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The Mission-Based Scenario: Rationale and Concepts to Enhance S&T Research Design

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ABSTRACT

In this paper, we propose a new approach to developing advanced simulation environments for use in performing human-subject experiments. We call this approach the mission-based scenario. The mission-based scenario aims to: 1) Situate experiments within a realistic mission context; 2) Incorporate tasks, task loadings, and environmental interactions that are consistent with the mission's operational context; and 3) Permit multiple sequences of actions/tasks to complete mission objectives. This approach will move us beyond more traditional, tightly-scripted experimental scenarios, and will employ concepts from interactive narrative as well as nonlinear game play approaches to video game design to enhance the richness and realism of Soldier-task-environment interactions. In this paper, we will detail the rationale for adopting such an approach and present a discussion of significant concepts that have guided a proof-of-concept test program of the mission-based scenario, which we intend to integrate into ongoing S&T research efforts.

INTRODUCTION

Current Virtual Reality scenarios specifically designed for experimentation with human subjects tend to be rigid and linear, providing few, if any, options for decision making and interactivity. However, using experimental results from such paradigms in the real world requires the virtual environment to have as much in common with the real world as possible. Minimizing the interactivity (i.e., the user's ability to make choices that determine how the scenario progresses), from the environment strips any agency from the subject, and makes it difficult or impossible to study the choices that may be made in a real-world environment. However, these scenarios provide limited interactivity for several nontrivial reasons: first, in order to analyze the behavioral and physiological data obtained from subjects, experimenters try to limit the differences of experience across subjects, to make the interpretation of effects relative to experimental variables possible within the constraints of

their statistical models, and to keep the experimental procedure from being confounded with extraneous variables and individual differences among the subjects, including differences relative to their unique experiences with the virtual environment. Second, a virtual environment with a high degree of interactivity requires much more time and cost to develop than a more limited virtual environment.

In order to increase the ecological validity of the observed behaviors elicited within these environments (and, in turn enhance the generalizability and impact of the research results), we are developing a new approach we have termed the "Mission-Based Scenario." The Mission-Based Scenario aims to: 1) Situate experiments within a realistic mission context; 2) Incorporate tasks, task loadings, and environmental interactions that are consistent with the mission's operational context; and 3) Permit multiple sequences of actions/tasks to complete mission objectives.

There are two main challenges to this approach. The first is to move beyond more traditional, tightly-scripted experimental scenarios, by employing concepts from non-linear game play and the field of Interactive Narrative, as well as "sandbox" approaches to video game design. The goal of adopting such an approach is to enhance the richness and realism of Soldier-task-environment interactions without drastically increasing development costs.

The second issue is more difficult, and arguably more important. One of the main reasons why interactivity is limited in these virtual environments is to make them more conducive to analysis within the confines of traditional statistical models for null hypothesis significance testing (NHST). Strict adherence to NHST procedures often entails artificially simplifying tasks and environments with the aim of controlling variables that would potentially confound the interpretation of results under the assumptions of such statistical models, challenging the potential generalizability or external validity of such experimental results. Moreover, a number of recent articles in the cognitive science literature have examined and discussed the limitations and misuses of NHST approaches to data analysis (e.g., [1,2,3]), calling into question the applicability the approach to examining complex phenomena such as brain and cognitive behavior. This suggests that it is not enough to make these environments more interactive, but that reliable methods for analyzing these environments must also be determined. And while a complete discussion of the potential methods is beyond the scope of this paper, much of the recent focus has been on Bayesian data analysis as an alternative to NHST (e.g., [4,5], see also [6] for example applications), as well as the use of graphical and statistical modeling and statistical learning approaches (e.g., [7]) to capture the multi-dimensionality of real-world data that have become more widely used in fields such as environmental science (e.g., [7]), ecology and evolution (e.g., [8]), and epidemiology (e.g., [9]). These methods offer a strong path forward in developing the analytical tools needed for inference and hypothesis testing under the mission-based scenario concept.

We are arguing for a significant conceptual change in the design of research simulation environments. This new approach reflects the belief that complex interactions among Soldier, tasks, and environment, can neither be readily reduced to simpler forms nor studied in isolation. If we are to fully understand the impact of these interactions on Soldier performance, and if we are to develop technologies to effectively mitigate against negative performance consequences, Soldier-task-environment behavior must be studied in situations where their complex interactions can play out in realistic ways.

This paper is organized as follows: in the next section, we will cover related work, including example virtual environments and design concepts that inform our proof-of-concept application. In section 3, we will provide a proof-of-concept implementation of the graph-theoretic procedural content system. Section 4 provides a discussion of the informal evaluation of the system that we performed. A final section will offer some conclusions and future plans for upcoming work that will extend this approach.

RELATED WORK

In this section we will discuss some related work in two primary related fields. First, we will briefly discuss the use of Virtual Reality (VR) environments in psychology and neuroscience. We will then introduce several interactive narrative and game design techniques that have informed our thinking and early work in this area.

Experimental Virtual Reality

The problem of limited interaction in VR environments used for experimentation has been around since early VR systems. For example, over a decade ago, Wiederhold et al. [10] described a VR application for helping an individual cope with a phobia of flying. This environment simply consisted of a seat in the passenger cabin of an airplane with a single window looking over the wing, and the only interaction with the environment possible was simply looking around the environment.

Current VR systems have made vast improvements in many areas, however many of them still have very limited interactivity with the environment. For example, the Virtual Reality Cognitive Performance Assessment Test (VRCPAT) [11] is a system that performs neurocognitive assessment in a military-relevant virtual environment. Two tests are described: during one, the subject performs a task intended to assess executive function while standing in place at a simulated Army checkpoint in Iraq. During the second, the subject performs a task that is intended to assess attention while in a HMMWV that travels a fixed course.

Neither of these systems is 'lacking' in interactivity, *per se*, in that both of the systems include the level of interactivity needed to achieve the goals to which they were intended. However, by increasing the interactivity of the environment, we increase the agency of the subject, making it possible to study the choices that may be made in a real-world environment.

Interactive Narrative & Video Game Design

Our plan is to improve the interactivity of experimental virtual environments by adopting and expanding upon existing techniques in designing interactive narrative systems and video games.

Before discussing interactive narrative and video games, we will first discuss classical linear narrative, as exemplified

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by a book or a movie, which lies in contrast to the approach we are advocating. In a linear narrative, the story takes place in one way. Each time the narrative is experienced, the same sequences of events are performed by the same characters. This is conceptually similar to the way the VRCPAT system works, with each subject in a virtual HMMWV that travels the same path while the same events occur.

By contrast, in an interactive narrative, the storyline often has "branching paths" where multiple decisions can be made at each step of the narrative. Common forms of interactive narrative include computer games [12], including systems designed for education and training (e.g., [13]), where the computer reacts to the player's decisions, and role-playing games, where the reaction is performed by a human storyteller (see [14] for a discussion of using linear narrative techniques in interactive narrative from an entertainment perspective).

However, developing computer systems that can provide multiple decisions in an interactive format is time consuming and expensive. As Smith points out:, "Manually setting up [branching paths] requires a lot of work on the part of the team, can result in inconsistencies, and generally only equates to a small number of possibilities for the player" [12].

In order to address this cost, several authors [12,15,16] argue for the use of procedural content. The term "procedural content" refers to generating the branching paths to allow for increased interactivity *automatically* through the use of computer algorithms.

Smith [12] argues, through the example of a video game, that improved interactivity can be developed through increased capability for simulation in the environment. This increased simulation allows the player to perform additional actions at any point in the environment, and have the environment react realistically to these actions. Then, problems can be defined, and the user can emergently utilize the actions available to them, and the resulting changes in the environment, to define the solutions that appeal to them.

In contrast, Mateas & Stern [15] used a different approach through their system, which is a conversational game where the player interacts with two virtual characters, and certain narrative goals can be achieved. To do this, a set of branching paths through the narrative are constructed from a set of narrative events, called beats, each of which contains a sequence of low-level conversational behaviors. By allowing the narrative beats to occur in different orders, and by allowing some of the conversational behaviors within beats to be reordered, many possible paths through the conversation are possible.

Our approach described below draws most heavily from the graph-theoretic approach described by Lindley [16].

Lindley provides a review of interactive narrative systems and techniques, and argues that many of these techniques can be fit into a formal graph-theoretic framework that uses three common levels of structure: the first level is an atomic graph level made up of nodes (such as plot points or game areas), links between the nodes (actions which can be taken), and constraints upon the links (for example, a door to the next area may not open unless the player possesses a key). The second common structure is topography; i.e. there is a structure to the narrative, constraining the player to move through the story in a certain way. The third common structure is a node substructure, where each node can have a set of arbitrary data, including entire sub-graphs containing the information necessary for a sub-plot to the story.

Our initial goal in increasing the interactivity of the crew station environment is to increase the number of paths that can be taken through a simulated map. Our approach is to address this by taking the interactive narrative techniques that are designed to allow additional branches in a narrative path, and applying those approaches to increase the number of paths that can be taken through a map.

A Graph-Theoretic Approach to Increased Interaction

Over the past several years, we have run a series of experiments utilizing advanced, crew station interfaces and simulation environments (e.g., [17, 18], see also [19] for a more general overview). During most previous experiments, we have restricted the vehicle to travel through the environment along a set path, often at a fixed speed. This allowed us to ensure that each experimental participant was exposed to the same set of stimuli occurring in the same order and at the same time intervals. Providing increased interaction by allowing the participant to more freely navigate through the environment, controlling vehicle path, direction, and speed of the vehicle has lead to the following four related problems: First, the participant can travel through the map missing stimuli and events important to the success of the experiment. Second, the participant can travel through the map, taking a path that causes them to be exposed to many of the stimuli and events in the environment repeatedly. Third, the high memory usage of the environment, coupled with the finite amount of memory available on the computers running it means that a limited number of objects can be placed in the environment at any time, making it difficult to place all possible stimuli along all possible paths in the environment. Finally, development of the virtual environment, including map generation and the placement of stimuli, is very time consuming. This makes it prohibitively expensive to place individual "smart" stimuli along each path that will ensure that the participant will be

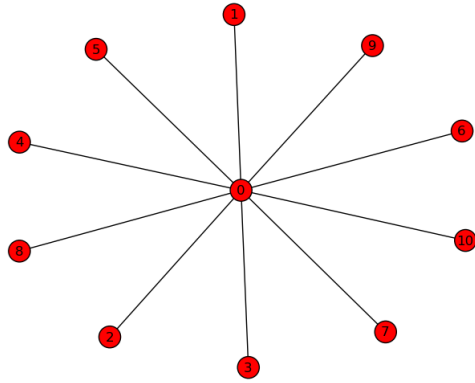The Mission-Based Scenario: Rationale and Concepts to Enhance S&T Research; Lance, et al.

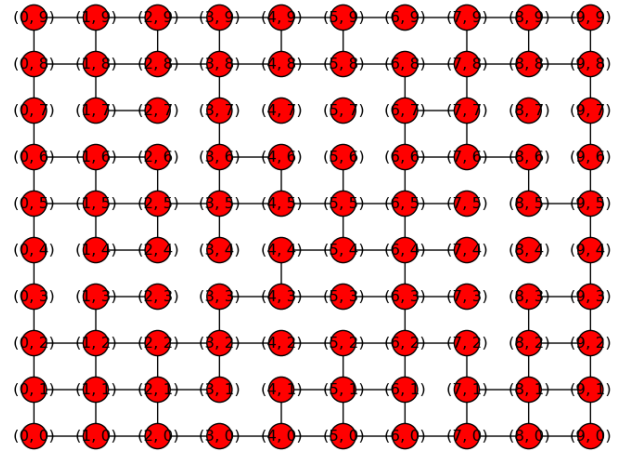**Figure 1: An example Graph, showing Nodes and Edges**

Figure 2: An example 2D grid graph with culled edges. The initial point was placed at (0,0) in the lower left hand corner. The goal point was placed at (9,9) in the upper right hand corner.

exposed to important stimuli and events without repeating them no matter what path they take.

Our initial approach to addressing these issues is to model the virtual environment using a graph-theoretic representation. We can then use this representation to provide a participant with control over their movement through the virtual environment while still being exposed to appropriate numbers of events and stimuli. Graph theory is a common approach in mathematics and computer science that is used to formally model certain types of problems to make them easier to solve ([20] provides a brief introduction). A formal graph-theoretic model consists of a set of "nodes" or "vertexes," which are connected by "edges" (see Figure 1). Both nodes and edges can have properties or labels assigned to them in order to better represent the problem. Modeling a problem as a graph allows it to be addressed through the use of many existing graph theory algorithms and techniques.

Proof-of-Concept Application

As a first step in this initial approach, we have developed a proof-of-concept graph-theoretic system that addresses these issues, although we have not yet integrated it into our virtual environment. The graph-theoretic system uses the networkX graph theory package from Los Alamos National Laboratories.

In the graph we are using, the edges of the graph represent the roads in the virtual environment, while the nodes represent the intersections of the roads. The nodes have three properties applied to them: the radius of the intersection, which we intend to measure from the center of the intersection to the nearest building, and a Boolean property, which indicates if the user is present at that node.

The edges have similar properties: width and length, representing the width and length of the road the edge represents; a property which indicates if the user is traveling along that road; a property which consists of a list of stimuli present at that edge; and a value which indicates whether or not the road is blocked (for example, by a Jersey barrier).

As part of the proof-of-concept project, we have determined two possible ways to utilize this graph definition. The first is in an "online" fashion, where the system would place stimuli along the user's path in real time. In order to do this, the online application performs the following tasks: it determines the position of the user in the graph, finds the shortest path from that position to a pre-specified "goal" node, and then lays the stimuli along that shortest path. The shortest path is determined, and the stimuli are then laid along the edges of the shortest path in a "reverse greedy" fashion, where the last stimuli appears closest to the goal node, and the stimuli are laid in equal intervals until all of the stimuli are along the path. The interval was determined by dividing the total number of stimuli by the total length of the path, but only the stimuli the user hasn't seen are placed along the path.

The second method for utilizing the graph is in an "offline" mode, where the algorithm will execute during the scenario development process, before the user interacts with the crew station. During the offline process, the system first performs a bounded depth-first search (DFS) that identifies all possible paths that are shorter than a predefined length that the user could take through the environment. The algorithm then lays stimuli along all of the paths identified

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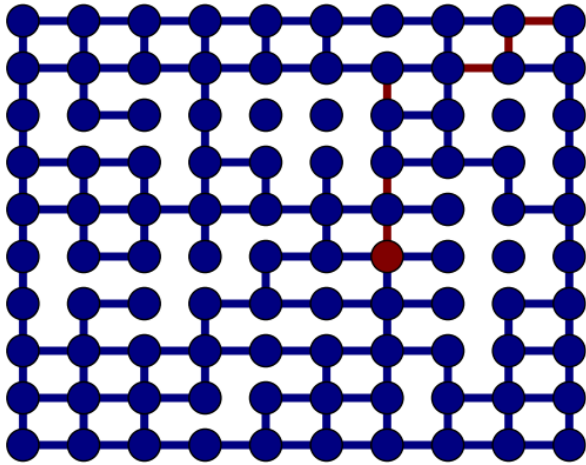
Figure 3: An example of the online application in use. The red node is a simulated user at an intersection. The red edges indicate edges with stimuli placed along them. Note the stimuli are placed on the edges along the shortest path to the goal.
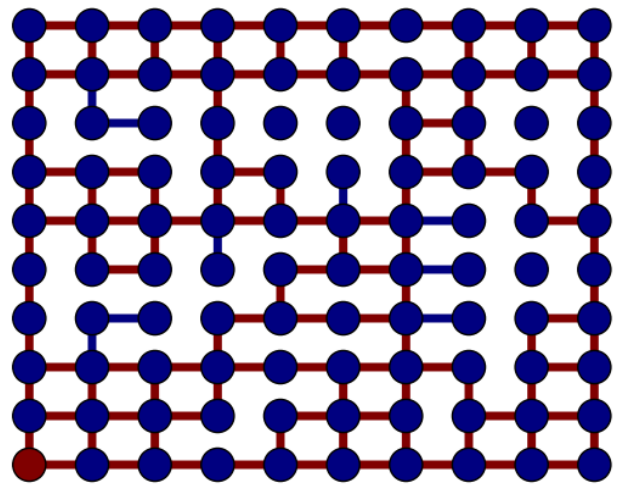

Figure 4: An example of the offline application in use. The red node is a simulated user at an intersection. The red edges indicate edges with stimuli placed along them. Note the stimuli are placed on most of the edges between the user and the goal.

by the DFS, using the same greedy algorithm utilized by the online application. The system then adds "tripwires" to the environment, which execute online, when the environment is actively being used. These tripwires activate or deactivate the stimuli depending on what path the user takes through the environment, ensuring that the user sees all of the stimuli in the correct order, without repeats.

Informal Evaluation of Online and Offline Systems

We performed an informal evaluation of both the online and offline systems. In order to evaluate the online system, we developed a sample application to move a simulated user through the virtual graph environment, while placing the stimuli in front of the user. For this evaluation we used a 10x10, two-dimensional grid of nodes with 50 edges randomly culled to provide a randomly generated maze graph. An example can be seen in Figure 2. The simulated user began at node (0, 0), and the goal was to move to node (9, 9). The simulated user would move through the graph by selecting a random point, and then moving (from node to edge to node) along the shortest path to that point. After doing this three times, the user would travel along the shortest path to the goal node. Ten stimuli were laid along the shortest path between the user and the final goal node at (9, 9), and the positions of these stimuli were updated every time the user moved to a new node or edge (See Figure 3).

Several observations, both positive and negative, became clear through repeated execution of the simulation. On the plus side, the user did always encounter all 10 stimuli, and the user encountered all of the stimuli in the correct order. However, the stimuli were heavily weighted towards the

end, generally being encountered by the user very close to the final goal; usually after spending a great deal of time moving through the graph without encountering a stimulus. It also became clear that a real user could compound this problem by taking an alternate path to the goal that was equidistant to the shortest path preferred by the algorithm; for example by taking a path parallel to this preferred shortest path. In this case, while the user would still hit all the stimuli in order, the stimuli could all occur very late in the graph, essentially all occurring right on top of each other.

We are using this reverse greedy method in order to lay stimuli out of the direct visual field of the user. However, the algorithm clearly needs to be modified to ensure that the stimuli are not so heavily weighted towards the goal node. To do this, we have a number of specific options: First, we could modify the calculation of the interval between stimuli so that it is only calculated based on the remaining stimuli.

Alternately, we could calculate all of the shortest paths to the goal, and lay the stimuli along all of them, or we could calculate the shortest paths to the goal that begins by moving along each edge of the node that the user is currently on.

The offline system (see Figure 4) was also tested using the same domain. Once the graphical grid had been established, we simulated a user moving through the domain, triggering and being exposed to stimuli. Using the offline preparation of the map, the user was again exposed to all stimuli in the correct order, without repeats. However, the offline system is more abstract than the online system is. In particular, it is not clear how exactly the triggers should be placed in the environment in order to keep the stimuli from appearing in the user's visual field; that is, "popping" into existence.

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Conclusion and Future Work

In this paper, we have described the development of a proof-of-concept system that can start to address the necessity to increase the interactivity of virtual environments used in experimental scenarios. We have argued that improving the interactivity of such scenarios is a critical step to enhancing the value of research aimed at understanding human behavior in more realistic settings. As this is a very preliminary proof-of-concept system, there is a lot of future work to be done. In particular, we need to address the issues found in the informal evaluation described above. The next step is to integrate the offline implementation of the graph-theoretic procedural content system into the authoring pipeline of the crew station environment. In order to do this, we intend to build the underlying graphical model from the existing VRML file that uses cubic splines to represent information about the roads in the simulated environment. This procedure should provide an automated process for producing the graphical models, which will support the final online implementation to control the simulated environment presented through the crew station to the operator. Moving past this, we need to take advantage of Jersey barriers and other blockades to modify the paths available to move through the environment online, thereby manipulating the graph structure in addition to the placement of stimuli.

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