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Distributed and interoperable simulation for comprehensive disaster response management in facilities

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ABSTRACT

Disaster-related simulations can be helpful for conducting various analysis on damage evaluations and response operations in damaged facilities. However, no single simulation can solve all the functional needs for complex disaster situations due to diverse disasters, damage types, and response efforts. To address these issues, the authors have developed a distributed simulation platform for a comprehensive analysis of facility damage and response operations, which can be flexibly applied to diverse disaster situations. The High Level Architecture is adopted to synchronize different federates such as simulation models and incoming data streams within an interoperable simulation environment. The developed simulation platform includes five different disaster-related federates such as the Fire Dynamics Simulator, USGS earthquake data feeds, OpenSees structure response simulation, evacuation simulation, and restoration simulation. The accuracy of interactions among different federates was confirmed with the case simulations of a facility fire evacuation and an earthquake restoration situation. The developed platform provides a flexible and interoperable distributed simulation environment for comprehensive disaster response management of unexpected disaster situations while promoting reusability and future extendibility of existing and newly-added disaster-related simulations.

1. Introduction

Rapid and appropriate response actions during and after disasters such as evacuation, rescue, restoration, and so forth play a paramount role in minimizing civilian and property loss. In order to carry out effective disaster response efforts in a timely manner, response plans should take into account sufficient information on the disaster situation and possible damage [1]. For example, providing information on the possible smoke propagation from a building fire can help occupants inside the facility to find a more safe evacuation route during an early response phase. In case of an earthquake situation, an immediate assessment of facility damage can assist in determining the scope of required works for the restoration phase [2]. In this regard, computer simulations for structural behavior analysis, seismic collapse prediction, fire/smoke propagation estimation, and response process (e.g., evacuation, restoration operation) can provide useful information on potential facility damage and consequent response efforts in a risk-free and low cost setting [3,41].

However, no single simulation can solve all the functional needs of different analysis requirements [4]. Particularly for disaster response management, it often requires responders to use more than one disaster simulation because the analysis deals with a combination of diverse disasters with different damage types (e.g., earthquake with structure damage and collapse, and fire with smoke propagation), complex and serial effects of disaster damage (e.g., aftershock of an earthquake), and various phases of disaster response efforts (e.g., evacuation and restoration) [3,5,6]. As such, seamless interactions between multiple disaster simulators are a pre-requisite to conduct comprehensive analysis on various types of disaster-response efforts. Furthermore, taking into account the possibilities for new types of disaster-response combinations with new analysis requirements in the future, the simulation platform's usability needs to be further extended with the extendibility

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to newly added components and the reusability of existing ones for different subsets.

To address these issues, the authors have developed a distributed disaster damage and response simulation platform using the High Level Architecture (HLA: IEEE 1516), which is capable of synchronizing different simulators (or incoming data streams and other analysis tools) within an interoperable simulation environment. The aim of the developed platform is to accommodate a simulation environment where various disaster damage and response modules interact with each other for multiple disaster-response combinations. In order to demonstrate the platform's capability to provide such an environment, this research considers two common disaster-response scenarios in facilities including an evacuation after a building fire and a restoration operation after a series of earthquakes. The analysis of two different disaster-response scenarios are conducted in the developed platform which enables the communication among three damage analysis modules including the Fire Dynamics Simulator, USGS earthquake data feeds, and OpenSees structure response simulation, and two response analysis modules including evacuation and restoration simulation. Then, the accuracy of interoperability between the components is tested for each scenario. Finally, the future applications of the developed platform in terms of reusability and extendibility, while maintaining the interoperability between existing and newly-added components, are discussed for assisting comprehensive and versatile disaster response management.

2. Technical hurdles in existing simulation approaches for disaster-response analysis

The prediction of complex disaster damages and preparation of diverse response efforts often accompanies a myriad of complexity and uncertainty. In order to overcome such a problem, many centralized simulations, wherein one or more simulation modules are located and operated within the same processer [7], have been developed for disaster damage and response analysis. Some of the examples of this approach include HAZUS-MH [8] for disaster simulation, OpenSees [9] and Fire Dynamics Simulator [10,11] for damage simulation, EVACNET+ [12] and EXODUS [13] for emergency evacuation simulation, and ClientRunner [14] and MEETSIM [15] for facility recovery simulation. These simulators were developed to serve their own specific purposes of either estimating disaster damage or managing response operations, which contributed to reducing huge complexity and uncertainty in a disaster situation. However, some simulations may not be flexible enough to accommodate new simulation combinations due to the use of specific pre-defined sub-simulation modules [7]. Toward considering the necessity of a more expansive analytic scope for the various disasters, efforts have been made to integrate several sub-simulation modules within a single simulator. A disaster simulation called HAZUS-MH, for instance, deals with natural disasters by combining hurricanes and earthquakes simulations [8]. However, an integrated form of centralized simulation can cause another problem in performing rapid simulations due to its heavy size [7]. In addition, their pre-defined interactions on specific sub-simulation modules in a single simulator may lead to the limited interoperability with other new simulators. With this limited flexibility and interoperability, the usability of one particular simulator can significantly decrease when different types of disaster occur and appropriate response efforts are required. In the case of a building fire, for instance, the sole use of an evacuation simulator may have limitations in analyzing evacuees' behavior under smoke. A combined use of a building fire simulator and an evacuation simulator can be helpful for considering the effects of smoke on the evacuation performance. However, this integrated simulation will not be suitable after an earthquake. In such a case, the evacuation simulator needs to be integrated with a seismic analysis simulator to estimate the effects of shaking or displacement of the structure to evacuation behaviors. As a result, it is required for disaster simulations to have flexibility and extendibility while promoting seamless interoperations among different simulators in order to analyze various disaster-response situations.

In this regard, this research adopts a distributed simulation approach that can concurrently utilize diverse simulators for their own purposes [6]. A distributed simulation platform is based on a paradigm in which certain parts of the simulation are simulated independently and communicate with each other in a distributed network environment [16]. Using such an ability, the platform can effectively provide the interoperable damage and response simulation environment that links different simulators (or incoming data streams and other analysis tools), each of which has its own specific ability (e.g., fire dynamics analysis, seismic intensity analysis, structure response estimation, and evacuation or restoration analysis). Specifically, for the purpose of promoting reusability and extendibility of the distributed simulation in the future, the simulation interactions in this research are implemented based on the principles defined in the High Level Architecture, which was standardized by the Institute of Electrical and Electronics Engineers (IEEE 1516).

3. High Level Architecture (HLA)

The High Level Architecture (HLA), which was developed and adopted by the U.S. Department of Defense, presents a general framework and a collection of rules to manage the interoperability and the reusability among different simulations in distributed simulation environment [17–20]. Based on the standards for developing and connecting individual federates (i.e., a federate is a single simulation model, an incoming data stream, a passive viewer, or other analysis tool in a distributed simulation platform), the HLA enables information exchange and action synchronization among different federates in the same or different platforms [16–18].

The HLA consists of three components including HLA rules (IEEE 1516), HLA interface specification (IEEE 1516.1), and Object Model Template (OMT) (IEEE 1516.2) [20–22]. First, the HLA rules describe proper interactions of federates in a federation (i.e., a federation is a set of federates that are integrated via the HLA and are running and interacting with each other) and the responsibilities of federates and federations. Second, the HLA interface specification defines the Run-Time Infrastructure (RTI) services and interfaces as well as identifies “call back” functions each federate must provide. Finally, the OMT provides standards for documenting the HLA object modeling information [16,19]. Specifically, as shown in Fig. 1, the RTI is an implementation of HLA which provides the binary executables for synchronizing federates and executing data transfers between simulators, as well as the application programming interface (API) for writing software that integrates with the RTI. In the HLA-compliant distributed simulation, the HLA rules must be followed for proper interactions among federates so that the RTI coordinates the synchronization among federates (Fig. 1b) without any direct interaction among simulation components (Fig. 1a). As such, the interoperability among different federates, each of which is based on different hardware platforms, development languages, and/or network environments, is supported by the HLA [23]. It can thus provide the open architecture where existing simulations can be reused and extended through combinations with other existing or new simulations. Such an architecture reduces the time and cost for creating a new integrated simulation while maintaining the advantages of each simulation.

According to these abilities, the HLA has been adopted for a number of distributed disaster simulation platforms for emergency evacuation and rescue management [5–7,24]. While the existing research contributed to integrate different types of information (e.g., network, sensing data) into disaster response simulations with an accelerated execution time, this research extends the application of the HLA into more comprehensive and versatile disaster response management by interoperating different federates that analyze possible damages of