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FIREGRID: INTEGRATED E-RESPONSE FOR THE MODERN BUILT ENVIRONMENT BASED ON ENVIRONMENTAL AND STRUCTURAL MONITORING

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Abstract

Sensing and monitoring devices of many kinds are gradually becoming ever more pervasive in modern buildings. The range of applications is getting broader, including environmental control for occupant comfort and energy efficiency, as well as monitoring of the environment to achieve early detection and warning of emergency situations (such as fire). Conventional actuation for environmental comfort and to mitigate the effects of an emergency (such as sprinklers) is also common place. Systems for "smart" early response are now being developed to provide a more robust and reliable suppression or mitigation of the emergency. The FireGrid concept is about integrating the independently developing sensing technologies with modelling tools, using distributed computing (high performance computation and Grid technologies) and achieving real-time response to mitigate the potential damage as a result of major emergencies. The first application of this concept deals with fire in buildings (hence the name), however the concept is generally applicable to most emergencies. In this work the authors will discuss the basic architecture of FireGrid and how it may be used to provide early warning of the loss of structural integrity in a typical steel frame composite structure subjected to a large fire.

INTRODUCTION

The collapse of the World Trade Centre Towers 1, 2 and 7 after the terrorist attacks of September 11th 2001, created a precedent for a scenario that had never been considered before. High-rise buildings collapsed with thousands of occupants, while emergency services conducted fire control and evacuation operations. No one had any knowledge of the impending collapse of the buildings. More than 3000 occupants (including over 300 fire fighters) died. Forensic investigations of these events are taking place, however they are unlikely to yield definitive answers as a very significant part of the evidence lay on the rubble that has been disposed-off. Nevertheless, consider the following scenario:

- A reliable computer simulation tool predicted the evolution of the fire, established its impact on the structure and also analysed the emergency services intervention alternatives and evacuation possibilities
- This information was continuously updated and, after appropriate processing, relayed to help the emergency services optimise the impact of their operations
- All the simulation, analysis and communication was much faster than real time evolution of the emergency
- There was effective co-ordination based on an intelligent execution support aid for the responders

Given the system implied here, if it was in place, would it have been possible to significantly reduce the ultimate life and material losses? In this particular case (and for most other emergency scenarios), the answer to this question must be yes. Being able to anticipate the evolution of an emergency will inevitably result in better planned interventions. More importantly, this scenario represents the technological future of emergency response in increasingly urbanised environments with ever-increasing population densities.

FireGrid [1] will exploit modelling and simulation technologies to provide a unique tool for prevention, mitigation and management of emergency events. The immediate application will be fire, but the methodology could ultimately be extended to handle hazards derived from crime/terrorism and in response to natural disasters (earthquakes, floods, etc.). The main focus of the research is on integrating the relevant technologies (see Figure 1). This includes: advanced fire and consequence models which predict the response of the building and its human occupants to the unfolding emergency, sensor networks, e-Science infrastructure (Grid) and high-performance computing (HPC) resources to perform super-real-time computations, and command and control (C&C) algorithms to translate simulation output into operational instructions for deployment of active systems and assistance by human responders. The primary application will be in emergency response, but the tool will facilitate responder training and have spin-off applications in design and research modes. FireGrid is thus a direct application of simulation and modelling to the design and management of the modern built environment.

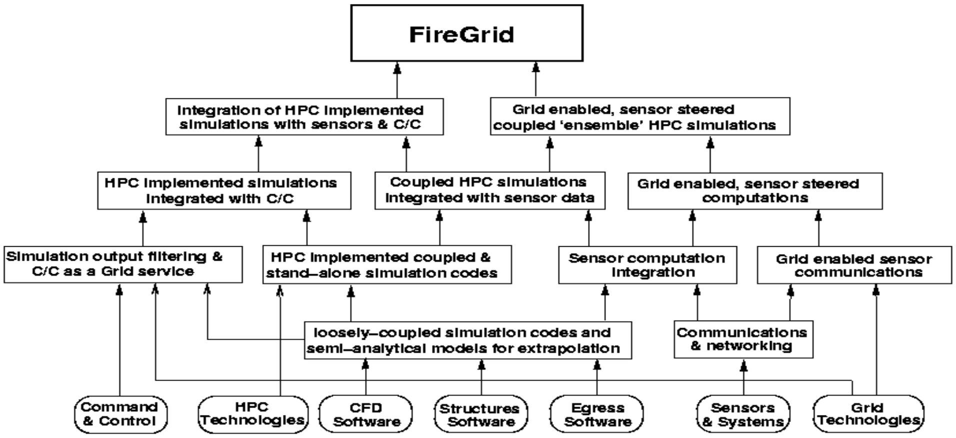

Figure 1. Integration of FireGrid technologies

The key innovation in FireGrid is the unique integration of a range of independently developed technologies to create a powerful new generic tool. A schematic of the integration strategy is shown in Figure 1. The novel aspects include: "loose" coupling of diverse physical models, effective leverage of the predictions by accessing real-time sensor data, high-speed processing using Grid and HPC resources, “on-demand” access of remote resources using

Grid technologies, development of robust self-organising wireless sensor networks, and the application of intelligent C&C algorithms. The main technical breakthrough sought is the speed-up of the model ‘prediction’ by coupling to sensor outputs for ‘correction’, so as to achieve the essential capability for super-real-time response.
The remainder of the paper reports on the work carried out so far in developing a prototype version of the FireGrid system. This consists of the development of the architecture and execution of a simple test demonstration involving prediction of “upward flame spread” [2].

FIREGRID ARCHITECTURE

The initial part of the high-level system architecture is illustrated in Figure 2. The diagram shows sample components – represented by square and elliptic boxes – plus the data and control connections between them, given in black and blue respectively.

On the upper left-hand side of Figure 2, one can see three generic sensor types: type 1 where data is simply pulled at a fixed rate; type 2 where data can be pulled at variable rates and where the sensor can accept action requests (i.e. switch off); and type 3, a variant on type 2 where the sensor has local memory. The sensors may, for example, represent a thermocouple or smoke detector. A smoke detector may have its own local disk (for storing a large number of events). Raw data (in the form of voltage readings (typically in the range 0V to +/-5V)) is pulled from each sensor by a Data Acquisition Unit (DAU). The sampling frequency is configured by the user for each individual sensor. Commonly employed frequencies for the majority of sensors are in the range 1-10Hz. For this initial architecture, we shall assume a frequency of 1Hz. All sensors give instantaneous readings, except for gas sensors that have a latency (time delay) to be accommodated (this will be done by the Data Translation Unit (DTU)). Each reading is translated by the DAU into a voltage that can be interpreted by a computer interface (e.g. -0.5V to 0.5V) and output from the DAU.

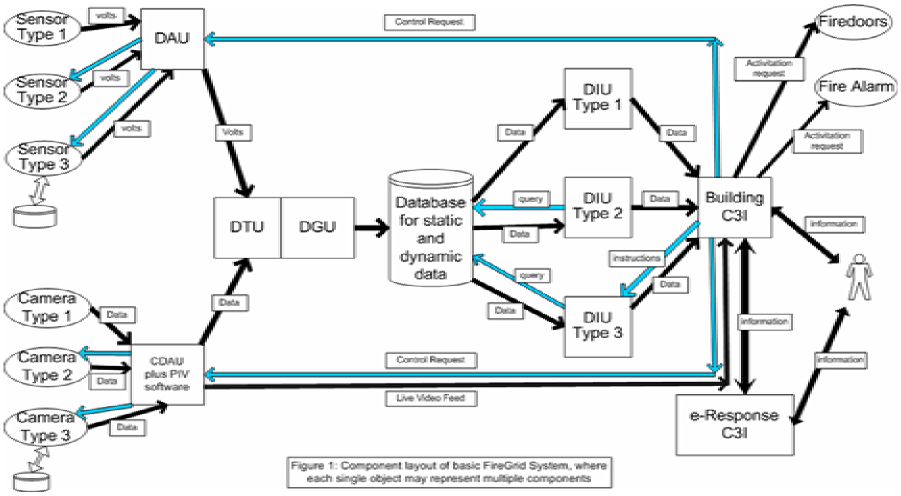

Figure 2. Proposed FireGrid Architecture

In Figure 2, located below the three generic types of sensors, are three generic types of digital cameras, which relay images of people/spaces/fires or laser sheets for subsequent Particle Image Velocimetry (PIV) analysis. These are also acting as a data source, like the sensors, though they generally produce output that is immediately suitable for consumption by a computer interface; hence, output from the digital camera is not handled by the DAU. There are three generic types of camera: type one is fixed and feeds data to the Camera Data Acquisition Unit (CDAU); Type 2 can react to requests from the CDAU to, for instance, redirect its line-of-sight to focus on a stairwell or the fire itself, etc; and a type 3 camera is, basically, a type 2 camera with local memory. The CDAU sends data to two units: the Building C3I (Command, Control, Communications and Intelligence - see below) which displays live video feeds, and the Data Translation Unit (DTU), which is now described.

The particular computer interface that consumes the output from both the DAU and the CDAU is called the Data Translation Unit (DTU). There may actually be more than one DTU: one for each class of sensor. This converts the digital input from the data sources into a meaningful form appropriate for human interpretation. For example, it could convert a voltage value that originated from a thermocouple into a temperature (degree C). As a further example, it could convert the raw data acquired from the digital cameras into a formatted movie file (i.e. mpeg using xawtv). These mpegs can then be used to create time-stamped still images image files (PNG or JPEG, for example). In practice, the DTU that consumes raw image data is likely to be a separate component from the DTU that is employed to collect voltage readings from basic sensors.

Information from the DTU is time-stamped, which is key in facilitating subsequent data analysis. The data then flows into the Data Grading Unit, or DGU, which will detect broken sensor data or data from sensors which are configured incorrectly (sometimes wired backwards in error). The subsequent error-checking analysis, currently done by a human and tricky to encode, would flag anomalies by assigning a quality grading to each data entry. The actions of the DGU are then recorded to the database, local to the DTU. This database also holds static information, which one may regard as a simple analogue of structural data. The matching of sensor output and static information is, at time of writing, an open question for the project. (Sensors with local memory usually record their own static data, i.e. their location within building.) All data that is produced by the DGU is augmented with static information about, for example, the type and location of the sensors in the system. Anomalous data is recorded, but flagged and its' usability is rated.

The augmented filtered data is then made available for consumption by one or more Data Interpretation Units (DIUs). There are three generic types of DIUs. DIU type 1 receives a response from a standing request on the database, processes the received data and then feeds this to the Building Command, Control, Communications and Intelligence (Building C3I, which is a local C&C unit). DIU type 2 queries the database at a regular frequency and processes the received response before feeding this to the Building C3I. Finally, DIU type 3 is triggered by a request from the C3I. This causes the DIU type 3 to query the database, process the received data, and then feed the data back to the Building C3I.

The following particular units are to be used in the initial system demonstrations:

- DIU type 1 consumes data from the database, triggered by a standing action on the database itself, and evaluates the likelihood that there is a fire. The output from the module is (conceptually) a logical YES or NO that is retrieved by the Building C3I.

- DIU type 3 represents the HPC simulation unit which is only triggered by the Building C3I registering the presence of a fire. The HPC simulation is then started to generate a selection of possible scenarios which can be presented to the Fire Chief, or equivalent personnel, upon their arrival.

All of the analysis results that are produced by the DIUs are retrieved by the Building C3I, which performs three functions. Firstly, it monitors the system for failure; secondly, it can display live video feed; and thirdly, it can perform early response. This early response would include activating the fire alarm, alerting a human to instigate the e-Response C3I, and triggering an ensemble of HPC simulations to pre-compute a set of possible future scenarios to be considered by the e-Response C3I.

It is envisioned that when the e-Response C3I arrives, it connects to the Building C3I (the e-Response C3I unit will consist of at least two subcomponents.) All e-Response C3I requests are routed through the Building C3I. Possible actions to be performed by e-Response C3I include:

- Activation or re-calibration of one or more sensors (for example, increasing the frequency of a sub-set of sensors located in the proximity of the fire).
- Activation of fire-fighting devices (for example, switching on sprinklers or extractor fans).
- Activation, deactivation, or re-configuration of one or more DIUs.
- Increasing/decreasing the frequency of sensor polling for particular regions within the building.

APPLICATIONS

Two possible applications of the above architecture are described in this section. As this work is in its early formative stages only very simple tests have so far been performed to test the ideas presented, however much more comprehensive demonstrations are planned in the next two years of the project. The first application below describes how structural integrity of a tall building may be assessed during the course of a fire event, while the second describes a simple upward flame spread prediction experiment.

Prediction of Structural Integrity of Tall Buildings in Fire

To provide early warning of the loss of structural integrity in a tall steel frame composite structure subjected to a large fire, FireGrid will rely upon a range of structural models (both computational and analytical) that will be initiated upon the detection of fire and monitoring of its progress. The outputs of the system will be one or more of the following:

- Continuously updated reports on structural integrity in the region of the fire (local) and remaining global structural integrity (based on a yet to be defined structural integrity coefficient)
- Alarms or voice alerts integrated with general evacuation plans for the building
- Status reports to responders to aid safe intervention
- Report on structural health after the end of the fire event (in the "cooling" phase) to apprise responders of the risks of entering the building and to help enable assessment of damage magnitudes and repair costs.

One or more of the following strategies will be adopted depending upon the resources available to FireGrid for structural integrity assessment:

- "Matching" of fire temperatures and growth from sensors against a large enough space of computationally generated fire scenarios and structural responses to assist early forecasts (possible use of Genetic Algorithms)
- Modelling for structural integrity assessment in real-time based on monitored, simulated, or forecast data. Choice of models will depend upon the computing resources available. Simple analytical models to small and large computational models could be used (all will have to be setup before the event and will be initialised and updated using monitored data).

1. Monitor fire at all floors adjacent to exterior columns
2. Forecast floor temperatures at appropriate intervals
3. Estimate structural temperatures
4. Determine floor and column deformation based on forecast
5. Estimate floor loading
6. Determine floor capacity to sustain loading in flexure, if insufficient, determine catenary capacity and consequent pull-in forces
7. Determine reactions at adjacent floors and deformations induced
8. Determine capacity of adjacent floors to sustain reactions (while subjected to combined bending and axial force), if the capacity runs out return possible failure for the given forecast temperatures
9. If weak floor failure does not occur, check for combined bending and axial force capacity of column under the applied loading and return failure forecast if the 3-hinge mechanism is formed.

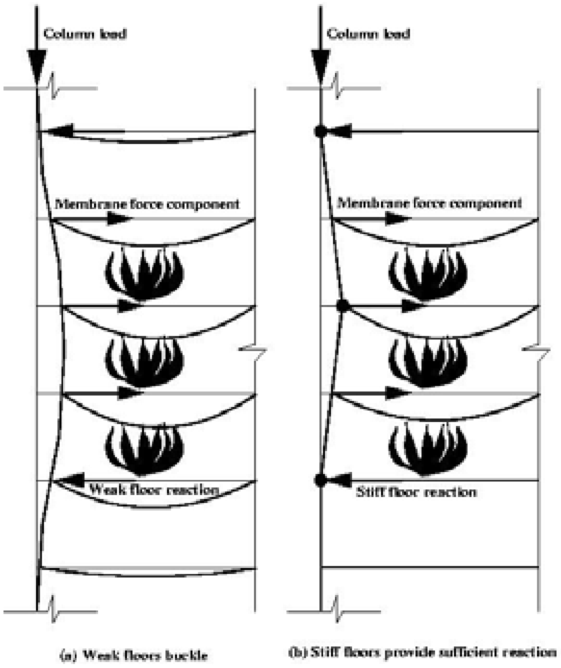

Figure 3. Tall building failure modes in fire and a forecast scenario: (a) weak floors buckle and (b) stiff floors provide sufficient reaction

Figure 3 shows two possible failure scenarios for a tall building when subjected to multiple floor fires [3]. Floors subjected to a prolonged fire invariably weaken and often undergo very large deflections, to the point where the main load carrying mechanism changes from flexure to membrane or catenary action. This creates pull-in forces on the column (as shown in figure 3) which requires large supporting reactions at the adjacent non-fire floors to maintain stability of the column. If the non-fire floors are unable to provide this resistance and buckle, a “weak floor failure” of the whole structure occurs. However, if the adjacent floors are strong enough to provide the reaction, the column may fail in a mechanism formed by reaching full plastic moment at three points (as shown) leading to a “strong floor failure”. A simple calculation procedure [3] can be exploited in assessing the structural integrity of the structure, as described in the left-hand column of Figure 3.

Super-Real-Time Prediction of Upward Flame Spread

A major challenge to the FireGrid methodology is the real-time integration of sensor data into the fire modeling process. This idea is similar to data assimilation [4,5] in the field of meteorology, but the characteristic time scale in fire applications is in the order of minutes, as opposed to days. FireGrid aims to provide predictions even when fundamental changes take place in an evolving emergency scenario. For example, if a window breaks or a sprinkler is activated during a fire in a building, the flame dynamics are significantly modified so a model should respond to this change by readjusting its predictions to the new conditions. This concept is demonstrated in Figure 4, where sensor data is assessed and then continually reassessed to recreate the fire environment and steer the computations.

A simple case of vertical upward flame spread is chosen as the initial step to validate the concept of super-real time predictions. Upward flame spread is chosen because it is simple enough to be plausible as a proof-of-concept and yet still a meaningful fire scenario. Experiments are conducted with PMMA slabs to feed measurements into a simple analytical model. PMMA is one of the best characterized materials for flame spread. Although downward spread would be easier to model, upward spread includes a proper definition of the pyrolysis length, thus adding a measurable variable to the analysis. A simple algebraic expression from the literature [6] linking flame spread, flame characteristics and pyrolysis is used to model the process.

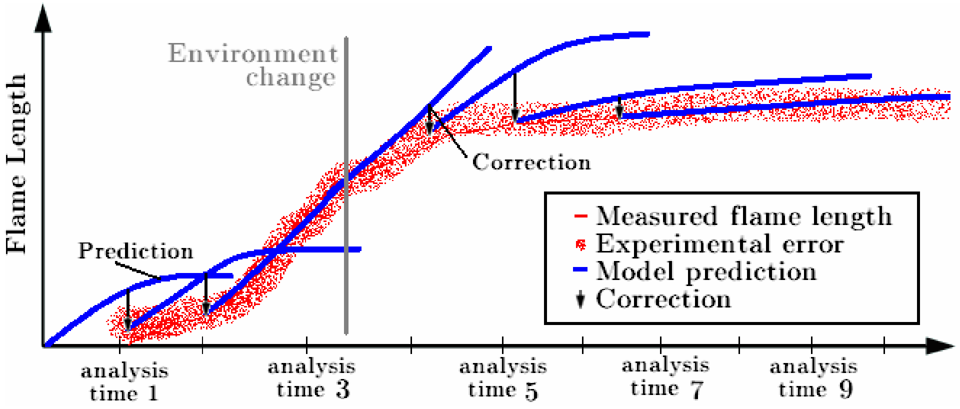

Figure 4. Schematic representation of data assimilation and updating of model

The experimental setup (shown in Figure 5), is designed in such a way that the sensor output can provide the majority of the analytical model’s inputs. This initial setup is also aimed to replicate as closely as possible the conditions, and therefore the results, described in [7]. In this way the techniques for sensing, data processing, and data interpretation can be validated without the need to excessively repeat experiments. The flame spread process takes place on a 40 mm thick, 200 mm high, 150 mm wide, vertically inclined PMMA slab. A horizontal line of flame is initiated by means of a Nichrome wire, embedded across the bottom of the face of the slab. A current is passed through the wire causing resistive heating and pyrolysis of the PMMA. A pilot flame is used to ignite the resulting combustible mixture. The flame front propagates to the top of the slab, upon where it is extinguished.

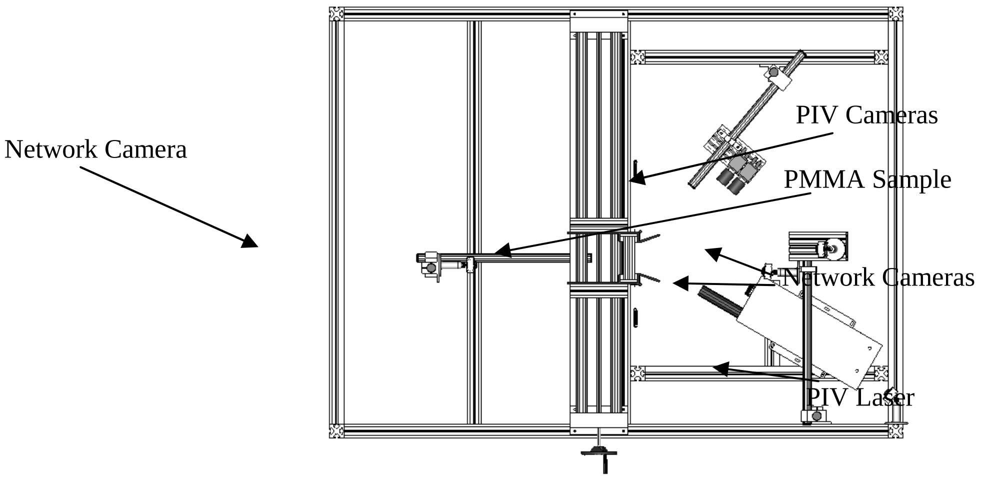

Figure 5. Plan view of experimental setup

The results and analysis of this demonstration experiment are reported in detail in [2].

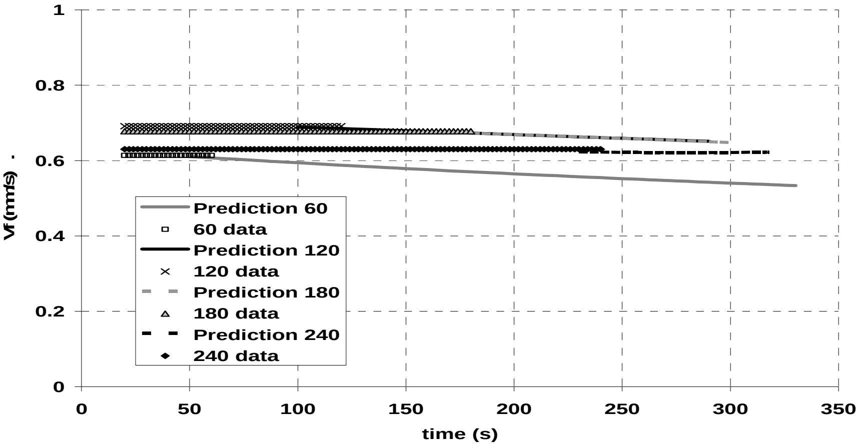

Figure 6. Evolving Flame Spread Prediction from 60, 120, 180 and 240 seconds of data

Once a prediction is made the subsequent incoming data points are checked against the prediction. When they appear to deviate significantly from this, a “linear-fitting” algorithm is used to re-calculate the constants of the analytical expression and time dependent variables. As time progresses and more data is collected, the predictions can be seen to converge (as shown in Figure 6).

CONCLUSIONS

This work is in a relatively early development phase and many of the ideas and concepts remain to be tested. However, the results from the very first, albeit simple demonstration, show that the concept of super-real time predictions made from sensor data, using simple optimisation techniques and simple analytical models can work.

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