3D Visualization of Port Simulation

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Three-dimensional computer graphics technologies have decreased in price/performance
and now fit comfortably into the toolkits of the simulation community. Applying these tech-
nologies offers the simulation modeler many significant opportunities to train and extend
their user base, but also presents challenges. Knowing the design goals of these technolo-
gies from their origins in the training simulator will help the modeler understand how to
select and manage those features which add the most value to the visual realism of their
virtual world. After defining the criteria for the physical representation of their virtual
world, the modeler needs to focus on how the user will navigate and learn about this
world and its activities. Borrowing from other disciplines will benefit the modeler in
designing compelling and engaging worlds with sufficient information tools for their users
to learn not only how the simulated operations take place, but how to identify the problems
the simulation has uncovered.

1.0 Introduction

Seaport operations involve a myriad of variables and complex operations resulting in plan-
ning errors that delay operations. For military deployments, these delays must be mini-
mized to ensure the proper delivery of supplies and equipment when needed so that forces
can complete their intended mission [Nevins et al. 1998 a]. Analysis remains complex and
requires frequent deployment exercises for the continued training of transportation plann-
ers, but these exercises require extensive and costly use of personnel and machinery
[MTMCTEA, 1994].

To reduce the costs of these exercises, other methods for analysis and training have been
sought. Simulation provides an excellent approach to quantify seaport operations [Nevins
et al. 1998 a, Hayath et al. 1994, Teo 1993], analyze port infrastructure and ship utiliza-
tion, identify potential bottlenecks, and propose alternative strategies for planning opera-
tions. The output of these simulations presents summary information of key port
conditions and performance. PORTSIM, the port simulation model discussed in this paper,
displays several meters while the simulation is running and produces reports, charts,
graphs, and tables after the simulation has completed. This summary form of information
is invaluable to the experienced planner, but can hide the underlying details from those
planners with less experience in seaport operations.
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Seaport simulations continue to benefit the deployment community, especially when used by experienced planners who have seen or engaged in actual deployments or exercises. For the inexperienced or novice planner, the opportunities to plan or witness an actual deployment are dwindling, mostly due to constant pressures to reduce training costs. For novice training, an accurate three-dimensional visualization of an actual port engaging in a simulated deployment offers them a tool to witness and repeatedly investigate the complex requirements and activities of a deployment. This tool, PortVis, intends to support the training and detailed analysis of the port simulation model, PORTSIM.

This paper discusses how port simulation (PORTSIM) and port visualization (PortVis) address military mobility problems. In a more general context, commercial seaport operations need to attend to similar problems, such as minimizing shipping delays, to remain competitive in the marketplace. Simulation can assist commercial seaport managers in providing their customers with reliable estimates of when cargo items will be delivered.

Other anticipated uses of the simulation and visualization involve testing new and untried port layouts and architectures. These “what if” designs can be simulated and visualized for verifying design expectations and analyzing the impact of various design parameters on seaport throughput and utilization. These tools have the potential to save significant expense in the construction of new seaports and the redesign of existing ports.

2.0 Port Simulation Model

The Port Simulation (PORTSIM) system is a model that has been developed to facilitate analysis of movements of cargo items through worldwide seaports. PORTSIM simulates all processes required to efficiently operate a seaport and provides detailed statistics on seaport throughput and utilization characteristics. Originally designed for the planning of military movements of forces through seaports, this model has a wide variety of commercial applications.

Operating as a discrete-event, time-stepped simulation, PORTSIM has the ability to simulate individual cargo movements through a highly detailed, spatially correct infrastructure database of a port. The port resources modeled include gates, staging areas, berths, inspectors, and material handling equipment.

PORTSIM addresses the following questions:

- How long does it take to move equipment and supplies through the seaport (closure)?
- What and where are the potential bottlenecks and limiting resources to movement through the seaport?
- Why are operations not completed within the required time?
- What are the implications if certain seaport resources are constrained or made available?
- What is the port throughput capability, given explicit assumptions regarding assets, resources, and scenarios?
PORTSIM addresses two modes of operation. The first mode addresses embarkation processes and encompasses the major activities of (1) reception, (2) staging, and (3) ship loading. Reception activities include all processes needed to accept cargo items at the entry points to the port and transport those items to the staging areas. The entry points are the gates for highway entry and interchange yards for railway entry. Staging activities encompass all processes necessary to park cargo items in appropriate locations before ship arrival as well as to inspect individual items. Finally, ship loading activities include all processes needed to call forward the cargo items to the berths when ships arrive and to load them onto the ships by means of the appropriate loading method, i.e., roll-on, roll-off (RORO), or lift-on, lift-off (LOLO).

The second mode of operation in PORTSIM addresses debarkation processes and encompasses the major activities of (1) ship unloading, (2) staging, and (3) clearance. Ship unloading activities include all processes needed to off-load the vessels that arrive at the berths and to transport the cargo to the staging areas. Debarkation staging activities are similar to the embarkation staging activities and encompass the parking and inspection of cargo items at the port. Finally, clearance activities allow the cargo items to be moved from the port onto the highway or railway infrastructure. This activity involves the loading of commercial highway assets such as flatbed trucks and chassis, as well as the loading of railway assets such as trains made up of flatcars and boxcars.

PORTSIM models all facets of the seaport and allows for:

- Multiple ships;
- Multiple port infrastructure resources such as gates, berths, staging areas, interchange yards, end ramps, and rail spurs;
- Port machinery and personnel assets such as forklifts (or fork lifters), container handlers, cranes, drivers, and inspectors; and
- Multiple cargo types such as roll-on/roll-off, container, and break bulk.

The simulation system is designed to assist port planners in determining seaport capability given the port and ship assets that are available to support the operation. Additionally, PORTSIM allows for flexibility in the manipulation of the arrival profile of cargo items to the seaport. Potential bottlenecks in the system are identified and limiting resources can easily be determined. Finally, the simulation system ascertains the implications if certain seaport resources are constrained or made available.

The PORTSIM model is general-purpose in nature and has been applied against several real-world seaports. For purposes of this paper, the seaport of Savannah, Georgia, USA, will be used to illustrate the visualization capabilities of the PortVis tool. Typical simulations of port operations for the port of Savannah consisted of a period of 30 days (at the minute level of detail) in which 10,000 items were processed through the port. Transportation modes to the port included military convoys, commercial highway assets, and commercial rail assets. The analysis was conducted for port of embarkation activities.
3.0 Graphics Tools Provide Opportunities and Challenges

Until recently, the availability of high performance computer graphics was confined to the visual simulation community who build immersive training simulators for expensive equipment such as fighter jets. These technologies have continued to increase in performance and lessen in price and are now available to the remainder of the simulation community. In addition to algorithms, graphic languages, and hardware, the methods to construct geometry, move objects, map textures, detect collisions, and perform level-of-detail switching have extended into the simulation toolkit.

These tools offer new opportunities but also present challenges. The design of an equipment training simulator differs markedly from the design of a observational simulation. The training simulator focuses on the man-machine interface and applies physics-based modeling to the equipment controlled by the user in an immersive world. The user directly controls, manipulates, or guides the equipment to perform tasks in that world and the simulator responds with appropriate feedback, commensurate with the trainee's actions. Engaged by the simulator, the trainee absorbs the feedback and learns how to operate the equipment.

However, providing feedback and engaging the users of an observational simulation so that they understand and learn about the virtual world and its activities without direct control present a significant challenge to the designer of that virtual world. The success of these observational tools depends on borrowing research from other areas. Designing a training tool for port simulations using 3D visualization combines the results of many different research and development efforts, from the visual simulation and geographical information systems communities to the situation awareness efforts of the air traffic control systems.

3.1 Computer Graphics Technologies

The results of the visual simulation community provide a rich, interactive, three dimensional texture mapped graphics environment which permits the user to navigate and interact. Developed by Catmull in 1974 [Catmull 1984], texture mapping offers the most powerful tool for realistic image generation beyond the ability to draw geometry. Textures can be synthetic or photographs, stored in files or dedicated hardware memory. These generate the visual realism of even simple 3D representations of vehicles and ports.

Objects in a scene will often be located far from the observer and, with a perspective frustum, will appear small or barely discernible. Sampling theory suggests that as the polygons representing the object become small with respect to the pixel spacing, the polygons no longer contribute to the scene. At other times these objects might be viewed at close range or a narrow field of view (zoom) and contribute much to the scene. In-between these two distances from the observer, the polygons have varying contributions depending on their size and human visual acuity [Buse et al. 1992]. To combine these cases into a general approach for constructing a 3D geometric database for this object, each model can be built as a set of alternate representations, each of which is to be viewed at a certain distance of screen-space size and contain just enough polygon complexity to represent the...
object. This level of detail switching provides a basis for the scene graph technology described by Rohlf et al. [1994] and Clay [1996].

3.2 Relevant Research

3.2.1 Training Effectiveness and Situation Awareness

Training effectiveness research offers a methodology to identify how well a training system performs. Measurement of training in the virtual simulator can follow a traditional scoring approach, where the trainees can be measured by recording their performance in accomplishing the tasks, such as takeoff and landing or moving a container from a ship to an awaiting yard dog. However, measuring how well a planner benefits from using an observational tool becomes more difficult and requires other methodologies. The work of Endsley [1990] describes SAGAT, the Situation Awareness Global Assessment Technique used by the air traffic control community. SAGAT offers a method of testing the trainee’s awareness of the state of the simulation. While the trainee is observing and interacting with the simulation at the console, a trainer will stop the scenario and ask the trainee a series of questions about the situation and compare the answers to what is actually happening.

3.2.2 User Interface Design

Simply giving the users a fairly expressive mouse control to self navigate a port may not sufficiently introduce them to the port layout and complexity nor to the simulated cargo movements. Other forms of information and navigation need to be presented to the users to ensure they gain as much understanding of the situation as possible. User interface design forms the basis for much of this work. Other contributors include robotics, cinematography, and civil engineering.

3D interfaces such as joysticks show promise and can be simple though non-trivial to use. Some people use them unconsciously, while others have trouble even after training [Boyd 1995]. These 3D interfaces also depend heavily upon button pushing, a modal interaction of switching states which demands that the user consciously remain aware of both the task at hand and the current interface state [Raskin 1997]. In contrast, keeping the user interface clean and the control stateless allows the users to keep their own task as the exclusive locus of their attention, a habit to be formed.

3.2.3 Virtual Cinematography

Other methods of introducing the port and scenario use virtual cameras to create pre-built user selectable flythroughs of the scene. These can be constructed using the databases underlying the simulation and 3D models, and take the user on a path which traverses the database, looking at the various infrastructure or material handling equipment. Work in virtual cinematography [He et al. 1997] [Geiger 1998] [Perlin 1996] presents various paradigms for automatically generating camera (observer) controls for capturing events in virtual 3D environments. PortVis uses similar ideas to generate observer vantage points.
which place the observer in a position to view a particular piece of infrastructure as well as the centroid of the port. Similar methods can be employed to position the observer to watch the development of a deployment problem, such as a bottleneck.

### 3.2.4 Synthetic Environment Database Design

Synthetic databases need to support many different components of visualization. 3D databases describe the geometry of the objects in the scene. Other databases offer an organization to present human-readable information to the user. Still others might be required for use by computer motion models.

Geographical Information Systems (GIS) and the multi-layered model approach by Fekete [1996] suggest ways of organizing data as overlays and methods for users to interrogate and extract this information. This is especially important in a training tool designed for situation awareness. Typically, a user selects an object using a mouse and accesses information stored with that object, such as a name and lading information. However, some 3D databases may not contain user accessible information, or selecting objects might be difficult because they may have such a small screen representation. Other objects might exist only at a single point, making their selection virtually impossible. Presenting overlays to describe the scene, such as textual labels to name key infrastructure locations, can markedly enhance the user’s awareness.

Additional data formats might be required for computer controlled activities as described by the Synthetic Environment Data Representation and Interchange Specification [SEDRIS 1998]. The models of computer generated forces use dynamic reasoning to move, but take directives such as “move down road X.” These models need to obtain information from the synthetic database. They cannot “see” that the chain of gray polygons with a yellow stripe is a road, but require topological data describing a linear feature with direction, width, etc.

Supporting polymorphic databases which describe the same physical location requires extra effort but offers advantages in flexibility as seen in information labeling and more compact descriptions of movements. Routes can be defined in databases shared between the simulation and visualization which allow the simulation to describe a movement using a route identifier and start/stop times, instead of a set of possibly many piecewise linear segments.

### 3.3 Animation

Research on the role of animation in simulation has shown that animation is very effective in communicating the operation of a simulation model and assisting in the validation and verification of the model [Swider 1994, Cyr 1992]. However, as Carpenter [Carpenter et al. 1993] demonstrates, the simple movement of icons presents the most information, not the color or detail of an icon. This suggests that the difficulty in presenting effective communication is not just adding information by adding colors or varying the detail of the icons, but in conveying what those colors or icon details mean. Map making techniques, such as legends, can provide a mapping between the icon and a name or a textual descrip-
tion, but those fail the user who does not know even the name of the object. A mapping to a photograph can be helpful but this requires the use of a much larger legend, since the photograph will not easily scale onto a space commensurate with an icon, or it requires the use of an additional user request to access a photograph of the item represented by the icon. This last interactive selection of a photograph of the vehicle type is employed in the 2D animation of PORTSIM and described in Nevins et al. [Nevins et al. 1998 b].

3.4 3D Database Automation

Database development remains expensive, requiring time, travel, and tools. Automated tools to extrude 3D models from 2D GIS data would greatly facilitate the process of visualizing more ports, but such tools have not emerged as of yet, despite a push by the National Research Council [NRC 1997]. Possibly more significant is the work at the University of California, Berkeley [Debevec et al. 1996] where they have extracted 3D data from 2D images such as photographs. This latter work shows promise in developing datasets for display, but, as discussed in this paper, PORTSIM depends on actual geospecific data for a port to provide the detailed analysis required to generate motion histories of cargo items.

4.0 Databases

4.1 3D Databases

4.1.1 Port Infrastructure

The creation of the 3D databases of the port begins with a 2D GIS description which is manually extruded, using computer aided drafting (CAD) tools, into a 3D model. The resulting model is then converted to a realtime database format for interactive display. Similarly, the 3D models of the vehicles are manually created by CAD tools.

This 3D database creation process can benefit from a technique often described as selective fidelity. Using this technique the database designer selects those areas or features which contribute most to the requirements of the visualization and concentrates resources there. Typically, the resources are additional geometry and texture to more realistically define an object, but might include the material properties of an object which define how sensor systems display the object. Other resources include internal moving parts in the equipment, different physical appearances of the same equipment representing various conditions, such as an extended or retracted crane, and stored animations, such as rotor animations on helicopters.

Using this technique in PortVis, the port databases are flat and contain only those buildings which have significance to the operation of the port. These buildings consist of the minimum number of polygons to produce the general outline of the building. Doors exist only as texture maps and contain no additional geometry or moving parts. Everything has a texture map, but only those features such as roads and railroad tracks require a strict
attention to the alignment of the texture map. Roads and routes must align with the GIS database describing the routes and segments where the simulation moves the cargo and vehicles. Deviating from these paths would seriously undermine both the validity of the simulation and reduce the realism of the visualization. A few buildings have different levels of detail, but in general they need to remain visible at all times.

### 4.1.2 Vehicle and Material Handling Equipment

The vehicle databases have several levels of detail, but the highest level still has only octagonal wheels. The windows in the vehicles are transparent, allowing the observer to see inside or through the cab. Most vehicles have no moving parts, they move as a unit; trailers do not articulate behind truck cabs. Articulated vehicles such as trains can be modeled as individual cars and move simultaneously without direct connections.

Material handling equipment has no moving parts, but needs different configurations to depict different activities. Crane booms are extended during loading operations, but retracted during ship movement. A ship's loading ramp is lowered after it arrives at the berth. These different configurations can be stored as separate 3D database representations, but some database formats can contain several representations of the same object. These different representations or states can be switched by the visualization to more realistically demonstrate the different activities.

Stored animations add significant value to the realism and to the suspension of disbelief. Some vehicles require moving parts. For example, helicopters appear broken without the rotating blades. These animations can typically be stored within the 3D database as a sequence of moves, and then driven by adjusting the rate of those sequences.

### 4.2 GIS database

Within the GIS database of a port, referenced extensively by PORTSIM, there exists position and extent data for all of the infrastructure elements, such as gates, berths, staging areas, and container cranes. PortVis uses this database to create a set of observer vantage locations, which, when picked from a menu, position and orient the observer to see the selected infrastructure and center of the port. These infrastructure positions are also used to overlay labels onto the 3D database to assist the users in identifying and orienting themselves in the virtual port.

These positions are also used by the automatic fly-through tool to create a 3D path traversing the database. This fly-through can be selected by the user to repeatedly move through the port to observe the areas and routes where activities are occurring.

### 5.0 Communication from PORTSIM to the Visualization

PORTSIM creates an event history file for input into the visualization system. Described in detail by Nevins [Nevins et al. 1998 b], this event history lists a series of piecewise linear movements of named cargo items along routes defined in a GIS database. PortVis uses
the names of the cargo items to reference a table of 3D objects and schedules moves for each cargo item. These moves have constant velocity, thus instantaneous acceleration. This use of selective fidelity does not detract significantly from the visual realism and conforms strictly to the movements simulated by PORTSIM. This strict conformance to the accuracy and precision of cargo movements as defined by PORTSIM is an inviolate requirement of the visualization system. These verification and validation requirements ensure that the planners using the system observe the exact results of PORTSIM. Unlike other visual simulation systems, the users do not control the outcome of the simulation.

In addition to the typical line segment point-to-point motions of PORTSIM, other motion models are supported. Arcs and rotations support ship and tugboat movements for ship arrivals because PORTSIM knows only when a ship arrives, not its route. Paths and route movements can also be specified by a set of line segments. Collision detection between vehicles can be used to advance vehicles lined up in queues awaiting inspection or other delays where a human is expected to control the minor movements of the vehicle. Other uses of collision detection allow for vehicles to climb ramps or travel on top of other objects such as rail cars.

Parking models are now in development to schedule the motions within staging areas. Previously these areas were treated as storage capacities with vehicles entering and exiting at known times, but without an internal representation. Tiling algorithms will approximate the areas, and internal parking movements will be handled by a separate parking model.

6.0 User Interface

The most difficult problem in these types of visualization systems is the construction of an effective tool or set of tools for the user to experience the virtual environment and extract the essential information while ignoring the useless details. Similar to filter design, the interface must not remove too much of the detail or amplify too greatly any particular information. This must involve a shift from cognitive computing to experiential computing. This will not be an easy process and only a modicum of success has been attained.

The notion of the user interface in PortVis has been to allow the users to quickly move throughout the port but never let them lose their bearings without a safety net to return to a known place or without a tool to allow them to find their location and line of sight. One menu offers the users a list of observer vantage positions which place them in a position to watch a key area in the port. This allows them to jump throughout the port and still know where in the port they selected.

Another method has been described as the virtual camera which takes the user on a fly-through course along a path marked by the key infrastructure locations. This allows the user to simply observe without any use of the mouse or keyboard. This path covers the important areas of the database and shows the areas where cargo movements are occurring.
At any time the user can use the mouse to drive through the scene, using the left and right buttons to change altitude, and forward and backward movements to move throughout the port. Pitch is controlled by the keyboard keys.

The user can also attach to any cargo item or vehicle in the scene and observe from the vantage point of that object as it moves through the port. The attachment is placed somewhat above the vehicle to limit the occlusion from the vehicle's own geometry.

Along with any other observer navigation or position, the user can select to look at any other cargo item or vehicle. As the users move through the scene, their heading and pitch change to keep that item in the center of their field of view.

Navigation is necessary for the observation of large areas such as ports, but getting lost in these spaces is also easy. Orientation tools assist the users in regaining their bearings. And if the orientation tools do not help, a quick return to the menu to start afresh is always an option.

One helpful orientation tool provided by PortVis is a popup 2D map of the port. Oriented north and south, this orthogonal map contains a live view of all vehicles and containers in the port. The user's position and orientation, line of sight, are highlighted on the map. Since changing the zoom or field of view is possible and greatly changes the perception of the user, the triangle defining the field of view is also displayed. With this overlay on a 2D map of the port, the users can quickly identify their relative location and heading and easily return to the 3D view with a renewed sense of the port around them.

7.0 Information Extraction and Situation Awareness

By navigating and observing vehicle movements, the user can reap useful information about the port and the progress of the simulation. Other information can be made available to the user, through various extraction, interrogation, and display methods.

One method, selecting an object on the screen with a mouse click, results from the use of the underlying scene graph technology. Unlike 2D orthogonal views, where each pixel represents a unique location and thus a unique object, a 3D perspective view might have several objects aligned on the selection path. The use of the scene graph technology allows one to identify the object closest to the observer. Highlighting the object identifies which object was picked and allows the user to further interrogate that object. In PortVis, the data structure representing that cargo object has a unique name which can be used as a query key to a database further describing that object's characteristics and other useful information. This name is also used by a labeling overlay to place a label on top of the 3D display.

Labeling cargo objects with their names offers useful information but might clutter the screen if the density of items is very high. Other aggregation labels or highlights have been suggested that might group objects with a similar characteristic, but these methods present symbology problems similar to the icon detail confusion experienced by 2D animators.
One area particularly lacking in these 3D renderings is the identification of the infrastructure landmarks. While the visual representation of berths might clearly identify and depict a berth, the name of that berth clearly requires some other presentation. Using labels greatly assists in the identification of these landmarks, and PortVis has a selection button to display labels for all infrastructure landmarks.

Selecting these landmarks manually as one might select an object does present a problem. Unlike objects which occupy space, a landmark usually is defined only by a single point. Picking those single point landmarks might be accomplished by a nearest neighbor algorithm. If the object is a building or another extruded 3D object, it does occupy more than a point, but it is typically embedded in the base port object and not independently selectable. PortVis is investigating the benefit of the individual selection of landmarks over the general selection of labeling all infrastructure landmarks.

Currently, the visualization does not keep track of simulation problems, such as bottlenecks, which could be used to evaluate whether the trainees discovered the problem during their visual examination of the simulation. How these problems will be tracked has yet to be determined, but the visualization has tools to support the observation of these interesting results. Time management tools allow the user to advance the simulation clock either more quickly or to jump to a particular time in the future. Jumping through time without overshooting is not trivial. With these time shift tools and the use of the virtual camera, the presentation of these simulation problems requires only the location and time of an interesting event. With these time-stamped locations, an event scheduler will offer the training system a method to ensure that the problems can be made available to the trainee. Incorporating a method to permit a trainer to schedule the observation of these problems is under investigation, as is the extraction of this information from the simulation.

8.0 Conclusion

Affordable and realistic three dimensional visualization technology can be applied to large scale constructive simulations such as the port simulation model, PORTSIM. These visualization tools enhance the experienced planner's ability to form mental models of how seaport operations will unfold when the simulation model is implemented and executed. They also offer unique opportunities to train new planners not only in the use of the simulation model but on the layout and design of seaports.

Simulation visualization capabilities are enhanced by borrowing from work on interface design, camera control, and data presentation. Using selective fidelity, the designers of these visualization systems can reduce their time and efforts by concentrating on those features which yield the most value for their simulation. Offering the user various observational tools allows the freedom to simply watch or engage in the simulation without getting lost. Identifying the underlying infrastructure or cargo items with labels can provide useful information at the risk of some visual clutter.

The PortVis visualization expands the PORTSIM user base which can benefit from the results provided by this capability, especially in strategic planning, mission rehearsal, and
training. Strategic planners will immediately reap the benefits of seeing the impact of increased throughput visually without keeping track of statistical data. Mission rehearsal and training users will have an effective training tool to supplement their operational training exercises which are limited in number because of their high costs. Having another effective training modality in this visualization system allows more training to take place and more personnel to gain an understanding of seaport operations. This simulation and visualization training can be accomplished at lower cost than would be possible for the operational training exercises alone. The application of PORTSIM and PortVis will lead to more efficient planning overall and ultimately increase port utilization and throughput, decreasing the amount of time required to transport cargo from its origin to its final destination.

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10.0 References


