Autonomous Virtual Reality Integration for Active Thermography: Engineering Education and Experimentation

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Abstract. The present study sets out the development and evaluation of an autonomous virtual reality (VR) environment designed to enhance the teaching and experimentation of active thermography in engineering education. This paper builds upon a previous version (VR_1), the limitations of which were revealed to be related to interface clarity and result interpretation. The present version (VR_2) has been developed to optimise immersion and pedagogical effectiveness. The novel application was developed for use with standalone headsets, such as Meta Quest 2 and 3. This development resulted in a substantial enhancement of accessibility and ergonomics. The updated system has been developed to consolidate all interactive elements into a single virtual scene. This development is expected to simplify operation and enable students to focus more intuitively on learning tasks and thermographic data analysis. The educational benefits of the application were evaluated using a practical case study involving defect detection in composite materials. It was indicated by the student feedback that VR_2 was superior in terms of navigation, data comparison, and overall usability. The immersive environment was found to be an effective tool in supporting students' comprehension of thermography principles and enhancing their analytical capabilities. These findings serve to confirm the relevance of VR in promoting engagement and comprehension in the field of engineering education. Subsequent enhancements are to be centred on the mitigation of extant technical constraints and the incorporation of features such as interactive tutorials and hand tracking, with a view to further enhancing the learning experience.

Keywords: Virtual reality (VR) · serious games · simulations · active thermography

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1 Introduction

Virtual Reality (VR) is a technological medium that enables interaction with three-dimensional environments through the use VR headsets and motion tracking systems. This offers new perspectives for the optimization of scientific and industrial processes. In the field of education, VR has been shown to facilitate the learning of abstract concepts and stimulate creativity [1]. In the field of architecture, VR has been shown to enhance collaboration and decision-making processes by integrating BIM modeling (Building Information Modeling) with VR [2]. In the aerospace industry, VR systems are used to optimize maintenance inspections [3] and improve cockpit design and reduce production costs [4]. The accessibility of VR has been significantly improved by standalone headsets such as the Meta Quest 3, which eliminates the need for wired connections or an external computer. Compared to its predecessor, the Meta Quest 2, the Quest 3 features notable advancements, including a Snapdragon XR2 Gen 2 processor, 8 GB of RAM, and a resolution of 2064 × 2208 pixels per eye, surpassing the Quest 2's XR2 Gen 1 processor, 6 GB of RAM, and 1832 × 1920 resolution. These enhancements enable more efficient processing of complex environments and advanced mixed reality applications.

The utilisation of standalone VR facilitates the exploration of abstract concepts in interactive immersive environments. The Virtual Hydrogen application, developed by Hiroya Suno and Nobuaki Ohno [5], employs three-dimensional rendering to facilitate the comprehension of atomic orbitals, thereby enhancing the understanding of quantum wave functions. The study by Ting Ren et al. [6] emphasises the merits of CFD simulation in VR for visualizing particle dispersion and ventilation flows in an underground tunnel. Furthermore, the HoloFEM system, developed for Microsoft HoloLens [7], demonstrates the application of Augmented Reality (AR) to interactive simulations of physical phenomena by leveraging an automatic meshing system based on a real environment.

This technology has also been integrated into serious games, with the objective of enriching learning processes. A serious VR game for first aid training, entitled Peter's First-Aid Adventure, has proven effective in improving reflexes in emergency situations [8]. Another study [9] presents a VR serious game simulating crises such as heatwaves or earthquakes, thereby strengthening urban community resilience to natural disasters.

Originally developed for video games, Unreal Engine, has become a key tool for scientific research and behavioral analysis in immersive environments due to its realistic rendering capabilities and advanced VR features. Its applications span several fields, such as aerodynamics, where Harwood et al. developed an interactive virtual wind tunnel by coupling Unreal Engine 4.16 with a GPU-accelerated CFD solver [10]. This approach allows direct interaction with airflow simulations in VR, reducing experimental costs and constraints. The study conducted by [11] highlights the significant interest in combining Unreal Engine 4.27.2 with VR to develop immersive metaverses accessible even to novice developers.

Our previous work [12] introduced an initial version of a VR-based application (VR_1), which allowed students to explore active thermography case studies in a simulated environment. While students appreciated the immersive experience, the evaluation revealed several limitations: some users struggled to correlate points on the VR panel with corresponding defects, and issues related to interface clarity and result interpretation were also reported.

This paper builds upon that initial development by presenting an improved version of the application, VR_2, designed to optimise the learner's sense of immersion and enhance the interpretability of thermographic results. VR_2 addresses the usability challenges identified in VR_1 and integrates new pedagogical features to support a more intuitive learning process. The main differences between the two versions include: a redesigned and more ergonomic user interface, the consolidation of all interactive elements into a single immersive scene, a program running on autonomous VR support and improved visual feedback for defect localization and analysis.

2 Methodology

A novel virtual environment is being developed, drawing upon the findings of a preceding study, with the objective of enhancing the immersive sensation. This novel environment is being implemented as a component of an active thermography course and will be evaluated in comparison with the existing environment. The control group has been divided into two segments, with the objective of facilitating immersive experience with one environment, followed by the other, and thereby enabling a comparative analysis of their respective interpretations.

2.1 Practical Case

The practical case study focuses on active thermography, a method employed to detect internal defects in a composite part, such as porosity or delamination of the carbon fiber. The experiment relies on the use of halogen lamps to thermally excite the plate, thereby enabling the detection of anomalies by means of the analysis of thermal variations captured by an infrared camera. The detection of defects is sensitive mainly to three heating parameters: the distance of the lamps from the samples, the angle of the lamps, and the heating time. Subsequently, these parameters are modified to establish diverse analysis scenarios, with the objective of ascertaining the most efficacious combination for defect detection in the plate. The six study cases under consideration are identical to those presented in the reference article [12]. The generation of results is achieved using a digital twin created explicitly to allow other scenarios to be proposed, such as a complex part subject to non-destructive testing or even a different material, making it easy to obtain the results after digital calculation and feed the virtual environment.

For each case, images are generated via COMSOL software and subsequently integrated into the virtual reality program for user analysis. These images represent the thermal responses of each configuration, which are analyzed using contrast curves shown in Fig. 1. These curves measure the temperature difference between healthy and defective areas over time. These curves facilitate the comparison of the effectiveness of each configuration in defect detection.

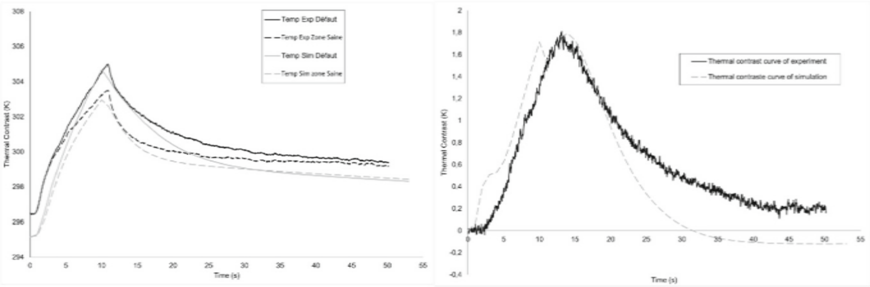

Fig. 1. Example of contrast curves

The objective of this study is to empower learners to ascertain the most suitable analysis case for detecting defects present on the plate. The simulations will be utilised to inform experimental choices in real-world applications.

2.2 Environment

The development of the virtual reality serious game was facilitated by Unreal Engine 5.3.2 (UE5).

The initial environment (VR_1) is employed as a reference point, corresponding to the program developed in the reference article. The program commences in a designated menu room, where users can select the desired analysis case. Upon selection of a case, the user is transported to a laboratory setting. In this setting, the user is presented with a visual representation of the thermographic apparatus, accompanied by an informative video that elucidates the principles of active thermography. From this room, the user can teleport to a second room for analysis. In this space, the participants are able to examine thermograms from the experiment on screens, analyse contrast curves for each point and for combinations of three points, and access additional information about the experimental setup. This progression path remains consistent for each case, and a mandatory requirement is the return to the main menu in order to transition between cases. It is possible to initiate this return from either the laboratory or the analysis room (Fig. 2).

Fig. 2. Program's room; (a) Menu room, (b) Laboratory room, (c) Analysis room

The initial version of the program was not viable for implementation on a standalone VR headset, owing to its substantial processing demands and resource duplication. In fact, the V1 environment depicted in Fig. 3 comprised a central room serving as a menu, a laboratory room, and an analysis room, each of which was duplicated for every case study. This configuration resulted in navigation complexity and interface overloading.

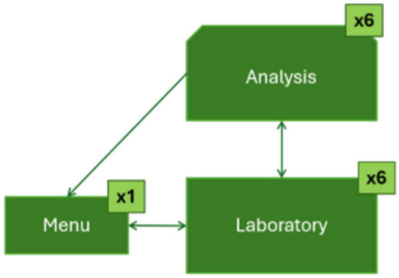

Fig. 3. Program structure plan of VR_1

The second program (VR_2), created in Unreal Engine 5, has been optimised for native compatibility with Oculus Quest 2 and 3 headsets. The project is exported to these headsets in.apk format, which is the standard installation format for Android applications (Jones, 2019). It is evident that this format comprises all the necessary files for the application to run correctly on the headset. Furthermore, it allows for direct installation from a PC or a compatible store.

However, to ensure the application functions optimally, it is imperative that Android Studio is configured properly to ensure compatibility with Unreal Engine 5.3.2. A salient constraint pertains to the maximum file size of 2 GB for the.apk. The approach to this limit can result in performance issues, including frame drops or screen tearing. In order to address the limitation, large files (for example, images, videos and other interactive elements) can be divided into smaller components known as OBB (Opaque Binary Blob) files. The utilisation of OBB files facilitates the segregation of substantial data from the.apk, ensuring that the application can access it when required. This approach has been demonstrated to optimise storage and performance.

In the context of employing OBB files, it is imperative to incorporate a designated call within the.apk to facilitate the program's seamless access and loading of these external files. This approach facilitates the development of comprehensive and sophisticated applications without compromising the performance of the headset, thereby ensuring a seamless and high-quality immersive experience.

The development of the serious game environment was undertaken utilising the Unreal Engine 5.3.2 VR template, which provides a pre-configured virtual world with the appropriate pawn and movement controls. In the interest of optimising the user experience, the environment was designed in such a way as to avoid overloading the user with superfluous information. This approach not only facilitates understanding of the content but also ensures optimal immersion. Concurrently, this streamlined design reduces the load on system resources, a crucial factor in maintaining smooth performance during the export process to the.apk format.

The environment is comprised of several distinct functional spaces. A main room (illustrated in Fig. 4a) is equipped with the thermographic apparatus and the theoretical test plate, while a designated analysis room (illustrated in Fig. 4b) is designed for the examination of results. The latter is equipped with interactive screens, allowing users to visualize and interact with thermographic data, providing an intuitive interface for reviewing the results.

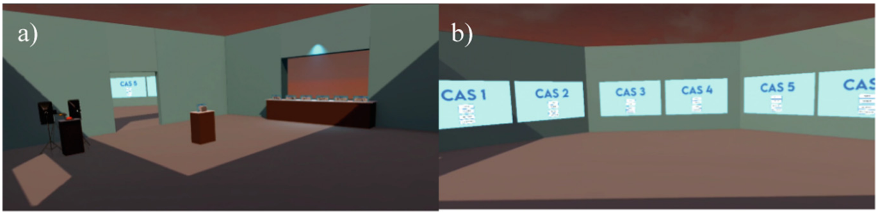

Fig. 4. Program's room; (a) Main room, (b) Analysis room

The analysis room is equipped with six screens, each corresponding to a specific analysis case, where the user can choose from multiple display options, including simple curves (Fig. 5a), providing a point-by-point view of the results, combined curves (Fig. 5b), showing the interaction of three different points, and reflection and transmission thermograms, allowing the observation of the thermal response of the material under different conditions.

This versatile interface enables users to visualise and interact with the results in a detailed and intuitive manner, facilitating a deeper understanding of the underlying principles of active thermography.

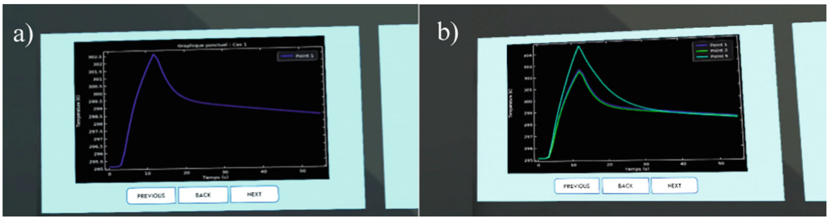

Fig. 5. Graph; (a) simple curves, (b) combined curves

The user interface of the serious game has been optimised with a cursor system controlled by the user's hand. This cursor, which is represented by a sphere, remains hidden unless it is activated by the user, thus preventing unnecessary visual clutter. To initiate interaction, the user is required to press a dedicated button on the controller. Upon activation, the phrase "hand active" is displayed on the right-hand side, while the left-hand side becomes responsible for selecting content on the screens, as illustrated in Fig. 6. As the user approaches the interface, the cursor sphere becomes visible, enabling precise selection of the desired content.

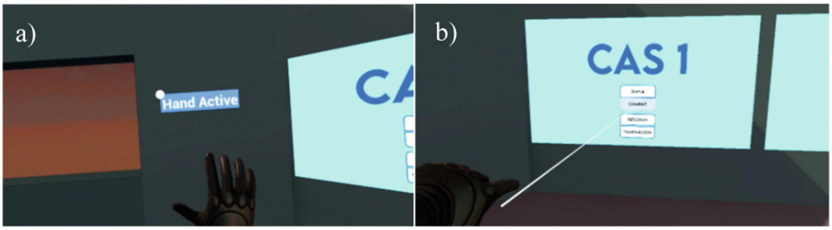

Fig. 6. Hand system; (a) Hand active, (b) selection line

When a user enters the room, they have the option to pick up the analysis plate with five predefined analysis points, as shown in Fig. 7a. This plate, which can be directly manipulated by the user's hand, is not affected by gravity, allowing it to float in the air without being held. This free manipulation enables easy adjustments to compare the plate with the different analysis cases. Additionally, technical information regarding the experimental setup is displayed on a separate designated support.

On a table (Fig. 7b), the user finds a set of predefined cases, each representing a different combination of thermographic setup parameters. These cases can also be picked up and carried by the user into the screen room to establish a correspondence between the cases and the results. This flexibility enhances interaction with the data, as the user can manipulate the program elements according to their analytical needs.

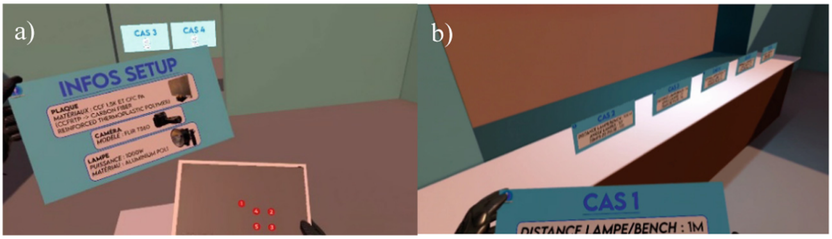

Fig. 7. Grabbable object in main room; (a) test plate with studied point, (b) cases

The thermographic configuration in the room constitutes a simplified version of the actual setup. The latter consists of two halogen lamps positioned at varying distances and angles, as dictated by the specific cases being tested. The virtual setup is employed principally for illustrative purposes, as demonstrated in Fig. 8.

It is important to note that scanning objects from the thermographic setup in a VR environment can be highly resource-intensive, potentially slowing down the program. The virtual setup, although not identical to the real equipment, allows users to understand the general functioning of the system without excessively taxing computational resources. The setup incorporates a button that activates the lamps, simulating the thermal excitation of the plate.

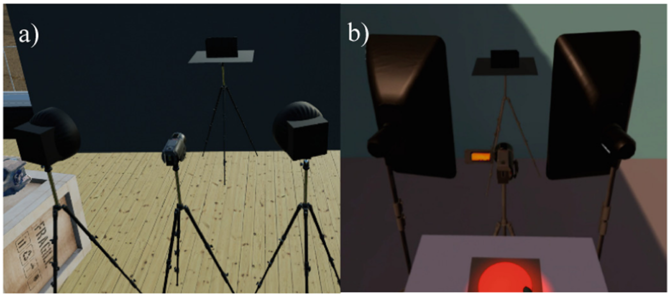

Fig. 8. Thermography setup; (a) VR_1, (b) VR_2

A plethora of FBX elements, sourced from the TurboSquid website, were employed in the creation and modelling of the environment, in conjunction with assets obtained from the TMHighTechPack plugin, available on the Unreal Marketplace. The theoretical plate for the serious game was created using Blender.

Movement within the environment is facilitated through the utilisation of teleportation and abrupt camera movements, thereby enabling the execution of turns. The present version has been developed to incorporate all features into a unified space, thereby facilitating more seamless and intuitive usage, as illustrated in Fig. 9.

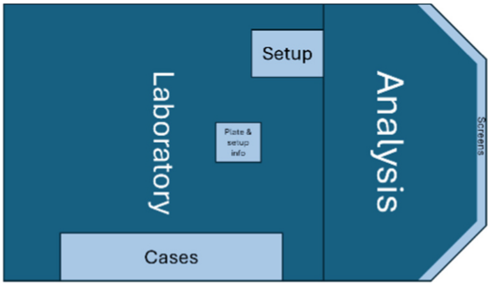

Fig. 9. Program structure plan of actual version (VR_2)

2.3 Evaluation

The evaluation of the virtual reality experience was conducted as part of a study aimed at analyzing its impact on learning thermography. For this, students participated in an immersive session as shown on Fig. 10 and answered a questionnaire based on a 1 to 5 scale, assessing several criteria: immersion in the virtual environment, ease of controlling the commands, interpretation of experimental results, effectiveness of the program in understanding thermography, and its ability to identify the optimal parameters of the study.

To observe the students' interactions with the application in real-time, the Oculus Remote functionality was used to stream the VR headset display to an external screen. This allowed instructors and observers to follow the students' actions, provide real-time support, and guide their analysis without interrupting their immersion. This tool proved particularly useful for remote evaluation and monitoring student performance throughout the experience.

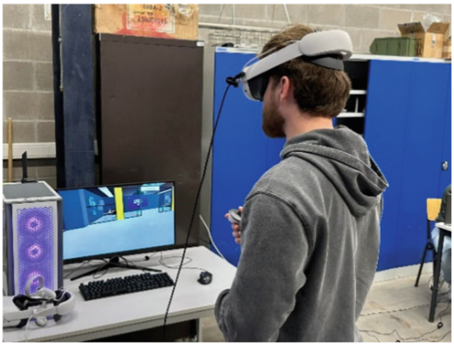

Fig. 10. User playing serious games during virtual evaluation.

3 Results and Discussion

The evaluation results indicate that students expressed satisfaction with the enhancements made to the VR experience, particularly regarding navigation and ergonomics. The new version has been developed to eliminate unnecessary movements caused by multiple rooms, with the objective of enabling students to focus more on experimental tasks than on navigation. However, a significant limitation was identified: the absence of thermograms due to an issue with importing the OBB format. This issue impeded students' ability to respond to inquiries concerning thermographic analysis, thereby diminishing their engagement with the subject matter. However, the evaluation of result comprehension suggests that the thermogram in the first study did not provide any significant benefit, as the results were understood just as well in the second study. Irrespective of the version utilised, students were able to accurately identify the anticipated outcomes.

Quantitative analysis of the questionnaire data (Table 1) provides further insight into the system's pedagogical impact. On a 5-point Likert scale, students rated the two programs.

The analysis of the questionnaires, as illustrated in Fig. 11a, demonstrates that most students found the experience to be immersive. This finding is supported by the observation that the median score was high, and the response variability was low. However, the presence of some extreme values suggests that a small number of students encountered difficulties related to ergonomics and command handling. Furthermore, the findings demonstrate that, irrespective of the VR program utilised, the identification of the optimal parameters was consistent between the two versions (Fig. 11b). A key issue

Table 1. Comparative mean scores (± SD) for VR_1 and VR_2 across key evaluation criteria

Evaluated aspect	VR_1 – Mean (± SD)	VR_2 – Mean (± SD)
Immersion in the program	3.5 (± 1)	3.8 (± 0.5)
Ease of commands' use	4.0 (± 1.2)	4.3 (± 1)
Understanding the results	3.3 (± 0.5)	3.8 (± 0.5)
Ease for understanding the thermography	3.3 (± 0.5)	4.3 (± 0.5)

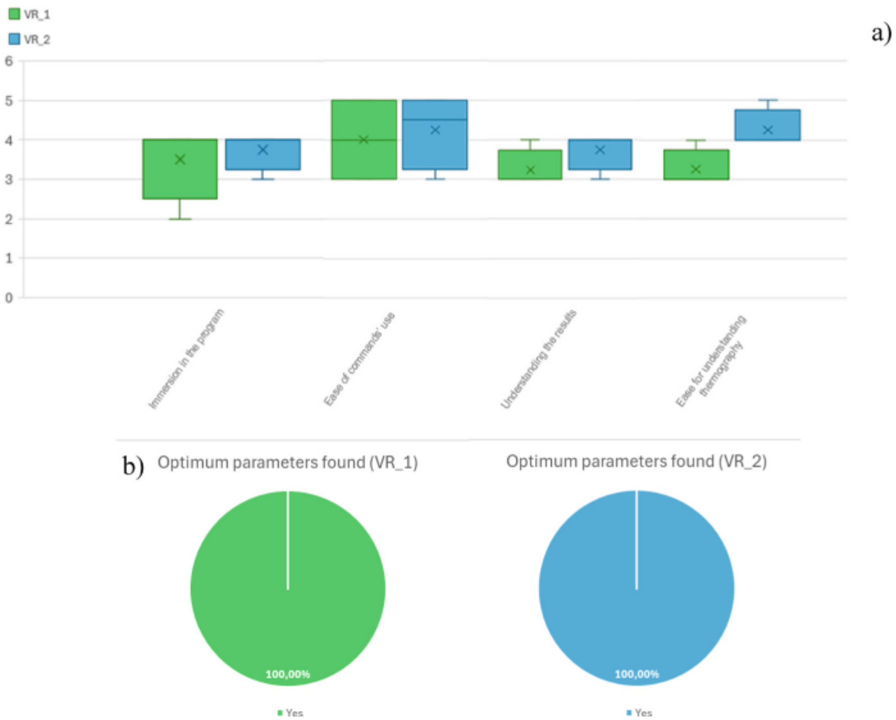

Fig. 11. Result graph of the survey: (a) qualitative part; (b) quantitative part

raised by students in relation to the second program pertained to the configuration of the screens, which facilitated enhanced comparison of the graphs for each case and improved interpretation of the results.

In order to enhance the experience further, several optimisations are under consideration. The integration of an interactive tutorial on the commands at the commencement of the session would facilitate the learning process and reduce the adaptation period. It is imperative that the issue with importing thermograms is resolved to facilitate a comprehensive and pertinent analysis of the results. In conclusion, enhancements to the user interface and the incorporation of interactive annotations would facilitate students' interpretation of thermograms, thereby augmenting the educational efficacy of the VR tool.

4 Perspectives

The improvement of this version includes several development areas aimed at enhancing user experience and optimizing program performance.

First, a tutorial could be added to facilitate learning of the program's commands, allowing users to quickly familiarize themselves with the interface and the necessary interactions.

Another major improvement focuses on implementing a system for importing CSV data and converting it directly into graphs, making interaction with COMSOL Multiphysics more efficient by providing a faster and more intuitive way to modify simulation parameters and add new study cases without requiring complex reconfiguration of program data.

Several technical challenges have been encountered, particularly regarding the configuration and loading of OBB files in the.apk format, which remains a key area of development to further optimize the program, reduce its size, and ensure the proper display of thermographic visuals, an issue encountered in this standalone version, where while thermal data is processed and analysed, the visualization of thermograms is currently not possible due to problems related to reading OBB files.

Additionally, new features could be explored, such as allowing users to switch hands for the screen selection system and developing a controller-free version, specifically designed to leverage the hand-tracking capabilities of the Quest 3, providing a more natural and immersive interaction without relying on external peripherals.

5 Conclusion

This study has demonstrated the potential of integrating virtual reality (VR) with active thermography for non-destructive testing of composite materials. Building upon these findings, the improved version of the project focuses on an autonomous VR solution, which simplifies the user experience by reducing the complexity of the environment. Unlike the initial version, which relied on multiple levels representing different rooms, the new approach consolidates everything into a single environment. This optimization makes the software more intuitive and easier to use, ensuring a smoother workflow for users.

The autonomy of the system provides significant advantages, allowing the software to be easily transported and tested in different locations. VR programs are perceived as immersive and effective learning tools. Additionally, the system can be monitored efficiently via a computer or a mobile device, improving control and supervision. One limitation encountered in the autonomous version is the loss of thermogram visualization, which reduces the number of interpretation types. But this lack does not provide significant disadvantages.

Overall, this research underscores the growing importance of VR technologies in engineering applications, particularly in enhancing the capabilities of traditional testing methods. The integration of active thermography with VR represents a promising step towards more efficient, accessible, and engaging non-destructive testing solutions for composite materials, with ongoing improvements aimed at further refining user experience and system performance.

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