FireGrid: Intelligence for Emergency Responders

Emerging Application Paper

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Abstract: Effective response to emergencies depends upon the availability of accurate and focused information. The goal of the FireGrid project is provide an architecture by which the results of computer models of physical phenomena can be made available to decision-makers in the context of fire emergencies in the built environment. A number of AI techniques have been applied in the development of this architecture, and are discussed in this paper.

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Abstract

Effective response to emergencies depends upon the availability of accurate and focused information. The goal of the FireGrid project is provide an architecture by which the results of computer models of physical phenomena can be made available to decision-makers in the context of fire emergencies in the built environment. A number of AI techniques have been applied in the development of this architecture, and are discussed in this paper.

Introduction

Timely access to relevant information is crucial if correct decisions are to be taken during emergencies. Technological developments have ensured that computers are now an important source of information in even the most difficult and demanding situations, with access to mapping tools, database information and other compiled information being widely accepted and assimilated into responders' systems of work. The vision behind the FireGrid project (Berry *et al.* 2005) is of a generic software architecture that provides decision-makers with access to the information generated by sophisticated simulation models applied to 'live' sensor data. In the first instance, the project has focused on supporting the response by emergency services to fires in the built environment.

Artificial Intelligence techniques and approaches to software development have played an important role in the FireGrid project, both in the development of software and of the underlying concepts that serve to link together the various components of the architecture. Following a brief description of the FireGrid project, in this paper we discuss the context in which AI is used and then provide an overview of the application of various AI technologies. Final sections described an experiment undertaken to test a FireGrid system and summarize the achievements of the project so far and the obstacles that remain.

The FireGrid Project

For obvious reasons, fire-fighters will rarely be aware of the exact conditions that hold within a building during a fire incident and, consequently, they will be compelled to make intervention decisions based on the information provided by their senses, on their training and on their past experience of fires. Furthermore, since fire is a complex phenomenon, the interpretation and extrapolation of its physical manifestations is a very difficult task. Advances in several technologies when taken together suggest a possible solution to the problem:

- Developments in sensor technology, and a reduction in unit cost, offer the prospect of deploying large-scale, robust and cost-effective sensor networks within buildings;
- Advances in the understanding of fire and related phenomena have resulted in sophisticated computer models which might be used to interpret sensor data;
- The availability of distributed High Performance Computing (HPC) and data processing over the Grid suggests a platform on which these models could be run quickly enough to make the use of their results during emergencies a practical proposition.

The FireGrid approach aims to improve – both in range and quality – the information available to fire-fighters. The emphasis of the project lies firmly on the integration of existing technologies in the areas mentioned above rather than on the development of new ones. In practical terms, this involves the coupling of diverse computational models, seeded and steered as appropriate by real-time sensor data, and processed using HPC resources accessed across a Grid, and all placed in the context of a system interface tailored to the target user working in his/her operational context. It is the role of AI technologies to provide this command-and-control layer and the underlying reasoning that supports it. An initial architecture along these lines has been developed; it forms the basis of FireGrid systems implemented and tested with a number of real fires.

AI and FireGrid: Contexts

In this section we describe the context in which AI is to be used within the FireGrid project. Specifically, we discuss the requirements and constraints that emerge from two stakeholder communities, namely fire-fighters (as the target user group) and fire modellers (as the core technology providers).

FireGrid and the Fire-Fighter

As is usually the case in AI-based applications, an early activity was to understand in more detail the nature of the task that a FireGrid system is intended to support. This was done by study of the available literature (which, in this case, take the form of best-practice field manuals) and a series of interviews with serving fire officers, which eventually led to the development of prototype interfaces to elicit feedback.

FireGrid aims to provide information of use at the tactical decision-making level; accordingly the most obvious target user is (using UK fire service terminology) the Incident Commander (IC) (or, more realistically, a senior support officer stationed in a possible mobile command room and detailed to monitor the FireGrid system and report directly to the IC). The IC is

> "…responsible for the overall management of the incident and will focus on command and control, deployment of resources, tactical planning, the coordination of sector operations…and the health and safety of crews." (HM Fire Service Inspectorate 2002), pp. 15-16.

Rather than being determined in advance, the range of possible incidents and contributing factors means that the response to any given incident is left to the experience and expertise of the IC in question, except when very specific or rare hazards are involved (such as incidents involving hazardous materials or aircraft). However, one decision is effectively universal when dealing with building fires, regardless of specifics: the decision of whether or not to send fire-fighters into the building. Fire-fighters may be sent into a building (and the IC is said to have adopted an *offensive tactical mode*) if and only if the IC considers that in doing so the chances of saving people (especially) or property outweighs the additional risk to fire-fighters. Otherwise a *defensive tactical mode* – the default – is adopted, whereby the fire-fighters say outside the building until such time as either the fire is extinguished and the incident closed, or else conditions are such that they are now considered to make an offensive mode appropriate.

Whether offensive or defensive tactics are adopted, this decision is subject to continuous review by the IC, through a process known as *dynamic risk assessment*. This process, which of necessity is often done rapidly and with incomplete or uncertain information, represents an attempt to rationalise the factors contributing to the tactical mode decision. This allows the most appropriate target for information from a FireGrid system to be identified: this information (and its modes of presentation) should be such as to contribute to the IC's dynamic risk assessment.

Moreover, the pressures of performing this analytical task on the incident ground are such that seemingly conflicting requirements emerged for information to be presented both in a manner that can be rapidly assimilated into this assessment process, and in a way that provides sufficient detailed rationale to allow its careful consideration. From discussions with senior fire-fighters emerged the idea that these requirements might be reconciled at the interface level through a 'traffic light' approach to information presentation to give an at-a-glance overview of the current status, with a point-and-click facility for delving into the reasons for the colour of light displayed.

FireGrid and the Fire Modeller

Central to the FireGrid concept is the use of computer models of physical phenomena to provide information to emergency responders. Given the initial focus of FireGrid on fire in the built environment, our interest lies in re-using existing models able to interpret and predict the behaviour of the fire, the movement of smoke, the reaction of the building and its occupants during the incident, and so on. Hence, the other major area of expertise influencing the command-and-control elements of the architecture surrounds the modelling of fire and its related phenomena. Experts in this field are usually academics, and, as became clear, their aims and objectives do not necessarily correspond to those of the FireGrid project.

The models in question can vary in complexity from relatively simple interpretations and abstractions of the current sensor data through to highly sophisticated (and computationally expensive) projections of future conditions. In respect of the latter in particular a number of issues arise (Potter and Wickler 2008). Of particular relevance here is the observation that, since these models have not been developed for emergency response purposes, their outputs will not necessarily contain that information most relevant to the IC. Furthermore, even when relevant the outputs may contain or express some degree of uncertainty, which again is potentially problematic for the IC who would prefer to deal in certainties.

In practical terms, this meant that, following the definition of a system ontology, effort would be required to develop knowledge-based wrappers of existing models so that the information they produce is more directly relevant. Furthermore, situating the FireGrid system in (from the perspective of the user) an agent-based framework through which models could be invoked and their results collected would allow the system to be constructed and deployed in a modular fashion. More details about the system architecture can be found in (Upadhyay *et al.* 2008).

AI and FireGrid: Technologies

In this section we describe the application of AI tools and technologies in the context of FireGrid. In particular, we discuss the ontology that was developed to underpin FireGrid systems and its uses; the application of belief revision to maintain a consistent view of the information provided by a FireGrid system; and of the use of a rule-based system to interpret the belief set for presentation purposes. First, however, we briefly discuss the I-X agent-based approach adopted for the implementation command-and-control layer of FireGrid systems.

The I-X Agent System

I-X (Tate 2000) is a generic systems integration architecture and accompanying tool-suite that was emerged from fundamental work in AI planning. At its most abstract, I-X is intended to support processes that create or modify one or more 'products'; in the context of emergency response a product might correspond to (the creation and enactment of) a response plan. An I-X system consists of some federation of communicating human and computer agents; the actual constitution of the system will be dictated by the circumstances (and may change over the lifetime of the system). The bond that unites the system is the *<I-N-C-A>* (Issues-Nodes-Constraints-Annotations) framework for representing shared activity (Tate 2003): in their communications the agents describe the state of the collaboration in terms of issues (essentially unanswered questions or unresolved problems), nodes (essentially activities), constraints (which effectively describe the state of the world) and annotations (that capture meta-information about the other categories). In addition, an I-X agent maintains a description of the other I-X agents it knows of, which can cover such things as the capabilities of the other agents, the appropriate means of communicating with these agents, and the organizational relationships that hold with these agents.

The FireGrid Ontology

A FireGrid system is intended to allow its fire-fighter user to relate the output from simulation and interpretation models to the risks faced in the current incident. In order to do this, some common ground must be identified within (or else imposed upon), on the one hand, the information emerging from the computer models, and on the other, that understood by fire-fighters as potentially relevant to the risks they face. In other words, in AI terms it is necessary to establish an ontology for use within the system. Based on discussions with both fire-fighters and modellers, we were able to identify a number of common concepts understood by both modellers and fire-fighters. In its underlying approach this ontology draws on other ontological work, in particular the categories defined in DOLCE (Gangemi *et al.* 2002). Here we summarize some of the high level concepts defined in the ontology.

State Parameters and Events The FireGrid ontology makes the high-level distinction between *state parameters* and *events*. State parameters are quantities that are considered to be continuously measurable for some place over some duration of time. Illustrative sub-concepts include *maximum temperature* and *smoke layer height*. Events, in contrast, are considered to be instantaneous occurrences at some location, such as *collapse* or *explosion*. Furthermore, it is asserted that events can only occur once (if at all) at a particular location during the incident – although multiple occurrences of an event are certainly possible, this constraint was imposed to ease the conceptual difficulties of knowing *which* occurrence of a particular event a model is referring to, since within the same system several models might simultaneously be referring to events. It is intended that both state parameters and events can be derived (albeit through additional knowledge-based interpretation) from the output of models – and, moreover, if a given model does not produce a recognized parameter or event, then its usefulness for and relevance to FireGrid is, at best, questionable.

Hazards From the fire-fighter's perspective, the values of state parameters and the occurrence of events can be related (again, through knowledge-based interpretation) to the concept of a *hazard*: a hazard is defined as something that can impinge upon the operational safety of fire-fighters at a particular place for some particular duration. For the purposes of relating this to the simplified 'traffic light' paradigm for information presentation, we can define the notion of *hazard level* as being a relative measure of a hazard that pertains at some time at some location; and, more specifically, we can identify three subclasses of hazard level and define these in terms directly related to fire-fighting operations:

- A *green* hazard level should be interpreted as "the system is unaware of any specific hazard to fire-fighters operating under normal safe systems of work at this location at this time";
- An *amber* hazard level as "additional control measures may need to be deployed to manage hazards at this location at this time";
- A *red* hazard level as "this location may be dangerous for fire-fighters at this time".

Space and Time Each hazard level (as well as each hazard, state parameter and event) is relevant to a particular location, which raises the question of the definition and extent of *location* within the system ontology. This is not as straightforward as may first appear; in models, differentiated spaces (usually) correspond to volumes of gas bounded by physical partitions (and hence correspond to rooms), but this may vary if the model is of either a large space or at a high resolution. For fire-fighters, on the other hand, the notion of location is situation-dependent and dynamic, depending on (among other things) the nature and scale of the building including its vital access and exit routes, the position of the fire incident and any occupants, the tactical operations that are currently underway and so on. To reconcile these views we have adopted a pragmatic approach, defining contiguous locations each of which corresponds to a room in the building in question, since this is one notion that seems to be mutually understood.

Similarly hazards, state parameters and events all occur in time, and the fire-fighters' decisions relate to both their understanding of what is currently happening and what is predicted to happen in the future. And, as for location, the handling of time within a FireGrid system is not a simple matter. It is necessary that all information in the system is tagged with absolute timestamps, rather than referring to relative times (and it follows that the clocks of system components that generate or present information are synchronized). We shall return to the representation of time in a FireGrid system in the context of the discussion of belief revision given below.

Applying the FireGrid Ontology The ontology defined in these terms is used to express and communicate the information that is generated by the models (which effectively correspond to <I-N-C-A> constraints). This usually requires the model to be 'wrapped' by appropriate interpretation code, developed with the assistance of the modeller, that is able to interpret the native output of the model in terms of state parameters or events. Another use is to provide the basis of a 'query language' that enables the user to construct and pose to the system requests for specific information. These requests are handled by an autonomous *query manager* agent able to invoke appropriate models based on their information-providing capabilities, which are also expressed in terms of the ontology. See (Potter and Wickler 2008) for more details of this query-answering approach.

From the end-user perspective, a system architecture of this sort entails the effective management and interpretation of potentially large amounts of information, derived from different models at different times (and hence potentially conflicting or contradictory), and referring to physical manifestations of the incident at particular points in time and space. The management of this information is implemented by a belief revision mechanism; its interpretation is implemented by a rule-based mechanism.

FireGrid Belief Revision

The information that is presented to the IC is based on a current belief set maintained by a user-interface agent. A *belief* is some proposition that is held to be true for some location and over some duration. In addition, every belief must have one or more justifications, indicating the rationale for believing it. The justification will usually be one or more messages from the models in the system whose content provide the basis for the belief. A continual process of belief revision is required to maintain the consistency of the set of believes as information is sent from the models. The belief revision required for FireGrid differs in certain important aspects from conventional AI approaches to belief revision such as (Alchourròn *et al.* 1985). Specifically, whereas common approaches to belief revision operate at an abstract logical and content-independent level, for FireGrid the revision must take into account application-dependent ontological notions.

When a new message arrives from a model, it will correspond to a proposition about either the value of state parameter or the occurrence of an event at some time at some location (and that is implicit that this proposition is 'believed' by the model; in this treatment, we ignore the degrees of belief implied by probabilistic models). The contents of this message have to be considered in the context of the existing beliefs. This process is best illustrated through the use of an example.

Consider a message sent to the user-interface agent consisting of the following elements:

- *sender*: max-temp-model
- *time received*: 12:54:34
- *contents*: maximum temperature = 230°C *in location:* room-A *at time:* 12:54:32

If the agent currently believed nothing about the *maximum temperature* in *room-A* and received the above message, and assuming that the source of the message (that is the *max-temp-model*) is trusted, this message would be the sufficient justification for the agent now believing the contents of the message. Moreover, since nothing else is known about the values of this state parameter in this location, the reasoning would assign a duration to this belief stretching from the current time to some indefinite time in the future. That is, since it is not believed otherwise, an assumption of the belief revision mechanism is that the values of state parameters persist, and hence in this case the *maximum temperature* would now be believed to remain at 230°C indefinitely – or at least until such time as some other message causes this belief to be revised with a definitive end-point.

If, on the other hand, something is already believed either about the current or the future values of the maximum temperature at this location, then a more complex train of reasoning begins, which attempts to reconcile this message with the existing belief(s). This may involve adjusting durations of beliefs or, where there seems to be a direct contradiction choosing to adopt one or other of the possibilities and disregarding the other. While this might be done on the basis of, say, one model being the more trustworthy, in practice we tend to trust models equally, and rely instead on two general principles encoded in the revision mechanism: one of favouring more recent information (and the beliefs it justifies) as being more likely to be true; and a second of favouring interpretations of current sensor data over predictions.

Contradictions of this sort occur when trying to reconcile inconsistent state descriptions about the same location at the same time. Since we have effectively compartmentalized the incident into distinct locations, determining whether the contents refer to the same location is straightforward. However, determining if the contents refer to the same time is more problematic; since absolute timestamps are used, the contents of a message and an existing belief about a state parameter may have widely differing values at times that differ by perhaps only fractions of a second. Of course, such a transition in values is possible (often coinciding with some event), but in practice seems more likely to result from the comparison of new information and a belief based on obsolete information. Accordingly, we choose to try to 'smooth' these transitions by defining that if the difference between the start times of a belief and message contents is within a tolerance (set experimentally to 30 seconds) then they refer to the "same" time. Furthermore, this tolerance helps to overcome the problem that interpretations of "current" state based on sensor data will always refer to the past due to the inevitable lags and delays in the system; with this tolerance, these interpretations can be assumed to be about "now", as in the example given above.

A further complexity arises when the content of a message is a prediction – that is, it purports to describe the value of a state parameter or the occurrence of some event at some location at some future time. While this might be adopted as a belief with a duration as before, the inexorable flow of time will mean that, assuming this belief has not been retracted or modified in the meantime, at some time the prediction will come to refer to the current time, and in the absence of other information a choice must be made about whether or not to accept the predicted value as an actual current value. While reasoning of this sort is difficult to justify on grounds of logical soundness, it can be justified on the basis of a cautious approach to the safety of fire-fighters in the absence of information to the contrary.

Hazard Rule-Based Interpretation

Assuming that the set of beliefs has been revised and is consistent, the next step is to interpret these beliefs by the application to them of a set of *hazard rules*. These rules represent expert knowledge about fire-fighting capabilities and practice; an example might be:

> IF maximum temperature ≥ 100°C at location l from time t_1 until time t_2
>
> THEN hazard level = amber at location l from time t_1 until time t_2

A hazard rule consists of one or more conditions and a single conclusion, which corresponds to an interpretation of the conditions in terms of a hazard level for the time and place in question. In addition, a hazard rule – especially one that refers to less commonly encountered hazards – may have an associated explanation and recommendations. So, for instance, a rule referring to excessive CO levels may offer the explanation that CO levels in that range can "cause headache, fatigue and nausea" alongside the recommendation to "avoid prolonged exposure or consider the use of breathing apparatus".

For each rule, then, a search is made in the set of beliefs for subsets that both satisfy all the conditions and are contemporaneous (that is, which have overlapping durations). If such a subset exists, then the conclusion of the rule can be drawn. An inferred hazard level results in what is essentially a new belief (or in the modification of an existing hazard level belief with an additional justification), with a duration delimited by the latest start time and earliest end time among the subset of beliefs satisfying the conditions. Note that changes to the belief set can effectively mean that earlier inferences about hazard levels no longer hold: this is a truth maintenance problem. However, rather than implement a TMS, we have adopted the simpler, but less efficient, expedient of re-computing the hazard levels following changes to the belief set.

Finally, since the application of the rules may have resulted in the inference of multiple simultaneous hazard levels, the inference engine must collate these into a single cumulative hazard level for each location at every time. This is a (relatively) straightforward matter of determining the 'worst' hazard level that is believed to apply. So, for instance, if from the state of room-A at the current time, two *amber* hazards and one *red* hazard had been inferred then the current overall hazard level of room-A is *red*. Note that the set of hazard rules is intended to be derived with the assistance of fire-fighting experts; and that, moreover, different rules might apply in different contexts (such as when there are hazards specific to a building), allowing the FireGrid system to be tailored accordingly.

In interface terms, then, the cumulative current hazard level at a particular location is used directly to colour the corresponding traffic light for that location in the graphical user interface (Figure 1). Furthermore, feedback from potential users suggested some indication of future hazard would also be useful, and so a second light was added to display the worst hazard level predicted to occur in the future. Clicking within a location causes a pop-up window to appear in which the hazard rules which fired to produce the hazard level are detailed. In addition a time-line indicates when any hazards are predicted to occur within a time-frame projected into the future (pragmatically set to 15 minutes for our experiments, but different incidents might demand different time-frames); moving a slider allows the user to explore the nature of these hazards.

FireGrid System Application: A Case Study

For reasons that should be obvious, validating the FireGrid architecture presents a number of practical difficulties. The project has adopted an incremental approach, gradually increasing the numbers of implemented components, and based on simulated, pre-recorded and live data collected from fires. As a result of this process, a number of different FireGrid systems have been implemented, culminating in a 'complete' system that was applied to provide real-time information during an experiment involving a real fire (under controlled conditions) that was conducted before a select audience at the Building Research Establishment (BRE), near London, in October 2008.

This experiment involved a fire initiated in a specially constructed rig representing a small 3-room apartment. A total of 125 sensors placed throughout the rig measured temperatures, heat flux, gas (O_2, CO, CO_2) concentrations and deformation of structural elements. Values from each of these sensors were polled in batch mode at roughly 3-second intervals, and fed to a database server housed off-site. This rig and its contents were intended to produce a 'flashed-over' fire in a relatively short time (in the event the whole experiment, from ignition to manual extinguishment lasted around one hour). An event in terms of the FireGrid ontology, flashover typically occurs when the gases produced by a fire in some enclosed space reach temperatures high enough (above 500°C, as a rule of thumb) to ignite simultaneously all combustible matter in the vicinity. From the perspective of responders, flashover represents a potential transition from a contained fire to an uncontrolled fire. In addition, certain structural elements of the rig were expected to deform and fail during the fire; the potential collapse of ceilings and floors is, of course, a major hazard for fire-fighters.

A number of different models were employed for both interpretation of and prediction based on the sensor data; these were run on various local and remote resources as demanded by their processing requirements. The principal graphical interface is shown in Figure 1. The notional scenario for the experiment concerned the possibility of occupants trapped in the apartment: the tactical decision was whether or not to send fire-fighters into the building to conduct a search (although no actual fire-fighting activities or any other intervention in the course fire was performed during the experiment). With a member of the FireGrid team playing the role of support officer to the IC (and with a senior fire officer in the audience), the experiment was conducted and was felt, in general terms, to be a success, with the AI components behaving as envisaged.

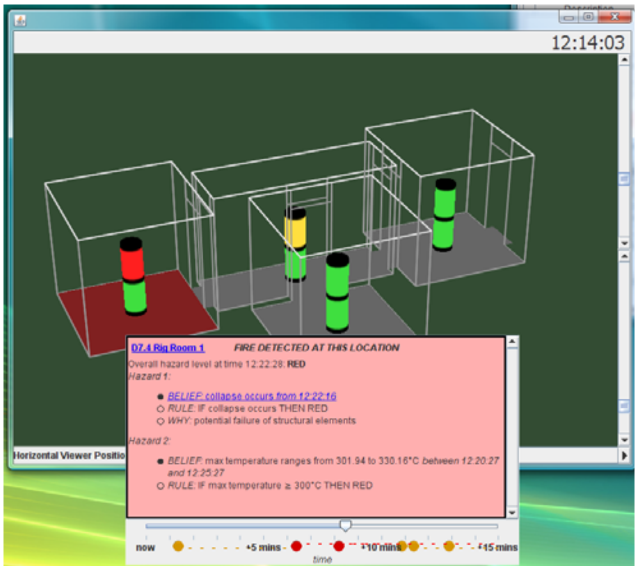

Figure 1. FireGrid system interface during experiment. The red floor indicates the location of the fire, and the user has clicked on this location for further details. The 'traffic lights' show the current (lower) and projected (upper) hazards at each location.

Summary

At the time of writing, the FireGrid project is approaching the end of its initial 3-year funding period. Notwithstanding the success of the experimentation reported above, the range and complexity of fire incidents, and the difficulties of interpreting and especially predicting fire conditions within buildings make unlikely that FireGrid systems will be deployed as real emergency response aids at any time in the near future. From an AI perspective, a number of diverse technologies have been applied in the project, and have already shown their worth. When one considers the possible implications of the decisions that fire-fighters make, however, the operational validation of the approach and any systems based upon it is problematical, as is often the case for AI applications which, by their nature, tend to deal with heuristic and approximate methods, rather than certainties and guaranteed results. Here, of course, system validation is compounded by the fact that large-scale emergency incidents can, at best, only be simulated under laboratory conditions, and then only at considerable cost.

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References

Alchourròn, C.E.; Gärdenfors, P.; and Makinson D. 1985. On the Logic of Theory Change: Partial Meet Contraction and Revision Functions, *Journal of Symbolic Logic*, 50:510-530.

Berry, D.; Usmani, A.; Torero, J.; Tate, A.; McLaughlin, S.; Potter, S.; Trew, A.; Baxter, R.; Bull, M.; and Atkinson, M. 2005. FireGrid: Integrated Emergency Response and Fire Safety Engineering for the Future Built Environment, *UK e-Science Programme All Hands Meeting (AHM-2005)*, See also http://www.firegrid.org/.

Gangemi, A.; Guarino, N.; Masolo, C.; Oltramari, A.; Schneider, L. 2002. Sweetening Ontologies with DOLCE In A. Gómez-Pérez, V.R. Benjamins (eds.) *Knowledge Engineering and Knowledge Management. Ontologies and the Semantic Web, 13th International Conference, EKAW 2002*, Springer Verlag, pp. 166-181

HM Fire Service Inspectorate 2002. *Fire Service Manual, Volume 2 Fire Service Operations, Incident Command*, HM Fire Services Inspectorate Publications, London: The Stationary Office.

Potter, S; and Wickler G. 2008. Model-Based Query Systems for Emergency Response, *Proc. 5th Int. Conf. on Information Systems for Crisis Response and Management (ISCRAM 2008)*, F. Fiedrich and B. Van de Walle (eds.), Washington DC, USA, May 2008.

Tate, A. 2000. Intelligible AI Planning. In *Proceedings of ES2000, 20th BCS Special Group on Expert Systems International Conference on Knowledge Based Systems and Applied Artificial Intelligence*, 3-16, Springer.

Tate, A. 2003. <I-N-C-A>: an Ontology for Mixed-Initiative Synthesis Tasks. In *Proceedings of the Workshop on Mixed-Initiative Intelligent Systems (MIIS)* at the International Joint Conference on Artificial Intelligence (IJCAI-03). Acapulco, Mexico, August 2003.

Upadhyay, R.; Pringle, G.; Beckett, G.; Potter, S.; Han, L.; Welch, S.; Usmani, A.; and Torero, J. 2008. An Architecture for an Integrated Fire Emergency Response System for the Built Environment, *Proc. 9th IAFSS International Symposium on Fire Safety Science*, Karlsruhe, Germany, September 2008.