the sensor, allowing the user to assess whether the alarm is triggered by genuine smoke or a false alarm (see Fig. 1).

2.4 Failure Mode and Effect Analysis (FMEA)

Various operational challenges may arise during the VR system usage. To ensure its reliability and safety, we must implement preemptive measures to mitigate potential damages to the environment or the device. Thus, we decided to employ a simplified FMEA methodology to reason about potential risks associated with our approach. Furthermore, such analysis was successfully used in VR system design [7]. The FMEA is driven by a number of questions concerning the stage of system usage at which potential failure occurred, how such failure can manifest or what potential consequences such failure will cause [6].

The results of our FMEA activity are presented in Tab. 2. These considerations are crucial for preemptively addressing and managing potential issues that may impact performance and safety in real-time scenarios. For clarity, we only focused on the stage when the VR system was being used when smoke detection occurred.

2.5 Prototype Design

To properly simulate the VR user immersion, the scene that simulates the engaging activity has been implemented in the form of a simple racing game in isometric view, created based on the GitHub tutorial³ and under his direct approval received in electronic mail communication. The prototype was implemented using the React JavaScript library. We also employed the *Immersive Web Emulator* to ensure swift prototyping.

³Domenico Brz, R3F-in-practice: <https://github.com/Domenicobrz/R3F-in-practice/tree/main/car-physics> [Last accessed: 21/07/2024]

Table 2: The results of *Failure Mode and Effect Analysis* (FMEA). The analysis is split between two main components of the system, i.e., (i) physical smoke detector and (ii) in-app adaptive visual alerts. For clarity, we only focused on the situation where the user is engaged in VR.

Module		Task step	Failure modes	Failure cases	Probability	Failure effects	Actions
Smoke Detector	1	gameplay	circuit shortage	environmental conditions (e.g. high-humidity)	medium	user unaware of hazard or mislead	repair or replacement
	2	gameplay	switched off	power shortage or drained battery	medium	user unaware of hazard	replacement or recharging
	3	gameplay	malfunction	detector wear and tear	low	user unaware of hazard or mislead	repair or replacement
Visual Alerts	1	gameplay	malfunction	headset wear and tear	low	user unaware of hazard	repair or replacement
	2	gameplay	switched off	power shortage or drained battery	medium	user unaware of hazard	removal or recharging
	3	gameplay	false alarm	misleading readout	low	user unaware of hazard or mislead	detection redundancy
	4	gameplay	alert non-visible	cues non-visible	high	user unaware of hazard	redundant and redesign cues
	5	gameplay	alert ignored	no user (re)action	high	hazard non-mitigated	discontinue gameplay

As the player engages in the VR gameplay, prompts appear if the sensor detects smoke. The intensity and visibility of these prompts vary based on the smoke level detected. To simulate the readings received from the sensor, each state has its display time slot, with the final alert remaining until the threat is removed. A traffic light color scheme (red, yellow, green) is used to familiarize the player with the alert levels. The system tracks the player’s location and adjusts the alert position to ensure their visibility, regardless of the player’s orientation.

1. Mild–State Green: Suggesting temporary rise in *CO* concentration. The user is notified without significant visual intrusion (see Fig. 1(a)). For the first state, the sensor detects a short-living trace of carbon monoxide but does not prompt the VR user to act due to possible false-positive detection. The alert automatically disappears if sensor readings drop.

2. Moderate–State Yellow: A more intrusive alert allowing the user to continue their activities while being aware of the situation (see Fig. 1(b)). The detection of carbon monoxide can be caused by overcooked food or indoor smoking. The VR user is encouraged to check the issue but can ignore it and continue the gameplay. The alert disappears if readings drop.

3. Critical–State Red: A constant, highly visible alert with an enlarged apartment floor plan, requiring immediate attention and preventing further gameplay until the situation is addressed (see Fig. 1(c)). The last state signals a fire or heavy smoke, requiring action. This alert persists until the smoke readings drop to safe levels. Visual cues (e.g. arrows) implicate the physical location where the *CO* was detected.

3 USABILITY VERIFICATION

The presented work is currently in its early development stage and is intended to demonstrate potential applications of our approach. Therefore, we decided to explore its usability with the help of well-established Nielsen’s heuristics [13, 14], which was already successfully deployed to verify various VR systems [18, 20].

- 1. Visibility of system status:** The system provides immediate feedback based on sensor readings (see Fig. 1). The alert location adjusts to remain in the user’s FoV.
- 2. Match between system and real-world:** Information is conveyed through a color-coded 3D floor plan model and textual cues to ensure clear situation understanding (see Fig. 1).
- 3. User control and freedom:** The user does not need to interact with the system itself; control remains with the user for the gaming environment after sensor data is displayed.

- 4. Consistency and standards:** The alerts use a traffic light color scheme (red, yellow, green) to reduce the need for users to learn multiple alert meanings (see Fig. 1).
- 5. Error prevention:** A manual is provided for carbon monoxide detector installation and maintenance, reducing the risk of errors during data reading.
- 6. Recognition rather than recall:** Limited interaction with the system negates the need for users to remember previous display states.
- 7. Flexibility and efficiency of use:** The system can be extended to support additional sensors while maintaining simplicity and data accuracy.
- 8. Aesthetic and minimalist design:** Only essential information is displayed, avoiding information overload such as canvas of the floor plan or arrows showing the path to the sensor.
- 9. Help users recognize, diagnose, and recover from errors:** The detector instructions discuss sensor placement issues or other faults. While headset calibration resolves VR display positioning errors.
- 10. Help and documentation:** The smoke and carbon monoxide detectors are provided with detailed usage instructions.

4 DISCUSSION AND CONCLUSION

Tackling the issues of providing real-world situational awareness for VR headset users addresses a critical need for enhancing user safety in immersive environments [5, 11, 12, 15]. By integrating real-time hazard detection with adaptive visual alerts, our approach ensures that users are immediately informed of potential threats without significantly disrupting their immersive experience. This dual focus on safety and immersion represents a novel approach to VR usability design. Moreover, the use of a traffic light color scheme (see Fig. 1) makes it easy for VR users to understand the severity of the threat. The alerts are supplemented with threat localization cues to aid the risk mitigation further. These visual cues could be further enhanced by showing positions and detected or predicted spread of *CO* for hazardous avoidance or evacuation planning. Another avenue for exploration should concern alternative visual designs, including different marker types (e.g. balls vs crosses) or floor plan presentations (e.g. 2D vs 3D floor plans).

In our initial work, we identified several challenges and limitations. One of them is ensuring the accuracy and reliability of the sensor data as well as its presentation form and persistence. Another caveat is the potential for users to become desensitized to

alerts if they occur too frequently or are perceived as false alarms [10]. Balancing the frequency and intensity of alerts is crucial to maintaining user trust and ensuring timely responses to genuine hazards. What is more, the user's engagement level can impact the reception of the notification [9]. Receptivity can also vary between individuals, depending on their preferences and previous experiences (e.g., types of alerts used on other platforms).

With the growing usage of various VR platforms and their increasing immersiveness and engagement levels, accurate alerting of potential hazards and threats is needed. Our preliminary work aims to inspire other researchers to consider problems of nearby situational awareness.

5 EVALUATION AND FUTURE WORK

In our future work, we first plan to focus on integrating our solution with a range of external sensors (e.g., smoke and carbon monoxide or air pollutants sensors) to detect a broader range of hazards and obtain a functional cyber-physical prototype. At the same time, we will refine our immersive interface to evaluate our approach under various immersiveness and engagement levels.

Next, we will inform iterative improvements to the system's design and functionality through a series of controlled user studies. This process will involve comprehensive usability testing with a diverse group of users who are balanced in terms of gender and prior experience with VR. The participants will interact with the system under strict health and safety protocols in a controlled lab setting, where various smoke scenarios will be simulated to evaluate system responsiveness and user reaction times. Furthermore, users' behavior, such as time and actions taken, will be analyzed to identify patterns and areas for improvement.

After optimizing the system based on gathered feedback, it will be deployed in real-world environments where users typically engage with VR, such as homes and offices. This will allow us to assess its effectiveness in natural settings.

The solution's adaptability could also be enhanced by incorporating machine learning algorithms to predict and respond to user behaviors more effectively. We could also detect signs of users' fatigue to display alerts in conjunction with their perceived state. This can involve analysis of behavioral signals, such as prolonged inactivity periods, erratic movements, or frequent headset adjustment, to determine user state. When signs of fatigue are detected, the system will display a prompt encouraging the user to take a break, ensuring a healthier and safer VR experience.

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