Managing Construction Operations Visually: 3-D Techniques for Complex Topography and Restricted-Visibility

Walter Rodríguez, Ph.D., P.E.
Florida Gulf Coast University, Fort Myers, FL 33965-6565

Augusto Opdenbosh, Ph.D. and Juan Carlos Santamaria, Ph.D.
XYZ Solutions Inc, Alpharetta, GA 30004

ABSTRACT- *Visual information is vital in planning and managing* ***c****onstruction operations, particularly, where there is complex terrain topography and limited accessibility and visibility. From visually-assessing site operations and preventing equipment collisions to simulating material handling activities to supervising remote sites and underwater recovery efforts, project managers rely heavily on visual cues and 3-D data gathered from the site and, preferable, before actual site construction or underwater recovery efforts begin. This paper presents the background and state-of-the-art in the development of construction visualization techniques for dynamic 3-D modeling, rendering, manipulating, evaluating, collaborating, and managing construction sites and underwater operations. A couple of real-life cases illustrate the application of these 3-D techniques.*

I. INTRODUCTION

Although a myriad of CAD, Geometric Modeling and Animation software systems are commercially available to model geometry for design and planning purposes, these tools have had very limited use in assisting site developers and project managers visualize, simulate, evaluate, and anticipate construction operations and processes. This is due to the complexity involved in creating the rich virtual scenes needed to accurately model construction scenarios. Further, the dynamic nature of construction operations and the complexity of its associated processes bring additional operational, three-dimensional manipulation, and surface-rendering challenges.

The new web-enabled, process-oriented, construction visualization techniques presented in this paper allow project managers to model, render, visualize, simulate, and manage construction operations under difficult site conditions and limited visibility. Further, the techniques facilitate collaboration with remote (off-site) members in the project management team. First, the paper reviews a few of the modeling, rendering and manipulation techniques that were developed by the authors—individually or collaboratively—during the last 15 years. From simple techniques for rendering topographical contours to help visualize terrain complexities (Figure 1) to proprietary state-of-the-art XYZ-solutions to analyze site operations underwater, the reader will gain insights into the world of site visualization and how it's used to solve real-life problems. The later solution will be discussed extensively and applied to an underwater recovery effort.

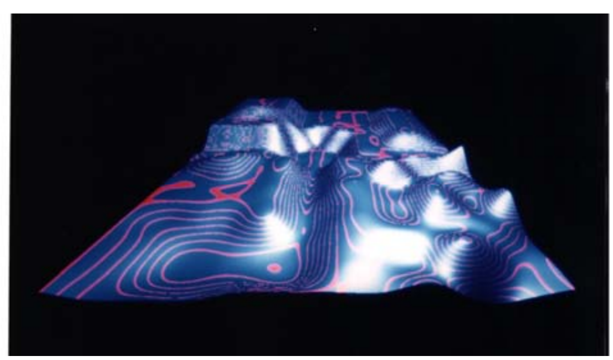

Fig. 1. Visualizing Complex Terrain Surfaces.

II. BACKGROUND

The authors have been working (individually or collaboratively) on developing a 3-D graphic language that allows project managers to visually-simulate construction site operations since they met at Georgia Tech 15 years ago. The first author is an academician and researcher, while the second and third authors (former Georgia Tech graduates) are practitioners developing and applying visualization techniques to real-life problems.

The first author interest in improving the design, planning and visualization of construction site operations dates back to the 1970's – as a young project manager working on the $20-million Federal Building and Courthouse project in Puerto Rico. In this project, the concrete batch plant was originally located at one end of a very large and relatively narrow site. Additional facilities and materials were dispersed everywhere in the site. Traveling-time was a major factor in the subcontractors' low operational performance. For example, it was usual to see workers waiting for material deliveries because the supply depots and facilities were inconveniently located on the site. He observed similar situations on a very crowded construction site for the University of Florida's football stadium while pursuing his PhD in engineering project management. At the time, he thought that it would be "groove" (neat) to be able to visualize the site before actual construction begins. Of course, the computational power to handle the necessary 3-D graphics was in its infancy. So, he developed a series of location optimization algorithms and site heuristics for designing construction sites in two dimensions—including crane location optimization (Rodriguez and Francis, 1983). For example, the angular movement of a tower crane arm's trolley was defined as

$$Aj(\theta) = \min[|\theta - \theta j|, 2\pi - |\theta - \theta j|] \qquad (1)$$

In every case the movement can be measured by either $|\theta - \theta j|$ or $2\pi - |\theta - \theta j|$, depending on the direction of the travel of the boom (arm), in which θ and θj are two given relative angular arm locations (positions) which respect to a polar coordinate system chosen so that the boom's pivot is at the origin. Obviously, the angular movement of the boom between two points should be the smaller, or minimum, of the two possible angular movements between locations, as shown in the equation (1). Of course, it was hard to imagine the contractor using even this simple mathematical formulation.

Further, during construction of the stadium, the contractor had to move the concrete batch plant three times, a street had to be closed, and the trucks involved still had difficulty loading and unloading materials! The contractor, operations project managers and site planners would have benefited from visualizing and simulating construction operations before actual on-site construction.

Organizing people, materials and machines to work effectively becomes easier with the help of web-enabled dynamic techniques for 3-D object manipulation on terrain surfaces (or any possible surface). The techniques address construction operations optimization and visual simulation of design and construction processes.

Both a functional framework and a test-bed for implementation process simulation were developed during the late 80s and early 90s. As background, the reader may consider viewing the streaming-videos I, II, III at URL http://www.fgcu.edu/wrodriguez (Please click "Web Presentations" to view videos as reported in CNN, Public Broadcasting and Discovery Channel documentaries.)

The initial academic research was mainly applied to the creation of a visual simulation test-bed or experimental visualization techniques. This technique used a construction metaphor to manipulate, display and visualize geometric primitives and operations on a virtual "site." Figure 2 illustrate a sample display output in a mining site operation. But, it has application to other fields such as aviation, military, ship-building and tracking, manufacturing, construction and underwater searches and so on.

Figure 2. Visualizing Mining Operations.

The techniques were initially designed to facilitate operations at a particular site by providing dynamic 3D solid primitives (constructed in AutoCAD and other commercial software) that represent people, materials, robots, cranes, trucks, front-end loaders, fork-lifts, and so on. Each primitive had its own interactive animation and simulation capabilities. The users control a "gyroscopic" viewing camera by moving the viewpoint.

Figure 3 illustrates the general data flow diagram for the construction site equipment operations.

During the development efforts, the researchers used the term "camera" instead of "viewing window" or "viewer." It's easier to think of the viewing window as an object that can be manipulated interactively.

Here is one of the problems that had to be solved: In the standard graphic libraries the **polarview** function defines the camera position in polar coordinates which determines the line-of-sight as the vector from the camera location to the origin. But, this function is limited in that "by itself" it will only allow the user to look from space toward origin. This is "fixed" if the translate (-nx,-ny,-nz) function is used to offset the origin to a new location (nx,ny,nz). Even after taking care of this problem, the user is forced to define the camera orientation and location using a combination of Cartesian and Polar coordinates which is unnatural and often confusing if camera manipulation occurs interactively. The researchers introduced a more robust function called **camera_view** which allows the user to define a viewing matrix for any possible camera orientation. This approach took advantage of the fact that a viewing matrix is nothing else but the product of the orientation and displacement matrixes (Opdenbosch, A., Ferrier, A., and Rodriguez, 1992).

Since the technique was developed in the C object-oriented programming language, and it runs on Windows and Unix-based workstations, it allows both multi-user and multi-tasking activities. These features allow all members of the planning team to work simultaneously in the creation, visualization, manipulation and evaluation of construction operations through the web---greatly helping remote collaboration.

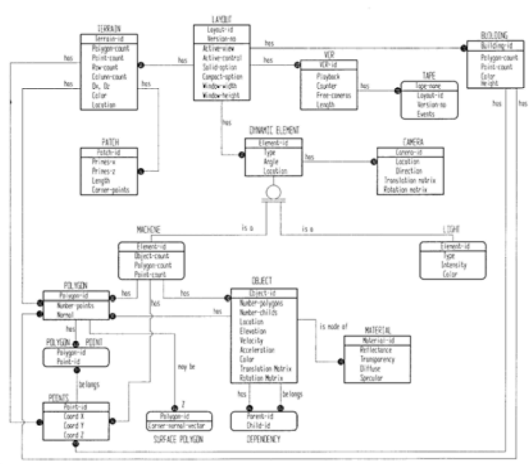

Figure 3 . Data Flow for Equipment Operations.

The technique can be used as a tool for visualizing and prescribing the best plan or site arrangement for a given time and location. For example, an option depicts a material hoister on a future construction project. Workers and equipment at different floors moving a variety of materials are also represented. In this case, actual simulation tells the planning team how long each person had to wait. The user can specify, for some reason, that certain workers are traveling between two floors a lot, and then change parameters to obtain the optimal arrangement. This visual simulation was used to determine the performance of personnel and material hoist (elevator) under different conditions. The simulation runs in real-time and allows the project manager to take action in the process. The simulation creates its own workers and materials and places them randomly at different building floors. The rate of arrival for the resources is controlled by an exponential random generator which can be set and manipulated for each of the stories of the building. The time that takes the elevator to move from floor to floor is a variable capacity of the elevator, number of stories in the building, etc. Two files are generated: One contains the history of each resource; the other contains the data for the 3-D output interface to visualize the hoisting process. (Opdenbosch, Patterson, Rodriguez, 1991).

An experimental prototype 3-D interface was developed based on a time-multiplexed stereoscopic display system implemented with monitor calls. The effectiveness of computer-generated realism cues for the visualization or construction site scenes has been investigated. Cues include motion, number of light sources, shading techniques, stereoscopic display, and hidden surface removal. This investigation uses a factorial experimental design to evaluate the effect of the type of computer graphics display provided for visual feedback on the user's performance on an object recognition and 3D manipulation task (tower crane hook to site supply depots.) The independent variables in the experiments are the presence of binocular cues, occlusion cues, surface shading cues, of other factor that may affect user performance on this task. The dependent variables in this investigation measures task performance, such as the time for task completion or task error rates (McWhorter, Rodriguez & Hodges, 1992).

Finally, an enhanced reverse ray tracing technique was developed to model and render complex geometry (topography) of construction sites and other surfaces. The topographical surface model is defined by control points using existing contour-data from the sites. An object is drawn by intersecting vectors with the computer screen (Figure 4).

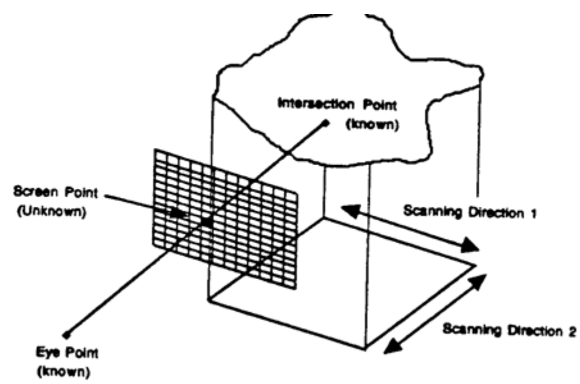

Figure 4. Tracing a point back to observer.

These vectors are traced from points on the object surface to the observer location. This technique was originally very slow due to the necessity of super-sampling points on the object surface. The performance of this technique has been improved by defining a relationship between the actual area and the projected area on the object and using it to control the sampling of the points on the object surface (Opdenbosch & Rodriguez, 1991). Figures 5 and 6 illustrate the graphic projection procedure and the resulting rendering output.

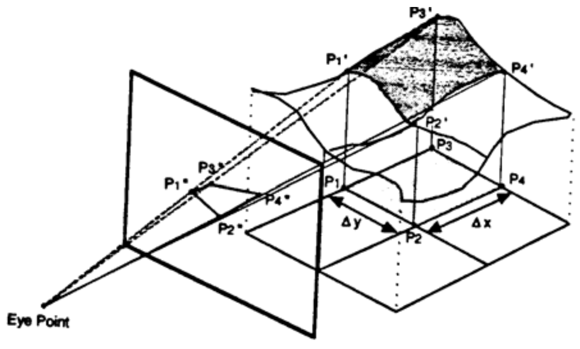

Figure 5. Subdividing the Surface.

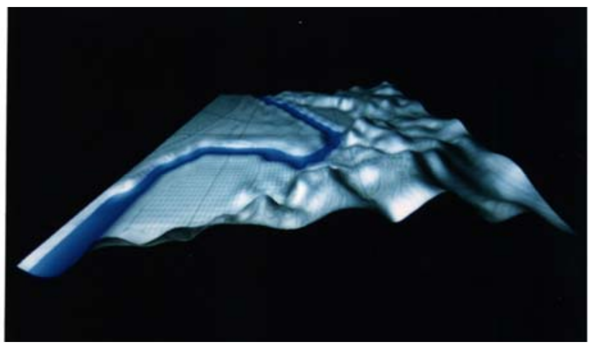

Figure 6. Rendered Parametric Surface.

III. STATE OF THE ART

Most of the techniques covered in the previous section were developed for ground terrain operations. But, what happens when the project manager encounters sites with limited visibility---as it's often the case in mining and underwater recovery operations? Obviously, a situation that deprives or diminishes the project manager's senses brings operational challenges, since his/her ability to make quick decisions lessens with poor visual perception. The ocean is without a doubt a perfect example of such a place. Depths of only a few hundred feet already pose serious challenges for any kind of operation. The drastic loss of visibility associated with depth, combined with the enormous pressures and low temperatures makes it a place where only tele-operated construction equipment and robots can operate. Robots and automated cranes and construction equipment provide limited feedback to the operators, making underwater construction a very expensive and time-consuming process. There are several factors responsible for the lack of useful feedback, many of which are bounded by the laws of physics. Communication technologies that thrive in air simply fail to work in water (e.g., radio waves). Position technologies such as GPS or laser tracking cannot be used underwater. Light can only travel a limited distance in water. As a result, the sensors currently used provide limited accuracy and frequency. The cameras available today can only provide an image of the immediate vicinity even under good visibility conditions. To complicate things even further, the data collected by all these sensors and cameras is often scattered across many systems, making its perception and analysis very difficult. All these factors lead to working scenarios where the people involved must make decisions with very little information and scattered data.

Poor perception conditions can be improved through visualization and visual data consolidation and management techniques An XYZ-solution was developed to improve the perception and understanding of underwater scenes where near real-time data is available. The solution can be used in all the construction stages and promotes collaborative and operational decision-making.

XYZ-solution architecture consists of three families of network-enabled applications and services: data distribution, data acquisition, and data visualization. The core of the data distribution suite consists of a real-time database server and a publish-and-subscribe service library. The real-time database server is responsible for maintaining an accurate representation or world model of all the elements that compose the underwater scene. The publish-and-subscribe library allows all other applications to synchronously and concurrently receive update notifications and query information about the world model. The data acquisition suite consists of applications customized to gather data from specific sources and publish the information to the real-time database server. This suite of applications also includes database access stubs and general-purpose simulators. Together, the data acquisition applications are responsible for updating the world model so that it accurately represents the underwater scene. The data visualization suite consists of applications that subscribe to the real-time database server, receive updates every time the state of the world model changes, and present the most current state of the scene to the user using 2D or 3D perspectives. In this manner, different viewers at different locations in the network can display the state of the underwater scene in a synchronous fashion. The following paragraphs describe the three components of the system architecture in more detail. Figure 7 shows a diagram illustrating the components responsible for performing the three main functions of the system.

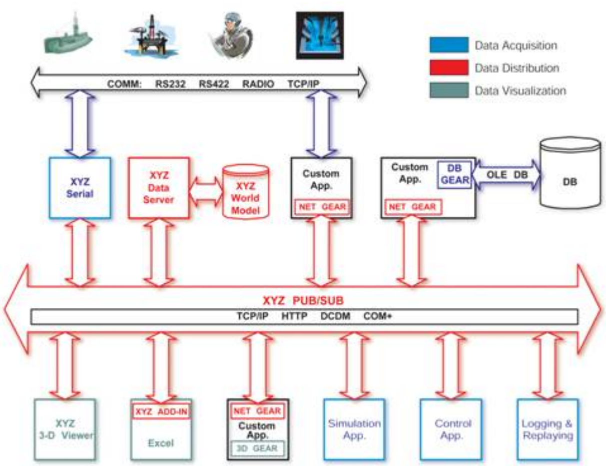

Figure 7. XYZ-Solutions Architecture

Data Distribution: The main objective of the real-time database server is to maintain and distribute an accurate representation of the underwater scene. The server represents the scene using an efficient data structure termed the world model, which consists of a list of entities with properties designed to represent their real-world counterparts in an underwater scenario. This model is expandable and flexible enough to adapt to the unpredictable nature of sub sea tasks. A scene in the XYZ-solution is made of five types of entities:

Surfaces: Due to the amount of points that surveying instruments can produce it was necessary to use a surface model capable of representing surfaces with hundreds of millions of polygons yet fast enough to render them at acceptable frame rates. A multi-resolution approach accomplishes both of these requirements by adjusting the amount of detail according to the location of the observer in the virtual scene. The multi-resolution surface model used in the XYZ-solution can be updated in near-real time making it useful for surveying applications and navigation as well as underwater construction.

Objects: Static and dynamic objects are represented using CAD geometry or basic shapes (e.g., cubes, cylinders, spheres, cones, etc.). Complex objects with high polygon counts can be handled through the use of interactive level of detail (LOD) management. Dynamic objects are updated through the use of bindings that link objects in the virtual environment with their counterparts in the world model. These objects can have multiple cameras, multiple lights and multiple indicators. In addition, parent/children relations between objects can also be modeled.

Cameras: This entity does not have a real-world counterpart, but it is used to represent the concept of a camera in the virtual environment. They can be attached to moving objects and can be configured to track entities as well.

Indicators: These entities are used to represent the value of a field or property according to some predefined behavior and/or appearance. These entities can also represent a conceptual property that exists in the real world; for example, the distance between two objects or a projection distance between an object and a surface.

Lights: These entities may not have a real-world counterpart in most scenarios, but they are used to represent the concept of a light source in the virtual environment.

Data Acquisition: The main objective of the data acquisition applications is to update the state of the world model by acquiring and publishing the data originating from disparate data sources. Specifically, each application represents the interface between a given data source and the world model since its main function is to acquire the data corresponding to the source and update the relevant components in the world model by publishing such data. There are three different groups of data acquisition applications:

Sensor gathering: These applications interface directly with the sensors that provide the data. Common examples range from simple embedded microcontrollers with Analog-to-Digital (A/D) converters to sophisticated survey computers communicating through serial cables.

Data processing: These applications commonly generate and publish new information by subscribing to the data gathered and published by other applications. Common examples are data filters and general-purpose simulators.

Database stubs: These applications serve as gateways to high-end databases and they are responsible for publishing information that is relevant in the world model.

Data visualization: These tools are a collection of specialized component-based modules, called 3D Gear, designed to shorten the development cycle of complex virtual environment applications. XYZ-solution 3D Gear provides three different levels of abstraction. The first level of abstraction (first gear) provides direct access to the software components that model the key elements of a virtual scene. At this level, the 3D Gear is a collection of interfaces and components that define the elements of a virtual environment, such as surfaces, static and dynamic objects, cameras, lights, and indicators.

The second level of abstraction (second gear) consists of managing components that create, destroy, manipulate, and track all the components in the world model.

The third level of abstraction (third gear) includes specialized versions of Microsoft Foundation Classes (MFC) for the Document and View classes that can give a custom application instant access and visualization of a world model.

Let’s now discuss the use of XYZ-solution during the Ehime Maru recovery mission that ended successfully on November 26, 2001 when the Ehime Maru was brought to its final resting place. The underwater operation involved many different tasks including underwater navigation, construction, and surveying, and therefore showcases the use of XYZ-solution as a decision-making support tool. The Ehime Maru salvage showcases the visual-managing of complex topography and limited-visibility operation concepts. The mission objective was to recover the vessel that rested on the seabed at approximately 2000 feet. The project consisted of four stages. The first stage was a reconnaissance survey of the area to establish the exact location of the vessel, to collect the bathymetry of the area, and prepare the vessel for lifting. Stage two involved the installation of a sensor array, the removal of debris from the area, and the installation of a lifting harness around the vessel. The third stage encompassed the lifting and towing of the vessel to a shallow water area where it was accessible to Navy divers for the search and recovery of 8 victims. The fourth stage consisted of the relocation of the Ehime Maru to its final resting place. The XYZ-solution was used during the planning, execution, and evaluation phases of the first and second stages of the recovery mission. During the second stage, the system consisted of five viewing stations located around the recovery vessel (Rockwater 2). The location of the computers were as follows: one at the bridge to support the captain of the Rockwater 2, one at the logistics room to support the project manager and other observers, one at each of the three ROV vans to support the operators of the ROVs (Manta, XL16, and Quest). Figure 8 shows snapshots of the XYZ Solution and real photos taken during the recovery operations.

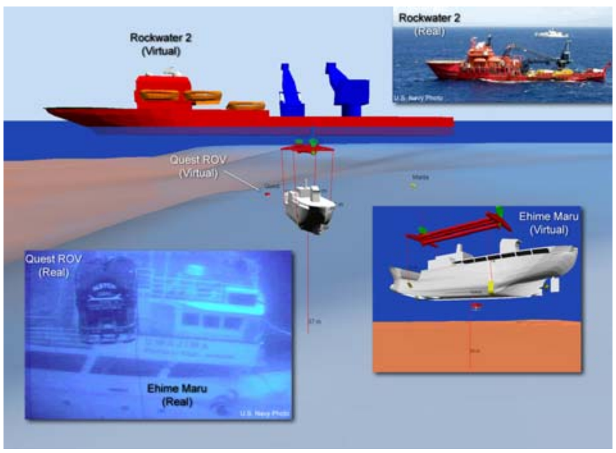

Fig. 8. Visualizing Ehimi Maru Recovery Operations

Planning: The key concept that allows XYZ-solution tools to be used during the planning phase is the fact that the server and the viewer applications are independent of the source of the information. Simulated positions, orientations, and other variables can be published, visualized, and logged in the same fashion as the real data. This allows users to plan the operations using the same environment they will later use during the execution phase of the project. The only difference between planning and execution is that during execution, the sources of the data are real sensors instead of simulators. It is important to note that the usefulness of this analysis depends on the accuracy and fidelity of the simulators that are used.

In this particular operation, the bathymetry data collected during the first stage of this project played an important role in the planning phase. Once the survey was completed, a more in depth analysis was conducted to determined optimal paths for ROV and vessel navigation, task durations, risk of collisions, and so on.

An additional application of a simulated scene was to present ideas to all the project members and clients. An interactive three-dimensional scene provided an understanding that otherwise could require time to explain.

Execution: During the execution of this job, position sensors for the ROVs involved collected their position and orientation and published it in real-time to the server. The five viewing stations subscribed to the server and obtained current data for all the objects in the world model. Virtual cameras were placed in key locations to provide feedback to the people operating the ROVs, the vessel and other pieces of equipment such as cranes and drillers. Distance indicators designed to measure clearances in critical locations were invaluable and alerted viewers of potential collisions before they happened.

During the towing phase, GPS position was published and used in the viewer stations to place the Rockwater 2 within the scene and show the crew what lies beneath the surface of the water. This allowed them to maneuver the Rockwter 2 and raise or lower the Ehime Maru. Figure 7 shows snapshots of the XYZ-solution and real photos taken during the recovery operation.

Evaluation: Since all the data published to the server was logged, a total reconstruction of the entire operation could always be accomplished. Visualization of the logged data was performed through the same viewer used during the planning and execution phases.

The data was logged by the server with time stamps that can be used during playback to reconstruct the events with temporal accuracy. Since navigation within the viewer is independent of the events taking place, the logged events can be viewed and studied from new locations and perspectives. Furthermore, tele-viewing can also take place, allowing viewers in remote sites to discuss and analyze the operation without having to travel to a meeting location.

IV. CONCLUSIONS AND FUTURE WORK

The visualization techniques presented in this paper have opened a door to new visually-oriented process technologies and a more productive design, construction, and underwater recovery industry. The techniques are currently being used as an educational tool for pedagogical purposes as well as to identify future design and construction research problems. The techniques have lead to software products, such as XYZ Solutions that are being marketed nationally as well as internationally. Independent contractors will also benefit from the resulting visual communication productivity tools. The integration of visual simulation techniques in design, construction, and underwater recovery should also assist in optimizing the use of the limited natural resources of our planet Earth and improve the competitiveness of the U.S. construction industry. We need to improve the way complex projects are designed – not just the way they are built. Since visual simulation allows the design team to manipulate time – the forth dimension – we can go back and forth in virtual-time and space to make design changes in response to problems detected while simulating the project. The next step is to develop visual thinking tools that would allow designers and builders to communicate and reason with images, rather than just with words and numbers. Such tools would enhance the user's ability to communicate and think visually, as well as verbally and mathematically. These visual thinking tools are not necessarily artificial intelligence or expert systems. They will be like adding another dimension to the human mind.

Besides the successful application of the technology described in this article during the Ehime Maru recovery project, real clients have further validated the technology in other fields. Applications in the areas of marine navigation, underwater construction and underwater surveying have been developed using XYZ Technology. Kongsberg Simrad's SPS2000 digital chart navigator uses a 3D viewer that displays a 3D surface of a digital chart area along with a virtual representation of the boat and surrounding objects (e.g., lighthouses, buoys, underwater structures, etc.). The view provided by the 3D display improves the perception of the boat's location in relation to the seabed and allows the crew to make better decisions while sailing (Figure 8). QPS's 3D Viewer uses a multi-resolution grid to visualize multi-beam data as it is collected; allowing the surveyors to visualize the area of interest and make sure that the target zone is covered. This prevents having to go back to the site due to missing spots. Several survey companies use XYZ's data collectors to publish data from sensors to an XYZ Data Server. By subscribing to it from multiple locations using XYZ 3D Viewers, engineers and contractors can visualize and manage their entire operation as it takes place from local or remote locations. In addition, this system has allowed survey companies to visualize not only the execution phase of projects but has assisted the company during the planning phases of key projects. In addition, the data logged during the execution phases of these projects has been useful to present results to the survey companies' clients and keep a record of the tasks completed. Existing users have validated the usefulness of XYZ-solution tools in a variety of scenarios.

There are other construction visualization efforts underway. In addition to the work done by the authors, one researcher at University of Michigan is investigating the requirements that will enable the 3-D animation of a construction operation to be automatically generated from the kinematics properties of the resources that perform that operation, and the geometry of the infrastructure (Kamat, V., 2004) under NSF sponsorship. Another NSF sponsored research effort at University of Texas Austin is developing methods for acquiring, integrating, and analyzing project site spatial data, including dynamic site information (motion of personnel and equipment) that allow scalability and robustness for real-time field deployment. The time has finally arrived to provide project managers with the graphics language and visualization tools to improve construction site and limited-visibility operations' efficiency and effectiveness. Should you have any questions about the 3-D techniques discussed here, please contact Walter Rodriguez at (239) 590-7360, or e-mail at wrodrigz@fgcu.edu .

V. REFERENCES AND SUGGESTED READINGS

Below is a listing of the cited literature and suggested readings and web sites.

1. Caldas, et al. (2005) "Real-Time Spatial Information Acquisition and Use for Infrastructure Construction and Maintenance," *NSF Award Abstract* posted at http://www.nsf.gov/index.jsp, URL accessed October 18, 2005.
2. Kamat, V. (2004) "Inverse Kinematics and Interoperability Standards for Visualization of Construction Activities at the Operations Level of Details," *NSF Award Abstract* posted at http://www.nsf.gov/index.jsp, URL accessed October 18, 2005.
3. Lindstrom, P., Koller, D., Ribarsky, W., Hodges, L., Faust, N., and Turner, G. (1996) "Real-time, continuous level of detail rendering of height fields," *Computer Graphics (SIGGRAPH '96 Proceedings)*, 109-118.
4. McWhorter, S., Rodriguez, W., and Hodges, L.F. (1992) "The Performance of Graphical User Interfaces in 3-D Interactive Animation Environments," *Engineering Design Graphics Journal*, ASEE, Volume 56, Number 3, Autumn, pp. 12-17.
5. Opdenbosch, A, and Rodriguez, W., (1991) "Visualizing Parametric Surfaces with the Enhanced Reverse Ray Tracing Technique," *Journal of Theoretical Graphics and Computing*, STCG, Vol. 4, No. 2, December, pp. 69-82.
6. Opdenbosch, A., Patterson, W., and Rodriguez, W. (1991) "Visual Simulation of Construction Hoisting Operations", *Journal of Theoretical Graphics and Computing*, STCG, Vol. 4, No. 1, pp. 59-68.
7. Opdenbosch, A. and Santamaria, C. (2002) http://www.xyzsolutions.com/tech/whitepapers.html, accessed October 18, 2005.
8. Opdenbosch, A., Patterson, W., and Rodriguez, W. (1991) "Visual Simulation of Construction Hoisting Operations", *Journal of Theoretical Graphics and Computing*, STCG, Vol. 4, No. 1, 1991, pp. 59-68.
9. Rodriguez-Ramos, W., and Francis, R. (1983) "Single Crane Location Optimization," *Journal of Construction Engineering and Management*, American Society of Civil Engineers, Vol. 109, No. 4, pp. 387-397, Dec.
10. Rodriguez-Ramos, W.E. and Jones, B., "Animation Tools for Extra-Terrestrial Construction", *Journal of Aerospace Engineering*, American Society of Civil Engineers (ASCE), Vol. 1, No. 4, pp. 238-247, October, 1988.
11. Rodriguez, W. (1992) "Visual Simulation: Considering the Dynamic Nature of Construction," *Construction Business Review*, Vol. 2, No. 4, July/August, pp. 56-61
12. Rodriguez, W. and Opdenbosch, A. (1995) "Design-Implementation-Based Simulation: A Graphics Tool," *Engineering Design Graphics Journal*, ASEE/EDGD, Volume 59, Number 1, Winter, pp. 18-26.