Proceedings of the 2020 IEEE International Conference on Information Technologies (InfoTech-2020)
17-18 September 2020, St. St. Constantine and Elena, Bulgaria

Building a Virtual Reality Fire Environment based on Fire Dynamic Simulator

MpesianaTzani[1], Jeries Besharat[1], Vlasis Charalampous[2], Chrysostomos Stylios[1,2]
[1]Computer Technology Institute and Press "Diophantus", "D. Maritsas" Building, N. Kazantzaki str., University Campus of Patras, 26 504 Rion
[2]Department of Informatics and Telecommunications, University of Ioannina, Greece
tzani@westgate.gr, jeries.besharat@kic.uoi.gr,vlasis.charalampous@kic.uoi.gr, stylios@cti.gr, stylios@uoi.gr

Abstract – **A virtual reality environment offers advanced simulation abilities for training purposes to increase interactive learning experience. The aim of this paper is the investigation and designing of a virtual reality environment to simulate the fire spread inside a room based on a well-known approach called Fire Dynamic Simulator (FDS). FDS achieves a realistic and accurate approach in describing any fire spread, due to its advanced mathematics formulas and models. The visualization of the fire spread in a VR system is more realistic by entering accurate data, which could be provided by the FDS. This virtual reality application could be used for fire extinguishing simulations. Utilizing FDS technical scientific methods, we can borrow and customize them so that we can make a more comprehensive application in Unity in the future to create a full environment with multiple possibilities. This might be supportive for firefighting training and knowledge about how fire evolves. This offers the opportunity to improve firefighting training in an ecofriendly virtual environment with affordable validity, leading in a safe evaluation of fire behavior in various scenarios that would otherwise be very dangerous to examine.**

Keywords – **Fire Dynamics Simulator (FDS), Fire simulation, Fire training simulator, Virtual Reality, Unity 3D**

I. INTRODUCTION

Fire initiation and spread is a complicated and a challenging operation. The simulation of indoor fire has been rendered in several computational attempts. First attempts to model such phenomena are the Zone models, introduced by Jones [1]. The physical and computational simplicity of these models in fire scenarios has contributed to their widespread use. However, the rapid development of computers, as well as the advances in Computational Fluid Dynamics (CFD) led to the development of new tools, widely used in indoor fire simulations. The utilization of those tools allowed the explanation of fire propagation processes through complex geometries, by integrating a broad range of physical properties. Such methods are based on time-completed Navier-Stokes equations and the average Reynolds equation (RANS) [2].

Fire is a complex topic that can be explained mathematically, physically, chemically and by various elements and factors, such as fluid dynamics, combustion, combustion of associated energy transfers such as radiation, etc. All these components, which are mathematically condensed, are part of the computational core of the software utilized in the particular study. Throughout this time, FDS is the most used software method by researchers around the world to forecast fire phenomena [3].

Fire Dynamics Simulator (FDS) is a powerful Computational Fluid Dynamics (CFD) model developed at the National Institute of Standards and Technology (NIST, Gaithersburg, US). It is written in Fortran 90, which has been used for modeling a variety of phenomena, such as pyrolysis, combustion products by fire, spread of fire and smoke. As its creators mention, ‘‘the model solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally driven flows with an emphasis on smoke and heat transport from fires’’ [4].

Our proposed approach, is based on the Fire Dynamic Simulator (FDS) 6th edition simulation fire models. Our study concerns simulating the spread of fire with FDS data in virtual reality. Thus we make the system more accurate if we rely on real features and data, so that the simulation is even closer to reality. The outputs of FDS are used as inputs in Unity 3D script. These measures boost Unity 3D fire engine models resulting in a more effective simulation of fire position and a more practical backfire model. In this paper, we demonstrate that VR is a promising complementary laboratory method for understanding the fire behavior and enhancing fire safety. This paper explores the development of a virtual reality program to teach non-professionals in the use of fire extinguishers. Virtual Firefighting is beneficial compared to firefighting training in a real environment in terms of health, simplicity and the preference of training scenarios [6, 7].

II. RELATED WORK

Visualizing models for educational functions is neither a new concept nor an idea tailor-made to the content material of contemporary virtual reality. New opportunities for continuous improvement are more and more arising. There are few similar papers to ours written for simulated fire spread. Each of them are operated in virtual surroundings with simulated fireplace scenarios, even as they face various obstacles and have different objectives and expectancies. Thus, we summarize various studies and research carried out on the simulation of fire and the corresponding training environments based on virtual reality. Most of the studies emphasize the benefits of this approach compared to conventional training methods.

D.L.Tate et al. highlights the importance of virtual reality in the simulation of fire for training purposes, as opposed to conventional training [8]. Similarly, studies have been conducted on the basis of serious games fire-scenario training to develop user skills in evacuation scenarios [9],

978-1-7281-6913-2/20/$31.00

education for victims 'rescue [10] and children's education in possible high-risk scenarios [11]. These studies relied on gaming technology, serious-game, not so much on the entertainment side as on the leisure side of this technology. They have thus shown that simulations in a virtual environment can and do play an important role in the field of training, much more in fire protection. However, precisely because they focus on this part of the research, they leave a large part that needs to be improved and developed, that of realistic fire simulation based on true fire behavior data.

The first attempt to simulate fire in a virtual environment was made by Richard et al. in the Walkthru-CFAST system [12]. Prior to the advent of Computational Fluid Dynamics (CFD) and Fire Dynamic Simulator (FDS), this system was widely used in studies and research if one considers the simplicity of the system and the quick results it generates. The weakness was the limited ability to capture geometries, but also the ability to capture them in 3D depiction.

Another study from Julien et al. (FCTVE), focuses on the development of a firefighting training system where users used avatars to execute user commands [13]. The aim of this study was a home scenario that set fire to rescue training in certain situations. Fire protection companies were to use this research, thus they needed a realistic simulation. As a result, they relied on the simulation of FDS using dynamic data to spread fire and smoke. However, no further development has been made in the processing of these data and, accordingly, accurate data on physical characteristics represented only the spread of smoke. Another paper [14], presents a different approach, in which they only use smoke effects. Smoke Coordinates based on FDS Simulation and they do not interpret the movement of the fire as it spreads.

An important difference between the particular work and the related proposals is that we consider other outputs such as burning time and Mass Loss Rate (MLR), not just the smoke produced while we use Unity directly without any simulation technology that can be integrated into real-time graphics engines and allows physics calculations. Based on this work we can appreciate that although these approaches have seen excellent results, they can also achieve more outcomes based on actual data, by applying FDS, that is fire modelling software to virtual reality instead of simply portraying or expanding the fire, thereby bringing it closer to expression.

III. Proposed Approach

This paper guides through the development of a virtual fire training application to offer an insight on designing a practical training alternative with an immersive learning practice in virtual reality. Applying VR methods to the firefighting helps the training process through the simulations and the potential they offer for easy alternation of fire scenarios [15]. A good training experience can help to recall right choices in emergency situations fast. Due to safety security requirements of real fire training, non-professional trainees are learning within limited circumstances and are not dealing with the impact of smoke development and the enormous fire growth in indoor rooms. Nevertheless, the lack of actual fire greatly improves protection and thus the protective precautions can be drastically decreased. There is a key iterative aspect from the point of view of such a VR simulation method for training firefighters: the simulation of how the fire progresses for simulation advances. When the trainees are given a rather unrealistic action of the flames, the immersiveness and reliability of the simulation will be drastically diminished, and the training objectives compromised. This is where the value of the FDS lies in the implementation of mathematical models describing the propagation of fire with high accuracy and thus giving the approaching VR system functionality (Figure 1).

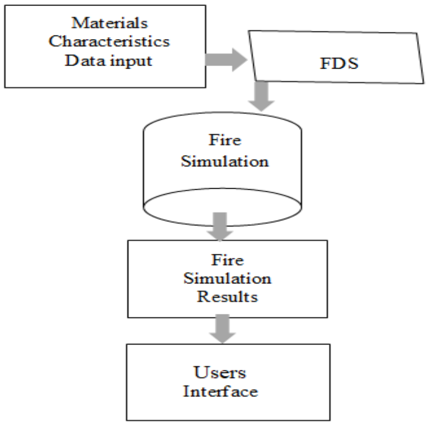

Figure 1. FDS simulation flow

The FDS code function is the estimation of several physical measurements (temperature, velocity, pressure, density, chemical composition, etc.) for each time step in each grid cell. It should also be mentioned that the amount of quantities that can be defined in each cell is considerably higher than the quantities that can be measured in an experiment [4]. The results of the simulation are represented using Unity 3D.

IV. System Design

In general, FDS code uses the 'mixture fraction' model. This model assumes that combustion is controlled by fuel mixing and oxidizing phenomena and that the reaction of the fuel with the oxidant becomes instantly fast. The basic characteristics of all materials and geometries used in the test room are based on prototype standards extracted from experimental studies and measurement of real objects and ISO standards. The basic characteristics of the materials we use were measured and modeled in a cone calorimeter heating system (ISO 5660) [16]. To use in mathematical fire models, such as Fire Dynamic Simulator (FDS), appropriate values for the material properties of heat capacity, thermal conductivity, surface emissivity and ignition temperature are given.

FDS usage must be legitimate and allow conveniently enhancing the parameters of the fire script they want to study. This means that the user only specifies a limited number of parameters for computations, based on the physical nature of the problem. The possibilities for data input mainly concern the geometry of the space required to be studied, the time in which it is desired to simulate the phenomenon, the properties of the materials being used (e.g.

to describe the furniture material), the combustion properties of such materials (density, temperature of ignition, etc.), and the computational domain initial external boundary conditions (e.g. density, temperature, air speed, etc.).

The user defines rectangular objects which are placed in specific locations, and which should be integrated harmoniously into the grid. The most important numerical parameter in the FDS code is the size of the grid, since this defines the degree of space accuracy. A &MESH is a single parallelepiped box. The coordinates of the grid follow the rule of the right hand. The starting point of a grid is defined by the first, third and fifth values of the integer number sextuplet, XB, and the opposite angle is defined by the second, fourth and sixth values. For example, in our test room we use the following:

&MESH IJK=10, 20, 30, XB=0.0, 3.0, 0.0, 3.0, 0.0, 4.0 /

This defines a mesh that spans the volume starting at the origin and extending 3 m in the positive direction (x), 3 m in the positive direction (y), and 4 m in the positive direction (z). The mesh is subdivided into uniform cells via the parameter IJK [4]. In this example, the mesh is divided into 10 cm cubes.

The FDS uses time and space calculations with second order precision. This means that if we reduce a cell's size to half the equation error will be decreased 4 times, while the simulation time will be increased 16 times. Consequently, the denser the grid, the greater the precision of the system, which is based on the ' high vibration simulation ' process [3]. In the FDS code, the dimensions of the grid must be 2l 3m 5n, where l, m and n are integers [4]. Via the parameter T_END the duration of FDS simulation is defined. For the particular experiment's test room the following command line is used to designate the time execution to 3000 seconds. Time step size has been specified with DT command

&TIME T_END=3000. DT = 0.01/

We define the properties of each material via the character string MATL_ID. The character MATL_ID is assumed to be a list of the materials in multiple layers, each layer consisting of only a single material component. These properties describe the velocity of heat and burn corresponding to a specific material. Each input of the MATL_ID character gives information about materials thermal properties. The following example (Figure 2) shows blocks of code material description used as input in FDS.

```
&MATL ID                    = 'Wooden_cendar'
      HEAT_OF_REACTION      = 1000.
      CONDUCTIVITY          = 0.2
      SPECIFIC_HEAT         = 1.0
      DENSITY               = 570.
      N_REACTIONS           = 1
      NU_SPEC               = 1.
      SPEC_ID               = 'cendar'
      REFERENCE_TEMPERATURE= 390. /

&SURF ID                    = 'table'
      COLOR                 = 'Brown'
      MATL_ID               = 'Wooden_cendar'
      THICKNESS             = 0.20
      BURN_AWAY             = .TRUE.
      BACKING               = 'EXPOSED' /
```

Figure 2. &MATL_ID, &SURF_ID character

The SURF command describes the properties of the boundary conditions (color, thickness, etc.). The MATL Command defines the thermal properties of each component (conductivity, density, etc.). Each MATL_ID is connected to a particular SURF command with the common element name or ID. The SURF command also helps one to evaluate the thickness of a wall or material which is a very useful element that can be used in Unity 3D plugin.

The command & OBST is inserted to describe the walls as for every solid object which occupies a dimension. In this particular case we explain the apartment's south wall. The volume filled by the wall begins for example (Figure 3), from the point 1.23 of the x-axis and expands towards 1.77.

```
&OBST XB= 1.23, 1.77, 0.45, 0.48, 0.03, 0.57 /
SURF_ID='wall out', SURF_ID ='wall in', OUTLINE=.TRUE./ south wall
```

Figure 3. &OBST command

In the FDS code it is possible to calculate a plurality of physical sizes (ignition time, HRR, MLR, pressure, chemical composition, etc.) in each grid cell for each time step. Typical amounts of output data are radiation or syncope heat flux, burning time, combustion rate, mass of liquid droplets per unit volume etc. All output quantities must be specified at the start of the calculation. In our simulation, the variables we decided to focus on are the burning time and the MLR Total (Table 1).

TABLE 1. I.E OF ATTRIBUTES AND VALUES EXTRACTED BY THE FDS

Time (s)	Q_TOTAL (kW)	MLR_TOTAL (kg/s)	ZONE_1 (Pa)
2.59E+00	5.21E+01	9.00E-07	7.62E+04
2.62E+00	5.83E+01	4.19E-07	7.74E+04
2.65E+00	5.64E+01	0.00E-07	7.86E+04

We focused mainly on the aforementioned characteristics because these two variables define the amount of mass each material loses over a predefined time step. Each time step in the output file corresponds to a specific mass loss of geometry. Hence the total time of burning is subtracted from the time that MLR has now reached zero and corresponds to that particular time. Similarly, for the MLR we can conclude that the average of the values gives us the average mass loss rate of the material. After the model experiments, it is reasonable to conclude that as we increase some variables, such as density, the burn time of the material increases and the rate of MLR decreases. On the other hand, if we retain the variables of geometry constant and adjust the runtime of the model, or the time step, we observe a slight divergence. This is vital because in the second case if we increase the timing step, the precision provided by the model decreases. These two variables (MLR and burning time) along with atmospheric conditions, orientation and air velocity are the key elements needed to visualize the spread of fire through Unity 3D.

V. SYSTEM INTERACTION

The purpose of the development is to provide an immersive learning application, which should also be customizable for further development. For the design, we chose Unity 3D, which is a high-level game engine and supports a fast-developing process. So from the CSV file of FDS, we mostly use burning time (the time required to burn the material completely) and the Mass Loss Rate (MLR) while we keep the same integers for Unity 3D plugin about the geometry of the room and the materials we want to include inside the room. In Unity3D engine, several functionalities are already implemented and ready to use. Particle systems are available and come with great adjustment possibilities. For identifying and developing 3D geometries, we used BlenderFDS [3], which is a tool that allows the graphical creation of simple or complex geometry. Specifically we created a chair, a sofa and a table for our experiment and the values we used for each one are presented in table1. [17].

TABLE 2. FURNITURE VALUES

Furniture	Dimension (cm)	Density (Kg/m^3)	Temp. ignition (C)	Thermal conductivity (W/m/K)	Specific heat (kJ/kg/K)
chair	52x48x96	510	390	0.113	2301
sofa	80x38x39	48	435	0.054	1900
table	23x23x19	630	400	0.12	1700

After the data is submitted, the FDS displays us something identical to the image (Figure 4).

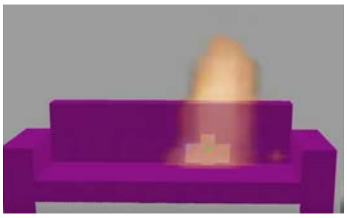

Figure 4. FDS depiction

We have inserted the thermal characteristics for this geometry into the algorithm, and FDs allocate us the time spreading of the fire and the resulting MLR for this geometry's combustion process. It seems like 3D visualization here can be further developed and improved through unity.

VI. CONCLUSION

The designed framework of this work guides trainees through a secure fire training experience without endangering human life or wasteful spending on the creation of unrealistic fire training. The fact that the simulation is based on real characteristics for our geometers, also the burning time and the MLR parameters resulting from FDS make a difference in this research providing a more realistic representation of the indoor fire spread by Unity 3D.

The current framework is also more advanced compared to related studies with respect to the training environment by providing indoor scenarios for simulated firefighting. Virtualizing the interaction workspace allows the fire system to be dynamically modified and does not require an unpleasant creation process, as would be the case in a true realistic fire scenario.

VI. FUTURE WORK

For our current research, Unity 3D was very useful at guiding us for the first simulation attempt. It appears, of course, that the Unity script is capable of developing for future research and so the test room. Since virtual reality systems and technology are increasingly developing, Unity is likely to increase the complex of geometers used and the complexity of the room materials. This means the incoming FDS data would be increased to provide the data needed for each material and geometry.

Yet another aspect of further research is the inclusion of expertise on the reaction of the system and even its interaction with humans in the process of firefighting training. The experts but perhaps more, the trainees themselves will help examine how user-friendly even practical the program would be, as well as data on firefighting training progresses. Finally firefighting experts will be interested in examining and modifying more virtual objects except extinguishers to dampen the fire, such as towels, blankets etc.

ACKNOWLEDGMENT

This research work is co-funded by the Operational Programme “Western Greece” 2014-2020, under the project “Virtual Reality Simulator for Training Against Fires, V-staff, Co-financed by the European Regional Development Fund (ERDF).

REFERENCES

[1] Jones, W. W., & Quintiere, J. G. (1983). Prediction of Corridor Smoke Filling by Zone Models. Combustion Science and Technology, 35(5-6), 239–253

[2] McGrattan, K., & Miles, S. (2016). Modeling Fires Using Computational Fluid Dynamics (CFD). SFPE Handbook of Fire Protection Engineering, pp1034–1065

[3]McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., & Overholt, K. (2015). NIST Special Publication 1018-2 Sixth Edition Fire Dynamics Simulator Technical Reference Guide Volume 2: Verification.

[4] NIST Special Publication 2019, Sixth Edition, Fire Dynamics Simulator User’s Guide, Kevin McGrattan, Simo Hostikka, Randall McDermott, Jason Floyd, Craig Weinschenk, Kristopher Overholt

[5] McGrattan, K., Hostikka, S., McDermott, R., Floyd, J., Weinschenk, C., & Overholt, K. (2013). Fire dynamics simulator technical reference guide volume 1: mathematical model. NIST special publication, 1018(1), 175.

[6] Cha, M., Han, S., Lee, J., & Choi, B. (2012). A virtual reality based fire training simulator integrated with fire dynamics data. Fire Safety Journal, 50, 12-24.

[7] D. L. Tate, L. Sibert and T. King, "Using virtual environments to train firefighters," in IEEE Computer Graphics and Applications, vol. 17, no. 6, pp. 23-29, Nov.-Dec. 1997.

[8] Tate, D. L., Sibert, L., & King, T. (1997, March). Virtual environments for shipboard firefighting training. In Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality (pp. 61-68). IEEE.

[9] Backlund, P., Engstrom, H., Hammar, C., Johannesson, M., & Lebram, M. (2007, July). Sidh–a game based firefighter training simulation. In 2007 11th International Conference Information Visualization (IV'07) (pp. 899-907). IEEE.

[10] Chittaro, L., & Ranon, R. (2009, March). Serious games for training occupants of a building in personal fire safety skills. In 2009 Conference in Games and Virtual Worlds for Serious Applications (pp. 76-83). IEEE.

[11] Smith, S., & Ericson, E. (2009). Using immersive game-based virtual reality to teach fire-safety skills to children. Virtual reality, 13(2), 87-99.

[12]Bukowski, R., & Sequin, C. (1997, August). Interactive simulation of fire in virtual building environments. In Proceedings of the 24th annual conference on Computer graphics and interactive techniques (pp. 35-44).

[13] St. Julien, T. U., & Shaw, C. D. (2003, October). Firefighter command training virtual environment. In Proceedings of the 2003 conference on Diversity in computing (pp. 30-33).

[14] Xu, Y., Kim, E., Lee, K., Ki, J., & Lee, B. (2014). Using PhysX Simulation Fire Model of Backdraft in Unity 3D Game Engine. International Journal of Multimedia and Ubiquitous Engineering, 9(6), 243-252.

[15] Freund, E., Rossmann, J., & Bucken, A. (2005, March). Fire training in a virtual-reality environment. In Stereoscopic Displays and Virtual Reality Systems XII (Vol. 5664, pp. 388-394). International Society for Optics and Photonics.

[16] Babrauskas V. (2016) The Cone Calorimeter. In: Hurley M.J. et al. (eds) SFPE Handbook of Fire Protection Engineering. Springer, New York, NY

[17] Blomqvist, J., & Andersson, B. (1985). Modelling of furniture experiments with zone models. Fire and Materials, 9(2), 81–87.