THE FIREWALK SYSTEM: FIRE MODELING IN INTERACTIVE VIRTUAL ENVIRONMENTS

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ABSTRACT

The authors present an overview of the FireWalk system, which combines the Berkeley Architectural Walkthru Program with the NIST CFAST fire simulator. The system allows fires to be created, controlled, and observed from directly within a virtual building environment.

INTRODUCTION

Integration of powerful simulation technology with virtual reality visualization systems affords the possibility of intuitive interpretation and visualization of the results of complex and powerful simulations via 3D computer graphics. We are attempting to realize some of these advantages for the benefit of fire safety in architectural environments by combining the National Institute of Standards and Technology's (NIST) Consolidated Model of Fire and Smoke Transport (CFAST) with the Berkeley Architectural Walkthrough (Walkthru) system. CFAST currently provides the world's most accurate computer simulation of the impact of fire and its byproducts on a building environment; Walkthru is an ongoing project at Berkeley that provides real-time (10 frames per second), interactive, three-dimensional walkthroughs of architectural environments derived from AutoCAD floorplans. Together, they provide real-time, intuitive, realistic and scientific visualization of building conditions in a fire hazard situation from the perspective of a person moving around inside a burning building. The viewer can observe the natural visual effects of flame and smoke in fire hazard conditions; alternatively, scientific visualization techniques allow the user to "observe" parameters such as the concentrations of toxic compounds in the atmosphere or the temperatures of the atmosphere, walls, and floor. Warning and suppression systems such as smoke detectors and sprinkler heads can be observed in action to help determine the effectiveness of those systems. VCR-style controls and point-and-click graphical interfaces simplify interaction with both the fire model and the building model, and our building model generator (BMG) provides the ability to directly derive both CFAST's architectural data and the Walkthru's virtual building model quickly from a set of two-dimensional AutoCAD floorplans. The system also allows the use of multiple computers or processors to provide real-time performance for both the simulator and the virtual environment visualizer.

BACKGROUND

In this section, we describe the two software platforms on which the system is based: the Berkeley Architectural Walkthru program, and the National Institute of Standards and Technology's Consolidated Model of Fire and Smoke Transport (CFAST).

Walkthru

The Berkeley Walkthru program was developed at the University of California, Berkeley, in the early 1990's. The goal of the Walkthru is to provide real-time interactive visualization of large (several million polygons), densely occluded building models at interactive frame rates (greater than 10 frames per second) [3]. To accomplish this goal, the Walkthru subdivides the "world" into rectilinear *cells*, connected by *portals*. In a preprocessing step, the system associates with each cell the set of all other cells that can be seen by an observer from any point within that cell. From this information, plus constraints on how quickly the observer can move through the database, the Walkthru can compute a set of cells for each frame that tightly, but conservatively, bound the set of cells visible in the next few frames [8]. This visibility computation is performed in real time and leads to the Walkthru's high frame rates. In the last few years, Walkthru has provided a testbed for several applications including database construction [1], large scale radiosity computation [7], and scalable distributed walkthroughs with up to thousands of simultaneous users [4]. This technology can now be leveraged into support for distributed virtual environment (VE) simulation, via the FireWalk project.

Figure 1: Scenes from the Berkeley Architectural Walkthru program running on a model of our computer science building, Soda Hall. On the left, a view overlooking the 6th floor atrium. On the right, a view of the loggia overlooking the street.

CFAST

NIST's CFAST is a state-of-the-art "zone model" fire chemistry and physics simulator [5]. It assumes an environment composed of rectilinear 3D volumes which are interconnected by portals (i.e. *vents*). Within each volume, physical quantities such as gas species concentrations, raw fuel density, combustion byproducts, atmospheric pressure and temperature, and wall, ceiling, and floor temperature are tracked. A system of differential equations monitors the flow and exchange of these quantities through vents into adjoining volumes. Although CFAST's building partition concept is analogous to the Walkthru's cell structure, CFAST does not require similarly precise geometry. Volumes have a floor and ceiling height as well as length and width, but only the area of the volume (length times width) is relevant. Volumes are not positioned in 3D space; only their size and height matters, and their connectivity through vents. Similarly, the exact X and Y location of the vents is irrelevant to the physics and is not represented; only orientation (horizontal or vertical) and cross-sectional area of the vent are needed, as well as the height at which it connects to the two prismatic volumes. Wall specifications include material and thickness information. The furniture database contains no geometry, but does include mass, materials, chemistry, and ignition and combustion curves for each type of object. Objects will ignite at predefined temperatures and burn as separate fires, producing appropriate physical and chemical effects on the environment. Other fire-related objects, such as sprinklers and HVAC ducts, affect the physics of the situation in realistic ways, but their only geometric component is positional information. Thus, the geometry of the CFAST situation can be derived from a Walkthru model, but the Walkthru model contains much more geometric information than CFAST represents; conversely, the unadorned Walkthru database contains none of the chemical, material, or "building systems" information (i.e. in-wall ductwork, piping, and wiring) needed by CFAST.

SETTING UP THE SYSTEM

There are two major preparatory phases involved in studying the physical response of a building to fire scenarios with the FireWalk system. In the first phase, the user must create a model of a building and populate the model with furniture, light fixtures, and other detail objects. This process defines the virtual environment, and once it is done, the user can use the Walkthru to "virtually" enter the building and walk around in it. The second step involves mapping the building structure to CFAST to define the volumes and vents to be used for simulation, and mapping the furniture and detail objects to the corresponding CFAST entities. In this section, we take a closer look at the population and mapping steps.

Model Generation

The traditional approach to model generation creates the geometric description of the building from scratch. The user runs some form of 3D CAD system such as AutoCAD (or even a simple text editor) to directly enter numerical coordinates of the structure's walls, floors, and ceiling. This method is slow, labor-intensive, and error-prone. A newer method has recently developed in the form of the Building Model Generator, or BMG, which was completed as a part of the Walkthru project [6]. BMG allows the user to load a two-dimensional AutoCAD DXF floorplan and create a complete, accurate 3D model with minimal user input. The DXF file must be partitioned into a specific set of layers, including interior walls, exterior walls, doors and door jambs, windows and window jambs, and room labels. This partitioning is often quite simple; architectural firms typically put these components onto separate layers, so in many cases the only work to be done is to relabel the appropriate layers with labels that BMG recognizes. Once the layers are properly labeled, the DXF file is loaded into BMG, where a series of operations is performed that takes the 2D model in DXF into a complete 3D model in the Berkeley Unigrafix format. The topological correction phase corrects small discontinuities at places where walls meet, making sure that walls are actually attached to each other at the corners, and that the contours of the floorplan are continuous and define proper interior and exterior spaces. A subsequent semantic analysis separates the interior space of the building into conceptual regions such as rooms and hallways. The 3D extrusion phase then takes the cleaned-up floorplans with consistent room contours and constructs complete 3D room boundaries by extruding the wall segments vertically and closing them off with floor and ceiling polygons. Door and window openings are added in a consistent manner. Finally, the building construction phase takes the 3D extrusion for each floor and combines them into a complete building model, adding a roof and stairwells that span multiple floors. During this process, the user supervises the work being done by BMG, correcting any errors made in the automated extrusion process. In general, BMG is far more robust than most existing packages that perform the same functions; its error-correcting capabilities are critical when attempting to extrude large, multi-floor buildings from architectural floorplans. Once a consistent 3D geometry description has been created, either manually or with BMG, the model may be compiled for the Walkthru program, creating an efficient internal binary representation which is used for real-time viewing.

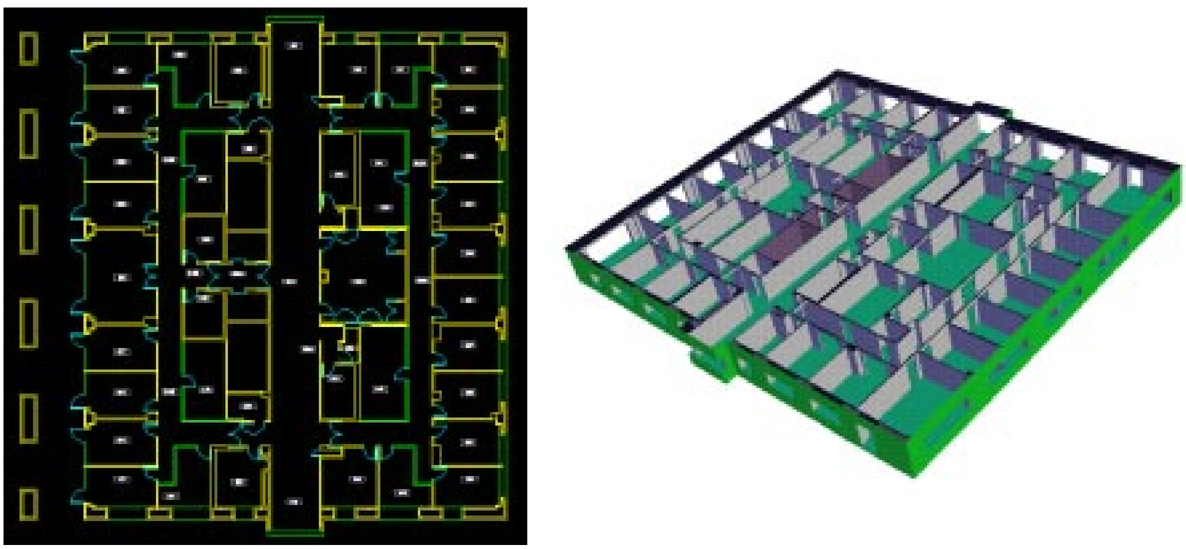

Figure 2: Extruding a model with BMG. On the left, an AutoCAD floorplan. On the right, the automatically extruded 3D floor.

Populating the Model

The initial modeling step results in a 3D building structure devoid of detail objects such as furniture, light fixtures, window panes, or doors. The empty building shell is furnished using the Walkthru editor. This gives the user access to the furniture models in the Walkthru library, which contains a large number of chairs, tables, desks, bookshelves, lights, and other furniture. Alternatively, new furniture can be designed and inserted by the user by creating a master Unigrafix model of the new piece. The editor's Object Association system allows the user to quickly and intuitively place furniture by clicking and dragging pieces to place desks, picture frames, and bookshelves against walls, position chairs and wastebaskets, and place books, cups, pencils, and desk lamps [1]. Realistic furniture layouts take only minutes per room, and are automatically properly aligned with the floor, walls, and ceiling. Standard cut, copy, and paste operations allow the user to duplicate entire desks or shelves full of other objects, easing the tedium of replicating furniture arrangements between similar offices.

Figure 3: Populating the model. On the left, a bare building model, with no furniture. On the right, a populated room with many objects, including tables, chairs, bookshelves, and books. The room on the right was furnished in about 6 minutes with the Walkthru editor.

Mapping the Building to CFAST

The third step in preparing a virtual environment for use with the FireWalk system involves creating three *simulator mappings* of the virtual environment's building elements. These mappings allow the CFAST subsystem to extract the needed geometric information and furniture burn profiles from the virtual environment model, freeing the user from having to type in room sizes, vent locations, and building materials each time a simulation is to be run.

The first major mapping, the *geometric mapping*, associates rooms with CFAST volumes, and doors and windows with CFAST portals. If the building model was extruded with BMG, the geometric mapping step is trivial: BMG produces the geometric mapping file as a side effect of 3D model creation. If the model was made manually, then the geometric mapping must also be done manually. The FireWalk system provides mechanisms that make manual geometric mapping more convenient. The user must walk to each room in turn and click on two opposing corners of the room, one on the ceiling and one on the floor. This establishes the *bounding box* of the room to the system. The portals between the rooms (i.e. the doors and windows) are specified in a similar fashion. Once the rooms and portals have been designated, the system generates the geometric mapping file for the building.

The *materials mapping* defines the composition of the walls, floors, and ceiling of the building. Materials for these structural surfaces may be selected separately for each room in the building. The FireWalk database currently contains all the materials included in the standard CFAST distribution; there are 45 types in all, ranging from acoustic tile to Vermiculite. Materials may be assigned to individual surfaces, or, if the building construction is uniform, the user can easily assign one material to all walls, ceilings, or floors in the building.

Finally, the *object mapping* must be generated for the building's furniture. This operation involves matching Walkthru furniture classes to CFAST object burn profiles. The user does not have to specify a correspondence for all of the Walkthru classes; however, any Walkthru class that does not have an associated CFAST class will not contribute to the evolution of simulated fires. When the system initiates a simulation, each of the volumes in the geometric mapping is queried for Walkthru objects that have corresponding burn profiles. For each such object, a CFAST simulation object with the appropriate burn profile is generated in the correct place in the volume. The current FireWalk object database contains all of the burn profiles provided with the CFAST distribution; unfortunately, this amounts to less than 20 burn profiles, most of which do not match any Walkthru object (e.g. Christmas trees, or paper bags). Additional burn profiles will be needed in order to make this capability more useful. Ideally, we would like to have a library of FireWalk object pairs, including common objects such as chairs, bookshelves, and desks, where each pair includes both a Walkthru model and associated CFAST burn profile. This database would allow the user to find an appropriate model for the simulation case at hand and insert both the Walkthru and CFAST data for the object at the same time.

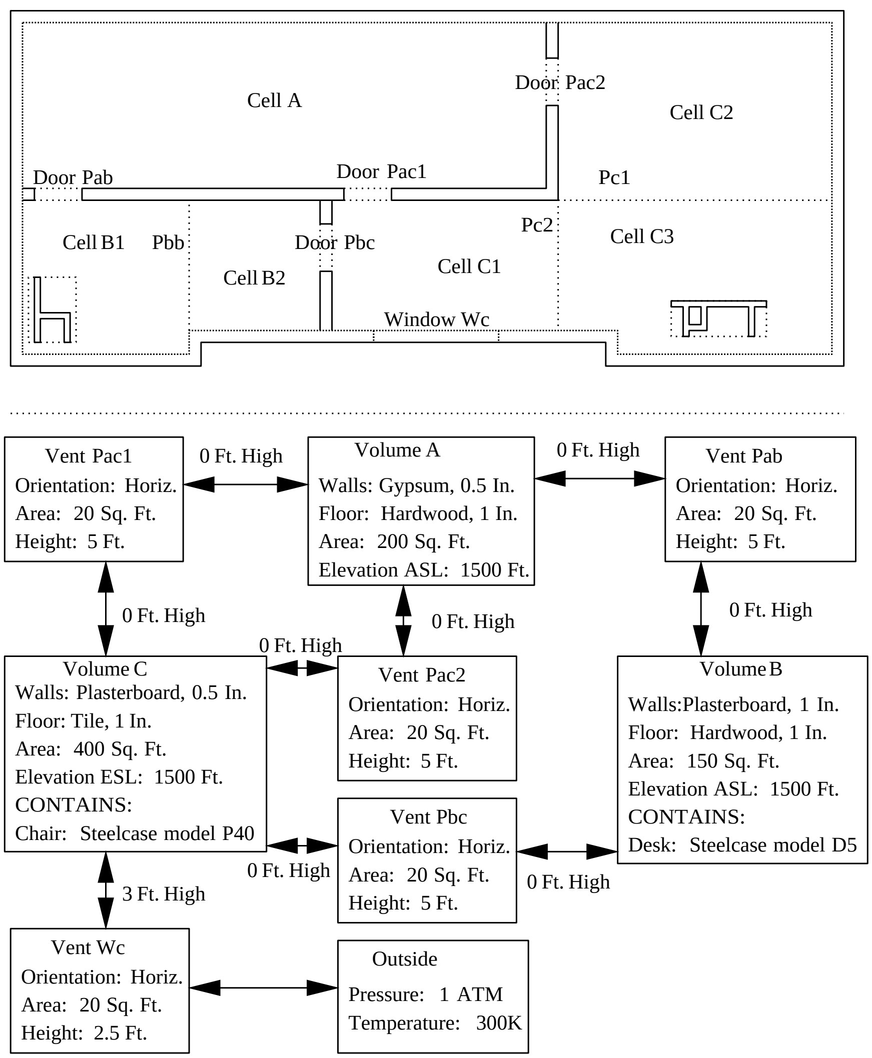

Figure 4: How Walkthru (top) and CFAST (bottom) would "see" the same model. The Walkthru model contains detailed geometric information, but little else; the CFAST model is geometrically much simpler, but contains chemical and materials information that Walkthru lacks. The various simulation mappings reconcile these two "world views."

INTERACTIVE SIMULATION

Once the virtual environment and its mappings to the CFAST system have been set up, the user can control and study the effect of a fire scenario from within the virtual environment.

Defining a Fire Scenario

There are two ways to define a fire scenario in the FireWalk system. The first is simply to use the existing CEDIT tools, which are a part of the CFAST distribution, to create a CFAST data file containing the chemical equations, burn profiles, and ambient conditions for the desired fire. When creating this file, however, the user need not specify any of the building geometry or material information which is expected in a typical CFAST data file; that information is already present in the virtual environment, and will be automatically exported to the simulator. This data file may then be loaded into FireWalk, which will extract all of the chemistry, burn, and ambient information from the file. Once this information is loaded, the user points and clicks in the main view window to "set" the fire.

The second way to define a scenario is to create the chemistry, burn, and ambient information within the FireWalk system itself. The system provides a set of input forms and graphs through which the user can set up most of the same physical fire information that can normally be set within CEDIT. The fire location is then set by point-and-click as before. Note that the user need not know the volume number of the room in which the main fire will start; the system derives the volume number from the surface on which the user designated the origin point of the main fire.

Simulating the Fire

During a simulation, CFAST may be running on the local machine (local simulation), or any other machine on the Internet (remote simulation). The advantage of remote simulation is potentially higher performance, since the computational load of the fire simulation, user tracking, and rendering the virtual environment are distributed among multiple machines. Furthermore, the remote machine might be much better suited to running CFAST than the user's own machine (i.e. a remote supercomputer), providing additional computational advantage.

Local simulation is the default; remote simulation requires installing and running the special "server" version of the CFAST simulator on the remote machine. This *simulation server* will remain inactive until the user's local machine requests a simulation. Communication and control of the simulation server is completely automatic; all the user has to do is make sure the server is running. We expect this capability to be useful to users in the field, who will be able to use cheaper PC-type computers to run the Walkthru front end while running the simulator on a mainframe or large simulation server over a modem connection. To this end, we have developed new simulation data transfer technology to support this project [2]. This new technology enables the FireWalk system to operate on large models interactively, in real time, over such relatively slow links as PC modems.

Simulations are initiated manually via a menu selection. After FireWalk starts CFAST on the local machine (if local simulation is being used) or initiates communication with the simulation server on the remote machine (if remote simulation is being used), it constructs a complete CFAST data file given:

- The virtual environment (i.e. the building model) and the mapping information, which allows the rooms to be identified, numbered, and measured as CFAST volumes, and also allows the portals to be converted into CFAST HVENT data statements;
- The detail object and material mappings, which allow the objects in the rooms to be classified as CFAST objects, and allows the system to compute their locations in the CFAST volumes and provide a complete object listing; and
- The fire scenario information, which completes the set of data necessary for CFAST to run.

All of this data is collated and transmitted to the simulator with no intervention on the user's part. Results are transmitted back to the user's terminal in real time, as they are generated, via a specially developed simulator-visualizer data transmission protocol [2]. In order to overcome the natural tendency of CFAST to produce its results in a "bursty" fashion (i.e. results for several seconds of simulation time all at once), FireWalk allows the simulator to get a "head start" of 10 seconds of simulation time before beginning to display simulation results. After that, the results of the simulation are "played back" in real-time; the user sees a representation of what a person in the burning building would see, at a realistic rate.

In order to better explore the results of the simulation, we present the user with a set of VCR-style controls. These controls include Play, Pause, Rewind, Fast Forward, and Reverse Play buttons, as well as a slider bar that spans the same range of time as the simulation itself. The normal mode is Play, which displays the conditions in the building at a time rate of 1 simulated second to 1 real second. The reverse play button allows the user to make time flow *backward* at a 1:1 rate. Rewind and fast forward display 10 simulated seconds to 1 real second, backward or forward in time respectively. Pause causes simulation time to stop; this is useful to observe events that happen very quickly, or to freeze time so that the user can explore the situation in the building at some particular instant. The user may also directly manipulate the slider bar to move directly to a particular simulation time point. This is useful for finding points in the simulation where something interesting happens; a point where the smoke reaches a window soffit, for example.

Realistic Visualization of Results

By default, the FireWalk system operates in *realistic visualization* mode. Fires are represented by a flickering flame texture which looks somewhat like a real fire, a smoke plume rises from the flame, and the rooms have flowing, grey, nearly opaque, smoke-textured panels at the zone interface. Portals between rooms that each contain smoke show a plume flowing through the portal from the lower smoke interface to the higher one.

Figure 5: The simulation controls provided by FireWalk. Note the VCR-style controls in the center under the time slider; these allow the user to control the flow of simulation time in the view window.

The graphics are sufficient to give an intuitive idea of what the conditions in the building would look like during the fire simulation scenario. Qualitative events like the fire spreading to nearby furniture, or the time that smoke reaches a room far from the main fire, can be observed, and the time of the occurrence can be noted from the simulation time readout on the control display.

Figure 6: Sample display screens from the FireWalk system in realistic visualization mode. On the left, a pool fire rages in a student office in a model of Berkeley's Soda Hall. On the right, the smoke fills the corridor.

Scientific Visualization of Results

Although the realistic visualization mode is useful to give a feeling for building conditions, fire safety evaluations require the ability to retrieve precise values for various physical quantities, as well as the ability to "observe" quantities that are not normally visible to a human observer. These quantities include concentrations of various toxic gases or oxygen in the atmosphere, and heat distributions in both the atmosphere and along the walls, floor, and ceiling. In order to relate this information, the FireWalk system allows for a set of *scientific visualization* modes. The selection of what quantities to visualize, and how to visualize them, is an ongoing research topic for both this project and the research community. To date, we have implemented one scientific visualization mode, which we call *thermal vision*. This mode allows the user to observe heat patterns on the walls, floor, and ceiling as a shading from room temperature (black) up to about 700 degrees Celsius (fully red). Thermal vision allows direct observation of how hot the environment is becoming. Fires are represented as red pyramids whose height is proportional to the thermal output of the fire in kilowatts. The smoke ceiling is disabled, so that the user can see the heat patterns on the upper walls and ceiling without obstruction.

To get quantitative information about the environment, the user can activate an ambient conditions readout. This presents all of the aspects of the condition of the volume the user is standing in (i.e. temperature, pressure, gas concentrations, and toxicity) in numeric form. Gas concentrations are presented as both absolute volume and mass fraction. To determine these values at various points in the building, the user simply walks to the point to be probed, and reads the values. To see how the values change over time, the user can manipulate the time controls and directly observe any changes. The pause control is very helpful in this context.

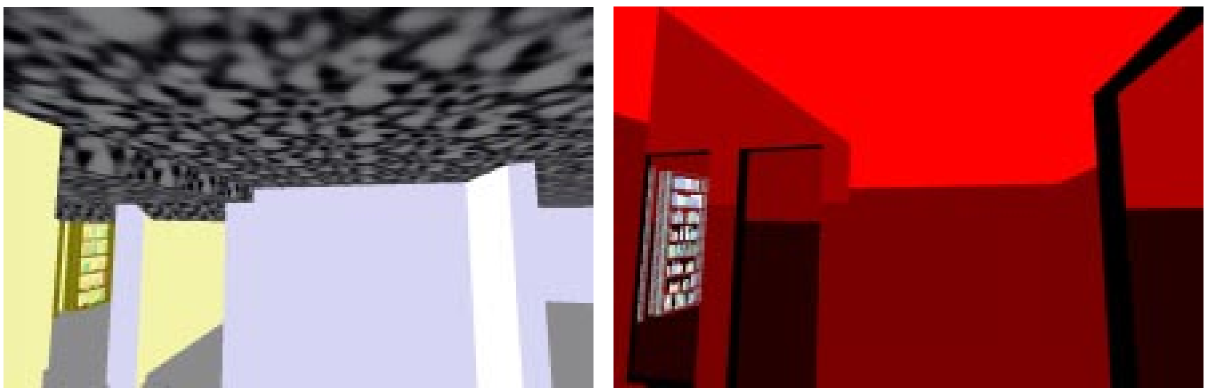

Figure 7: A comparison of the realistic vision mode with the thermal vision mode. On the left, a smoke-filled hallway. On the right, the same view in thermal vision mode. Note how the heat pattern on the walls and ceiling corresponds to the height of the smoke interface.

Interactive Exploration

The structure of the FireWalk system affords the ability to do "What-If" studies through natural interaction with the environment. For example, consider a user who is trying to determine which parts of a home are survivable for how long when a fire starts in the basement. The user sets the fire in the basement, starts the simulation, then walks to an upstairs bedroom and uses the ambient conditions display to determine when the levels of toxic gases in the room become lethal. The next step might be to assess how closing the basement door would affect the gas concentrations over time. In the old system, the user would have to get the information in the first place by running CFAST and extracting the information with CPLOT. To perform the study, he would then have to add a CVENT line to the CFAST text data file, rerun CFAST, and postprocess the output file again with CPLOT, noting the time on the plot where the toxicity reached lethal proportions in the volume number assigned to the bedroom.

In FireWalk, the user does this experiment by walking down the stairs, closing the door, walking back upstairs, "rewinding" a bit, and returning to observe the conditions in the bedroom. When the door is closed, the system *automatically* informs the simulator that conditions have changed, and how they have changed. The simulator then invalidates all the data from the moment the door closed onward, and re-simulates and re-transmits conditions in the house from that moment forward. No text file editing or postprocessing is required; the user simply performs an action, and observes the consequences. It is our belief that this capability will make CFAST a more useful tool for both fire safety engineers and laymen who, until now, were daunted by the textual and batch-processing interface of CFAST. In the FireWalk system, an action produces its logical consequences in an easily understandable way.

FUTURE WORK

The FireWalk system is an important research platform for the Berkeley Walkthru group, and a great deal of work lies ahead. Here are some of the projects for the near future:

- A port to Windows NT and OpenGL, to be developed on and primarily targeted toward 3DFX Voodoo graphics hardware, which costs somewhere in the vicinity of $200 per unit.
- More and improved scientific visualization modes. Visualizations of gas and thermal flows, and differentials in time. Visualizations of 3D chemical and gas concentrations within the air, and how they change over time.
- Access to CFAST's other major modeling capabilities, including warning and suppression systems (i.e. sprinklers and smoke alarms) and HVAC systems, from within the FireWalk virtual environment.
- Complete distributed simulation support; i.e. the ability to run parallel simulations in a single virtual environment, with multiple viewers visualizing and interacting with that environment simultaneously.

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References

[1] Bukowski, R.W. and Séquin, C.H. Object Associations: A Simple and Practical Approach to Virtual 3D Manipulation. *Proc. of the 1995 Symposium on Interactive 3D Graphics* (Monterey, CA, April 1995), pp. 131-138.

[2] Bukowski, R.W. and Séquin, C.H. Interactive Simulation of Fire in Virtual Building Environments. *Proc. of SIGGRAPH 97* (Los Angeles, CA, August 1997), in press.

[3] Funkhouser, T.A., Séquin, C.H. , and Teller, S.J. Management of Large Amounts of Data in Interactive Building Walkthroughs. *ACM SIGGRAPH Special Issue: 1992 Symposium on Interactive 3D Graphics*, March, 1992, pp. 11-20.

[4] Funkhouser, T. A. RING: A Client-Server System for Multi-User Virtual Environments. *Proc. of the 1995 Symp. on Interactive 3D Graphics* (Monterey, CA, April 1995), pp. 85-92.

[5] Peacock, R.D., Forney, G.P., Reneke, P. et al. CFAST, the Consolidated Model of Fire Growth and Smoke Transport. NIST technical note 1299, U.S. Department of Commerce, Feb. 1993.

[6] Lewis, R.W. *Generating Three-Dimensional Building Models from Two-Dimensional Architectural Plans.* Masters' Thesis, University of California, Berkeley, Berkeley, CA.

[7] Teller, S., Fowler, C., Funkhouser, T. and Hanrahan, P. Partitioning and Ordering Large Radiosity Computations. *Proc. of SIGGRAPH 94* (Orlando, FL, July 1994), pp. 443-450.

[8] Teller, S.J., and Séquin, C.H. Visibility Preprocessing for Interactive Walkthroughs. *Proc. of SIGGRAPH 91* (Las Vegas, Nevada, Jul. 28-Aug. 2, 1991). In *Computer Graphics*, 25, 4 (Jul. 1991), pp. 61-69.