Abstract of Dissertation

Title:

Distributed Object-based Software Environment for Urban System Integrated Simulation under Urban-Scale Hazard
Case Study: Integrated Earthquake Simulation

都市災害統合シミュレーションを可能にする 分散オブジェクト型ソフトウェア環境の構築「統合地震シミュレータを例題として」

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Abstract:

Sustainable urban development/regeneration is now a worldwide pressing issue. Yet, progress in urban disaster preparedness/mitigation plans has been slow and far outbalances the urban risk caused by the explosive population growth. The informal, dynamic, and evolving characteristics of the urban system interdisciplinary simulation participants create many challenges for the disconnected system simulation. It is understood that individual participants perform their simulation services in separate environments, bartering service exchange relationships to get what they need to resolve their part of the problem. There are many examples of research efforts to develop distributed systems for collaborative engineering. This research is also founded on a vision for distributed collaborative simulation where the key barriers are: heterogeneity, interoperability, and accessibility to models or expertise; system complexity and size; and the sharing of proprietary knowledge embodied in subsystem models.

In this research, a Distributed Object-based Software Environment (DOSE) has been developed to facilitate the integrated simulation of the urban system under the risk of urban-scale hazards such as earthquakes, tsunamis, and blasts. Environment infrastructure allows the urban system interdisciplinary simulation participants of heterogeneous simulations operating in different locations, using different models, and different tools to be integrated. An overview for the distributed nature of the urban system interdisciplinary simulation participants has been introduced where five main participants, third party applications, have been identified: the Geographic Information System (GIS); Computer-Aided Design (CAD); Underground Soil Modeling (USM); Hazard Simulation; and Vulnerability Analysis. An earthquake hazard application scenario has been used as a case study to clarify the development of the underlying environment infrastructure. In the case study, the Hazard Simulation is replaced by the Earthquake Motion Simulation (EMS). The basic environment building blocks are: modularity;

scalability; and interoperability. An object-based, modular, architecture has been developed to enable system flexibility and extendibility. Scalability; however, has been enabled through decomposing the overall integrated simulation process into distributed processes that interact through service exchange network. In addition, environment interoperability with vulnerability analysis third party applications has been enabled based on Industry Foundation Classes (IFC) standard that is being developed by the International Alliance for Interoperability (IAI). DOSE environment application for real-world urban systems has been addressed and results have been discussed.

The modular design of the DOSE environment layered architecture has been described. Four distinct layers have been developed where the gravity rule of reference has been applied. The first is *Resource Layer* that provides the computational and software resources. The second is *Core Layer* that provides objects that are common for all structures. These objects are responsible for handling urban system data of: GIS; CAD; USM; and Hazard. The third is *Domain Layer* that provides domain objects such as building, bridge, and pipeline. Reference relationships have been defined among Core and Domain layers classes so that a domain object can retrieve its physical data (GIS, USM, and Hazard) and CAD data effectively. The fourth is *Interface Layer* that provides interface objects that further reference domain objects that need to communicate with each other or with a third party application to handle an interaction. It consists of three parts: *InterfaceBasic*; *InterfaceExecutable*; and *InterfaceI/O*. It is worth noting that DOSE environment architecture has been designed in a layered form because: (1) the layered architecture of the Industry Foundation Classes (IFC) object model, that is being developed by the International Alliance for Interoperability (IAI), was successful in integrating construction industry participants; (2) seamless connection/interface with IFC object model is intended for DOSE environment interoperability with vulnerability analysis third party applications; (3) the layered architecture enables system flexibility and extendibility.

Environment scalability has been enabled in terms of both domain size and vulnerability analysis third party application complexity through adopting two levels of decomposition. The first level decomposes the overall urban system into domains, such as the Building, Bridge, and Pipeline domains, in order to consider them simultaneously in the solution. The overall process of urban system integrated simulation has been decomposed into several environment processes that interact and communicate with each other through service exchange network to retrieve the overall objective. The second level; however, decomposes the vulnerability analysis process for each domain in order to conduct the analysis in a parallel form. The service exchange network among environment processes has been built on the Message Passing Interface (MPI) standard. This, in turn, has enabled, optionally, cluster network, local area network (LAN), or wide area network (WAN) for communication and interaction. The *InterfaceBasic* part of the interface layer provides interface objects for external and internal communications. The external communication is handled through a *Third Party Application Interface* object that bridges the communication between the environment and the third party application. The internal communication, however, is handled through the *Inter-domain Interface* and *Domains Interface* objects for inter-domain and domains communication, respectively. On the other hand, the *InterfaceExecutable* part of the interface layer provides environment processes, interface executables. An adopted Mater-Slave technique based on *Signal-to-Start* and *Signal-of-Finish* has been employed for controlling and scheduling processes communication through a master process that is Environment Control Room. It is worth noting that environment interface has been automated to ease the generation of both interface objects and executables for different environment applications.

In order to enable environment interoperability with different vulnerability analysis third party applications, an adopted analogy between the DOSE environment and Construction Industry has been employed. Construction industry obligates different parties to interact and communicate with construction manager to produce the construction product. On the other hand, DOSE environment obligates different vulnerability analysis third party applications to interact and communicate with the environment to produce an integrated simulation. The IAI has developed IFC object model to act as a *Shared Product Model* between construction manager and different industry participants. Analogously, the IFC object model has been interfaced through environment data model semantics in order to build a *Shared Integrated Simulation Model* between the environment and different vulnerability analysis third party applications. This, in turn, has afforded environment interoperability. As a result of that the domain object in addition to its relevant CAD objects are required for vulnerability analysis, the domain and CAD objects have been interfaced from IFC model. The current IFC object model is able to represent different domains such as the Building, Bridge, and Timber House. In addition, the *IfcProxy* object can be used for any domain that is not specified within IFC model. For CAD objects; however, the current IFC object model supports only the mechanical model of structure where the CAD representation in terms of the discrete model is demanded by construction industry in order to complete the interoperability vision within the structural design process. Consequently, the author has launched an extension project within IAI, namely ST-7. The developed model in this study/project is called the *Shared Computer-Aided Structural Design (SCASD) Model* that is considered as part of the aforementioned *Shared Integrated Simulation Model*. Model schemata have been described in details. In addition, model exchange formats have been illustrated in four distinctive types. The *InterfaceIO* part of the interface layer has been built on the *STRCOMplus*, which is an Application Programming Interface (API) that is implemented by the author for the *SCASD Model*, in addition to an IFC middleware tool called *IFCsvr* that is developed by SECOM Co. Ltd. They have provided an IFC-compliant data model (for DOSE environment domain and CAD objects) and a tool for I/O IFC-compliant exchange format, respectively. The *STRCOMplus* API and, in turn, the SCASD model schemata have been tested in a numerical experiment that performed dynamic analysis for a virtual city of eighty buildings. A pseudo-code and an example I/O command of the DOSE environment interface executables have illustrated the robustness and effectiveness of data model structure that, in turn, has enabled an effective control and manipulation for data.

A business implementation, through IAI, has been proposed for the industrial application of the *SCASD Model*. The problem statement of conventional distributed structural design has been described in terms of wide range of drawbacks that result in, mainly, quality degradation and time/cost ineffectiveness. The model, however, enables a new methodology of interaction among structural design participants, namely Electronic Interaction (E-Interaction). A Data Center is able to manage such interaction through an operating system and a group of messages. The roadmap of business plan realization has been illustrated based on a pre-defined IAI IFC integration steps while the current step of the model is at the review process. The business plan will provide significant economic and social values such as: time/cost effectiveness, spur construction industry toward adoption of CAD and Information Technology, automation of structure design checking process, compatibility between structural/architectural designs, and transparency that secures design cheating.

The problem statement of implementing the conventional seismic soil-structure interaction within the DOSE environment has been discussed. In addition, a computational procedure has been proposed for the distributed interaction. The procedure has been built on the message passing of dynamic boundary conditions, which have been developed in the *SCASD Model*.

In the application of the DOSE environment, the earthquake hazard application scenario is applied to real-world urban systems that have been chosen based on: some earthquake history; a representative range of structure types; some basic building inventory data that can be acquired; and the active development of mitigation plans by urban authorities. The city of Kobe (Kobe district) with domain size of (700x500 [m]) and Bunkyo ward (Tokyo district) with domain size of (800x600 [m]) have been chosen for this application. The objective is to show an evidence for the DOSE environment: modularity, scalability, and capability to simulate and reproduce the mechanical behavior and collapse mechanism of the overall urban system structures in response to a spatially varied earthquake ground motion.

In the integrated simulation of the city of Kobe, the domain (14 bridge piers) has been simulated under the earthquake hazard scenario. The stored GIS and geometric data have been compiled to construct the CAD representation for each bridge pier (DFM representation, Discrete Fiber Model). Vulnerability analysis has been conducted for bridge piers using the DFM third party application. Three different cases of earthquake ground motion have been studied by changing ground surface topography and earthquake wave incidence. The results have shown an out-of-phase dynamic response and different mechanical behavior for the consequent bridge piers. This, in turn, gives an evidence for the real damage of bridges during Kobe earthquake, 1995.

In the integrated simulation of Bunkyo ward, the domain (1767 wooden houses) has been simulated under the earthquake hazard scenario. The stored GIS data have been compiled to construct the CAD representation for each building. Vulnerability analysis has been conducted based on the Multi-Degree-Of-Freedom (MDOF) and the Distinct Element Model (DEM) systems using the relevant third party application. A locally complicated distribution of structures response and damage has been resulted due to the complicated distribution of the input earthquake ground motion and the dynamic characteristics of each building. In addition, the sensitivity of DEM vulnerability analysis results to the quality of GIS data has been investigated through choosing the typical floor height of the building as a key factor of GIS data quality. The investigation showed a significant dependency between vulnerability analysis results and the typical floor height value.

In both Kobe and Bunkyo analysis studies, each structure (bridge pier or building) has received its at-site Hazard having all the affecting characteristics from GIS and USM data included. In addition, based on the calculated at-site Hazard and the CAD data, the vulnerability analysis has been conducted. the integration of DOSE environment interdisciplinary simulation participants (GIS, CAD, USM, Hazard, and Vulnerability Analysis) and the emergence of the urban system integrated simulation from the distributed service exchange network (interface objects) among different modules and objects (Domain objects, Bridge and Building domains, for Vulnerability Analysis and Core objects for: GIS; CAD; USM; and Hazard) is an evidence for DOSE environment modularity that has lent itself to facilitate the integration process.

The vulnerability analysis that has been conducted based on the detailed DEM method for 1767 wooden houses gives an evidence for DOSE environment scalability in terms of domain size if compared with Kobe analysis that has been conducted for fourteen bridge piers using the detailed DFM method. The MDOF analysis; however, gives an evidence for DOSE environment scalability in terms of third party application complexity where the simplified MDOF and the detailed DEM methods have been applied to the same domain size of Bunkyo ward. It is worth noting that, DOSE environment scalability draws an inspiration for the feasibility of conducting tradeoffs among different proposals for disaster preparedness/mitigation plans and, in turn, sustainable urban development/regeneration strategies by, simply, changing the values of simulation variables.

In conclusion, this research has developed a proof-of-concept prototype system that is capable of supporting integrated simulation for urban systems under the risk of urban-scale hazards. The current functionalities of the DOSE have been demonstrated. The software environment, which includes an infrastructure and a *SCASD Model*, provides the basic building blocks for further developments and applications. In the future, continuing research and developments are needed to address the issues of environment performance, security, GIS data quality, ST-7 integration, and seismic soil-structure interaction.