Collaborative Training Tools for Emergency Restoration of Critical Infrastructure Systems

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Abstract. Large-scale disasters can produce profound disruptions in the fabric of critical infrastructure systems such as water, telecommunications and electric power. The work of post-disaster infrastructure restoration typically requires close collaboration across these sectors. Yet the technological means to support collaborative training for these activities lag far behind training needs. This paper motivates and describes the design and implementation of a multi-layered system for use in cross-organizational, scenario-based training for emergency infrastructure restoration. Ongoing evaluation studies are described in order suggest directions for further work.

Keywords: disaster response, critical infrastructure, computer-based collaboration.

1 Introduction

Recently, considerable attention has been devoted to opportunities for minimizing the impact of large-scale disasters on the services provided by infrastructure systems such as electric power, telecommunications and water [1, 2]. Pre-disaster, this may involve training exercises developed around anticipated hazards; post-disaster, this may involve collaboration across the organizations tasked with restoring the services which these infrastructures typically provide. Yet progress in understanding and supporting organizational in infrastructure restoration is hampered by the rarity of large-scale disruptive events, and the difficulties inherent in observing those that do occur [3, 4], thus reducing the potential for systematic observation and comparative study. Taken together, these conditions present considerable barriers to the development of tools, techniques and training approaches for achieving organizational *resilience*: that is, an ability to retain control, to continue and to rebuild [6].

The work described here concerns the development of techniques and technologies to support training in the emergency restoration of infrastructure systems. These immediate post-disaster activities are undertaken to provide services through water, electric power, telecommunications and other critical infrastructures. Laboratory research in this domain faces a two-fold challenge: on the one hand, to develop and test experimental apparatus that will provide a credible representation of the domain

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of application; on the other hand, to incorporate tools for measuring and analyzing data associated with emergency restoration. New technologies—such as human-computer interfaces for multi-person interaction, as well as advanced simulation techniques [7] and analytic tools—offer the potential to address this challenge.

The technologies discussed here, combined with a physical platform for its deployment, are being used to create a *synthetic environment* in which phenomena associated with organizational resilience may be investigated. A synthetic environment is defined by the Defense Modeling and Simulation Office as an "environment within which humans may interact through simulation(s) and/or simulators at multiple networked sites using compliant architecture, modeling, protocols, standards, and databases." The technology consists of a database representing an existing system of critical infrastructure systems—together with the capability for multi-person interaction with this database—mediated by a simulation engine that provides feedback on decision making. Following a brief discussion of the research objectives (Sect. 2), work to date (including a pilot evaluation) is presented (Sect. 3), along with a discussion and concluding comments (Sect. 4).

2 Background and Objectives

An examination of post-disaster infrastructure restoration shows that disasters continue to be sources both of system renewal and of system redesign. Indeed, in the immediate aftermath of a disaster, infrastructure systems erected on an emergency basis rarely mirror pre-event systems. Instead, their design is likely to be provisional, and may even precipitate modification of the design of pre-event systems. For example, in one well publicized example from the response to 9/11 in New York City, normal ferry service from Manhattan was suspended after the event, primarily due to the ferries themselves being used to carry thousands of injured and other persons to New Jersey as part of an improvised waterborne evacuation. The ferry system is now an essential component of the evacuation function with the emergency services infrastructure.[1]

Emergency restoration of services provided by critical infrastructure systems typically requires deployment of multiple decision makers [8] acting under time constraint and under multiple (and possibly conflicting) objectives. These personnel may be deployed to an emergency operations center (EOC), where the number of personnel may vary, but are typically drawn from management rather than operations staff. Activities within the EOC include monitoring operations during normal conditions, selecting an appropriate procedure when planned-for contingencies arise, and revisiting the appropriateness of these procedures as other potentially disruptive events occur [9]. These procedures are intended either to restore service (thereby resolving the emergency), or to enable a return to planned-for procedures [10]. If no planned-for procedure applies to the current situation or if an appropriate planned-for

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[1] Pérez-Peña, R. (2001). "A Day Of Terror: The Government: Trying To Command An Emergency When The Emergency Command Center Is Gone," *New York Times*, New York, p. A7.

procedure cannot be executed, EOC personnel must develop and deploy new procedures [11]. Given their centrality to the emergency restoration process, EOCs are data-rich hubs of interpersonal communication and collaborative decision making [12].

Resources available to EOC personnel for responding to the event may be under the control of a diverse set of stakeholders. Consequently, personnel may have incomplete information locally but complete information globally, requiring them to seek information across organizational boundaries in order to meet emergency restoration goals. Additional factors such as time constraint may further influence decision making processes. When there is a time limit for a task, time constraint exists; when a person feels stress associated with time constraint, time pressure—defined as the "subjective perception of stress or of being rushed" [13]. Another salient feature of the work of EOCs is the complexity of their task [17], particularly with respect to the degree of interconnectedness of their organizational resources.

The first objective of this work, therefore, is to develop and analyze an emergency restoration task which can be used to examine EOC decision making in response to planned-for and unplanned-for contingencies, under varying degrees of task complexity and time constraint.

In the post-11 September world, data on actual physical infrastructure systems are, somewhat paradoxically, more difficult to obtain than in the past—despite the urgent need for ensuring the resilience of these systems. As a result, researchers are now employing realistic (as opposed to real) data for use in observational and training studies. One project [14], whose data have been adapted to the work described below, employs realistic data associated with four infrastructure systems in New Hanover County, North Carolina (USA). This database was created through extensive collaborations with the managers of the infrastructure systems in New Hanover County, as well as collaborations with the county's emergency management office.

The data are organized at the level of U.S. Census tract, and consist of information on electric power, telecommunications, transportation and water infrastructures. Nodes are fixed components in the system that occupy points (e.g., transformers in the electric power network). Arcs are fixed components that occupy lines or line segments (e.g., power lines in the electric power network). The database is expressed within commercially available softwares (ArcGIS and Microsoft Access), coupled with purpose-built programs for forecasting damage from an emergency event and for assessing the quality of emergency restoration decisions [14]. The database may be explored using built-in tools, enabling users to examine properties of the various infrastructures and to conduct limited what-if analysis (e.g., "what if a particular trunk line in the electric power network is removed?").

The database is embedded within a system—denoted MUNICIPAL, for Multi-Network Interdependent Critical Infrastructure Program for the Analysis of Lifelines—containing three decision analytic modules: (1) a *vulnerability* module, which models the impact of hurricane scenarios by converting weather information into hazards caused by the hurricane such as wind gust, flood and storm surge and estimating the impact of these hazards on interdependent infrastructure systems [15], (2) an *optimization* module, which does the computational work to find the best scheduling and assignment for recovery and restoration [14, 16], and (3) a *geographic information system* (GIS) module, which provides a visual representation of layers of the infrastructure systems, the interdependencies among them, and the results produced by the optimization module.

However, it should be noted that the MUNICIPAL system cannot be employed interactively, and is thus suited to training in planning rather than decision making activities. As one example, the contents of the database cannot readily be modified. Moreover, MUNICIPAL is expressed within two "closed" (commercial) softwares, thus limiting the extent to which it can be transferred to other uses. The second objective of the research described seeks to addresses these limitations, as follows:

The second objective of this work is to develop a synthetic environment in which the emergency task may be embedded, and which may be exercised with emergency restoration personnel.

3 Results

This section reports on the results of research completed on the design and implementation of infrastructure restoration tasks and the environments within which these tasks are embedded.

3.1 Task Design

The task of EOC personnel is to allocate scarce resources (here, work crews) to repair non-functioning infrastructure components and thus to restore the services they provide. This task must be undertaken under time constraint: EOC personnel are given a time limit in which to complete restoration, and repair tasks take time to execute. Personnel must also consider their decisions in light of the complexity of the systems [17] and of the repairs themselves. Interdependencies designed into the systems (e.g., electricity is required to run water pumps) require EOC personnel to collaborate in order to restore system functionality. Because resources are insufficient to solve all non-functioning components simultaneously, EOC personnel typically seek to prioritize response efforts and to make subsequent decisions in light of feedback received on prior decisions.

Representation of the data for the task relies on a network abstraction of the infrastructure systems involved: most of the relevant information about each case is embedded within a network structure, so that inspection of the network via direct manipulation is required in order reveal this information. Other information (e.g., time remaining, available vs. committed work teams) is presented through text which is continually visible on a large-scale computer screen visible to all participants, as discussed below. In these terms, work crews are allocated to nodes or arcs in the system. Nodes are facilities, such as power generation stations, hospitals and water distribution centers; arcs are the links within and across these systems, such as power and water lines.

3.2 System Architecture

This work includes the design and evaluation of a synthetic environment in which performance on the above task (and others like it) can be measured and evaluated. The architecture of the system is depicted in Fig. 1, and consists of the following elements: a *flexible physical environment* in which to situate personnel and supporting technologies; a group of *EOC personnel* functioning as decision makers, interacting with each other and their *staff*, and a *database/simulation engine* which is accessed by participants via a multi-user interface; and a range of *instrumentation* (embedded within users' tools) for capturing the dynamics of interaction between decision makers and the simulation.

The *data* within MUNICIPAL have been normalized, verified and exported to mySQL, an open source database software package. The database is currently running on a Linux-based computer. The result is a more robust database architecture, with data that may now be accessed via other open source applications. Multiple client machines connect to this database through standard networking protocols both to pull data for visualization and to update and edit data (e.g., hurricane damage, proposed repair to existing and addition of new elements, service coverage analysis, etc.)

A kernel *simulation engine* processes participants' decisions and provides them with feedback on the consequences of restoration decisions. The simulation operates on the basis of a decision cycle which begins with participants submitting work crew assignments to their staff, who then submit them via an interface to the simulation. Once the work of a crew is completed, new service levels are calculated and the database updated. The simulation builds on work on MUNICIPAL through the inclusion of its programs for calculating initial damage from an extreme event (via the vulnerability module) and calculating the effects of those decisions on level of service (via the optimization module, which serves to optimize the distribution of work crews in order to maximize service provision for affected infrastructures) [14, 16]. Finally, the display presenting the information is redrawn. Time runs continuously through the simulation.

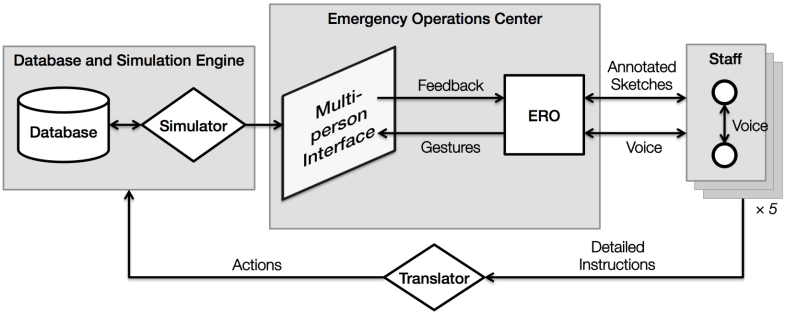

Fig. 1. Architecture of Synthetic Environment

3.3 Interaction Design

The current system includes a number of tools to support simultaneous, multi-person interaction and visualization of the scenario. The use of both novel and established tools enables logging of interaction with the system, focusing on visualization of network structures [18] at larger scales [19, 20]. EOC personnel interact with a 10mX6m projection of the infrastructures (along with various map layers) via a gesture-based system utilizing common laser pointers. Advanced computer vision capabilities are used for tracking these gestures [21]. The current prototype is depicted in Fig. 2. Personnel may choose which infrastructures to depict on the screen by using the laser pointer to circle (and thus "click") the corresponding button on the left of the left-most screen. Their gestures are read and interpreted by ceiling-mounted cameras (not shown), and an update sent via the server to the computer running the projector, which then refreshes the display. Additional infrastructures may be overlaid, and personnel may use a variety of gestures to zoom and scroll through views on the screen, as well as to make elementary edits by selecting the appropriate mode on the right of the screen. Pilot testing has shown that it is possible to take advantage of differential frequencies in the laser pointers in order to identify the corresponding user in an unobtrusive, unsupervised way.

Decisions on work crew allocation are input via a form-based interface available to EOC staff (shown in the right-most screen in Fig. 2). This screen also provides information on current level of service for different infrastructures, as well as committed vs. available work crews for each infrastructure. Interactions with these tools are time-stamped and logged for each participant. Interaction with a visualization client is at real-time rates (approximately 30 Hz). Communication with the database (pulling or pushing updates and new elements) is at interactive rates.

Fig. 2. Visualization and Interaction System

The interfaces have been developed using a flexible and modular programming design. The visualization client software written in C++ and OpenGL provides fluid display of the complex geometric position and inter-connectivity of the infrastructure elements in the database. The team used a standard software version control system (e.g., *svn*, *git*) to share updates and new features between programmers, and to allow other members of the research team to test and provide feedback on the most up-to-date iteration of the system.

3.4 Flexible Physical Space

The physical space in which the system is being deployed is easily reconfigurable, and can accommodate the required number and configuration of participants (approximately ten), associated computer hardware and software, and other tools (e.g., telecommunications capability). The system is installed in a "black box" studio space with an area of 232m^2 and a completely open floor plan. An overhead grid spans the entire surface of the floor at a height of 5.5m. Lighting, cameras and sensors can be positioned anywhere in the space above and below this grid. The studio is acoustically of the highest quality and includes a lighting system driven by sine-wave dimmers. The information technology, video and audio infrastructures are laid out to latest technology and bandwidth requirements. The space is located within Rensselaer Polytechnic Institute's Experimental Media and Performing Arts Center, a 2044m^2 facility that includes several different large physical spaces, all with both fixed and re-configurable seating, large format projection screens, high-resolution projection equipment, multi-channel audio, wired and wireless networking, video recording capabilities, and a full production and technical support staff.

3.5 System Evaluation

System evaluation is ongoing. This section reports on the results of a pilot study to test instrumentation and interaction capabilities, as well as the scenario itself.

Instrumentation. Data are logged both periodically and on the execution of key events such as work crew allocations. The periodic data, which is collected every ten seconds, contain the zoom level and location of the map and all expanded nodes and edges. It also shows which infrastructure layers were active. This allows analysis of the search process as nodes are expanded to query their status. The events included node and edge expand/collapse and layer visibility toggle. Each event is associated with a user and given a time stamp. All other mouse actions (e.g., pan) are also captured, but not analyzed here.

Participants. Five experienced participants (all with backgrounds in emergency services) took part in the pilot test. Each participant was provided with a laser pointer. An additional individual served as a staff member implementing the group's decisions. Participants first gave their informed consent, then took part in a training scenario which gave them an opportunity to learn the interface, ask questions, and become familiar with the types of problems they would be solving. The training scenario took 53 minutes to complete. They were next given the full scenario, which took 111 minutes to complete. An informal debriefing was then held.

Scenario. The full scenario—an infrastructure restoration task—is built around two issues: a small outage in the water infrastructure and a larger outage in the power infrastructure. The water outage is caused by two downed power lines which affect two water wells. However, the wells are not connected to the water infrastructure due to a broken pipe. This portion of the water infrastructure is isolated by other parallel sources due to a broken pipe and damaged water storage tank. The power outage is caused by a damaged distribution station. Several additional downed power lines to waste pump stations are also present as well as broken pipes. In contrast to the first set of problems, all of these issues must be fixed in order to restore service. The damage by area and initial service levels is shown in Table 1. For example, two instances of damage to power arcs are associated with the first issue, and four with the second issue. The seventh instance of damage to power is associated with the second issue. The problem can be solved by repairing either (i) the water storage tank or the second broken pipe or (ii) either of the power lines and the first broken pipe.

Table 1. Total Damage and Initial Service Levels

Infra	Nodes	Arcs	Service	Total
Power	0 + 1	2 + 4	98%	7
Water	1 + 0	2 + 0	82%	3
Waste	0 + 3	0 + 3	89%	6

Interaction. The users are able to continuously interact with the map and submit service requests. All requests remaining from the prior decision cycle are executed at the beginning of the current decision cycle. For this group, a total of 50 service requests were issued. After each decision cycle, participants were presented with a status of their crews for each infrastructure type as well as an update on the service levels. As described previously, inquiries on the status of nodes and arcs can be made via laser pointer-based gestural interaction with the map display.

Group Processes. Considering only at the events directly related to information seeking (node/edge expand/collapse), the number of each type of event was tabulated for each user. These cross tabulations are shown in Table 2. Participant 1 appeared to focus more on edge exploration (55.9%), while participants 2 and 3 focused more on node exploration (64.0% and 80.9%, respectively). The workload was predominantly carried by participants 1 and 2 (88.32% of the total number of events). Participant 4 did not initiate any events (he later reported that he preferred to defer to the other participants). Ongoing research is exploring how these data relate to problem solving.

Table 2. Count of Events by Participant

Participant	Node Expand	Node Collapse	Edge Expand	Edge Collapse
1	146	153	193	186
2	178	177	119	73
3	69	62	14	17
4	0	0	0	0

4 Discussion and Conclusions

Modern society depends on the operations of critical infrastructure systems—such as transportation, energy, telecommunications, and water—now recognized as dependent on one another. The work discussed here focuses on novel computational tools to support emergency restoration of services provided by these infrastructures immediately following the onset of a large-scale disruptive event. This paper has motivated and described a set of prototype tools for investigating and supporting post-disaster restoration of critical infrastructure systems in training exercises. The system employs large-scale displays, novel interaction capabilities, realistic data and a discrete event simulation to enable monitoring and assessment of group decision making processes. All software is built using open source tools and deployed within a flexible physical space. The parameters of the scenario-based simulation may be tuned to alter the time available for task execution, as well as the complexity of the networks.

Future work is proceeding along two parallel tracks. In the first, additional interaction modalities are being developed and tested. These include additional and/or refined gestures for querying the information presented on screen. The interfaces themselves are under continuous development to provide greater usability. Second, the functionality of the simulation engine and database is being extended, particularly to provide greater realism. For example, future work is likely to include more precise estimation of time and effort required to repair different types of damage in the system.

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