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3D Virtual Thermal Imaging for Enhanced Scene Thermal Imaging Interpretation and Perception

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Abstract

This paper presents the progress of activities towards the development of 3D virtual thermal imaging software of (static and dynamic) scene objects and of interactions of the user with the virtual objects and in the framework of project PICTUM (Fully customizable thermal imaging simulation software) [1]. More specifically, it describes the development of thermal imaging simulation software for the training of personnel towards understanding and correctly perceive the content in the field of view of a thermal camera, for the surveillance and guarding of outdoor and indoor spaces, under different environmental and lighting conditions, and through immersion in the virtual environment of the field of view of the thermal camera. Activities include 3D imaging of virtual objects based on the thermal coefficients and properties of static and dynamic objects of interest, 3D volumetric performance of thermal models, multimodal surface/volume modelling, simulation and visualization data and motion performance in the virtual environment. The aim is to provide a functional prototype which will allow the dynamic interaction of the trainee with the virtual objects and of the trainer with the content of the training scenarios in real time.

1. Introduction

Thermal imaging allows the discrimination among objects in a scene, based on their respective differences in temperature. Due to limitations of CCD cameras to operate properly, under conditions of limited or no optical visibility (night, fog, smoke etc.), thermal imaging is widely used for the enhancement of vision and for the detection of objects in surveillance applications. The operating principle of the technique is based on the fact that any object at a temperature above absolute zero (-273°C) emits heat in the form of radiation. The emitted radiation is detected by special sensors and through appropriate processing is provided as an image to the user. As opposed to conventional cameras, thermal imaging cameras do not provide a direct image of the object per se, but rather the thermal profile of any object inside the field of view. This makes it difficult for the "inexperienced" user to identify and point out suspicious events, especially at long observation distances.

Virtual Reality (VR) is a powerful knowledge tool that allows the virtual transport of the user to a space of his choice and his interaction with virtual environments. With the use of VR headset the user can be completely immersed in a virtual space in which he navigates and observes events. Interaction of the user with the virtual environments is achieved by rendering the user's movements in real time and using basic graphics environments, which do not require programming skills for the user. Rendering of images that correspond to different viewpoints generate photorealistic 360 ° scene. Image-based rendering [2] from image sequences has dominated in applications where 3D geometrical information is scarce or absent. However, most graphics applications always have some form of scene geometry, represented either explicitly (i.e. the use of 3D meshes) or implicitly [3]. More recently, advances in machine learning have enabled neural rendering [4] techniques to be applied with great success in both indoor and outdoor scenes [5, 6], by generating novel views from a given, fixed scene representation.

Furthermore, due to the available hardware and new algorithms, accurate lighting and shading, particle generators, and scattering phenomena can now be implemented in real time, enchaining the visual quality of the scene, with applications ranging from gaming to medical imaging [7, 8].

In the context of the current application, we stick to classical rendering techniques for creating a fully customizable scene using objects represented as triangular meshes. This makes the need for real life thermal data obsolete, and all visualizations are performed through the simulation of the thermal camera. Deferred rendering [9] methods are used to minimize the resource usage of the computationally demanding VR application.

This paper presents activities towards the development of thermal imaging simulation software for the training of personnel to understand and correctly perceive content in the field of view of a thermal camera in applications for the surveillance and guarding of outdoor and indoor spaces, under different environmental and lighting conditions, and through immersion in the virtual environment of the field of view of the thermal camera.

Nomenclature

CCD charge-coupled device

FoV Field of View

DoF Degrees of Freedom

NETD Noise Equivalent Temperature Difference

IR Infrared

GUI Graphical User Interface

2. Methodology

The proposed workflow includes the creation of virtual 3D thermal imaging of the virtual objects which will be created based on the thermal coefficients and thermal properties of the static and dynamic objects of interest, the 3D volumetric rendering of thermal scene models, the multimodal rendering of surface/volume models, the simulation and visualization of data and motion performance in the virtual environment. The aim is to provide a functional prototype which will allow the dynamic interaction of the trainee with the virtual objects and with the content of the training scenarios, in real time, while it will be fully extensible with new script libraries allowing the adaptation to personalized training scenarios in order to address the needs of different trainee and application scenario. Modifications of the basic system could regard camera characteristics (focal length, use of cooled/non-cooled camera, camera resolution, etc), atmospheric conditions (day/night, rain/smoke/fog), vehicle movement and speed (Options: cold, hot-recently moved or moving), clothing of people in the scene of the scenario (winter, summer, gloves, hat, etc.), presence of glass objects (glass is opaque in thermal imaging), expected response time of the trainee (depending on the training level), type and dimensions of animals and other objects. The functional prototype will be tested in a pilot study for the surveillance of a marine area and for the training of students of the Hellenic Naval Academy [10] which provides academic and university level naval education.

2.1 Virtual 3D thermal imaging

In order to familiarize users with concepts such as thermal radiation and thermal imaging principles, as well as with basic physical phenomena such as heat transfer, electromagnetic radiation transmission, atmospheric attenuation, and scattering, a use case with Leslie's cube interaction and IR Basic Principles has been defined. Leslie's cube is a cubical structure/device that is used for demonstration purposes and/or for measurements of the thermal radiation emitted from different surfaces of the same temperature. The difference in the IR radiation emitted from the surfaces of a Leslie cube is due to one of the most important factors in thermal radiation, the emissivity parameter. Modelling the behavior of a Leslie cube and allowing the user to interact with it (rotate, touch, bring closer) serves as the first step in developing a high-quality IR thermal camera simulation tool. For the first use case heat transfer models, radiation transmission, attenuation, and scattering models have been created and tested, and research has been performed on how numerous system parameters can affect the final IR image in a more controlled manner. Temperature, material (conductor, non-conductor), surface type, angle of direction, background temperature difference, NETD, sensor type. Sensors, lenses and spectral bands are all parameters that can be tested, and their effect can be easily perceived by the user. Atmospheric conditions can be tested as well. With the realistic search and rescue scene we will be able to verify that our models proposed and tested in the simplified scenario above can be applied in more complex environments, while trainees will have the opportunity to be trained in real-life scenarios where on the spot evaluation of the scene can be critical.

The enhancement of scene thermal imaging interpretation and perception is based on the volumetric rendering of thermal models of scene objects dynamically adapting to training needs, and on the simulation of thermal imaging of scene objects with immersion in a virtual environment according to training scenarios. Immersive VR is experienced with the use of Oculus Rift S (88° FoV, 1280x1440 per eye resolution, 80 Hz refresh rate, 6 DoF tracking), while interaction with 3D virtual objects is achieved with the use of the two 6 DoF controllers of the VR headset. For the implementation of the PICTUM system, Unity engine has been chosen.

For the 1st use case, the trainee is in a controlled indoor environment and is able to observe the different emission of thermal radiation for each side of Leslie's cube due to the temperature variation, the different materials and textures across and among the sides of the cube, also while the virtual camera moves following head movements. The trainee can also observe the "virtual hands" while using the VR headset controllers with which movement and rotation of the cube is possible. Towards realistic results, the simulation needs to follow the architecture of the real thermal imaging system. An important step is the correction of pixel values due to imperfections in the response of the system's optical sensors. These errors are completely normal and are present in most systems that contain clusters of sensors (sensor arrays). By design, there are subtle differences between the responses of each sensor, which creates noise in the image being processed. These non-uniformities are linear and are treated with calibration applied either in the factory settings of the device or during its operation to better adapt to the context of each scene. Before entering the next step, an image based on ambient thermal radiation values has already been created, and any discontinuities / unevennesses have been addressed. The next step includes correction of dynamic range of the image values so that they are as evenly distributed as possible over the entire spectrum of color values (contrast enhancement). In real scenarios, and especially in scenarios containing sea area, thermal radiation is observed in a very small range of values, corresponding to the temperature and properties of seawater. Thermal radiation for other targets that may be present in the scene (such as people or objects), correspond to much larger range of values (since they are composed of more materials and temperature variations), even though they are a small percentage of the image, leading to a blurry result, and making scene objects detection and identification particularly difficult task. This problem is greatly mitigated by contrast enhancement which redistributes the brightness values of the pixels so that their distribution looks more like a uniform one. Bilateral filtering is used for image denoising while preserving edges for objects' detection and identification. Parameterization includes window length of the bilateral filter, focal depth of virtual camera, near and far focal plane position.

For the representation of scene objects according to the thermal radiation they emit, several levels of information are needed:

- 3D representation of models, in the form of points in 3Dspace and triangles formed between them. This representation, known as a mesh, is widely used in computer graphics applications, and is preferred over alternatives due to its simple structure and low memory requirements. Additionally, newer graphics cards contain chips that are specifically designed for geometry processing and scaling a model's number of triangles.
- Appropriate texture which describes the distribution of heat in the various areas of the model’s surface. An example of such a texture for the Leslie cube scenario is shown in the following Figure. Brighter values correspond to warmer areas.

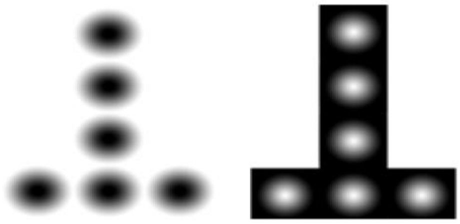

Figure 1: Examples of temperature distribution textures

The accuracy of the specific texture unfortunately is a particular limitation for the simulation, as an object can consist of many materials with different parameters. For such cases it

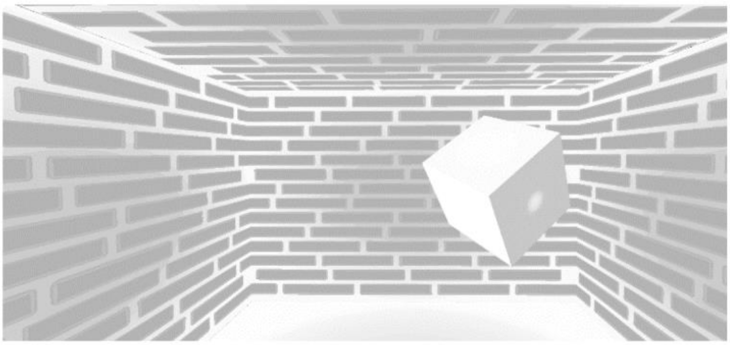

Figure 2: Leslie's cube: thermal rendering in a white-hot color palette

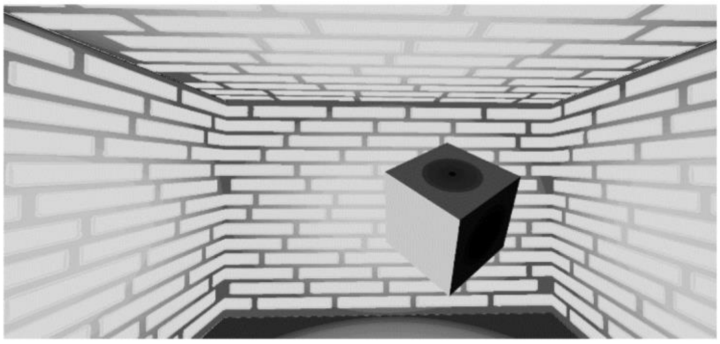

Figure 3: Leslie's cube: thermal rendering in a black-hot color palette

is difficult not only to find the appropriate parameters of the respective material, but also to design the texture itself, since each pixel needs to be mapped to the material of the object at the specific point. Although these problems are unavoidable, they do not significantly undermine the quality of the simulation. An additional and important parameter is the color palette in which the object is depicted. The thermal imaging system provides three options for the user: white-hot, black-hot, and pseudocolor. Each of these options has its own advantages and disadvantages, not only in terms of the preferences of each user, but also based on the weather and environmental conditions in which it is used. The white-hot option displays hot objects in bright grayscale colors. It is particularly useful in target recognition problems. The color contrast offers noticeable benefits in finding targets, especially in environments with low temperatures or when the user is looking at the horizon. Finally, the understanding we have of human vision and perception in general, highlights the importance of the use of pseudo-color. Specifically, humans associate cold with the blue color and warm with red color. In addition, a version of the pseudo color, red-hot, has been implemented. It is useful for target detection, especially in "crowded" scenes containing many objects. Thermal rendering of the 3D object in the 1st use case (Leslie's cube) in a white-hot and black-hot color palette can be seen in Fig.2 and Fig.3, and in a red-hot color in Fig.4.

The trainee can interact with virtual with the use of the controllers of the VR headset. The cube has 6 degrees of freedom; therefore, the user is able to move the cube in all directions, and to rotate it with respect to all axes. Moving the cube in the x-y plane (up and down) is done using the left thumbstick while moving in depth (z plane) is done with the

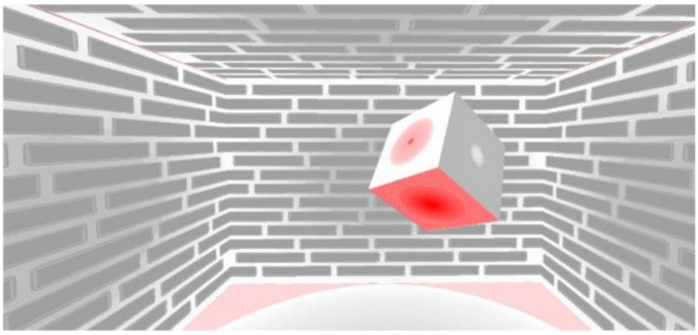

Figure 4: Leslie's cube: thermal rendering in a black-hot color palette

left trigger. The rotation of the cube is done with the right thumbstick. This option is the most "instinctive", i.e., it is easy for the user to understand even if they are not given instructions for use.

2.2 GUI and communication system

The design and development of the trainee-trainer interface and communication system includes the definition and development of GUI components, networking, and the architecture of the communication system. To this end the following have been designed, implemented and optimized: 1) the parameter selector (a large vertical sub-window on the left side with a multitude of selected widgets responsible for setting a specific parameter of the training scenario); 2) minimap (allows the trainer to view the field of view of the trainee and to understand each trainee's progress, if there is a need for help, and offer tailored support); 3) participant list (widget that shows which trainees are participating in the simulation, and gives the trainer various options and possibilities to interact with specific trainee(s); 4) chat (the trainer has the ability to compose messages and send them to the trainee of choice, ability for participants to select and exchange predefined messages from a list using the joystick; 5) stream widget (streaming frames from the trainee's virtual camera to the trainer's sync app allowing him to give informed advice to the trainee, seeing exactly what he sees). The dimensions of widgets of the interface have been designed considering the percentages of the screen that each widget should cover, maintaining the correct proportions regardless of the size of each screen. For the communication of trainee-trainer server-client model has been adopted which addresses the requirements of asynchronous communication. Listener is responsible for incoming connections and messages, while the Dispatcher reads metadata of each message, identifies the sender and the "purpose" of the message, and forwards the message to the responsible operator. Handler includes a set of message processing procedures, each designed to handle a specific type of message; it stores the data in common registers, to be used by the main program. Data processing and networking are performed in the background, and all the necessary processes are automated. The trainer defines through the input components of GUI the parameterization of the scenario, setting up and adjusting the training, during its initialization.

3. Conclusions and future work

Towards finalization of virtual 3D thermal imaging of the Leslie's cube, next steps include flickering correction of thermal rendering for the sides of the cube. For the realistic scene and for the needs of search and rescue training scenario for the surveillance of a marine area, volumetric rendering of thermal models of the defined scene objects will be developed, while the simulation of thermal imaging of these objects with immersion in the virtual environment needs will be performed along with the design and development of user interactions with 3D virtual objects, addressing the needs of the training scenario. In addition, the GUI for the trainer needs to include parameters for the training scenario of the 2nd use case. The system prototype will be tested and evaluated by trainers of the Hellenic Naval Academy in a pilot study for the surveillance of a marine area. Evaluation results will drive the development of the final PICTUM system.

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