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Virtual Reality Integration for Enhanced Engineering Education and Experimentation: A Focus on Active Thermography

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Abstract: The interconnection between engineering simulations, real-world experiments, and virtual reality remains underutilised in engineering. This study addresses this gap by implementing such interconnections, focusing on active thermography for a carbon fibre plate in the aerospace domain. Six scenarios based on three parameters were simulated using ComSol Multiphysics 6.2 and validated experimentally. The results were then integrated into a virtual reality serious game developed with Unreal Engine 5.3.2 and aimed at educating users on thermography principles and aiding rapid experimental condition analysis. Users are immersed in a 3D representation of the research laboratory, allowing interaction with the environment, understanding thermographic setups, accessing instructional videos, and analysing results as graphs or animations. This serious game helps users determine the optimal scenario for a given problem, enhance thermography principle comprehension, and achieve results more swiftly than through real-world experimentation. This innovative approach bridges the gap between simulations and practical experiments, providing a more engaging and efficient learning experience in engineering education. It highlights the potential of integrating simulations, experiments, and virtual reality to improve understanding and efficiency in engineering.

Keywords: virtual reality (VR); serious games; simulations; active thermography

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1. Introduction

The fusion of engineering simulation, experimentation and virtual reality opens new perspectives in the engineering field, offering innovative and effective solutions to today's technological challenges. This project aims to establish a technological bridge between these areas, encouraging their mutual interaction and reciprocal enrichment.

Virtual reality, often abbreviated to VR, is defined as the computer simulation of an immersive three-dimensional environment, allowing users to interact with and explore that said environment using sensory stimuli. Typically, these stimuli are presented through head-mounted headsets and other interactive devices [1].

Virtual reality (VR) environments are generally classified into three categories according to their degree of immersion [2]:

- Partial participation, which provides a sense of reality and is often used in contexts such as flight simulators;
- Fully immersive participation, which involves a computer-assisted virtual environment where all their participants' sensory perceptions are fully integrated;
- Multiple participation, which allows several users to connect and interact in virtual worlds. These environments facilitate the exchange of ideas by allowing individuals to participate in virtual environments via their computers.

The benefits of virtual reality include three-dimensional visualization, interactivity, remote collaboration through telepresence, and on-site task simulation [2].

The advantages of VR in training were studied by comparing two training groups: one using VR and the other having access to a two-dimensional (2D) educational video. The results indicated that the group using VR showed better knowledge retention, superior task performance, increased learning speed, and a higher level of engagement than their peers learning from a 2D video [3].

The usefulness of VR increases importantly in education, offering unique learning opportunities. A recent review highlighted the potential of VR in this area, identifying over 500 educational research studies published between 2016 and 2020 [4].

Various virtual reality headsets are listed in the scientific literature. Among them, the Meta Quest 2, also known as the Oculus Quest 2, is widely cited as one of the most common used VR entertainment headsets to date. Developed by Meta Platforms Inc, the headset immerses users in a fully simulated environment. It is equipped with a Qualcomm Snapdragon XR2 processor, an LCD screen with an eye resolution of 1832 $\times$ 1920 pixels and refresh rate of 120 Hz. It runs an Android 10-based operating system and is available with 128 GB or 256 GB of internal storage [5].

This headset is widely documented in the scientific literature and is involved in numerous projects such as its a collaborative application for evaluating structures [6], the simulation of the constructability of dynamic process [3], and in remote thesis supervision meetings [7].

The Oculus Quest can operate autonomously and is equipped with both Oculus Touch and manual controllers and supports gestures without the need for controllers [8].

Zarco et al. [9] examined 24 game engines in terms of their applicability to the modelling and simulation of complex production systems, and the authors identified the modelling environments best suited for production, based on the technical characteristics of each engine as well as market developments. By integrating a modular machine into two of these engines, the article presents the results obtained in terms of applications and limitations, particularly regarding functionality, scale, accuracy of physical simulation, redundancy of resources and visualisation. Game engines have developed rapidly in recent years, demonstrating their ability to represent complex systems in a reliable and user-friendly way. As a result, they offer promising potential not only in entertainment, but also in other sectors of industry and technology. Unity and Unreal have been identified as the two most promising engines to use in such projects.

The Unreal Engine game development engine is also examined in the scientific literature. It was used to create a virtual reality environment to compare the performance of controllers and virtual hands [10].

An approach was developed that integrates unified quadtrees for more efficient data indexing, an EMT-based scheduling strategy for unified scheduling under different production standards, and a parent-child elimination method with an asynchronous loading strategy using binary encoding for quadtrees. These methods, implemented in the Unreal Engine (UE), offer significant advantages in terms of real-time visualisation efficiency and overall memory utilisation [11].

Extended reality (XR) is also mentioned in the literature. It encompasses virtual reality (VR) and augmented reality (AR), allowing for improved interaction between real and virtual environments. A study focused on four aspects: existing XR game engines, their main features, supported serious game attributes, and sustained learning activities. The results show that XR engines have the ability to improve the learning experience through serious games and gamified applications [12].

Various initiatives in the augmented reality (AR) and virtual reality (VR) fields have been implemented, particularly in the automotive sector. Car manufacturers have integrated AR technology into manufacturing environments to facilitate assembly, maintenance and inspection tasks [13].

Virtual reality is widely applied in a multitude of sectors such as the military, aviation, medicine, sports, construction, real estate, security, advertising, promotion and many others [1,8]. It also has advantages for operator training, offering the possibility of training operators even before a factory is completed.

In the context of the study of finite elements, another application is examined. This application allows designers to modify the shape of a component and observe the updated stresses interactively. Using prior sensitivity analysis, linear interpolation is used to estimate stresses in real time. The load acquisition module acts as an interface between the simulator and real loads. Using offline pre-calculations, the simulator can update the results in real time [14].

An innovative method was proposed for developing immersive metaverses for industrial training. Using version 4.27.2 of Epic Games' Unreal Engine software and the Oculus Quest 2 headset, this research aims to extend the development of virtual reality applications for industrial training. Despite challenges relating to safety, cost, liability and repeatability, the study highlights the importance of immersion in promoting active learning, with increased immersion leading to better learning outcomes [15].

A collaborative VR application has been developed to allow remote experts to simultaneously assess bridge structures. The process begins by faithfully capturing the bridge using UAV photogrammetry and LiDAR, then integrating it into a VR environment. An engineering assessment is carried out using FEM or operational model analysis, with the result also integrated into the VR environment. The application supports multi-user functionality, allowing up to 20 people to connect simultaneously. Users can collaborate in real time, chat by voice, and choose avatars to represent their virtual characters. This feature facilitates effective communication and decision-making between geographically dispersed team members [6].

Another collaborative project has been presented, involving remote theses supervision meetings. This initiative is based on a web platform enabling participants to upload documents and personalise their avatars. The meetings take place in closed virtual rooms or outdoors, enhanced with relevant 3D models. Participants can interact with files, write, and draw on virtual whiteboards. However, limitations such as the lack of physical contact and the restriction on viewing facial expression are frustrating to both teachers and students [7].

We also find virtual reality in the medical field where an immersive game development has been realised in order to constitute a complement to the conventional treatments of schizophrenia. The potential is promising, and VR treatments could become more effective and accessible to a wider population [16].

Virtual reality can also be a tool to raise awareness of phenomena as for an application that aims to increase attention on the importance of wearing the seat belt. A motorised rollover simulator, synchronised with a VR app, allows users to feel the sensations of a real car rollover, demonstrating the dangers of not wearing a seat belt. The perception of the importance of the seat belt increased from 23.17% to 86.63% for the rear seats and from 62.57% to 97.33% for the front seats, while the actual use of the front belts increased from 53.12% to 92.69% [17].

A virtual reality training application has been realised for the maintenance of induction motors, aiming to improve engagement and the effectiveness of learning. VR offers an immersive and interactive experience, covering components, motor assembly, and power signature analysis to detect failures. This application has proven its effectiveness in learning practical maintenance skills, while reducing the costs and risks associated with using new equipment [18].

As part of the electronics laboratory, a virtual learning environment was developed to train students in the use of electronics laboratory equipment, including the function generator and oscilloscope. As with most of the VR learning and training applications, the results of the study show that the VR approach has a significant positive impact on students' knowledge, motivation to learn and cognitive understanding. In addition, students in

the treatment group showed a better understanding of laboratory teams and increased confidence in their use [19].

Carvalho et al. [20] stresses that serious games use the motivation and immersion inherent in games to achieve educational, marketing, social awareness, health, etc. Education benefits particularly from these approaches, strengthening the motivation of learners through gamification processes. Various case studies have been conducted on gamified physics experiments in primary school or an interactive game to teach JavaScript programming.

Gamification is an interesting approach to motivate students in learning. As demonstrated by Cubela et al. [21], a problem-based, gamification, and data-driven approach encourages students to, for example, improve their STEM perspectives in this paper.

We also find gamification used when organising an escape room in the engineering department of the University of Messina. The goal was to motivate students and foster collaboration. The results showed that gamification is a good method of education and improves organisational and teamwork skills [22].

Sim et al. [23] explored the innovative concept of the educational metaverse, focusing on creating immersive virtual environments for industrial learning and training. A concrete example is the "NTUniverse", a digital twin of the Nanyang University of Technology (NTU) campus. It allows distance learning and professional technical training, facilitating the analysis of abstract concepts. The European Union has made several initiatives in this field. This digital twin integrates STEM disciplines to improve student learning, enables a collaborative approach, improves visualisation, and reduces the risks and costs of training on real equipment using virtualisation.

The integration of the metaverse into STEM education is also mentioned as a way to improve student engagement and learning. Improvements due to this integration were noted, such as presentation skills and interactive learning [24].

There is also the adoption of the metaverse and mixed reality in aircraft maintenance. This aims to offer an innovative educational and training method for aircraft maintenance, relying on digital twins. This approach allows one to improve the accuracy in the prediction of defects and to strengthen the effectiveness of the training. The expected benefits include a reduction in costs and necessary resources through this methodology [25].

This work falls within the scope of active thermography, a crucial area of materials inspection, with a particular focus on carbon fibre structures. In this field, a study was carried out for training on early detection of defects in kinematic chains. This training is carried out in a virtual reality based on real thermographic data. This module offers a cost-effective and actionable training solution, reducing the costs and risks associated with training on physical equipment while being efficient [26].

The solid foundations laid by the THERMPOCOMP project serve as a basis for this research [27]. The main objective of this study is to determine the optimum parameters for detecting defects in carbon fibre structures after heating, while preserving the properties of the material.

The aim of this paper is to present an immersive serious game that places the learner at the centre of a non-destructive testing process using active thermography. This virtual simulation is based on results obtained from multiphysics engineering software. This innovative approach stems from an in-depth exploration of 3D modelling using the Unreal Engine and Unity game engines. By taking advantage of virtual reality, the aim is to provide more effective and immersive tools for experts and researchers in the field of materials inspection.

This program is designed to meet a number of objectives, particularly educative ones, by raising awareness of thermography and saving time in choosing the optimum experiments. By enabling users to navigate efficiently through different inspection cases and choose the one that best suits their needs before embarking on the actual experiment, it greatly facilitates the process of developing and optimising experiments.

In addition, it serves as a powerful educational tool, allowing students to explore thermography in an intuitive and engaging way, reinforcing hands-on learning and developing their skills interactively.

By establishing a close link between simulation, virtual reality, and real experimentation as we can see in the relation diagram on Figure 1, this program aims to create a circular feedback loop, offering more powerful tools for researchers and experts in the field. Each component allows one to feed the other two through a theoretical input, feedback from field experience, new technical findings, new use of materials, or even user experience feedback.

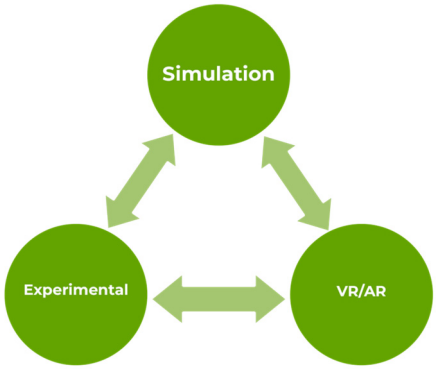


Figure 1. Relation diagram of the project.

In this article, we will explore in detail the tools used, such as the choice of headset after multi-criteria analysis, the game engine selected after extensive testing, the thermographic setup used, the COMSOL Multiphysics 6.2 software, and the cases determined. In addition, the method used to build the VR program will be detailed and a practical case study will be explored, followed by an in-depth discussion of the results obtained.

2. Methodology

2.1. Practical Case

The "THERMPOCOMP" project, which represents the practical case used for this project, was aimed at comprehensive numerical modelling of non-destructive testing of composite parts using active thermography. The need for such a model originally stems from the increasing use of composites such as carbon-fibre reinforced thermoplastics. These materials, which are attractive for their mechanical properties, also suffer from manufacturing defects such as high porosity. The importance of developing an effective non-destructive testing method to verify the structural integrity of the parts was paramount to ensure their effectiveness.

The part inspection technique used in this research is therefore active thermography technology. The principle of this method is based on some form of thermal excitation of the component which, in response to this excitation, emits infrared radiation, which is then captured by an infrared camera. The method can be either passive, in which case no external heat source is used (the thermal excitation being the environment itself), or active, which is our case, where halogen lamps are generally used to heat the component. Once our parts have been irradiated, the analysis will then take place during the transition period, when the part returns to the initial state, where a disturbance will be created by the presence of defects such as porosities, making them observable with the thermal camera.

The setup used for experimental active thermography, and on which we based the model, comprises two 1000 W halogen lamps, as shown in Figure 2.



Figure 2. Thermography setup.

The coupon was created by additive manufacturing using an Anisoprint A4 printer, and its geometry consists of a rectangular plate 220 mm long, 140 mm high, and 2.8 mm thick. It contains 16 internal defects of different sizes and shapes and located at different depths. These defects are intended to reproduce possible delamination or porosity defects in real components. The delimitation of a layer is represented by creating a 250 µm thick void in the benchmark as shown on the plan. The different sizes used in the benchmark give an idea of the resolution of active thermographic inspection. As these are internal defects, only additive manufacturing could be used to produce the real benchmarks. The geometric model of the benchmark used is shown in Figure 3.

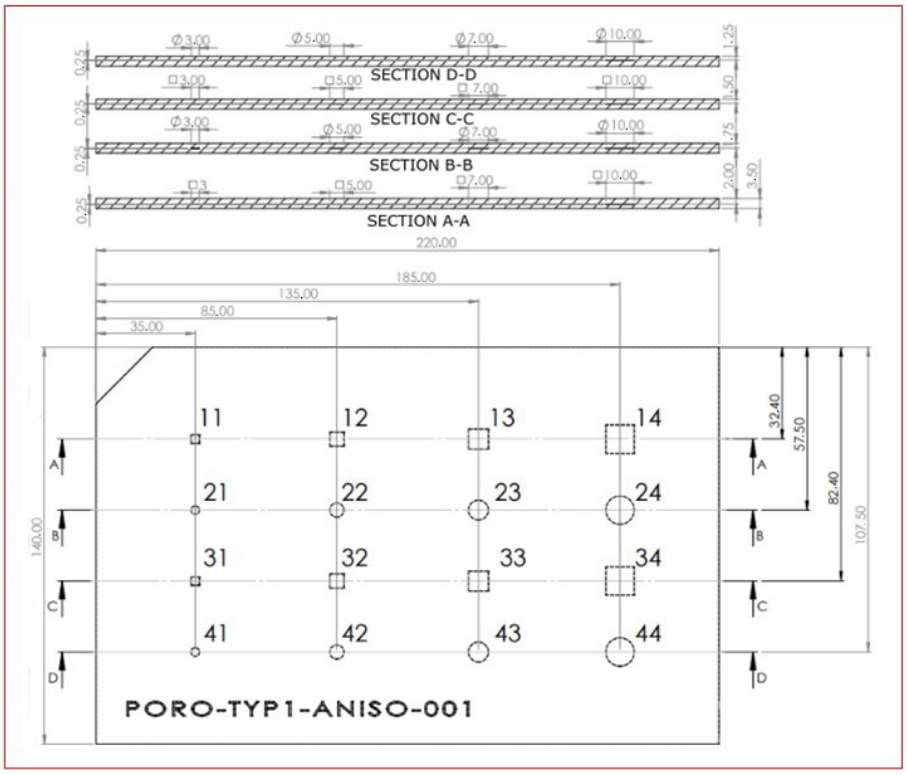
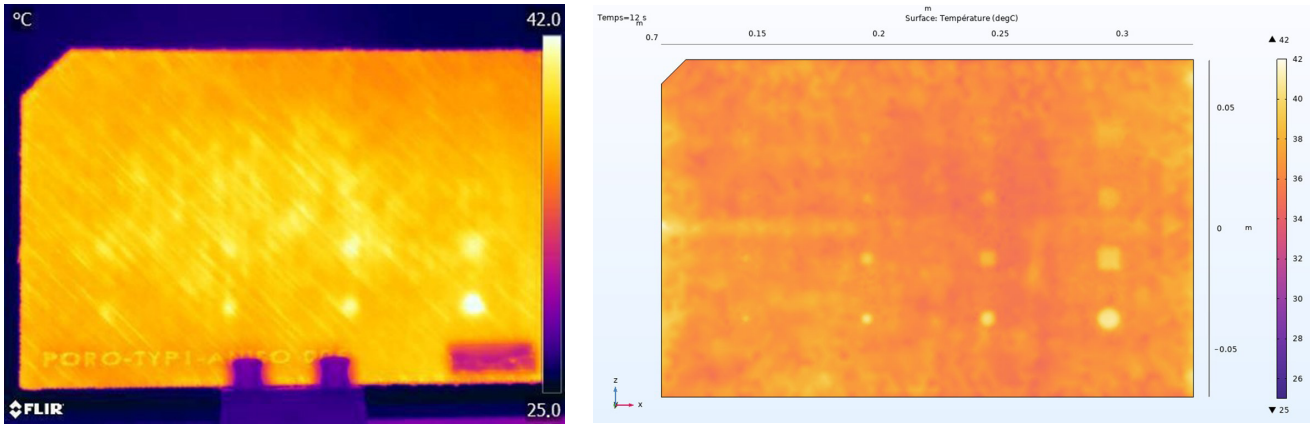


Figure 3. Benchmark plan taking into account the delaminated areas produced using a 3D printer.

Once the geometric model had been created, we were able to import it into COMSOL Multiphysics 6.2 and create our finite elements simulation. As previously stated, the model developed as part of this research is therefore a complete model. It recreates the entire

heat source to take direct account of most of the physical mechanisms that occur during active thermography. In Figure 4, there is a comparison between a thermogram made with the thermic camera and a numerical thermogram made with the software. To show the difference between software and experiment, some examples of contrast curves are shown in Figure 5.



Reality Numerical

Figure 4. Example of Thermograms.

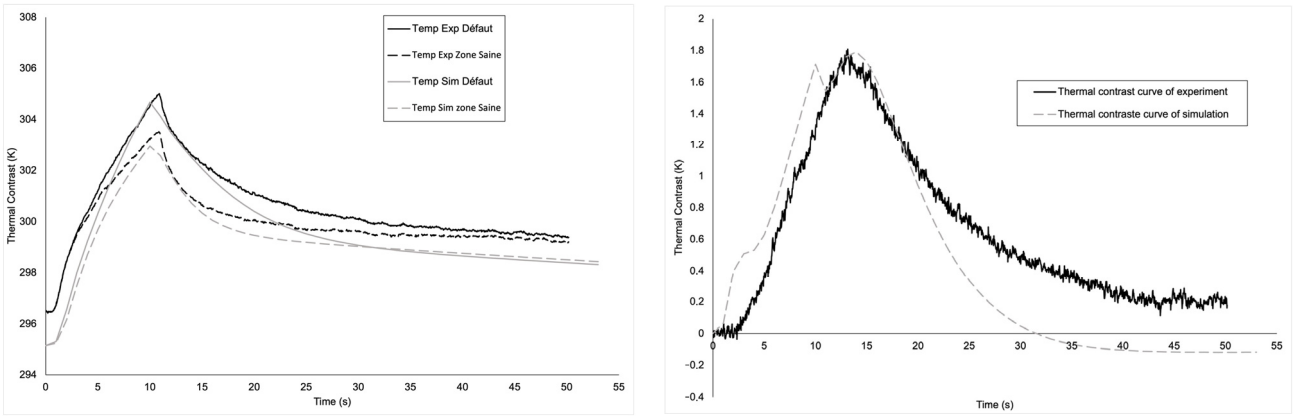


Figure 5. Example of contrast curves.

To assess the effectiveness of the serious game developed, a practical case study was carried out with a class of 12 master's students in aeronautics. The experiment was carried out on a computer built with an Intel I7-13700KF 3.4 GHz with 32 GB of RAM and an RTX4070 12 GB, with an Oculus Rift VR1 virtual reality headset from 2016, the only one available in the laboratory.

The objective of the test was to determine the optimal analysis case for detecting defects in a carbon fibre part. This determination is made by the analysis of contrast curves and thermograms for different value combinations of parameters. For each case, one of the three parameters' values is modified, which allows one to evaluate its influence on the results. Then, one selects the optimal combination of values for these parameters to find the optimal case. The test was divided into two parts, each lasting 1.5 h. In the first part, the students used real experimental equipment to carry out several analysis cases using the experimental setup. They then analysed the results to select the optimum case.

In the second part, the students were immersed in the serious game and had to analyse the results of each case. In addition, the students had to identify which points on the plate, previously defined in our experiment, are the ones with defects.

This approach allowed us to compare the effectiveness of the analysis of the results between the real experiment and the use of the serious game. The students were thus able to assess the serious game's ability to faithfully reproduce the conditions of the real experiment and to provide an interactive and effective learning experience in the field of thermography applied to aeronautics.

2.2. Environment

Unreal Engine 5.3.2 was chosen for the creation of the serious game. This is an advanced game engine developed by Epic Games. This engine is renowned for its ability to create photorealistic and immersive environments. The 5.3.2 version offers enhanced tools for real-time rendering, physics, and animation.

The program was developed using the Oculus Rift VR1 virtual reality headset. This headset has been designed to offer an immersive experience with features such as high-resolution screens, precise motion tracking using external sensors, and touch controllers for intuitive interaction with virtual environments.

Numerous FBX elements from the TurboSquid website were used to create and model the environment, as well as elements from the TMHighTechPack plugin on the Unreal marketplace for computer elements. The textures were applied using a web-based Unreal program called Quixel Bridge 2023.0.8, and the sky was created using HDRIs from the PolyHaven website. Blender 4.2.0 was used to create specific objects, such as the lamps in the thermographic setup. The 3D scans were also taken using LumaAI 2.1.1. All these elements have been used to create the menu, shown in Figure 6, that welcomes the player at launch, and also, the virtual laboratory, in Figure 7, recreated almost identically to its real-life version and the analysis room shown in Figure 8 for curves, setup information, and thermograms.

Displacements are also created using teleportation and jerky camera movements to turn around. A cursor system that allows the user to make selections on the interface is added to the program. The cursor is a sphere that is integrated directly into the player camera (named camera pawn) and controlled by the hand. At each moment, an imaginary projection line corresponding to the sphere emanates from the player's hand. As the user approaches an interface and makes the end of the projection line touch it, the sphere appears and is used to select the desired content. This principle is illustrated in Figure 9.



Figure 6. Menu of the serious game in Unreal Engine 5.3.2.

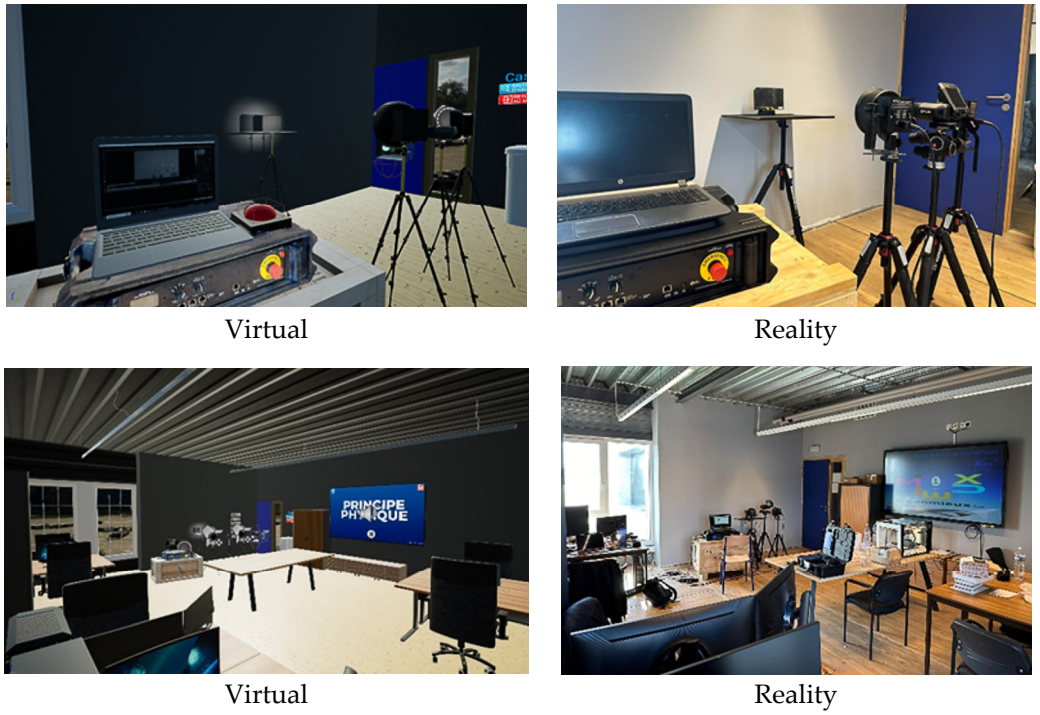


Figure 7. Comparison between the real laboratory and the virtual in Unreal Engine 5.3.2.

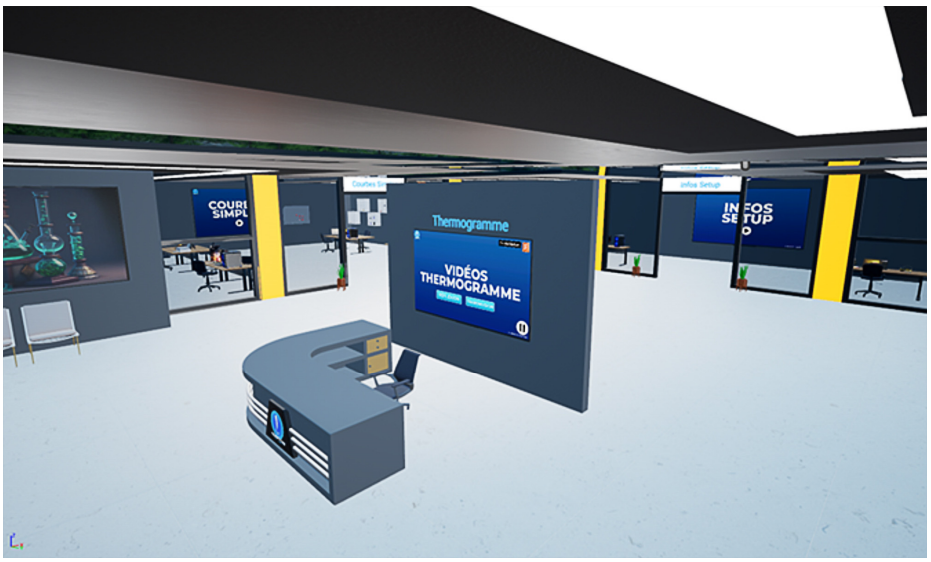


Figure 8. Analysis room of the serious game in Unreal Engine 5.3.2.

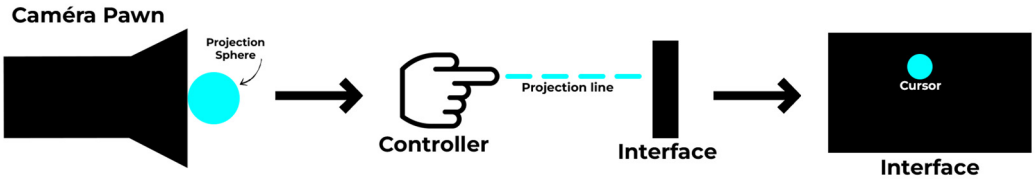


Figure 9. Diagram of how the cursor works on the interface.

In the environment, the interfaces are placed in screens or near doors. They are used to move between rooms (menu, laboratory, and analysis room) or to select the desired content (launch a video, select curves, display the thermogram, etc.).

2.3. Data and Cases

In the program, the data are taken from simulations carried out using comsol Multi-Physics 6.2 software, based on the project carried out for THERMPOCOMP [27].

The parameters studied are as follows:

- The distance between the lamp and the benchmark;
- The angle between the lamps;
- Lamp pulse time.

Based on different combinations of these parameters, the cases are defined in Table 1.

Table 1. Parameters by case.

Case	Distance (m)	Angle (°)	Pulse Time (s)
1	1	20	10
2	0.7	20	10
3	1	20	15
4	1	20	2
5	1	35	10
6	1	10	10

For each case, 2 videos and 15 images are taken from COMSOL. This creates a database of 12 videos and 90 graphics within the program. These data are placed in the corresponding interfaces for each case. For every case, the user can analyse the data and combinations corresponding to 5 points previously defined on the plate.

2.4. Program Construction

The program aims to immerse users in a virtual environment where they can explore and analyse the results of a specific thermography case study. To ensure simple and intuitive navigation, three distinct rooms have been created: the menu, the laboratory, and the analysis room.

The menu room shown in Figure 10 offers users a user-friendly interface for selecting the specific case they want to explore. This interface allows fluid and rapid navigation between the different thermography scenario available.



Figure 10. Menu selection in VR.

The laboratory room in Figure 11 has been designed to allow users to familiarize themselves with the dimensions and operation of the thermography device in an environment similar to a real laboratory. Users also have access to videos explaining the principles

of thermography, giving them a better understanding of the context and challenges of the experiment.



Figure 11. Video of thermographic principle in the Laboratory in VR.

The analysis room presented in Figures 12 and 13 gives users the chance to examine the results of the experiment in detail. They can consult the graphs corresponding to the selected cases, view the results of the experiment in the form of the reflection and transmission thermograms, and explore the parameters of the experimental setup in detail. This room allows the users to analyse the data in depth and draw precise conclusions about the different experimental configurations.

This three-room structure (Figure 14) offers to the users an immersive experience, enabling them to explore and analyse the results in an efficient and intuitive way, while providing the information they need to understand the fundamental principles of thermography.

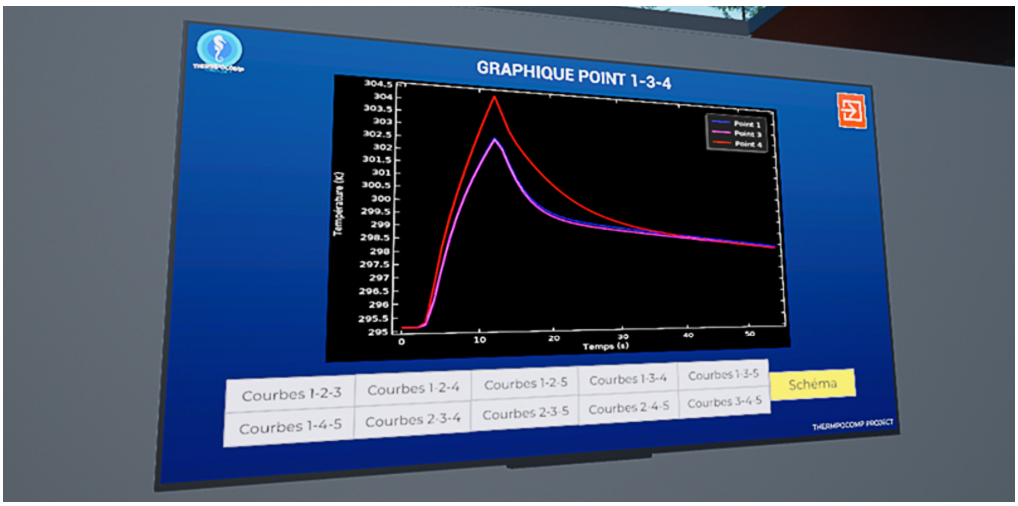


Figure 12. Example of graphic in the analysis room in VR.

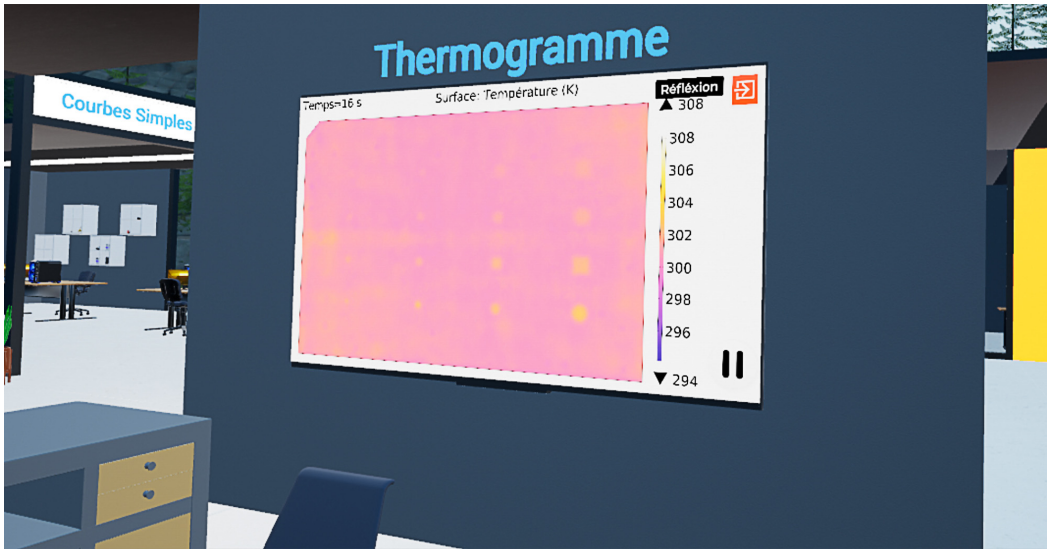


Figure 13. Example of thermogram in the analysis room in VR.

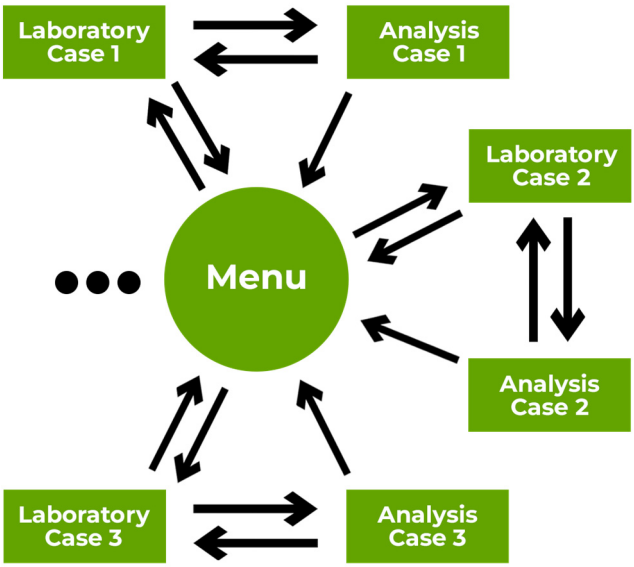


Figure 14. Navigation diagram of the serious game.

2.5. Virtual Evaluation

This case study was designed to compare the effectiveness of the serious game with real experimentation in the field of thermographic analysis. The evaluation took part in an ex-cathedra course of «Non destructive control». The serious game was tested during a laboratory realised for this course as shown in Figure 15. This evaluation was monitored by Mr. Strazzeri regarding the VR part and Mr. Notebaert for the experimental part, all supervised by Dr. Demarbaix. This laboratory was carried out in Gosselies in Belgium on 5 April 2024 during which each student took part in the study by answering a 1 to 5 point-based questionnaire. This questionnaire's goal was to compare the two parts of the test: real experimentation and use of the serious game. This tool was therefore created to measure the scale of immersion in practical work, which was from 1 to 5. This tool was created on the basis of the immersive feedback of a real trial in order to avoid the bias of virtual reality. The evaluation was organised around the possibility of making the learning of thermography and its equipment more immersive, something that was not present the previous school year and was requested by students.



Figure 15. User playing the serious game during virtual evaluation.

The aim was to determine to what extent the serious game met its objectives of rapid analysis, time savings, and being a potential guide to choose for the real experiment, in the event of a correlation in the choice of the optimal case. If not, the aim was to identify areas for improvement to make up for any shortcomings.

This methodology made it possible to collect quantitative data on the effectiveness and user-friendliness of the serious game compared with the real experiment. The students' responses to the questionnaires were analysed to assess users' satisfaction, their perception of the usefulness of the serious game compared with the real experiment, and the possible advantages and disadvantages of each approach.

The aim of this comparative approach was to provide valuable information on the performance and limitations of the serious game compared with real-life experimentation, which would help to guide future efforts to improve the serious game to better meet the needs of users and optimise its uses in the context of thermographic analysis in aeronautics.

The questions in the paper are:

- Assess your level of immersion in the experiment of active thermography inspection of a part with defects;
- Assess your understanding of how to set up the inspection setup for the experiment;
- Assess your ease of use of the tool used to carry out the experiment;
- Assess your understanding of the production of thermograms for the different cases;
- Assess your understanding of how to produce contrast curves;
- Assess your ability to interpret the results obtained from a thermogram;
- Indicate the optimum parameters chosen;
- Indicate the number of lines with faults detected for the optimum parameters;
- Indicate the number of columns with faults detected for the optimum parameters;
- Assess your ability to interpret the results obtained from the curves produced;
- Indicate the maximum of the contrast curve for the optimum parameters chosen, based on the coarsest defect observed.

3. Results & Discussions

The results of the study showed that most of the students were satisfied with their immersion in the experiment, although they slightly preferred the real experiment (Figure 16a). They understood the setup in the same way, whether it was real or virtual (Figure 16a). As far as manipulation was concerned, the students found it easier to manipulate using virtual reality rather than the experimental setup (Figure 16a). They have encountered an issue

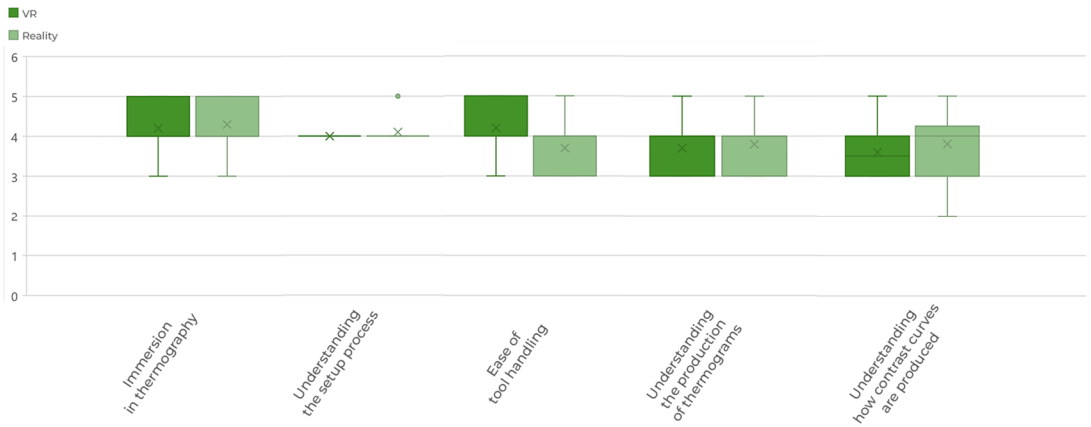
with the angle of the lamps that was hard to set up in the reality. This issue is fixed and already setup in VR for each case, which is better. The production of thermograms was generally well understood regardless of the conditions, but the contrast curves were slightly better understood in virtual reality (Figure 16a). The results obtained by thermogram were better understood in experimentation (Figure 16a). Although the number of defect lines found was identical in VR and reality (Figure 16b), for the number of columns, virtual reality provides better accuracy (Figure 16b). Although the interpretation of the results seems simpler after the real experiment (Figure 16b), 100% of the students managed to find the correct optimal parameters at the end of the virtual experiment, whereas only 50% did so after the real experiment (Figure 16b).

The general comments at the end of this test case concerned the adjustment of the angle of the lamps, which was difficult in experimentation, whereas in virtual reality, everything was already prepared. The students found that the graphics were easier to read in virtual reality and that the program was intuitive. But some found it complicated to make the analogy between the predefined points on the plate in virtual reality and the corresponding defects. Some students also noted that more practice was needed to get used to real experimentation than virtual reality. There were a few problems for some users, such as bugs for selection in the virtual reality interfaces. Some students experienced trouble during results interpretation in virtual reality. They found that the real experimentation process took longer because the plate needed to cool. And blurry images were reported since the Oculus VR1 headset is not the latest version of headset on the market.

The results of our study are conclusive, confirming that virtual reality is equivalent to traditional experiments in terms of results and interpretation. This initial objective has been achieved, demonstrating that the VR experience can be transposed effectively and without the need for expensive equipment. This means that every student could potentially use a VR headset, facilitating access to immersive educational experiences.

VR offers several significant advantages over traditional experimental methods. In VR, there is no need for the plate to cool down between sessions, which saves time and speeds up the process. Stand-alone VR headsets are easy to transport, making simulations accessible anywhere. They also allow several students to manipulate the same models simultaneously, encouraging collaborative learning.

It is crucial to stress the importance of prior training to use VR effectively. Adequate training is needed to ensure that users can fully exploit the capabilities of VR technologies. This initial training would be just as important in real experimentation. Because of this, pedagogical limitations can also be present at the level of the learning curve because even if VR can simplify learning, there is a learning curve for users not familiar with the technology, which may limit its initial adoption.



(**a**)

Figure 16. *Cont.*



(**b**)

Figure 16. Result graph of the survey: (**a**) qualitative part; (**b**) quantitative part.

In this perspective, to cover a wider range of the three parameters studied, several new cases will have to be added. These new cases include the possibility of changing the materials analysed as well as the experimental setup parameters, such as lamp power. This extension of the case database allows users to explore a wider range of experimental setups, enriching the learning experience. The possibility of analysing more than five points on the plate for a given case is also considered. All these elements allow the case database to be expanded to make a complete and more diversified program, offering a richer and more in-depth experience to the users. But the addition of various use cases may limit

the generalisation of the results. Thermographic applications can be highly varied as each field or industry may have specific requirements which are not fully covered by a general application. Moreover, the results obtained in a VR environment need to be validated in real contexts to ensure their reliability and generalised applicability. In view of these considerations, a future direction would be to study the possibility of adapting the application to other scientific and technical fields, such as fluid mechanics, thermal electronics, etc.

To improve the efficiency of navigation and optimise the time spent in the analysis room, the space of this room will be reduced. This means that users can spend less time moving around and more time analysing the results.

The user interface must also be redesigned to avoid overlapping during selection and to make the interface more user-friendly. The aim of the redesign is to make navigation more fluid and intuitive for users, contributing to the overall experience.

The virtual reality headset used has to be changed to the Oculus Quest 2 or Quest 3, which are among the top headsets on the market for this type of purpose. They also allow much more free movement since they can be used without a cable linked to the computer. This change enables the possibility to gain in terms of user proactivity, a better vision of the virtual environment, a standalone use, and a clearer analysis of the thermographic curves.

The scalability and generalisation of virtual reality (VR) application results may have several potential limitations. These include technical limitations in computing power and hardware because VR applications require powerful computers and advanced VR headsets. There may also be a limitation on software compatibility to ensure that the VR application is compatible with various operating systems and platforms, which can be complex, especially with the rapid evolution of technologies.

4. Conclusions

The serious game was perfectly integrated into the circular diagram alongside the simulations and experimentation. It was able to take data from the simulations and serve as data for the launch of the experiments in the choice of an optimal analysis case. It also saved time by avoiding the need to test each case experimentally and the associated cooling times.

Every part of the virtual environment, from the laboratory to the menu and analysis room, has been carefully designed to provide an immersive and realistic experience for users.

The user interface has been designed to facilitate navigation and provide relevant information on the various cases studied, whether in the form of simple curves, combined curves, information on the thermographic setup, or thermogram videos.

The results of our study are conclusive, showing that VR comes very close to reality, and sometimes even surpasses it in terms of teaching effectiveness. The students were able to handle the serious game and understand thermography without difficulty, demonstrating the ease of use and clarity of the concepts taught via VR.

VR is proving to be a powerful and interesting teaching tool, offering exciting prospects for the future of education. Its potential to provide immersive and interactive experiences makes learning not only more accessible but also more engaging and effective. The positive results of this study show that VR can be successfully integrated into educational curricula, enabling a better understanding of complex concepts while offering a more practical and cost-effective alternative to traditional experimental methods.

Despite certain obstacles, the project offers considerable potential for improvement and already constitutes a solid basis for learning thermography and pre-analysis in the choice of a real case study. The serious game represents a successful combination of technology, immersive modelling, and application in the field of composite thermography. With ongoing efforts and targeted improvements, it is set to become a valuable tool for research and analysis in this constantly evolving field.

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