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Investigation of technologies to improve the visualization of design documents and construction process

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For the Major Program

To Drs. Edward J. Jaselskis and Russell C. Walters

My family

And in loving memory of my father

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The process of developing a transportation project contains many sophisticated activities, requiring large volumes of design documents and construction data to be created and communicated. Recently, members of the design and construction project team (e.g., owner, designer, and contractor) have become more interested in improving the communication, coordination, cooperation, and efficiency during the project development and execution process. Computer visualization can be employed to enhance the design and construction process by providing clear documentation and illustrating of project requirements.

This study first examines the shortcomings of current two dimensional (2D) drawings and possible improvements by using color and other approaches to improve the clarity of the drawings. Further, a feasibility study is presented for using object-oriented computer visualization technology to graphically portray standard construction objects. The required information is embedded into each object to completely describe the design details, materials and construction requirements. Applying three dimensional (3D) laser scanning technology to acquire 3D drawings of existing construction is also presented.

The results show that implementing these technologies will lead to safer, more efficient, and higher quality construction projects. The study discusses the benefits and limitations of these technologies, and time and economic analyses are also conducted.

CHAPTER 1 – GENERAL INTRODUCTION

Transportation facilities can significantly benefit a community as well as foster economic growth. The level of effort required to build and maintain these transportation facilities is high, and comprises a major portion of the engineering and construction market. These projects are quite costly, and require significant time. The annual value of transportation construction is nearly 86 billion or 10% of total construction value (year 2002 data). Because the users of transportation projects always look for the improvements to transportation safety and efficiency, as well as reductions in cost, challenges have recently increased due to their new knowledge and needs on technologies, materials, and traffic demands.

The process of developing a transportation project contains many sophisticated activities including planning, design, construction, operation, and maintenance. This process requires establishing and exchanging large volumes of design and construction data such as drawings, specifications, and field records. However, it is not surprising that the project team such as designer and contractor has been hindered by the lack of a common and effective system to acquire, utilize, and exchange these data. Recently, members of the design and construction project team as well as the public have become more interested in becoming more efficient and improving their communication, coordination, and cooperation during the project development and execution process. This broad research and practice can be categorized into (1) developing a generic data representation and file format to effectively exchange the design and construction data, such as eXtensible Marketup Languages (XML) and (Industrial Foundation Classes IFC) (Harrod, 2003); and (2) visualizing the design and construction documentation and the process of efficient data collection and manipulation.

This study first examines the problems of current two dimensional (2D) drawings and investigates possible solutions – specifically the use of color within design drawings. A feasibility study was conducted using object-oriented computer visualization technology that graphically portrays standard construction objects such as pavement and traffic control signs. Pertinent data is embedded into each object to completely describe the design details, materials and construction requirements for proper installation. The study also examines the use of laser scanning because the majority of current highway development projects in the United States are related to rehabilitation of existing roads, which require the characteristics of the existing roads to be analyzed, the modeling activities of visualization can be combined with three dimensional (3D) capturing technology such as 3D laser scanning to make the process easier and more effective.

PROBLEM STATEMENT

The design and construction documents, mainly consisting of drawings and specifications, provide the "road map" necessary for the contractor to build a project. Currently, for either hard copy (paper) or electronic documents, the drawings are in 2D format, while the specifications are text. While the current design documents provide a solid base for construction, some disadvantages and problems associated with them are often found within industry practice.

Poor Readability and Inconsistency of Drawings and Specifications

The state-of-the-art method for current drawings prevents the contractor and other users from easily accessing the desired information. The 2D drawings and text-based specifications restrict their readability and therefore, required information can be difficult to read and interpret due to its size, type, and organizational format. This can confuse contractors who must then spend valuable time poring over the documents. Meanwhile, conflicts frequently exist between a provision of the specification and related drawings. The users have to examine each for inconsistency and choose one to follow. This results in extra work during the construction process and may cause errors.

Poor Visualization and Inefficiency in Communication

On the other hand, individuals learn about the project requirements for construction activity by studying various contract documents in a combination of paper and electronic formats. Besides drawings and specifications (standard and supplemental), other documents are also involved such as the standard plans, design details, addenda, and change orders. To obtain the complete picture of a project, one needs to go back and forth between these documents. The visualization of these documents is poor. Therefore, the process to read these documents can be quite time consuming and tedious, especially for a new engineer. As such, the communication between the designer and contractor is hindered and inefficiencies appear in the project.

The problems described above often result in less than optimal project cost, quality, and schedule. Thus, some of the inefficient characteristics of the current design process need to be identified and improved. It is valuable and important to take advantage of appropriate innovative technologies that improve the way that designers and construction personnel access and understand the project requirements. Computer-based visualization, which attaches supplemental information into the design documents, can make a better design in a visually intelligent way.

STUDY OBJECTIVES

The purpose of this study is to investigate ways to make parts of the design and construction process more efficient by using advanced approaches such as color differentiation and 3D visualization. An object-oriented (OO) design and computer aided design (CAD) and other technologies cab be employed for providing more direct specification linkages to standard details used for designing and constructing projects in a graphical or visual front end system. The objectives of this study are to:

- Examine the limitations of the current 2D drawings and specifications and suggest possible methods for improvement.
- Investigate the leading edge 3D technology such as laser scanning to more quickly acquire the construction data and therefore improve design and construction effectiveness.
- Conduct the feasibility of using object-oriented method for standard design and specifications.

METHODOLOGY

There is an opportunity to improve the overall competitiveness and efficiency of the current design and construction process by applying advanced technologies such as colored drawings, 3D laser scanning, and object-oriented design. The study examines current problems, possible technical solutions, related software and hardware, and the required time and cost of such proposed technologies. Empirical and anecdotal data is obtained to support the effectiveness of studied processes. The following tasks are performed to achieve the study objectives.

Task 1 – Examination of Existing Problems

The literature review and a questionnaire survey examine the current industry problems. The goal of the detailed review is to avoid duplication of effort and identify the existing disadvantages and problems with current 2D drawings. Appropriate suggestions and concepts from the previous work are considered for the study. A survey approach is used to request information such as the need for and actual consideration of enhancing plans from DOT design and construction offices nationwide, as well as some contractors in the transportation area.

Task 2 – Investigate an Advanced Approach to Acquire Construction Data

The investigation identifies the required 3D laser scanning equipment and the related software. Appropriate pilot projects are chosen to test the capabilities of this technology. The benefits and costs associated with using this technology are determined and compared to conventional approaches.

Task 3 – Feasibility Study of Object-Oriented Design and Specifications (OODAS)

A modified focus group method is used to develop user requirements of an OODAS system. The major features for such a system are established from this effort. This study includes a literature review and the testing of possible software packages. Based on the software selection and result of user requirements, a prototype system is developed. The assessment of the prototype is analyzed and the full system implementation plan is conducted to determine the development and maintenance costs.

PROJECTS INVOLVED AND MY CONTRIBUTION

This dissertation describes my contributions to the research efforts on three projects. The general information of these projects and my contributions are briefly listed as below.

1. "Enhancing the Design Process to Facilitate More Efficient Construction Operations (2001)" for the Iowa Department of Transportation – My contributions as a research assistant to this project were to (1) conduct the literature review, (2) design the survey questionnaire, (3) collect the response data, (4) analyze the data, and (4) write the draft report and paper.
2. "Pilot Study on Improving the Efficiency of Transportation Projects Using Laser Scanning (2002)" sponsored by the Iowa DOT – My contributions as a research assistant to this project were to (1) conduct the literature review, (2) attend training sessions, (3) scan the objects in the field, (4) process the scanned data in the lab, (5) compare results to other methods by Iowa DOT staff, and (6) write the draft report and paper.
3. "Development of Object-Oriented Specifications for Iowa DOT and Urban Standards (2003-2004)" sponsored by Iowa Highway Research Board – My contributions as a research assistant to this project were to (1) conduct the literature review, (2) test the suitability of software with the help of other research assistant (Manop Kaewmoracharoen), (3) collect requirements and feedback from users, (4) analyze the design standards and specifications, (5) partly develop the prototype, (6) evaluate the prototype and improve the concept, (7) develop the structure of the full system, (8) conduct the economic

analysis, and (9) write the draft report (with help from Manop Kaewmoracharoen) and paper.

ORGANIZATION OF THE DISSERTATION

This dissertation has six chapters. Chapter one (1) provides the general introduction and purpose of this study. Chapter two (2) consists of the detailed literature review on various concepts involved in the study. Chapters three (3) through five (5) present three papers showing the results of the objectives noted above. The main conclusion of this study is summarized in Chapter six (6), along with suggested areas of further study.

CHAPTER 2 – LITERATURE REVIEW

This chapter will serve as a detailed explanation and literature review for concepts or topics in Chapter 3 through 5, which include the drawings, specifications, and object-oriented concept.

DRAWINGS AND SPECIFICATIONS

The drawings and specifications mentioned through this dissertation are the key documents required to design and build a project. The organization and accessibility of these documents have a strong impact on the performance of design and construction process. The drawings define the geometry of a project including dimensions, form, and details while the specifications define the qualitative requirements of the project. The definition of drawings and specifications by the RS Means Construction Dictionary (RS Means, 2001) is cited below:

> "**Drawings** (1) Graphic illustrations depicting the dimensions, design, and location of a project. Generally including plans, elevations, details, diagrams, schedules, and sections. (2) The term, when capitalized, refers to the graphic portions of project's contract documents."
>
> "**Specifications** Documents that define the qualitative requirements for products, materials, and workmanship upon which the contractor for construction is based."

While the format of drawings is consistent among different projects, the specifications are of several formats (Fisk, 2003). Some of these formats are briefly described below, including CSI master format, AASHTO standard format, Iowa DOT format, and SUDAS format.

CSI Master Format

The Construction Specifications Institute (CSI) created a standard for general arrangement and method of writing construction specifications. It is titled the Uniform System for Building Specifications, also popularly known as the CSI Format. The CSI is intended for managing building projects. It is widely used, having been adopted by organizations such as Associated General Contractors (AGC) and American Institute of Architects (AIA). The CSI format has 16 divisions as illustrated in Figure 2-1 that cover most if not all perspectives of the construction work. To make the specifications in a simple and orderly process, each division is divided into three-part format: General, Products, and Execution.

Division 1: General Requirements
Division 2: Site Work
Division 3: Concrete
    03100 Concrete Formwork
        Part I – General
        Part II – Products
        Part III - Execution
Division 4: Masonry
Division 5: Metals
Division 6: Wood and Plastics
Division 7: Thermal and Moisture Protection
Division 8: Doors and Windows
Division 9: Finishes
Division 10: Specialties
Division 11: Equipment
Division 12: Furnishings
Division 13: Special Construction
Division 14: Conveying Systems
Division 15: Mechanical
Division 16: Electrical

Figure 2-1 List of CSI 16 divisions and section example

AASHTO Standard Format

The American Association of State Highway and Transportation Officials (AASHTO) publishes a book of "standard specifications" that covers in detail all general contract conditions and technical specifications for all anticipated types of highway and bridge construction projects. This standard format provides a basis for a state Department of Transportation (DOT) to develop its own standard specifications. One example is the *Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects* developed by the U.S. Department of Transportation, Federal Highway Administration (FHWA). As shown in Figure 2-2, FHWA specifications contain ten main divisions, each of which consists of various sections to cover the principal construction materials and methods. Although the AASHTO format is different from CSI format, there is one thing in common namely – the materials are strictly separated from the construction execution.

Division 100: General Requirements
Division 150: Project Requirement
Division 200: Earthwork
Division 250: Structural Embankments
Division 300: Aggregate Courses
Division 400: Asphalt Pavements and Surface Treatments
Division 500: Portland Cement Concrete Pavement
Division 550: Bridge Construction
Division 600: Incidental Construction
Division 7000: Materials

Figure 2-2 The divisions of FHWA specifications based on AASHTO format

Iowa DOT Format

Many states developed their own formats of specifications. Most of them are slightly different. The Iowa Department of Transportation (Iowa DOT) develops the Standard Specifications for Highway and Bridge Construction (Iowa DOT, 2001). It is based on the

AASHTO format but does not separate the technical sections into separate divisions or sections. Actually, the Iowa DOT specifications use the CSI concept to separate various basic construction types into different divisions, as shown in Figure 2-3. These standard specifications are also modified by the General Supplemental Specifications every six months (Iowa DOT, 2004).

Division 11: General Requirements and Covenants
Division 20: Equipment Requirement
Division 21: Earthwork, Subgrades, and Subbases
Division 22: Base Courses
Division 23: Surface Courses
Division 24: Structures
Division 25: Miscellaneous Construction
Division 26: Roadside Development
Division 41: Construction Materials

Figure 2-3 The divisions of Iowa DOT specifications

SUDAS Format

Besides the state DOT specification format, there are some local formats in use such as one developed by American Public Works Association (APWA). In Iowa, Statewide Urban Designs and Specifications (SUDAS) developed the specifications for urban area, called *Iowa Statewide Urban Standard Specifications for Public Improvements Manual* (SUDAS, 2004). The SUDAS manual contain revised and expanded sets of design and specifications standards originally developed and adopted by several central Iowa urban jurisdictions in the 1990s. The SUDAS includes federal, state, and local specifications. The SUDAS specifications format (Figure 2-4) follows the urban specifications of the American Institute of Architects, which absorbs the concept of CSI format to separate each section into three parts: general, materials, and execution.

Division 1: General Provisions and Covenants
Division 2: Earthwork
Division 3: Trench, Backfill and Tunneling
Division 4: Sewers and Drains
Division 5: Water Mains and Appurtenances
Division 6: Structures for Sanitary and Storm
Division 7: Streets and Related Work
Division 8: Traffic Signals
Division 9: Site Work and Landscaping
Division 10: Utility Service Location Details
Division 11: Demolition

Figure 2-4 The divisions of SUDAS specifications

OBJECT-ORIENTED METHOD

In the past, attempts to manage transportation design and construction specifications have been based on various kinds of text-linkages. For example, Jahren (CTRE, 1999) and Walters (2003) developed a Hypertext-based Electrical Reference Library (ERL) for the Iowa DOT to manage standard specifications and construction manual. The Hypertext-based data management system was based on upon the format of original paper-based specifications, which is somewhat different with the natural workflow. Using object-oriented data model could eliminate the data management discrepancy.

Basic Concept

An object-oriented approach to software design is significantly different from a procedural approach. It combines data and behavior to organize the interacting objects (Blaha and Premerlani 1998). Object-oriented modeling can naturally map the computer world to capture real world features. An object-oriented system is full of objects (physical or conceptual) containing required information. The object-oriented approach began in the 1970s (occasionally mentioned in 1960s) and the details of concept can be referenced to

Goldberg and Robson (1983) and Stroustrup (1986, 1988). Although the definition of object-oriented varies in the literature, its common meaning covers at least two features (1) encapsulation of data and procedures inside objects and (2) interaction among objects. The advantages of using object-oriented approach can be outlined (Powell et al. 1989) as: (1) clear mapping; (2) enforced modularity; and (3) data abstraction. The suitability of an object-oriented approach to solve problems in software design is discussed more thoroughly in the literature in 1980s and 1990s (for instance, Mullin 1989; Booch 1990; Fenves 1990; Wasserman 1990). Object-oriented technology has also been investigated to meet the data management requirements of concurrent engineering (Spooner and Hardwick 1993).

Application in Civil and Construction Engineering

Object-oriented design has been were widely studied for use within the civil and construction industry since early 1990s but was investigated as early as in the 1980s (Fances, 1988). Sause et al (1992) presented a formal object-oriented model of engineering design. Rigopoulos and Oppenheim (1992) employed design objects to represent structural components and substructures. Baugh and Rehak (1992) addressed the use of object-oriented to support data abstraction for designing, implementing, and maintaining engineering software. Abdalla and Yoon (1992) presented an example of object-oriented design to isolate the details of finite element models. Garrett and Hakim (1992) developed a flexible object-oriented representation of design standards and integrated it into design software. Bullock and Oppenheim (1992) investigated the object-oriented approach for a laboratory system for robotic excavation.

More recently, a simulation of a hydraulic model was developed by Solomatine (1996) and also an earth-moving operation model was investigated by Marzouk (2003) based on object-oriented concept.

Object-Oriented Data Sharing Methods

Object-oriented models were investigated for managing the large amount of data for design and construction (Johnson 1989). A database is an important tool for centralizing and organizing the large amount of data associated with projects including civil and construction projects. Many researchers remain active on issues related to database and data distribution. Luiten and Tolman (1997) investigated a method of integration of sharing of data, knowledge and information among all project participants. Zaneldin et al. (2001) showed the research effort on representing design information, documenting design rationale, and managing design changes

Object-oriented database systems can avoid the limitations of relational database invented by E. F. Codd at IBM in 1970, which is a collection of data organized as a set of tables and from which data can be accessed in many different ways. Kim and Ibbs (1992) compared a data model based on an object-oriented design to one based on the relational model for managing data associated construction projects and identified the strengths and weaknesses of the approaches. They pointed out that the object-oriented approach shows significantly more promise from a semantic expressiveness perspective and provides clearer mapping. Stumpf et al. (1996) researched using the object-oriented model to integrate the construction product and process information. Badrah (1998) described the way to access a specifications database. Qi (2001) investigated a Web-based Street Construction Permit System using a database.

The issues of sharing design and construction data are still waiting to be fully solved although various approaches have been proposed. Peltonen et al. (1993) addressed several of the issues of object-oriented modeling and CAD-to-database integration, as well as developed an Engineering Document Management System (EDMS). Zaneldin et al (2001) investigated ways to store information, record design rationale, and manage design changes using an object oriented model.

A critical factor for data management is the way to share and convert the different data and standards in one common place. Marir et al. (2001) proposed an interactive system for integrating CAD and construction related applications. In their research, the Industrial Foundation Classes standard (IFC) was mentioned. This is one of two solutions to solve the data format issues (Harrod, 2003). The other is eXtensible Marketup Languages (XML).

There has been a lot of research behind implementing object-oriented systems for design and construction. However, the picture is still not clear enough to effectively and efficiently solve the problems related to use of design and construction documents – especially for faster and easier accessing the drawings and specifications.

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CHAPTER 3 – APPROACHES TO IMPROVE THE READABILITY OF CONSTRUCTION DRAWINGS

A paper to be submitted to *The Journal of Construction Engineering and Management*

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ABSTRACT: Members of the construction project team (e.g., owner, designer, and contractor) have increasingly become more interested in and concerned about improving their communication, coordination, and cooperation during the drawing and specification development process. The current state-of-the-art method for drawings is not clear enough to permit designers and contractors to communicate efficiently and accurately. Little research, however, has focused on approaches that improve the quality and efficiency of current drawings. This study examines methods to improve the readability of drawings. Input data came from a survey titled, "Enhancing the Design Process to Facilitate More Efficient Construction Operations." The designers and contractors provided their view of using colored drawings and other approaches that improve drawing readability. Through data analysis, the best approaches practiced in the construction industry were determined. They are (1) using colored drawings, (2) improving design details, (3) reviewing drawings and specifications, and (4) developing 3D drawings.

Key Words: Colored Drawing, Drawing, design, design details

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INTRODUCTION

Members of a construction project team (e.g., owner, designer, and contractor) have increasingly become more interested in improving their communication, coordination, and cooperation during the drawings and specification development process. Most, if not all, current drawings are in 2D format. The drawings, along with the specifications, provide a solid base for the contractor to build the construction project. They include the necessary drafting nomenclature as well as material and installation requirements. Although the current drawings style has a long history contribution to the design and construction industry, the current state-of-the-art method for drawings does not permit the designer and the contractor to communicate efficiently and accurately. Construction industry people, especially field engineers, often comment about the poor quality of current design details or design technology in drawings (Kagan, 1995).

The issues of poor-quality drawings and ineffective specifications often result in less than optimal project cost, quality, and schedules. Thus, the authors believe that at least some characteristics of the current drawing process need to be identified as inefficient and improved. This study investigated approaches that enhance the communication process between the designer and contractor by improving the quality of design documents such as contract drawings. The paper addresses this need, describes current practices, and recommends reasonable approaches to improve current drawing characteristics.

OBJECTIVES

This study determines the advantages of and opportunities for enhancing transportation project drawings by such reasonable methods as using colored and possibly 3-dimensional (3D) computer-aided design and drafting (CADD). The study seeks to identify:

- Concerns with current blue or black line drawings.
- Best practices from nationwide Departments of Transportation (DOTs) and other organizations associated with bridge design and construction.
- Approaches that modify current drawings.
- Leading edge technologies, such as colored drawings and 3D CADD, that improve drawing effectiveness.

METHODOLOGY

The study hypothesized that the overall efficiency of the construction industry (specifically bridge design and construction) can be improved by enhancing project drawings. The study methodology involved collecting and evaluating both design and construction practices that improved drawing efficiency. This included the following tasks:

- Literature Review. The literature review was conducted to discover suggestions, concepts, and practices from previous studies.
- Data Collection. A survey approach was used to request information such as the need for, motivation for, and actual consideration of enhancing drawings from DOT design and construction offices nationwide and the top contractors in the transportation area.
- Data Evaluation and Best Practices Identification. The data was analyzed, summarized, and reported in a best practices format.

LITERATURE REVIEW

Previous work was reviewed on issues with current drawings and on approaches that improve the quality of drawings. Because it depends on the requirements of the construction operation and of the design process and on the evaluator's background, the efficiency of drawings may not be viewed objectively.

Kagan (1995) reviewed and discussed construction claims resulting from inaccurate design documents including drawings and specifications. In his opinion, design claims result from (1) inconsistencies within specifications (i.e., massive specs and cut-paste specs), (2) the interpretation of "Or Equal" clauses (i.e., approval requirements in the specs), (3) change orders (clarification of connection or intersection design in drawings lacking sufficient details and an excessive number of change orders), and (4) conflicts between drawings (i.e., conflicts between architectural and structural or between structural and mechanical drawings, coordination of drawings).

Hegazy and Khalifa (1996) conducted a survey on coordination within a design team and coordination among different design teams. They found that the following issues led to an unsuccessful design: (1) numerous changes and changes occurring too quickly, (2) inadequate structural headroom or design load for mechanical or electrical equipment, and (3) lack of appropriate filing systems to organize the numerous drawing files, their several updates, and other related documents.

Other literature (Boehmig 1990, Gakuhito et al 1993, Knight 1993, and Maddox 1993) examines the disadvantages of the 2D drawings and specifications. In general, the following problems can be found within current drawing system:

- Poorly prepared drawings. Errors or flaws often exist in the contract drawings and shop drawings.
- Inconsistency between the drawings and the specifications. Frequently, conflicts exist between a provision of the specification and of the drawings

(for instance, the type and size of material and equipment).

- Use of standard details that are not fully applicable. Many standard details on drawings do not fully apply to the current project, causing confusion. This situation may be caused by the relative ease that details are copied from other project designs and applied to the current project.
- Lack of construction input into the design. Typically, design and construction activities are performed separately. Ideally, however, the contractor's knowledge and input would be solicited during the design phase, making the project easier to construct.
- Unclear information on the drawing. Required drawing information can be difficult to read and interpret due to its size, type, and organizational format, confusing contractors who must spend valuable time poring over the drawings.
- Inefficient use of technology. Civil engineering has progressed from drafting boards to computer-aided design (CAD) systems, leading to increased efficiency and higher productivity. In the field, however, technologies such as CAD are rarely used.

A few, although not too many, sources in literatures have also considered how to enhance the design process and thus benefit construction operations. Kagan (1995) concluded that the following procedures are likely to improve design quality: (1) provide clear cut criteria on "Or Equal" clauses, (2) establish schedules and priorities for review of shop drawings with contractors, and (3) avoid the use of shop drawings to modify designs, (4) coordinating design documents. Written specifications should be reviewed to avoid ambiguities and conflicting requirements. Design drawings should be reviewed to avoid conflicts between architectural and engineering drawings.

Hegazy and Khalifa (1996) suggested design coordination rules-of-thumb to improve design quality. Some of these suggestions are as follows: (1) start drawings on CAD and finish them on the drafting board, reducing the number of times a drawing is plotted, (2) show dimensions once, (3) use simple hand calculations for main forces, (4) take all drawings from an original 3D model, ensuring that the designer and contractor use the same model, (5) use design and drafting checklists, (6) produce all drawings using a single scale, and (7) use third-party reviewers.

The literature search revealed some sound ideas to improve the design process. However, research investigating what approaches can be used during the design process to obtain more efficient drawings is needed.

DATA COLLECTION

A survey was designed to collect information from designers and contractors. Both groups were asked to complete the survey and provide appropriate supporting documentation. The questionnaire was sent to selected organizations including the top 25 contractors in bridge construction listed in the Engineering News Record Website (ENR, 2001), five other contractors who also construct bridges and have used the colored drawings in the past, and 49 bridge and structure design offices in nationwide DOTs (other than Iowa DOT). An electronic version of the survey was sent to each respondent for efficiency. The initial idea was to capture the methods actually practiced during both design and construction process.

Survey Purpose

The survey focused on collecting information about colored drawings and other methods to improve drawing quality and the communication process between designers and contractors. This included both contract drawings and shop drawings. The main purpose of the survey was to collect and review data in an attempt to identify best practices.

Survey Structure

The survey consisted of four parts: (1) Respondent Information, which collected contact information from respondents such as organization name and e-mail address, (2) General Questions, which collected the organization's primary operational function, project types within the last year, the likelihood of improving drawing quality, and the general ways to improve quality, (3) Questions Related to the Use of Colored Drawings, which collected the experience, importance, motivation, challenge, standards, and benefits of colored drawings, and (4) Other Approaches to Improve the Drawings, which collected the approaches, other than colored drawings, and potential suggestions that might improve drawing quality and readability.

In the survey directions, a (chief) bridge engineer was asked to complete the questionnaire, which was structured so respondents could answer with the maximum possible degree of freedom and objectivity. In addition, respondents had also been asked to provide a copy of any supporting documentation that they might have, such as a colored drawing design standard and a sample of colored drawing.

Respondent data characteristics

General characteristics pertaining to the respondents and to the type of organizations are discussed along with the type of projects. Specific characteristics related to the survey data can indicate its reliability and representatives.

The data collection went well from designers. However, only three contractors responded, and only one of them provided some ideas. No contractor completed the entire survey. Thus, we had to focus on the designer's perspective. Table 3-1 summarizes the general characteristics of the survey data. The data includes a total of 27 organizations (28 responses), with about 96% being DOT design offices (most of them bridge design offices) and about 4% percent (only one) being an engineering/architectural firm.

The survey respondents hold a variety of positions. However, in general, about one-third of the respondents are managers, which includes bridge design supervisors, design managers, or directors, and two-third are engineers, which includes design engineers, project engineers, or even chief engineers.

The distribution characteristics of the projects in the data are also summarized in the table. According to their distribution, almost all of the responding organizations design bridges (96%). Of those organizations, 36% design highways, and some of them also design buildings, airports, and marine facilities.

[Insert Table 3-1 Here]

PROBLEMS WITH CURRENT 2D DRAWINGS AND SPECIFICATIONS

The survey responses were examined in terms of existing problems and approaches to improve current drawings. The responses to the question "Do you feel that the quality of the drawings used today to build projects could be improved?" clearly shows that most designers expect the quality of current drawings to improve; 19 of the 28 designers said "Yes" (68%) although some designers thought that the quality of current drawings was adequate. It is believed that the effort of investigating the approaches to improve the current drawing design and specifications would benefit the design and construction industry. The details of problems will be discussed below, followed by methods of improvement next. The problems identified by the industry somewhat verify the points from literature review.

Overall Presentation and Clarity of Drawings

Many respondents indicated that the quality of drawings would be enhanced if the clarity, printing quality, and the amount and kinds of information that can be expressed in drawings are improved. It is worthwhile to expedite shop drawing development and review phases by encouraging the design professionals to emphasize overall presentation and detail clarity in the drawings that they draw for the fabrication. Using different colors in widening and repair projects could differentiate between new and existing construction, areas that are to be removed, and reconstruction limits. Readability would undoubtedly increase if designers limited the information they included on drawings to that specifically needed for construction. Too many unnecessary details are often included on the same page of drawings, which clutters the drawings and makes them difficult to read.

One best practice involves establishing a design standard by documenting detailing practices (details and detail representations) such as dimension stack spacing and by improving the style of current detail designs such as the point size (sometimes too small), the line weight, and the font selected for details.

Capability of Communication

The efficiency of the communications with contractors would increase if designers defined and established a workflow appropriate to the process of construction. The combination of design documents and construction process and standards will benefit both parties and finally benefit the construction project.

The capability of communication is also reduced from inconsistency among and between drawings and specifications. Currently, different companies need to strive to maintain consistency of drawing quality. Different design offices working on the same project also need to strive for uniformity in details. The inconsistent level of details can reduce the quality of communication between project team members.

Integration of CADD and visualization

The use of CADD design software needs to be integrated with other software such as structural analysis tools and construction management tools as well database software. This can speed up the construction process and enhance the accuracy of construction project. The integration process also includes the follow methods:

- Use an Electronic Library, which collects either standard design details or creates a database of existing drawings from past projects.
- Standardize the CADD software. CADD fonts and standardized details have significantly improved current drawings compared to old drawings.
- Print CADD drawings using electrostatic copiers instead of blue lining. Electrostatic plotters can interface directly with CAD machines to make multiple, high quality prints.

On the other hand, it is difficult for current 2D drawings to show 3D information, such as multiple layers of reinforcement or odd bends or juxtapositions in the reinforcing. This really addresses the need of 3D drawings and multiple dimensional visualization technology.

The above information is consistent with the literature that we reviewed and clearly reveals that designers are concerned with the quality and efficiency of current drawings. In general the drawings and specifications need to be made clearer, easier to read, more accurate and more visual.

SUGGESTED SOLUTIONS TO IMPROVE 2D DRAWINGS

Almost all of the respondents described the approaches that they had used or are presently using to improve the layout quality and readability of their drawings. Those approaches included improving design details, drawing and specification review, using and enhancing technology such as CADD, and reducing information and double dimensioning. Below, we discuss these approaches in more detail.

Use Colored Drawings

Among the possible solutions to the problems above, using colored drawings is a good choice to improve the drawing readability still based on 2D format. The major reasons to use colored drawings include (1) project quality needs, (2) personal interest, (3) available technology, (4) client/partner requirement, (5) marketing challenges, (6) enhanced clarity, and (7) project schedule needs. Clearly, the respondents agreed that the most important reason to use colored drawings was the need to improve project quality. Although not all respondents had experience in using colored drawings, they still are interested in it. The major obstacles are the printing equipment and the cost of the color printing. They believe color would be more attractive to use in the future. Actually, some respondents draw the drawing in color although they do not print in color. They even have standard colors and line weights for features in these drawings, and the color makes the drawings easier for in-house personnel to understand.

Response Distribution

The survey responses showed that only three state DOTs (12% of DOT respondents) have experience providing or using colored drawings. In 1985, the Nevada DOT became the first DOT to use colored drawings. Besides Iowa DOT, however, only two DOTs (Louisiana and Nevada) are currently using colored drawings. Among the projects that these two DOT design offices designed, 10% of the projects with existing facilities were drawn in colored drawings, indicating that differentiating a new project for an existing facility is one motivation to use colored drawings. However, highways, bridges, airports, and other transportation facilities have also been drawn in colored drawings. Of these projects, bridges are most often drawn in colored drawings at the present time.

Of those DOTs having no experience in using colored drawings, 12 of the 23 think that colored drawings might be helpful for complex reinforcing layouts, especially for highway drawings and layouts, and to a lesser extent, for bridge detail drawings. One DOT respondent noted that they frequently used color for aesthetic renderings presented to the public during project development and for layout drawings showing a proposed highway project but did not use color for final contract drawings for bidding or construction. He further stated that different colors are used for lanes, shoulders, retaining walls, and other features in preliminary drawings that communicate the project's scope.

Only 7 of the 26 respondents answered the question about the importance of color in improving drawing efficiency. As shown in Table 3-2, the mode of Importance Index is 4 out of 10, which indicates that most respondents think colored drawings are less important; however, the data average is 5.29, which shows that overall colored drawings are still considered of value. Surprisingly enough, one of the respondents who stated that colored drawings are less important worked in a design office that had used colored drawings but was not currently doing so. The respondent offered no further explanation.

One respondent stated that because they lacked color copiers and printers, and that it was time consuming to plot multiple colored drawings with their present equipment, they just used color monitors for CADD drawings and colors for the draftsperson's benefit. However, they never made color plots for construction.

Benefits of using colored drawings

The respondents ranked drawing quality improvement and project communication as significant benefits of using colored drawings. One respondent also thought colored drawings would favorably benefit project schedules.

The biggest benefit of using color is the additional means of separating types of objects, such as separating the reinforcements in a deck drawing from the concrete lines. For example, designers currently assign different weights to differentiate between two objects. With color, different bar nomenclatures can be assigned different colors, making a confusing reinforcement configuration easier to understand.

Improving project communication is an obvious benefit. Because color provides them with more choices, designers can more effectively show different types of features. Currently, some designers use color for drawings and charts used at presentations, public meetings, and permitting agency meetings/submittals. Although the actual details for drawing production are in color in a system such as Microstation, they are plotted in black and white and are only printed in color to clarify any issues arising during production.

Some technical advantages of colored drawing are listed below. The colored drawing can:

- Provide greater clarity. Most contractors who worked with colored drawings thought color made drawings clearer, easier to read, reduced errors, and made organization quicker.
- Increase visualization. The contractors welcomed colored drawings because they make reinforcing steel and concrete lines, which often seem to merge on current drawings, much easier to visualize.
- Improve rebar detailing. The colored drawings proved to be extremely beneficial in all areas of construction but are especially helpful in rebar detailing. The various colors made the dimensioning and spacing details easy to quantify, and the colored details made material organization considerably less tedious. The colored drawings are also very helpful for lift drawings when pouring a concrete structure because they highlight different elevations of formwork. The mechanical subcontractor also used colored drawings for the coordination drawings for mechanical and electrical project overhead work mainly to separate the different ducts, pipes, and wires.

Although most respondents had no experience in using colored drawings, the colored drawing is on their lists of ideas to improve future drawing quality. They also indicated the reasons they are not using colored drawings. The major obstacles are the printing equipment and the cost of the color printing. They believe color would be more attractive to use in the future. Actually, some respondents draw the drawing in color although they do not print in color. They even have standard colors and line weights for features in these drawings, and the color makes the drawings easier for in-house personnel to understand.

Challenges of using colored drawings

However, respondents also noted some disadvantages of colored drawings. In addition to consideration of additional expense of colored drawings, some contractors thought of color as only applicable to as-built drawings and would be good in certain situations but in general the color would be not be helpful for a designer or architect to use on contract documents. The details of the major challenges are as follows:

- A set of color standards must be agreed upon.
- The print shop would require the capability to generate large numbers of prints in a short time, requiring the purchase of new equipment and print drivers as well as additional training. The current printers print too slowly.
- It increases the printing costs. For example, a typical building project requires around 600 sheets of drawing documents. Sending that amount of sheets to 50 subcontractors requires a lot of color printing. Furthermore, that amount does not take into account the number of full-sized sheets that must be printed when changes are made.
- The colored drawings provide less scanning options.
- It would be very difficult to post colored drawings with any changes. Construction drawings are typically black and white, making it easy to post items in red so they emphasize changes or additional information but it would

make it harder to read with colored drawings. For example, some current building drawings use color for layouts, by which the details look cluttered and difficult to read.

In addition, contractors and designers apparently have different ideas about using colored drawings. Although the contractor information was not complete and thus its statement cannot be characterized as typical, designers still need to consider it when weighing the advantages of colored drawings.

Enhance Design Details

This is the major factor that can be improved to enhance drawing quality and efficiency. In the survey data, respondents emphasized that design details are the main issue affecting drawing quality. Thus, as previously mentioned, consistency of details also strongly affects construction efficiency. There are two ways to enhance design details: one is to organize the details; the other is to standardize the design details.

Organize the design details

Details should be large enough to be clearly viewed with the 11 x 17 format using Adobe Acrobat Reader. Font sizes should never be smaller than 8 point Arial. CADD has given users unlimited font size control. Small printing is hard to read and easily results in misunderstanding. It also creates the necessity for high Dots Per Inch (DPI) scanning and all of the issues associated with it.

Some respondents mentioned that there is no need to clutter up the detail drawings by dimensioning the reinforcing steel bar clearances because the required clearances can be clearly defined in the General Notes.

When details or structural elements are complex, use at least two drawings: one for dimensions and one for the reinforcing steel bar details.

The inconsistency of details can be avoided by developing a tool within design process to automatically generate the details for drawings, which could improve the consistency of details and reduce errors. For example, some respondents have made attempts at automating various kinds of details where the user fills out a menu and software creates the sheet. In the future, more could be done in this area.

Also, removing unnecessary "boilerplate" notes can reduce the duplication of specifications. One respondent suggested that designers should show a dimension only once in a set of drawings, unless repeating a particular dimension is absolutely necessary for clarity.

Standardize design details

The standardization is accomplished primarily through the use of detail manuals, guidelines, and libraries of standard graphic details known as cells. The approaches include (1) standardizing the layout of all drawings among all designers to provide consistent details, (2) paying close attention to drawing detail, (3) stressing drawing layout, (4) maintaining standardized locations for certain details and types of information, (5) standardizing line types and weights, fonts and font sizes, and line breaks, (6) avoiding the overprinting of information, (7) eliminating clutter, and (8) ensuring legibility when drawings are reduced in size.

Improve the Overall Organization of Drawings

A good overall organization of drawings can improve communication, reduce errors, and benefit the construction schedule and estimating process.

Organize drawings to follow the workflow

This concept can be illustrated by arranging drawings in their sequence of construction activity. For example, place substructure drawings first with the piers presented sequentially and then follow them with the superstructure elements.

Use different shading, different line types, and cross-hatching

These approaches differentiate between stages of construction work or between existing and new construction almost as well as color. While color is better, some designers lack color copiers and printing machines to make the multiple color copies required for distribution. With their present equipment, plotting multiple color copies would take too long. Therefore, this approach became the alternative.

Use special symbols

To achieve a consistent effect, custom fonts and custom keystrokes can be used for special text symbols. For example, use the main survey line for geometric control and for dimensions other than references and offsets from such things as the "bridge centerlines."

Reduce information and double dimensioning

A few designers mentioned such details as reducing the amount of double dimensioning by detailing each bridge component separately, even if it is similar and opening up drawings by showing less information on each sheet.

Improve the Design Process

The respondents brought some ideas to improve the design process and expected the improvement of drawings quality. These are (1) to review drawings and specifications, (2) to involve draftsmen, (3) to increase designers' knowledge, and (4) to improve communications among parties.

Review drawing and specification

This review includes such practices as (1) reviewing project submittals at each design stage, (2) incorporating independent reviews, (3) using isometric views for bridge slopes design, for example, (4) using electronic checking, and (5) spending more time during design, during quality control checks, and during staffing and staff training.

Involve draftsmen in the design process

To increase production, some architects/engineers have taken on the role of producing the final drawing product printing in recent years, perhaps compromising a part of drawing quality. In the past, technicians/draftsmen often performed this work. To enhance quality, some companies may want to consider reverting back to the technician/draftsman setup.

Increase designers' knowledge

The design process and drawing products would likely benefit if designers increased their knowledge of fabrication as well as construction methods and practices. This knowledge can help a designer to understand the construction methods and materials better. Therefore, a designer can possibly design drawings in a more constructable way and to follow the natural workflow.

Improve communications among parties

Drawing quality would undoubtedly improve if communication between design, fabrication, and construction teams was increased.

Adopt Advanced Technologies

Technology is often the one of best ways to help people get where they want to be. The best practices gleaned from the survey data include (1) enforcing CADD standards such as line styles and layer conventions, (2) using electronic document management systems, (3) standardizing the CADD software or automation, (4) creating a special program for design details, (5) using pen tables that automatically adjust line weights for D or B size plots without changing weights in the CADD file, and (6) developing Master Data Library (MDL) commands that draw details from input dimensions for common details.

With the special program, designers can automatically set standard levels, fonts and font sizes, dimension lines, reinforcements, and line styles, weights, and color. For example, the software could be used to ensure that everyone's drawings are consistent. As another example, a BARLIST program, which standardizes the process of rebar design, used by at least one State DOT, assists both construction personnel and designers by checking the accuracy of the reinforcing steel bars.

Developing 3D drawings

Occasionally, it is difficult for current drawings to show 3D information, such as multiple layers of reinforcement or odd bends or juxtapositions in the reinforcing. Monochrome cross-hatching also can be confusing. 3D drawings could solve this issue by providing designers, project managers, engineers an easy understanding of complex graphic designs. This is because many points of view are available with a 3D drawing.

CONCLUSIONS

Over 50% of the total survey questionnaires were returned. Although the answers to some individual questions were incomplete, the data still provided designer input about ways to improve or enhance the design process, making construction activities easier, faster, and better than they used to be. From the designers' perspective, the following methods are generally the best practices.

- **Using colored drawings.** Although some challenges such as cost and equipment still exist, colored drawings could reasonably improve drawing quality, construction project communication, and even the construction schedule.
- **Improving design details**. Design detail issues are the major issues facing the design and construction process. Drawing quality could be improved by completing and better organizing design details such as different types of shading or of line types, cross-hatching, and special symbols.
- **Reviewing drawings and specifications.** This approach includes project submittal reviews and electronic checking. Qualified staff should independently conduct the reviews. This approach could significantly reduce errors and maintain consistency, improving overall drawing quality.
- **Developing 3D drawings.** Advanced technology is often the best way to improve drawing quality. Electronic document management systems, standardized CADD software or automation, auto-checking programs, and many other applications are likely to enhance the design process and produce better drawings for construction. Further, the 3D drawing will definitely help construction engineers determine the challenging aspects of current drawings.

Other approaches include involving draftsmen involved in the design process and increasing designers' knowledge. Due to the poor responses from contractors, the proposed methods only represent designers' perspective. As a research direction in future, the practice from contractors' perspective must be obtained. Also, the standard and procedures of each method must be established before it can be implemented to the design and construction industry.

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Table 3-1 Respondents' general characteristics

Description	Organizational Characteristics			
	Number		Percentage	
Respondent's Title	**28**			
Manager including	9		32	
Bridge design supervisor		1		11
CADD supervisor		1		11
Bridge design director		5		56
Assistant administrator		1		11
Standard manager		1		11
Engineer including	18		64	
Bridge design engineer		3		17
Bridge engineer		10		56
Transportation engineer		1		5
Project engineer		1		5
Chief engineer		3		17
Other	1		4	
Types of Organizations	**28**			
DOT design office	27		96	
Engineer/Designer firm	1		4	
Design-Build contractor				
Types of Projects (# of responses)	**28**			
Bridges	27		96	
Highways	10		36	
Buildings	3		11	
Airports	2		7	
Marine and port facilities	1		4	
Culverts, retaining walls, signs	1		4	

Table 3-2 Important index of colored drawings

I^2	10	9	8	7	6	5	4	3	2	1	Mode	Avg.
No.	1	1	0	0	0	0	4	0	1	0	4	5.29

* I^2 = Importance Index, 10 = Very important and 1 = Not important

* No. = Number of responses

CHAPTER 4 – IMPROVING TRANSPORTATION PROJECTS USING LASER SCANNING

A paper tentatively approved by *The Journal of Construction Engineering and Management*

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ABSTRACT: This paper describes a case study investigating the use of laser scanning to efficiently and safely acquire design and construction data. It is intended for both industry practitioners and academics who are interested in the capabilities of this relatively new technology. Included in this paper is a brief description of the technology, discussion of the case study tests conducted for the Iowa Department of Transportation, lessons learned, and results. Projects involved in the case study included a local street intersection, existing highway and pair of bridges, new pavement and bridge beams under construction, and a stockpile and a borrow pit so that different perspectives (elevation, smoothness, camber and volume) of the application were tested. The study proved that laser scanning is ideally suited for measuring the volume of soil and rock, determining road surface elevations and bridge beam camber, and assisting in the creation of as-built drawings in a 3D environment. Based on results from the study, it was discovered that this technique can be used quite effectively for safer and more accurate construction measurement. Time requirements, cost comparisons to photogrammetry, and limitations are also discussed in the paper.

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Key Words: Laser Scanning, Photogrammetry, Beam Camber, Data Collection

INTRODUCTION

As transportation projects become more complex, it is important to take advantage of appropriate innovative technologies for reducing project cycle time. Laser scanning is one such technology that has potential benefits over standard surveying techniques such as total station or aerial photogrammetry for providing accurate as-built drawings. Laser scanning is a terrestrial laser-imaging system that quickly creates a highly accurate three-dimensional (3D) image of an object for use in standard computer-aided design (CAD) software packages. Laser scanners offer a wealth of information about a structure's surface in the form of a dense set of 3D point measurements using a laptop computer, laser scanner, and tripod. Images are developed from a pulsing laser beam capable of capturing approximately 2,000 data points per second up to 150 meters away. Several terrestrial laser-imaging systems have been developed by the following companies: Cyra, Maptek I-Site, Soisic, and Mensi. The operating principle is similar for all devices (Patterson, 2001). Figure 4-1 shows a photograph of the Cyra 2500 Laser Scanning Unit that was used in this case study.

[Insert Figure 4-1 Here]

The laser's pulsed and visible green beam is moved across a target in a raster scan (Cyra, 2002). Once an object is encountered, the laser beam is reflected back to the unit with the time of flight, which generates a measurement of distance. These measurements produce an impact location, which is displayed as a cloud of points. Measurements taken from the "cloud" can be used to conduct interference detection and constructability studies. As an object is being scanned, each 3D measurement appears immediately as a graphical 3D point image on the laptop screen. This cloud of points is a dimensionally accurate representation of the existing object. The result is a 3D visualization that gives clear outlines and color differentiation to geometric elements.

Besides obtaining 3D images from laser scanning and the manufacturer's software, it is possible to export point cloud data to CAD applications such as AutoCAD, MicroStation, and 3ds max. This is because each point has embedded x, y, z data, so the point cloud can be directly loaded into a CAD program without any need of digitizing.

Laser scanning technology has been successfully demonstrated on numerous projects related to developing bridge as-built drawings, highway widening, refinery expansion projects, water utility construction project archives, rock face surveys, dam foundation surveys, cave scanning, tie wire inspection, and visual effects for movies (Cyra, 2003). Laser scanning can capture fine detail from specific parts of a scene (Sawyer, 2002); therefore, it will benefit the collection of existing structures data for reconstruction (Angelo, 2003). In several cases, field and office time was reduced using laser scanning compared to conventional methods.

PROJECT OBJECTIVES

The objective of this study was to investigate the use of laser scanning to assist the Iowa Department of Transportation (Iowa DOT) in delivering projects in a safer and more efficient manner. Specific tasks included:

1. Learn how to use the laser scanner and software.
2. Select appropriate pilot projects to test the capabilities of this technology.
3. Determine the benefits and costs associated with using this technology and compare them to conventional approaches.

4. Provide recommendations regarding the future use of laser scanning for the Iowa DOT.

LASER SCANNING TRAINING

A Cyra trainer provided the training of the Cyrax 2500 laser scanner and Cyclone software (Cyra 2002) to six people using a two-session format. The training was conducted in Ames, Iowa at the Iowa DOT facilities and took approximately five days to complete. Training began with an overview of the Cyclone software then moved to the field where a complete instruction of the laser scanner was provided. A training manual was also provided, which helped to further explain the details of the hardware and software. A more detailed discussion is provided of the field setup and data processing procedures in the following sections.

Field Setup

Hands-on laser scanning training was performed using the intersection of Grand Avenue and Lincoln Way, and the Union Pacific railroad bridge at Grand Avenue in Ames, Iowa. Several important steps were learned during the field training exercise. First, it is important to create a database for the soon-to-be-scanned point cloud data to reside. A unique database is established for each pilot project. Second, it is important to establish a coordinate referencing system that ties all of the scans together during the registration process and identifies the location of all points in a known reference system. Globe targets were introduced into the scene as registration objects and were scanned and surveyed to identify their x, y, z coordinate location. Each target needs to be acquired after the initial scan and given an identification number. A coordinate file from survey control is then imported into the scanworld (defined as the image captured for one single scan) database before the registration process begins. Third, it is vital to include at least three targets in each scan as this is essential for precise registration of the various scans. Fourth, laser scanning time varies depending on the scanner resolution. For example, the highest resolution (999 x 999 pixels) required about 16 minutes whereas a 250 x 250 pixel scan took about 5 minutes to complete.

Data Processing

Hands-on data processing was demonstrated during training and included point cloud registration, fitting and editing, mesh editing, developing contours and line drawings, and using the virtual surveyor function. A brief description of each data processing function is described below.

Registration is an essential step that ties together all of the individual scanworlds into a complete image of the scanned object. It is during this stage that errors are identified with the target numbering and coordinates assigned to the targets. After registration is completed, a model space is created for the registered scanworlds. Scanned images may contain superfluous points (or noise), such as vertical lines representing traffic, that need to be removed. The process of cleaning the noise and modifying the registered images is called fitting and editing. The Cyclone software provides the capability to remove the superfluous data using segmenting, region growing, and other special editing tools. To make a cleaned and edited point cloud more manageable in Cyclone or for further use by exporting to other CAD packages such as MicroStation, a mesh must be created. In order to measure the clouds and meshes and export the object to 2D drawing software packages, contour and line drawings must be created.

Virtual Surveyor is a useful tool in Cyclone to easily obtain information without physically being at the site. Using scanned point cloud data, one can easily select coordinates, assign codes and notes, and export data to other applications. It is possible, for example, to determine the x, y, z location of a manhole cover in the middle of a busy intersection without ever physically standing there.

DESCRIPTION OF PILOT PROJECTS

In total, there were six test areas involved in this pilot study: (1) an intersection including a railroad bridge, (2) a section of highway including a pair of bridges, (3) new concrete pavement, (4) bridge beams on an unfinished bridge structure, (5) a stockpile, and (6) a borrow pit. Table 4-1 summarizes the purpose for each pilot project. These projects were selected because they were of particular interest to the Iowa DOT as areas where greater efficiencies could be attained. The intersection of Lincoln Way and Grand Avenue in Ames, Iowa, was selected for training to learn how to use the laser scanner as described above. This site provided a suitable location since it is across the street from the Iowa DOT facilities where the training class was conducted.

[Insert Table4-1 Here]

The Iowa DOT is particularly interested in comparing the elevation accuracy using both laser scanning and aerial photogrammetry for roadways surfaces and determining the level of detail that can be provided on bridge structures. Thus, approximately 400 meters of I-235 and a pair of bridges (Figure 4-2) at Broadway Avenue, located immediately south of the I-80/I-235 intersection in Des Moines, Iowa, was scanned.

[Insert Figure 4-2 Here]

In order to investigate the accuracy of the laser scanner in determining the smoothness of pavement and to perform a comparison to a profileometer, a newly paved concrete pavement was chosen for the study. The location was Highway 5 approximately one mile west of Highway 28 at mile marker 98. Meanwhile the beams on an unfinished bridge, located on Highway 520 in Hardin County, Iowa, were selected to determine the camber on the main bridge beam members prior to the deck placement.

It was suggested by a materials engineer at the Iowa DOT that the research team should test how accurately the laser scanner can determine the volume of a stockpile, which is important for determining contractor pay quantities. A selected stockpile was approximately 1/4 mile west of the railroad bridge on Highway 520 in Hardin County, Iowa (Figure 4-3). Similar to the stockpile, a borrow pit was scanned in order to accurately determine pay quantities to the contractor. The location of the test borrow pit was in the northeast corner of the I-35/I-80 East mix master. However, there were some difficulties registering all of the scanworlds associated with the borrow pit pilot test. Consequently, it was decided to discard this borrow pit project and rely on volume-measuring capabilities using the stockpile pilot project.

[Insert Figure 4-3 Here]

FIELD OPERATIONS

Field operations involved two major tasks: (1) set up survey control points and targets (i.e., globe targets mounted on tripods) and (2) scan the desired objects and acquire targets. The research team consisted of the surveying crew and the scanning crew. The scanning operation involved several activities related to properly using the Cyclone software such as creating a database, operating scan control window, and acquiring target.

The survey crew consisted of five surveyors and one coordinator. The survey crew used traditional methods to set up targets and tie them into the Iowa state plane coordinate system. Thus, different scans could be registered and matched to each other with a high degree of accuracy. The surveying time was not specifically tracked but should be similar to the scanning time. This is because the surveyors worked the same hours as the rest of the team.

The scanning crew consisted of two operators. Table 4-2 shows the basic information related to the number of scans and duration of each scan. Scanning time defines the difference between start and end times of scanning. Start time is when the scanner begins to take the point cloud image while end time is the time point of disconnection from computer to scanner. Scanning times varied per scan primarily because scans were performed using different resolutions.

[Insert Table 4-2 Here]

There were several lessons learned during the field portion of the laser scanning pilot test. Since the research team had adequate control on each target, it was not necessary to have common targets in every scan. Overlapping targets are necessary when there is no knowledge of the x, y, and z coordinates for each location. To obtain proper registration, at least three targets need to be common in each scan when control is not established on the targets.

Target acquisition is a critical issue for scanning and registration later. During the scanning process a few different types of mistakes were made that created additional work in the field and office. Some of the more common examples are listed below:

- Targets were completely missed during the initial scan. This reduced the number of targets in the scanworld and caused difficulty during the registration process.

- Failure to scan the correct targets. This was typically detected during the acquisition process and required the operator to reacquire the correct target.
- Paired targets were mislabeled (switched). This could be corrected during the registration process.
- Targets with labels that do not exist in the control files. This could be corrected during the registration process by including the correct coordinates.
- Targets without labels. This lead to difficulties during the registration process because it was hard to tell which target was being used.
- Targets with double labels. This happened because the same two targets were acquired during the acquisition process using different labels. This problem was corrected during the registration process.

It was found that vibrations or scanner movement during the scanning operation makes it very difficult to align images during the registration process. This is because the scanned image becomes distorted once the scanner is moved from its initial position. Thus, it is important that the laser scanner be mounted on a stationary, non-vibrating surface.

DATA ANALYSIS

Not all of the projects required each of these steps above (data processing) as the requirements were dependent upon the desired outcome. Sometimes special steps were necessary in order to meet the unique requirements of the pilot tests. Table 4-3 provides details related to the image processing for each of the pilot projects (except for the intersection and railroad bridge training exercise).

[Insert Table 4-3 Here]

Section of Highway and Pair of Bridges

This project has 30 scanworlds, with one scanworld not being used due to scanner movement during scanning. The roadway portion of I-235 has 17 valid scans out of 18.

Registration

This project was the first one that the research team did on its own after training. As a result, there were many mistakes related to correct target acquisition, which made the registration process more time consuming. A total of nine targets in eight scanworlds had target problems. It was found that checking and measuring target locations and distances between targets in the control space is an efficient and effective way to identify the problems once large errors appear. The corrective action was performed in model space and then a new control space was created from model space.

Because some mistakes were made with the first few scanworlds, extra work was required to minimize the registration errors. After registration and related cleanup work, there were still some targets with errors slightly larger than the original tolerance of 0.009 meters although most targets with errors ranged from zero to 0.007 meters. Those errors could have been caused by either not properly setting the targets or distortion of the laser beam. Because the greatest errors were in pairs of targets with distances greater than 50 meters, distortion is most likely the reason.

Fitting

The process of removing the noise and modifying the registered scanworlds went smoothly for I-235 and primarily involved removal of superfluous data representing traffic on the roadway surface. Because the scanned images are 3D objects, different perspective views had to be checked in order to make sure the traffic noise was completely removed. Although the research team expended a significant amount of effort on mesh editing the point cloud file, this step was not really necessary since elevations could be measured directly using the virtual surveyor routine.

Using the virtual surveyor routine

Figure 4-4 shows the virtual survey of I-235. The surveyor generated a text file by picking points along the desired path. The coordinate text file for I-235 includes the identification number Y, X, Z coordinates, features (location of points) and codes (the abbreviation of the features). The identification number for each point can be integrated into any identification system. Identification of the elevation coordinate values (z) of the I-235 roadway was the major goal of this pilot project.

[Insert Figure 4-4 Here]

Bridge Beam Camber

This project has five scanworlds, one of which was disregarded due to a deficient field scan (two of the targets were acquired twice using a different identification number). This problem was solved by deleting the extra target and correcting the incorrect labels during registration. A total of 11 beams on the bridge were scanned. Five analysis trials were performed for the Hardin County Bridge. The last (fifth) trial resulted in the final analysis results. Because the Hardin County Bridge was under construction, there was no traffic noise and thus minimal data cleanup was required. Determining camber involved measuring the elevation of many points along the top of each beam. Therefore, meshing is not necessary and the virtual surveyor can be used directly on the point cloud image.

A few new special features were applied to the Hardin County Bridge because the beams were not parallel to the reference plane axis, and establishing the true top of the beam surface was challenging because of the protruding steel reinforcing loops present on the top surface. To be able to use the virtual surveyor routine along the beam, a new coordinate system was created by drawing a line on the beam, which was set as a new x-axis instead of the default system (Figure 4-5). Also, one end of that beam was set as the new origin. The new x-z plane was used as new reference plane to cut the beam into slices. By defining a proper thickness of each slice, the top boundary line can clearly be determined by the front view of the beam slice. After this step, the normal virtual surveying process can be applied.

[Insert Figure 4-5 Here]

Stockpile

This project involved most of the data processing steps. Registration of targets and scanworlds was simple and without any major problems due to a small number of scanworlds and satisfactory target acquisition in the field. Because of the irregular shape of the stockpile, the fitting and editing processes were more difficult than those for the other projects. In particular, it was difficult to remove some of the brush and vegetation without removing portions of the stockpile.

Fitting

Vegetation removal on the stockpile was the most difficult part of the editing process. After numerous trials, a set of parameters was determined as a best solution to remove the brush and vegetation with minimal disruption to the stockpile. After applying the region growing routine, some leftover target tripods still required removal using a manual approach. This usually also deleted some of the stockpile but did not influence the final result because the density of the point cloud was sufficiently high. Figure 4-6 shows a graphical representation of the contours on the stockpile pilot project.

[Insert Figure 4-6 Here]

To measure the volume of the stockpile correctly, the mesh volume had to be measured taking into consideration the sloping ground below the stockpile. Since it was not possible to establish a curved reference plane that follows the upward sloping stockpile, it was necessary to create two separate meshes with one reference plane. The top mesh is based on the entire cleaned point cloud (Figure 4-7). The bottom mesh is based on the surrounding area of this point cloud (Figure 4-8). The desired volume of the stockpile is calculated by taking the volume difference between the top mesh relative to an arbitrary reference plane and bottom mesh relative to the same reference plane. The reference plane can be randomly chosen but must be below the top of the bottom mesh in order to simplify the calculation.

[Insert Figures 4-7 and 4-8 Here]

STUDY RESULTS

The results include information from the pilot tests, time expended to perform the pilot tests, and a cost comparison between aerial photogrammetry and laser scanning.

Technical Results

Elevation measurements of the I-235 roadway centerline, lane edges, and shoulders were taken using the Cyclone virtual surveyor. The results were exported into an ASCII format file. To determine the accuracy of those data points and to compare them with those from other surveying methods such as aerial photogrammetry, an ASCII file was converted into a GEOPAK file to create the plan views of I-235. While the difference between those methods can be clearly seen from the MicroStation file, a detailed accurate comparison was also conducted. The average difference for measuring elevation at the lane edges between traditional surveying and Cyra laser scanning ranged from 0.001 meters to 0.009 meters, while the difference ranged from -0.006 meters to -0.023 meters between aerial photogrammetry and Cyra laser scanning. This comparison demonstrates that much more accurate measurements can be obtained from Cyra laser scanning technology than from the photogrammetry method.

The stockpile volume was calculated assuming that the reference plane is established at 300 meters. Using this assumption, the top and bottom mesh volumes are 2,176.849 and 1,669.78 cubic meters, respectively. Thus, the stockpile volume is 507.07 cubic meters. The volume of this stockpile was calculated using a traditional surveying approach and GEOPAK software and was found to be 512.96 cubic meters. It can be seen that the results of both surveying methods are fairly close to one another (1.2 percent difference, or 6 cubic meters).

Results show that it is possible to measure bridge beam camber using the virtual surveyor routine in the Cyclone software. Camber differences varied from 0.4 mm to 10.1 mm. It was not possible, however, to adequately determine the smoothness of the pavement surface. The primary reason is because the laser scanner has an accuracy of two to six millimeters. Most smoothness irregularities will fall within or below the accuracy range of a laser scanner. Therefore, the application of this new technology, in its current state, is not sufficiently sensitive to monitor the smoothness of freshly paved concrete.

Time Requirements

Overall, a total of approximately 870 effort-hours (15.1 effort-hours per scan) were spent on this pilot study, including 403.1 hours for fieldwork, 153.5 hours for lab analysis, and 313 hours for training. Different groups of participants, including a training group, a scan crew, a survey crew, and lab analysts were involved in different phases of the learning process. Some people who attended the training course did not participate further with the project. Also, an assumption was made that the same field time was spent by the scan crew and the survey crew. All of these facts make the time tracking and analysis a complicated process.

Table 4-4 summarizes time spent on the entire project. In order to evaluate the project more accurately, the time spent by people who attended training but who were not involved in any other tasks was removed from the total hours, yielding the actual hours. Clearly, the learning time is more significant than may be expected. In order to maximize production and efficiency, the size of the training and scan crew can be reduced to one scanning operator and one coordinator while the survey crew can be reduced to three surveyors and one coordinator (the same person as the scan coordinator) without influencing work quantity or quality. Therefore, projected hours were calculated based on these crew sizes and are also listed in Table 4-5. The total hours are reduced to 477.5 from 805.6 (a 40 percent reduction). The field time, lab time, and learning time account for 55 percent, 17 percent, and 28 percent of the total hours, respectively. The total hours above can be converted into hours per scan. The actual hours per scan are 14 (7.0 in the field, 2.7 in the lab, and 4.3 for learning). Learning time is a one-time investment and will have less impact on total time as more projects are scanned and analyzed.

[Insert Table 4-4 and 4-5 Here]

Cost Comparison

According to the data from the Iowa DOT, aerial photogrammetry costs approximately $2.66 per linear foot. Based on the pilot study on elevation of I-235 roadway, laser scanning costs $3.43 per foot. Although the laser scanning cost is approximately 30 percent higher than that for aerial photogrammetry, laser scanning offers advantages in terms of accuracy. Due to this characteristic, it may be possible to use laser scanning for the initial project planning and design phases. However, scanning would need to be carefully coordinated, as the scan makes no distinction between the differing surfaces involved. Aerial photogrammetry does offer some benefits here because features such as centerlines and shoulders can be visually identified. Laser scanning costs can be reduced if the scanner were to be mounted on platform vehicle, allowing both sides of the divided highway to be scanned at the same time. It is surmised that the costs would then be comparable to aerial photogrammetry.

CONCLUSION AND RECOMMENDATIONS

Laser scanning appears to have applications for transportation projects. Applications requiring a significant amount of detail that needs to be captured and/or applications where safety may be an issue (such as providing accurate measurements on an active roadway) will benefit the most from the strengths of this technology. Laser scanning performed quite well on determining quantities of soil and rock. Laser scanning was also able to determine the beam camber quite efficiently and accurately.

The laser scanner is not yet suitable for measuring concrete pavement smoothness on newly paved concrete. It takes a significant effort to become proficient with this technology and continued practice to maintain a level of sharpness. If there are sufficient opportunities to use this technology, then it is recommended that the user purchases the Cyclone software and purchase or rent the scanner; initially, it may be prudent to rent the scanner. Surveyors should use more traditional approaches to capture these data or hire a consulting firm with this expertise to provide the laser scanning services if they would only use laser scanning infrequently.

ACKNOWLEDGEMENTS

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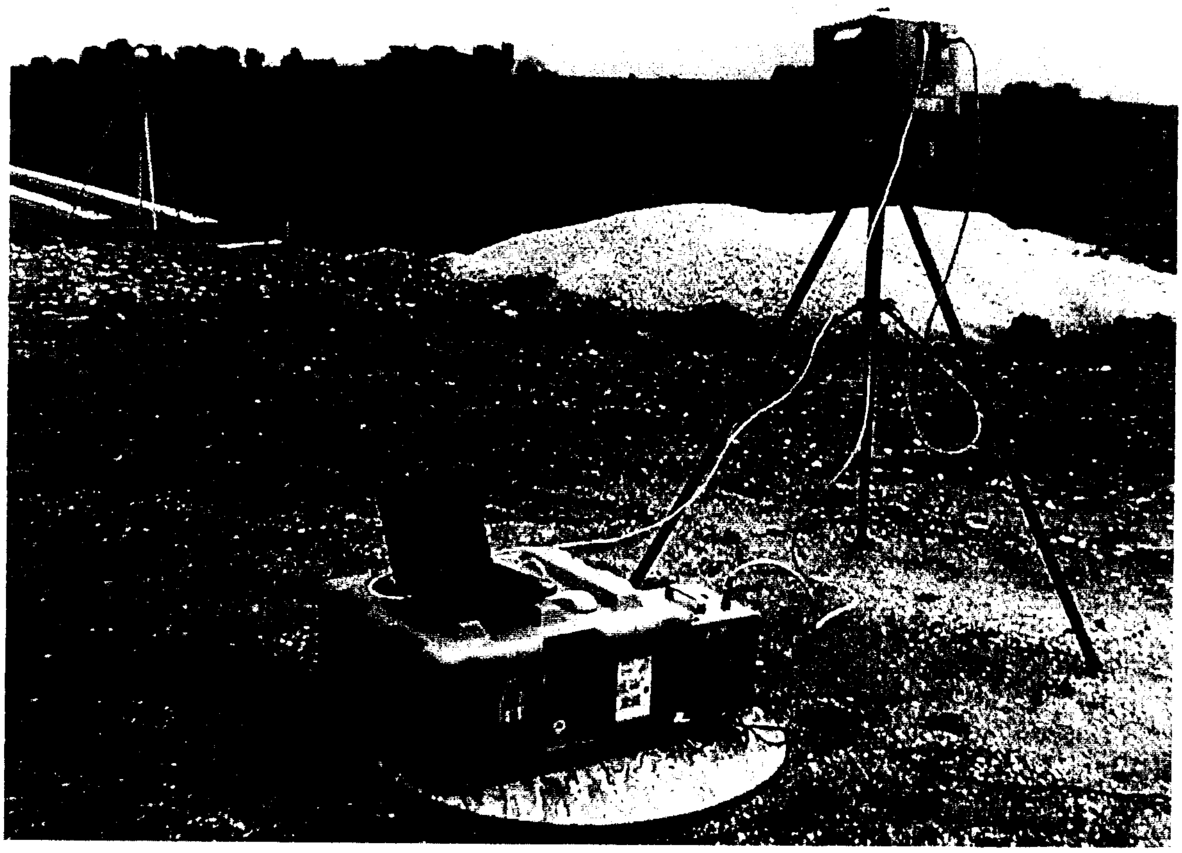

Figure 4-1 Cyrax 2500 laser scanning unit

Figure 4-2 Southbound Broadway Bridge (pair of bridges)

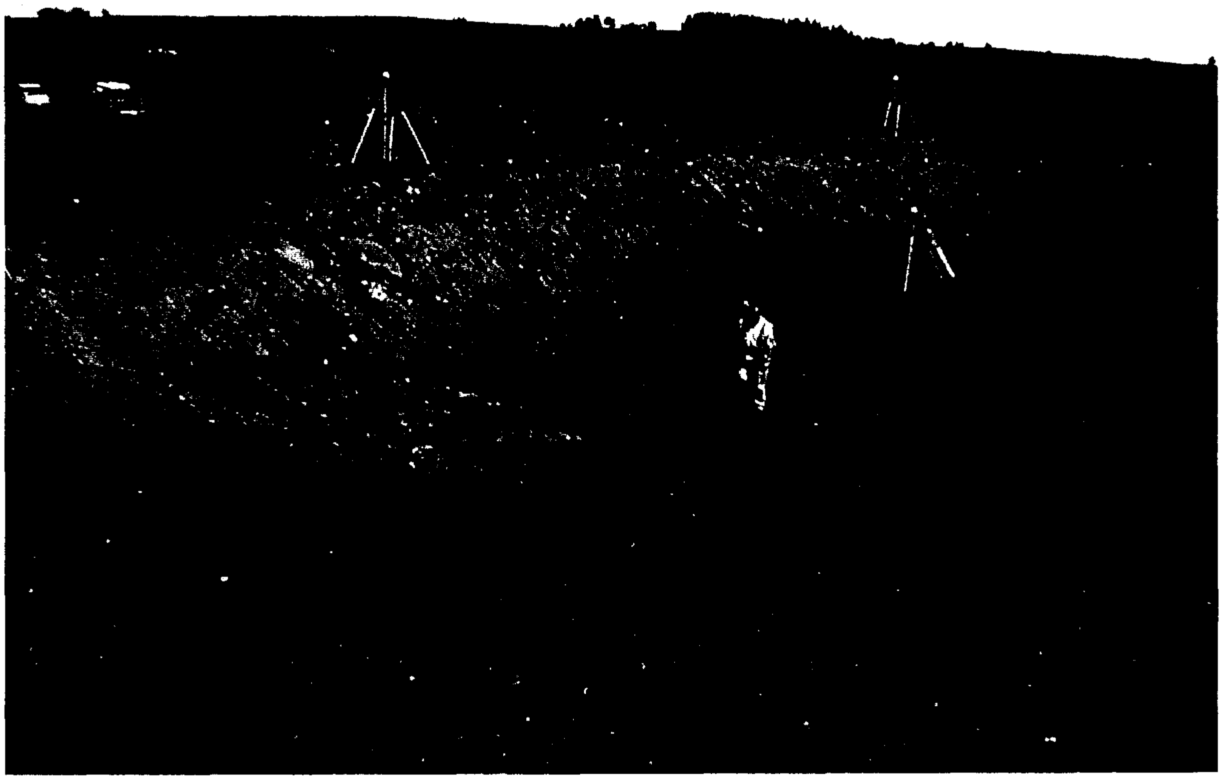

Figure 4-3 Top view of stockpile

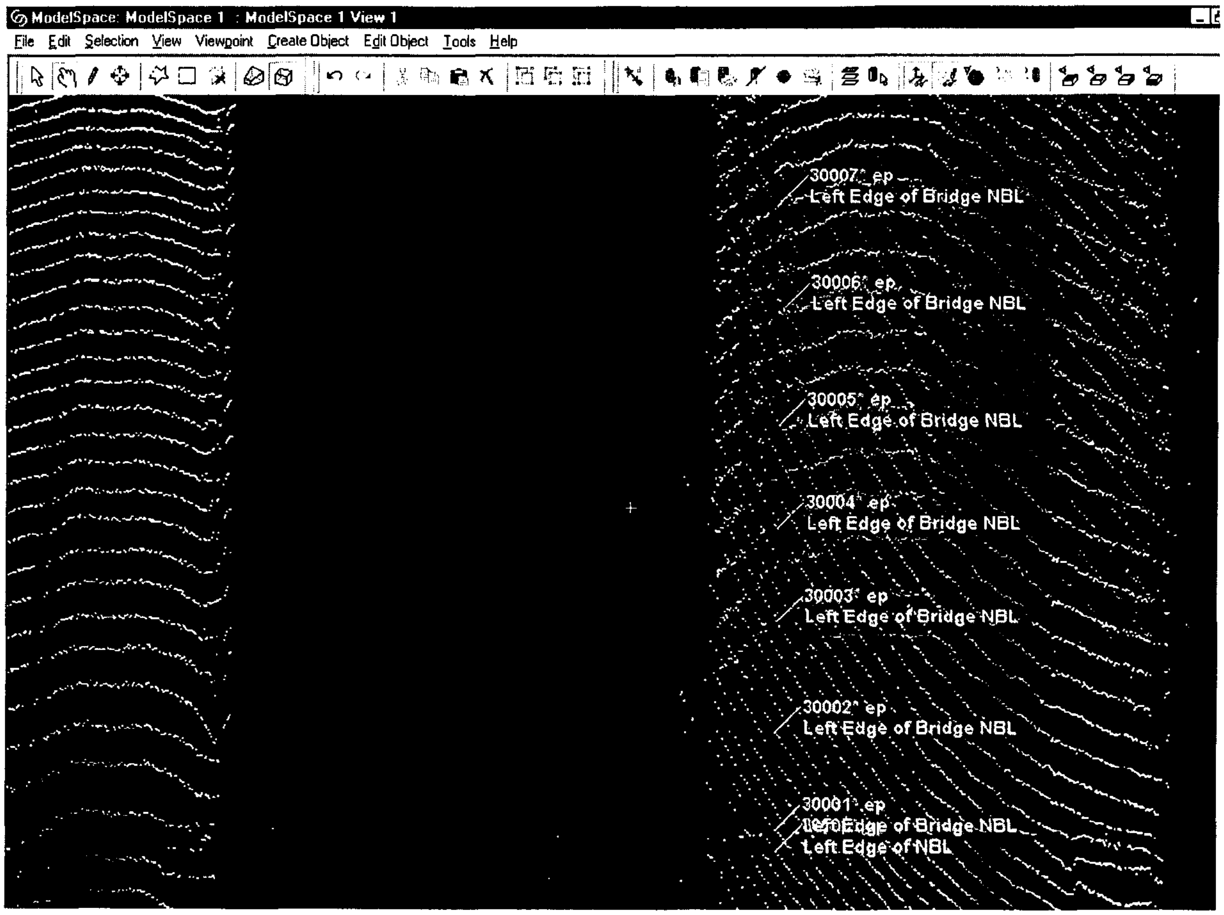

Figure 4-4 Virtual surveying at left edge of I-235 northbound lane

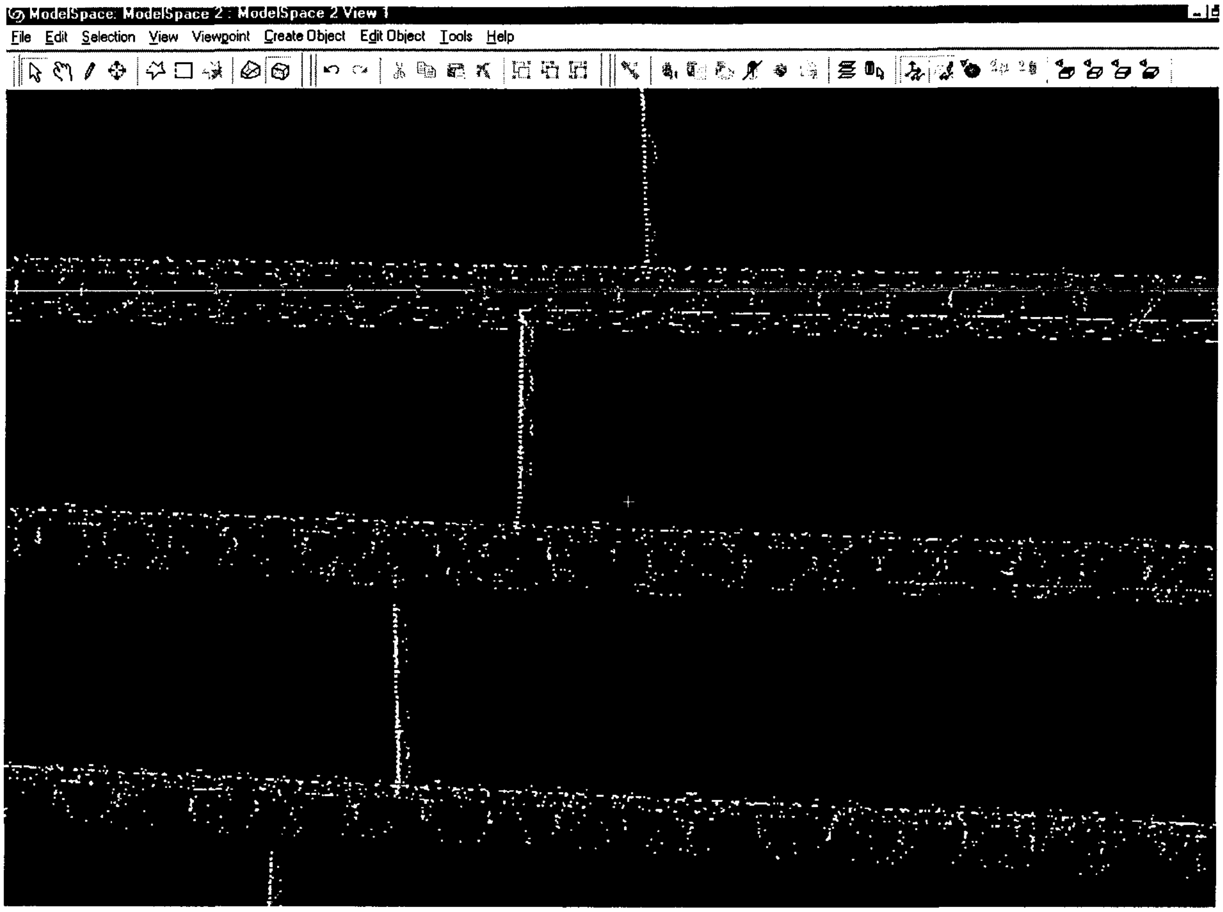

Figure 4-5 X-axis reference plane used on Hardin county bridge

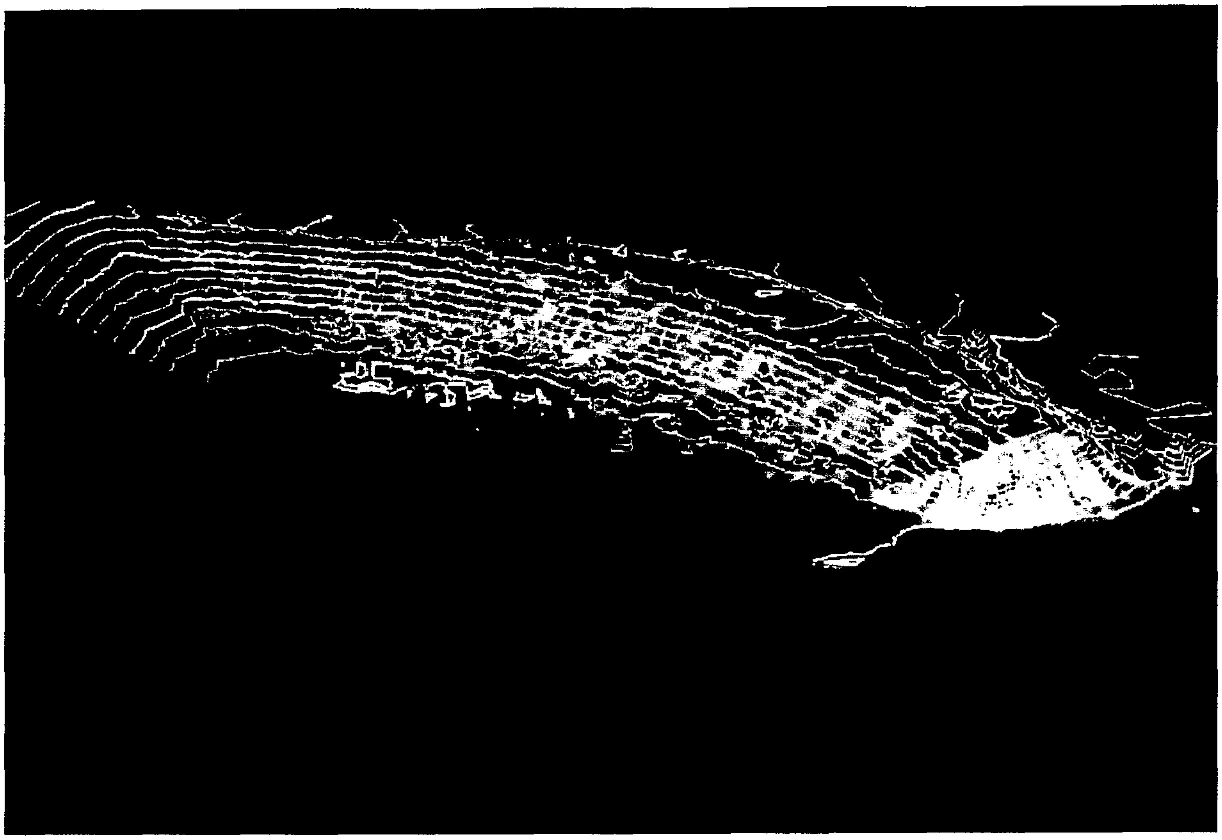

Figure 4-6 Contour lines for stockpile

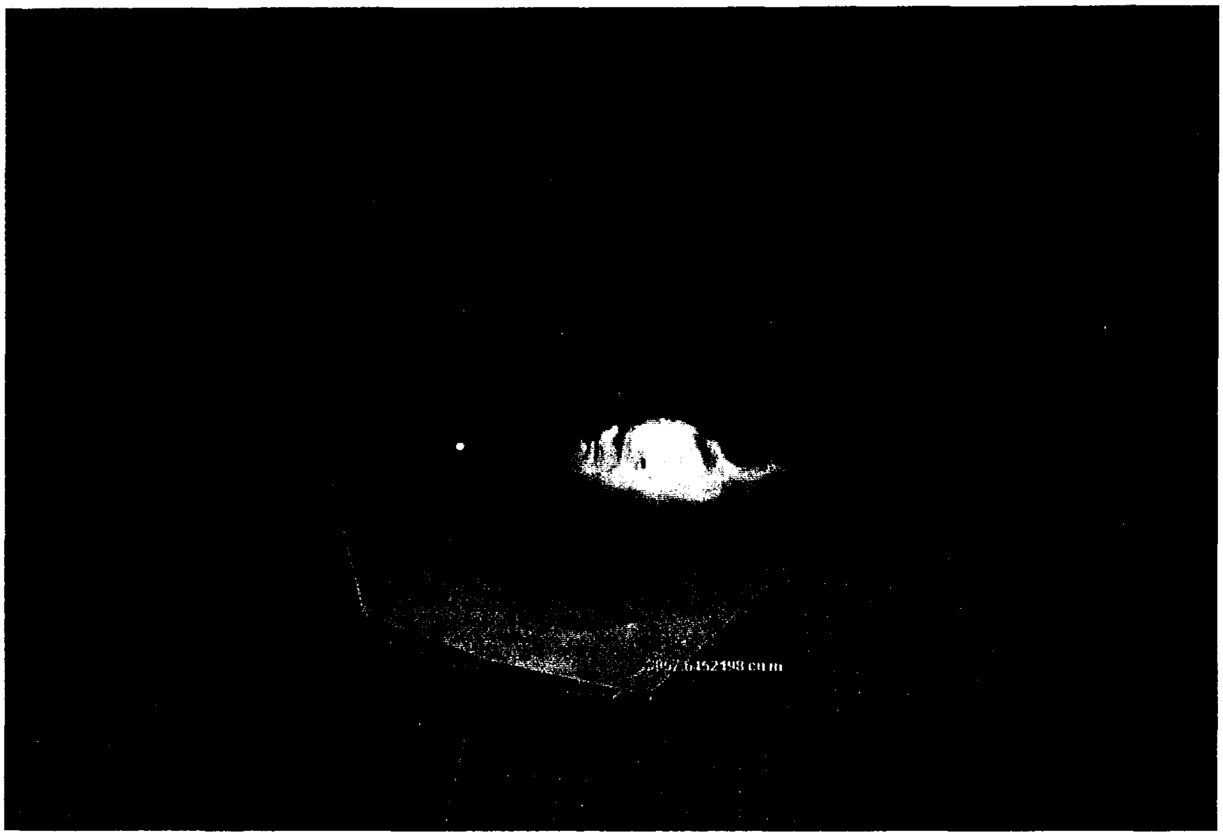

Figure 4-7 Top mesh of stockpile

Figure 4-8 Bottom mesh of stockpile

Table 4-1 Purpose of pilot projects

Pilot Project	*Purpose*
Intersection and railroad bridge	Learn about the Cyrax 2500 scanner and Cyclone software (training exercise).
Section of highway and pair of bridges	Determine surface elevation of highway and compare to aerial photogrammetry. Also, determine the level of bridge detail available using laser scanner.
New concrete pavement	Determine smoothness of freshly paved concrete.
Bridge beams on unfinished bridge	Assess camber on bridge beams for determining optimal loading requirements.
Stockpile	Determine volume of stockpile and compare to traditional methods.
Borrow pit	Determine volume of borrow pit and compare to traditional methods.

Table 4-2 Field scanning information for pilot projects

Pilot Project	*No. of Scans*	*Total Scanning Time (hrs.)*	*Average Scanning Time (min.)*
Intersection and railroad bridge	-	-	-
Section of highway and pair of bridges	30	14.0	28.0
New concrete pavement	3	1.6	32.0
Bridge beams on unfinished bridge	5	2.9	34.8
Stockpile	3	1.5	30.0
Borrow pit	17	4.4	15.5

Table 4-3 Analysis of pilot projects

Analysis and Facts	*Pilot Projects*					
	Section of Highway	*Pair of Bridges*	*New Concrete Pavement*	*Bridge Beams*	*Stockpile*	*Borrow Pit*
Importing coordinates	X	X	X	X*	X	X
Registration	X	X	X	X	X	X
Fitting and editing	X	X	X	X	X	
Mesh editing	X	X	X	X	X	
Contouring		X	X		X	
Virtual surveyor	X		X	X	X	
Exporting	X	X		X	X	
2D drawing		X				
No. of Scans	18	12	3	5	3	17
No. of Valid Scans	17	12	3	4	3	17
Coordinate problems	Many	Many	None	Few	None	Many
Amount of cleanup	Substantial	Substantial	Less	Average	Average	Less
Extra procedures	Yes	Yes	Yes	Yes	Yes	Yes

*Not tied to sate (of Iowa) plane coordinate system.

Table 4-4 Summary of total time spent on pilot study

Type	*Actual Time[1] (hrs.)*	*Projected Time[2] (hrs.)*
Field Time[3]	403.1	262.5
Scanning operation	187.4	121.0
Transportation	114.0	75.0
Breaks	57.0	37.5
Setup	38.0	25.0
Support	6.7	4.0
Lab Analysis Time[4]	153.5	80.0
Learning Time[5]	249.0	135.0
Training course	120.0	80.0
Reading and studying	40.0	20.0
Watching videos	30.0	15.0
Defining procedures	9.0	10.0
Discussion	20.0	10.0
Meetings	30.0	0.0
Total	805.6	477.5

[1] Actual hours equal total hours minus learning time from one participant (64 hours).
[2] Projected hours are projected time to complete the same study by reducing unproductive resources.
[3] For field time, some non-operation time (e.g., transportation, breaks, setup, and support) were counted because these are necessary for performing fieldwork and are counted in the total work time.
[4] Lab analysis time includes time for all of the trials regardless of productivity as well as note-taking time.
[5] Learning time includes several different learning methods: training, reading, video watching, and discussion. Among them, the two-session training (basic and advanced) is the primary approach to starting this project while the video watching is the review of the training course.

Table 4-5 Actual scanning time by classification

Classification	*Total Time (hrs.)*	*No. of Scans*	*Time Per Scan (hrs.)*
Field	403.1	58	7.0
Lab analysis	153.5	56	2.7
Learning	249.0	58	4.3
Total	805.6		14.0

CHAPTER 5 – FEASIBILITY STUDY OF OBJECT-ORIENTED DESIGN AND SPECIFICATIONS FOR HIGHWAY AND URBAN STANDARDS

A paper to be submitted to *The Journal of Construction Engineering and Management*

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ABSTRACT: This paper concludes that objected-oriented technology is now advanced enough to allow developing an object-oriented design and specifications (OODAS) system to make it easier for designers and construction personnel to grasp the project requirements in a quick and efficient manner. OODAS allows users to point-and-click on portions of an object-oriented drawing linked to relevant databases containing information such as specifications, procurement status, and standard drawings. Projects based on OODAS could ultimately reduce the chance of error, improve quality, decrease rework, and shorten the duration of projects. A case study was analyzed in terms of technical considerations and time and cost effectiveness. The case study result shows that OODAS system is a useful tool to convert the design standards and construction specifications into a visual environment. Based on this case study, the time and cost forecast can be made for developing a full system. The plan is established for full system development, maintenance, and update. The limitations of OODAS system and the consideration for improvement are also discussed.

Key Words: Object-oriented, Specification, Transportation, Database

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INTRODUCTION

Currently, designers, contractors, and owners learn about project requirements by studying a combination of paper and electronic copies of the construction documents. These sources include the drawings, standard and supplemental specifications, road and bridge standards, design criteria, contracts, addenda, and change orders. This can be a tedious process since one needs to go back and forth between the various documents (paper or electronic) to obtain information about the entire project. There are also special provisions as well as standard specifications referenced in the contract documents that need to be understood. Object-oriented design and specifications (OODAS) graphically portrays standard construction objects such as traffic signals, utilities, and pavement. Additional information is then embedded into each object to completely describe the material and construction requirements for a proper installation. The graphics reduce interpretation errors by ensuring that all project team members are working from a common project model. An additional benefit addressed by this project is that an OODAS system can be a common interface for multiple specification systems.

BACKGROUND

Object-oriented computer aided design (OO-CAD) technology has long been touted to create more intelligent CAD systems. In OO-CAD the design objects contain all of the data necessary to fully describe each object. For instance, a drawing object representing a traffic signal would contain all of the standard specifications and drawings necessary to describe the material and installation specifications for a traffic signal. The idea behind this concept is that the design involves several objects that have information associated with them. When the user clicks on an object, information pertaining to that object appears. This information can be fixed or dynamic in a sense that the information about that object changes with time. This appears to become possible with the introduction of OO components in many of the popular systems (e.g., AutoCAD with objects defined in C++) (California Software Laboratories, 2003). Major CAD packages such as AutoCAD (AutoDesk, 2003) and MicroStation are presently working towards greater interoperability in the Windows environment by supporting such emerging tools as Architect/Engineer/Contractor eXtensible Markup Language (aecXML) (Harrod, 2003).

In Iowa there is already an effort currently underway to make it easier to find required specifications. In order to make it easier for design and field personnel to locate Iowa Department of Transportation (DOT) specifications (Iowa DOT, 2001), an Electronic Reference Library (ERL) (CTRE, 1999) has been created. The ERL is a fully cross-referenced and searchable version of the Iowa DOT Standard Specifications, Supplemental Specifications, Material Instructional Memorandums, Standard Road Plans, Standard Culvert Plans, Flagger's Manual, Construction Manual, and the Iowa Statewide Urban Design and Specifications (SUDAS) Standard Specifications, which is distributed on CD ROM format for state-wide distribution (thousands of copies have already been distributed). State agencies, local agencies, and construction contractors using the Iowa DOT specifications can quickly and efficiently identify relevant specifications using key word search capability. New CDs are released on a six-month basis reflecting updates to the specifications, and ensure that the users (i.e., designers, contractors, inspectors, field engineers, suppliers, FHWA, counties, cities, and other state DOTs) have access to the most current information. Thus far, users have found electronic specifications to be useful for quickly locating information.

Transportation design and construction organizations often must operate with fewer resources due to budgetary limits. This constraint means that fewer skilled people are available that can effectively understand construction documents. Although the seasoned professional can integrate such documents as the drawings, specifications (standard and supplemental), road standards, contracts, addenda, and change orders, new team members find that this can be a tedious process. Therefore, the need exists to use information technology to develop a new specification system that can help designers and contractors improve project performance.

VISION

As illustrated in Figure 5-1, the vision of study is to turn paper-based design standards and construction specifications into an Object-Oriented Design and Specification (OODAS) system or Visual ERL located in a server. Individuals can utilize the system through a handheld wireless book-size laptop which includes all necessary software for operating in a 3D environment. All of the parties involved in the transportation project design and construction process can access the standards and requirements at one time and in one place using a 3D graphical interface with high accuracy and completeness. By using this system, the user will have all of the design elements and all of the specifications in hand and does not need to worry about omissions. The entire concept is that a graphical system makes the process of visualizing construction projects consistent, and information can be released faster.

[Insert Figure 5-1]

STUDY OBJECTIVES AND METHODOLOGY

The purpose of this study is to test the feasibility of the concept of developing a full scale OODAS system including technical considerations and an economic analysis. The impact of such a system on the design and construction process will be also assessed. Both Iowa DOT and SUDAS specifications (SUDAS, 2001) will be included in the system. The end product will be a graphical or visual front-end system for the ERL.

The methodology includes several steps:

1. Define concept vision for OODAS system.
2. Conduct a case study that involves:
    a. Understand and determine the user requirements through a series of meetings and face-to-face interviews with designers and field personnel.
    b. Research various OO-CAD software packages and file formats and make a selection.
    c. Develop a prototype model in object-oriented format and link it to the appropriate specifications.
3. Evaluate the case study:
    a. Gather the user feedback.
    b. Analyze the workability of the prototype.
    c. Investigate the improvement to the case study.
4. Develop a comprehensive plan to develop a full scale OODAS system:
    a. OODAS overall structure.
    b. Technical considerations.

c. Time and cost analysis.

5. Analyze the benefits or advantages of OODAS system including how such an approach would affect the Iowa DOT's standard operating procedures.

OVERVIEW OF CASE STUDY – PROTOTYPE

While the details of technical programming can be found in other documents (CTRE, 2004 and Kaewmoracharoen, 2004), this section presents an overview of the research activity and the major features of the prototype.

Description of Research Activity

At the Center for Transportation Research and Education (CTRE) at Iowa State University, research is being conducted for the development of an OODAS system. In the OODAS model, the design standards and standard designs are converted into 3D active objects that dynamically link to all related construction specifications. Such a model allows users to visualize the construction objects and process as it would be actually built. The users can also access the details of project requirements by clicking on portions of a 3D object.

The research team conducted a case study in phase I to substantiate the feasibility and effectiveness of an OODAS model. First, the current design standards and construction specifications were studied by choosing typical objects for the case study. Then, the research team used a modified focus group method to get initial user requirements and determine the start objects. Focus groups involve an informal technique that can help researchers assess user needs and feelings about a product or idea (Nielsen, 1997). Instead of strictly following the rules to organize the focus group, the team used the SUDAS steering committee and its subcommittees as a modified focus group because the engineers have broad design and construction experience. To meet these requirements, various software packages were researched and reviewed to determine whether or not they fit the scope of project (CTRE, 2004). The team then created a 3D prototype to test the concept and workability of an OODAS system. The prototype was brought to several focus group meetings and improved based on the feedback. The prototype and its demonstration revealed that the concept is valuable and that the current ERL can be fully reused. A cost-benefit analysis was also conducted.

Software and Programming Involved

Various software packages that have object-oriented capability were reviewed. The selection process can be reviewed in interim research report (CTRE 2003). In summary, as illustrated in Figure 5-2, MicroStation (Bentley, 2003) is used to view and edit standard plans related to specifications. 3ds max (Discreet, 2003) is used to create the 3D models. The specifications are stored and managed by a Microsoft Access database (Microsoft 2003). Finally, Macromedia Director (Macromedia 2003) is used to combine the 3D model with the database to create a dynamically updated, 3D interactive environment for the user. The product can be in two types of formats: one is an executable application program and the other is a Shockwave movie. Shockwave is the media type defined by Macromedia, Inc. and can be played on the Web by Shockwave player, which is the media player produced by Macromedia, Inc. and is freely distributed on its website.

[Insert Figure 5-2]

Programming involved in the case study includes Lingo, C++, HTML, and HTML HELP. Among these, Lingo is the major programming tool. Lingo, the programming language used by Macromedia Director, can set up navigation control, define 3D object behavior, link the model to the outside database, and apply a Macromedia Director Xtra. Xtras are software components that extend the functionality of Macromedia Director Movies, projectors and Shockwave movies (Macromedia 2003). A small portion of C++ programming was used for Macromedia Director Xtra and Application Programming Interface (API), which provides access to the support functions defined in the classes as well as provide additional useful functionality. The HTML programming was used to modify the existing ERL data file when needed, and to display Scalable Vector Graphics (SVG) file. SVG format is a new standard for web graphics which exceeds the capabilities of older style raster image formats such as JPG with consistent quality at different zoom levels and on different sized screens (Software Mechanics PTY ltd, 2003).

Objects and Related Design Standards and Specifications

The prototype developed for the case study is a typical local street intersection. To help researchers quickly set up the 3D models in a meaningful way, the Lincoln Way and Grand Avenue intersection in Ames, Iowa was used as a physical reference (Figure 5-3). This recently rebuilt intersection is representative of current standard design and specifications including double left lane, single left lane, right turn lane, median, complicated traffic control devices, and underground utilities. Therefore, different objects can stay in the same scene to illustrate the research concept quite satisfactorily. However, the computer generated 3D scene was not exactly same as the physical intersection. Instead, the objects were rechecked with the standard design and modeled following the design standards and specifications.

[Insert Figure 5-3]

The objects created in the prototype model include, as illustrated in figure 5-5 and table 5-1, a portion of a street, driveway, traffic signal devices, street light, and intake, each of which contains several sub-objects. For example, the object of street was further divided into pavement (including joint and sealant), subbase, undisturbed soil along with sidewalk and curb, sanitary sewer, storm sewer and underground utilities. The objects were created following the dimensions from standard drawings while related specification data were linked to sub-objects. All standard drawings and specifications are from both Iowa DOT and SUDAS standards. For example, the 2D views of the street pavement object can be found in Iowa DOT standard drawing RH47B, as reprinted in Figure 5-4.

[Insert Table 1 and Figure 5-4]

Major Features of Case Study Prototype

The case study prototype contains a 3D street scene that contains the objects and data above with some commercial buildings along the street to make the model more realistic. As implied in the software selection section, the objects were developed into 3D models with 3ds max or Light Wave 3D (graphic modeling package used at the beginning of research) followings three major steps: (1) create a wire frame consisting of polygons, (2) assign textures, and (3) then export the textured model to W3D (Web 3D) format. The W3D files are imported into Macromedia Director, where the models are linked with the database. The product made by Macromedia Director is in two formats: one is a self executable application while the other is a Shockwave file. The Shockwave file can be viewed by anyone who has an Internet browser with the free Shockwave plug-in (Macromedia, 2003).

The prototype model is illustrated in Figure 5-5. The prototype interface consists of four parts including a view window along with a function toolbar, selection menu and 3D control button panel. The details of each part are also listed in the intersection snapshot located in the middle of figure. The view window displays the scene view for selecting an object and the object view for selecting a sub-object. The design and specification data can be accessed from a sub-object with a context menu. The context menus actually link the data in ERL through a database control table (Microsoft Access or XML). The next section describes the major features of this prototype.

[Insert Figure 5-5]

Uses object-oriented 3D interface

The prototype was constructed by building a repository of high quality, reusable graphics and components of specifications, which can be combined in various ways to produce new reusable components at higher and higher levels of abstraction. Specification objects in the database store non-graphical data in a logical structure together with the standard graphics that, in three dimensions, are in object-oriented CAD formatted files. Because of its 3D format, the main scene and objects can be rotated, panned, and zoomed. Each component (sub-object) of an object is associated with certain specification information, stored in the ERL database. By moving the object to a certain position, the user can click on any aspect of the model. Then, a context menu appears directing the user to the database containing the relevant specification information for that portion of the design. Therefore, users can easily locate information and project requirements from a graphical object as shown in the Figure 5-5.

Combines multiple standards

In Iowa, different specifications are used depending on the project type and location. Iowa DOT specifications are used on state, federal, and county highway projects. SUDAS specifications are used primarily on city projects, and may vary by city. The prototype accommodates multiple specifications into one graphical object by using a selection pull down menu. The user can access the different project requirements at same time for the objects being constructed. The provisions from different standards for a same physical object can be tracked.

Accesses multiple versions of specifications

The prototype allows a user to get the specific data from the right version of the applicable specification providing a pull down menu to select the specification released at a different time. This can benefit those who are building a project over a year or with multiple contracts. The critical changes between different specification versions can also be shown on an object model.

Utilizes current ERL database

One of greatest advantages of this prototype is that it completely reuses the ERL database. This saves time and effort to develop the new database, and meanwhile, the current ERL users can easily accept the fully developed OODAS system in the future. On the other hand, in order to allow users to obtain the data as specific as possible, the current ERL data file (in html format) may need to be further structured. For example, more tags or bookmarks are needed for information within the sub-section of the specifications or even each paragraph. However, this can also be done in the process of updating ERL.

Although the OODAS system was initially proposed to be a Web-based product (store the data in the server and release the updates through the Internet), a CD/DVD version is still under consideration due to user preference, internet availability, and performance of current computers. Actually, the CD/DVD version may have advantages over the Web version such as a better search engine and index.

ASSESSMENT OF CASE STUDY

The concept and prototype have been presented to groups of potential users to gather evaluation comments using a modified focus group approach. The details about the modified focus group method and evaluations can be found in a CTRE research report (2004). Some users' feedback is listed below along with the analysis of the case study.

Users' Feedback

The comments from modified focus group meetings are summarized as follows:.

- Standard pictures/scenes should be designed to allow the user to get specification information by clicking on the various objects.
- The system should provide a tool to deal with the issues related to periodic updates to the standard drawings and specifications. A dynamic update function should be provided.
- The graphics must cover all pertinent specifications. The system is designed to be a graphical object-oriented standard. When you click on each item, the user will get all information related to that object. OODAS will insure that the user does not miss any important information.
- The system should facilitate quick decision-making and help new engineers learn. However, it should be useful to anybody in the construction industry such as engineers, consultants, contractors and inspectors.
- The final product should integrate the various codes and standards. Designers and contractors could learn about the specifications from this system.
- A search function should be provided within the system.

Case Study Analysis

Based on the users' feedback and results of the case study, OODAS system can be a useful tool to visualize the design and construction process. The object-oriented organization of specifications can allow a user to obtain required information at one time and potentially solve the inconsistency problems between drawings and specifications. The system can also provide a platform to combine the Iowa DOT and SUDAS Standards together.

There are limitations. The main concern is whether OODAS provides a professional user much more than ERL. The user might not return to the 3D scene after clicking on the sub-objects in the ERL database because he can search all the information within ERL. However, OODAS was not intended to be designed as a graphical front-end to ERL. The advantage of the OODAS system is to allow users to access all the information from a realistic 3D object. The next section will address this point. On the other hand, while the authors developed the prototype, significant time was spent on 3D modeling. Therefore, the maintenance and updating of OODAS can be costly when the design standards and specification change significantly. Therefore, some new features were incorporated into the prototype to answer these concerns. A possible solution should be further tested based on the new concept and available tools as discussed below.

Improvements to the OODAS System

To solve the above limitations, a few possible solutions need to be added to the current development plan. First, more tags or bookmarks are needed for the data files in ERL so that all the data can be organized and retrieved in an object-oriented environment, i.e., one click on a sub-object must cover all of related design standards and specifications and also exclude all non-related data. Therefore, the user does not have to worry about the completeness and accuracy of the data. To minimize the development effort and cost, this process can be integrated with the next ERL database update. Also, a standard format (order) to organize the data has to be set up. Unlike the current ERL, in which the index follows the table of contents of paper-based specifications s and the search results in a random sequence, OODAS should organize the data a in a way considering the procedures to design and construct a specific object. Meanwhile, a search engine is embedded within OODAS running in the background to check whether the object model provides all of the related information.

Next, the OODAS system can be designed to tightly integrate with ERL. If a user starts with OODAS, he can access the specifications and standard 2D drawings and design standards from the 3D object model as shown in the case study prototype. However, if a user begins searching within ERL, he also can access the 3D model for applicable information and then access the other parts of information such as design standards and 2D drawings. This solution involves a two-way communication between ERL and OODAS which will eventually merge ERL and OODAS into one interface during a certain update period in the future. However, the ERL interface has to remain with OODAS because people still want to use it.

Furthermore, although a 3D model is the key element to visualize the objects, the models in the prototype require a large amount of time to develop, are hard to update, and lack measurement details consistent with corresponding 2D drawings. In addition, the process of developing a 3D model is disconnected from that of developing 2D drawings. Therefore, a better CAD tool must be used to integrate the 2D drawings and 3D model creation. The 2D drawings developed by designers can converted into 3D models. The 3D models also contain the 2D drawings and their complete measurements, i.e., any section of a 3D model will become a 2D drawing.

The realization of these improvements will allow users to visualize the design and construction objects and process, make access to the project requirement easier and faster, and solve the inconsistent problems from having different standards and media. In addition, it will also enhance the design process and products, simplify the OODAS and ERL maintenance and update, and integrate the management processes of the Iowa DOT and SUDAS standards.

COMPREHENSIVE PLAN OF DEVELOPING THE FULL OODAS SYSTEM

In order to develop the complete OODAS system and maintain it, a study of the operational and benefit/cost analysis of such a system was performed. There are four principal questions for the study:

1. Is the proposed system able to improve the current design and specification accessibility and either replace or supplement the current ERL system?
2. Based on the factors from prototype development, are the time and cost to develop such a full system reasonable?
3. Assuming the answers to above two questions are yes, are the distribution, maintenance and update of such a system technically operational and economically affordable?
4. What is the impact of such a product and its technology on the design and construction process related to transportation projects?

In general, the above questions investigate the feasibility of such as concept, regarding its prototype development, long term needs, and future revenues and expenses, and also how such a system would affect the Iowa DOT and SUDAS standard operating procedures and formats. To answer the above questions correctly, a few aspects of the OODAS prototype and proposed full system were examined based on the past work and reasonable assumptions. These include system structure, technical consideration, and cost and time analysis.

OODAS System Structure

Figure 5-6 illustrated the structure of the OODAS system. The OODAS basically includes two scenes: urban and rural. The urban scene contains arterial streets, collector streets, and local streets. The development of an urban scene involves a minimum of 150 objects (9 high complexity, 30 moderate complexity, and 111 low complexity objects). The assumptions of object complexity are defined later in this paper. The development of a rural scene involves a minimum of 121 objects (9 high complexity, 18 moderate complexity, and 94 low complexity objects). Among these low complexity objects, 73 objects are identical or very similar in both the urban and rural scenes. The object details can be found in a CTRE research report (2004). Each object also contains a few sub-objects that link to standard designs and specific specification information in ERL.

[Insert Figure 5-6]

Technical Consideration

There are important technical factors to consider when developing a full OODAS system. These factors include: (1) size and growth of the database, (2) numbers of users, (3) performance and reliability, (4) operating software required, and (5) maintenance and update issues.

Size and growth of the system

By maintaining the design and specification database in a file that is external to the 3D model, the gradual increase and growth of OODAS through the addition of records or changes can be accommodated. It is also possible to anticipate the step-growth or changes if the records of other standard documents are added or records of certain standards are merged such as the combination of Iowa DOT and SUDAS standards. There are no problems associated with the ability of the search function to cater for the database growth and changes.

Number of users accessing the system

Limits on software components of OODAS associated to the numbers of users can be solved because of the following points:

- Either Microsoft Access or XML were chosen to develop the database. The Access or XML file is used as backend software and the Shockwave movie reads the data from that file by programming. Therefore, the computer without Access will run the system. Actually, as a backup, Microsoft Access is usually part of Microsoft Office, which is running on most of the computers, if not all. In the future, with the increase of database size or the change of database, it might need the database to be run separately. If the product is distributed or accessed through a website, the database can run by local copy of software instead of by one on the server. Also, the Shockwave player, which is a major component to play the models, is freely downloadable to run under the internet browsers such as Internet Explorer and Netscape. The worst case is that users run software on the server, in which case Microsoft Access allows up to 100 users to log on per minute.

- The accessibility to the system is dependent on the accessibility of the server. Because the server for OODAS is going to be the same one that the ERL is running, this problem does not exist.
- OODAS can also be distributed though CD-ROM or DVD-ROM. The system is not involved in the accessibility issue except when related to online updates.

In summary, there is no real user accessibility problem associated with the OODAS problem.

Performance and reliability of the system

It will be necessary to ascertain the performance and reliability of the OODAS system in retrieving and managing design and specification models and data. In the current development process, the database was shared or imported from ERL, which proved efficient and accurate. The generic model was created based on a related design manual, standard design, and design details. Full specifications are available along with detailed object-oriented sub-objects from a 3D generic model in the scene. The design details are still in 2D drawing format, which can be accessed through a 3D model. All of these factors assure the accuracy of the information while the required information can be obtained faster and more specifically.

The current prototype runs evenly and reliably both in a self-executable or web format. Specific specification information should be able to be accessed generally within three mouse-clicks starting from main scene where a 3D object locates and other related information can be found using a built-in search function.

However, the performance of OODAS system is constrained by the performance of its search function system and the computer system on which it is run. The performance of a search engine can have a strong impact on the user regarding the speed, coverage, and understandability of information that the user is acquiring.

Required software

Based on the prototype development, the necessary software has been located (see software selection section) including discreet 3ds max, Macromedia director, and Microsoft Access. These are needed for developing and updating, not for using the system. For the system server and updating center, the following factors need to be considered:

- Record retrieval for resource discovery
- User authentication
- Compatibility of Windows and Macintosh system
- Diagnostics and errors

The method of record ordering, record formats available on different systems, consistency of record content for index, search results and full records, and standardization of record formats all have to be considered in the design. Certain technical solutions need to be further investigated.

Currently the ERL system does not have any user authentication. If the OODAS system involves many perspectives of design and construction process with Iowa DOT and SUDAS, this may become a problem. This would bring about an administrative overhead of handling user IDs and passwords.

Because different users might be using different machines and operating systems, the OODAS system needs to have the capability to run on all systems. Although the details of different systems are pending a survey in the further study, this issue can be solved within the web format of OODAS.

Maintenance and update issues

Maintenance and update issues become a key to OODAS system once it is developed. Several important items must be determined or best analyzed before the start of full system development, such as following:

1. Release of new components for model library (at the same time as the design and specifications revisions).
2. Real time changes of the database besides twice a year update cycle.
3. Administrative procedures and overheads of maintaining the OODAS system.
4. Maintenance of facilities and inclusion of new facilities.
5. Quality of service and user expectations.
6. User's instruction and training issues.

The maintenance and update of OODAS can be combined with the current ERL system.

Time and Cost Analysis

The time and cost spent on the case study were tracked. Based on the case study and some assumptions, the time and cost of developing a full scale OODAS system can be estimated with an appropriate analysis method.

Method and assumptions

Due to the uncertainty and variance of objects in the full OODAS system compared those in the case study, there is no way to use point estimates to specify the time for future development. Therefore, a range estimate method is employed with assumptions of the researchers' best judgments based on the pilot study. The procedure for this method includes the following considerations:

- Tracking the time and cost for case study and categorize them.
- Separating the meaningful time from that spent on the pilot project but not applicable for the full scale system development.
- Making assumptions to develop a set of time modules for different levels of objects.
- Making assumptions and defining the total number and complexity of objects for the full scale system.
- Simulating the time ranges for developing the full OODAS system and its cost.

The case study provides the authors a possibility to assume the minimum, maximum, and an inspired guess of the time required to develop an object with an assumed complexity. This falls into the scope of statistical triangular distribution because the tracked data can meet the three necessary conditions for a triangular distribution:

1. The optimistic (minimum) effort-hour needed to develop an object is known (best assumed).
2. The pessimistic (maximum) effort-hour needed to develop an object is known (best assumed).
3. The most likely effort-hour falls between the optimistic and pessimistic values, forming a triangular shaped distribution, which shows that values near the optimistic and pessimistic values are less likely to occur than those near the most likely value.

During the process, decision-making software – Crystal Ball (Decisioneering, 2001) – was used for simulation.

There are also two types of assumptions made for objects in the full system: (1) the full system uses typical 3D objects to link the drawings and specifications instead of using all the possible objects, and (2) the complexity levels are best judged by authors based on the experience from developing the prototype. The objects are grouped in three levels of complexity based on the modeling effort for objects in the case study: high complexity, moderate and low complexity. A high complexity (HC) object is one with many sub-objects and complicated geometrics such as a portion of street. A HC object usually has more than 5,000 polygons in 3D modeling process. A low complexity (LC) object is one that has few or no sub-objects and has a simple geometry (such as a STOP sign). A LC object usually has less than 100 polygons. Any objects between HC and LC are grouped into moderate complexity (MC) objects.

Time spent on the case study

In order to make it more understandable and meaningful, the time spent on project phase I can be categorized into project planning, system development, and wrap-up time. The system development time is the critical factor to forecast the full system, which is further categorized to include project preparation, 3D modeling, data indexing, model and data matching, and programming time. The definition or scope of each category is described as notes to Table 5-2. As shown in Table 5-2 and Figure 5-7, the case study duration is 17 months or 3500 effort-hours; however, the research team spent much time on planning, developing a comprehensive plan, and testing different software and features of modeling that will not occur again in the next phase. Therefore, only system development time will be meaningful to estimate full system developing time. Table 5-2 gives effort-hours of each activity in system developing. A total of 1,248 effort-hours was spend on developing the prototype including preparing, 3D modeling, data indexing, model and data matching, and programming. Among these activities, the 3D modeling and programming activities occupy a large portion, approximately 72% or 900 effort-hours, of time (Figure 5-8). In addition, the 3D modeling took 200 effort-hours or 16% of development time. Table 5-2 also gives the 3D modeling time of each object for the case study prototype. As seen in Table 5-2, the street object has nine (9) sub-objects (curb, lane marking, subbase, subgrade, pavement, and median) and therefore took more time (80 effort-hours) than a simple traffic sign (6 effort-hours).

[Insert Table 5-2 and Figures 5-7 and 5-8]

Time estimated for developing the full system

Based on the case study and an assumption of continuing the development with the same research team, a set of modules was determined in terms of time per object. As mentioned in the method and assumptions section, the objects are grouped into three complexity levels based on the modeling effort for objects in the case study: high complexity, moderate complexity, and low complexity. Table 5-3 gives the optimistic (minimum), most likely, and pessimistic (maximum) effort-hours for developing an object regarding different complexity levels (high, moderate, and low) as well as for each activity of development. While the point estimated effort-hours are also showed in the table as a comparison, the Crystal Ball simulation was run to get the range of effort-hours as shown in Figure 5-9. In general, with 95% certainty, the time to develop an object is ranged from 95 to 145 with a mean of 117 effort-hours for high complexity, from 40 to 58 with a mean of 48 effort-hours for moderate complexity, and from 13 to 22 with a mean of 17 effort-hours for low complexity.

[Insert Table 5-3 and Figure 5-9]

As mentioned above, a workable full system should contain, as shown in Table 5-3, a total of at least 198 objects being developed (18 high, 48, moderate, and 132 low complexity). It should be noticed that the system may include more than 198 objects because some objects can be reused. By combining the number of objects and the effort-hours of developing one object, the Crystal Ball simulation resulted in a range of 6,185 to 8,111 with a mean of 7,107 effort-hours to develop the full system (Figure 5-10).

[Insert Figure 5-10]

Development of the full system can be further divided into three phases: (1) urban scene development, (2) rural scene development, and (3) the finishing phase including the OODAS distribution, training and maintenance. However, the urban and rural scenes can be combined into one phase. Based on the past experience and data from the ERL project, the finishing phase is going to be approximately six months, which means 1,500 crew hours. In addition, the development phase(s) needs six months extra time for writing the report and other project related activities, which is about 1,500 effort-hours (estimated as three half-time graduate students for six months). All the above will turn the total time into a mean of 10,107 effort-hours, within a range from 9,185 to 11,111 effort-hours. Assuming 14 effort-hours of research time a day (3 half-time students with 2 supervising researchers) it approximately equals a mean of 32 months development time with a range from 29 to 35. However, these numbers could be significantly reduced by bringing in more students.

Cost for developing the full system based on case study

The cost anticipated for performing the entire study is illustrated in Table 5-4. These costs include the purchase of the hardware and software, researcher's time, and report preparation costs. The total cost of developing a full OODAS system, just for specifications and related standard design based on a set of typical objects above, ranged from about $305,000 to $361,000 with a mean of $343,000. In case the full OODAS system includes all of the design manuals, standard road plans, and design details as well construction manual, the total cost would be much more.

[Insert Table 5-4]

In general, besides the technical considerations, the development of a full system with minimum typical objects will take an average of 32 months and cost about $350, 000 for Iowa DOT and SUDAS specifications and related standard drawings. Note that comments from design and construction professionals should be obtained before any actions are taken, especially, the typical objects should be finalized by these professionals in consideration of needs for the industry and practice. Eventually, the developing time and cost may vary with the analysis above.

ADVANTAGES OF USING AN OODAS SYSTEM

Based on the case study, the above analysis, and feedback obtained from designers, contractors, and other engineers, several advantages or benefits are anticipated by developing and applying such an OODAS system.

1. It provides 3D visualization of design drawings and the construction process. This graphical approach will make it easier for new designers to quickly learn about standards and specifications. This would also allow users to image the project before it is built and potentially speed up the design and construction preparation time.

2. It will be easier for designers, field personnel, contractors, suppliers, and manufacturers to find the relevant specifications for a specific portion of the design. This should improve the efficiency of preparing the design documents and interpreting them in the field.
3. This approach will make it easier to combine both the Iowa DOT and SUDAS specifications. The specification updating function might ultimately become more centralized, thus freeing up resources at the city and county level to help maintain the system.

Additionally, it will help Iowa transportation agencies in maintaining a cutting-edge presence in information technologies since this may be a new paradigm in which projects will be constructed in the future.

CONCLUSIONS

This study involves integrating both the Iowa DOT and SUDAS design and specifications into one graphical OODAS system. The system can be used by designers and construction personnel involved with transportation projects in Iowa. This would centralize the specification process, thus, saving on resources and provide a visual format for accessing the design standards and specifications. Using a visual interface will also make it easier for designers and contractors to more readily understand project requirements.

However, such a system still has some limitations in terms of time and cost for 3D model development and maintenance. As a research direction in the future, integration between the design of 2D drawings and the creation of 3D models should be developed using more advanced technologies; therefore, the time and cost of 3D model development can be significantly reduced. Also, 3D data acquiring technology such as laser scanning can be used to rapidly create 3D models from existing structures. Furthermore, the visualization provided by the 3D interface within OODAS can be used by immersive virtual reality facilities such as portable cave in the future. Finally, the OODAS system may be customized into a project specific system.

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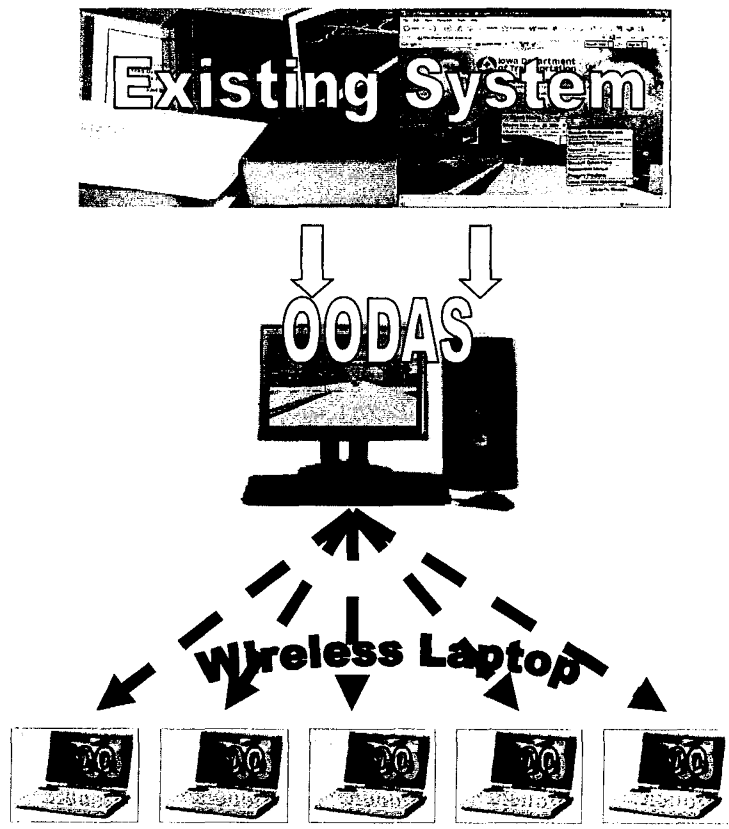

Figure 5-1 Vision of object-oriented design and specification study

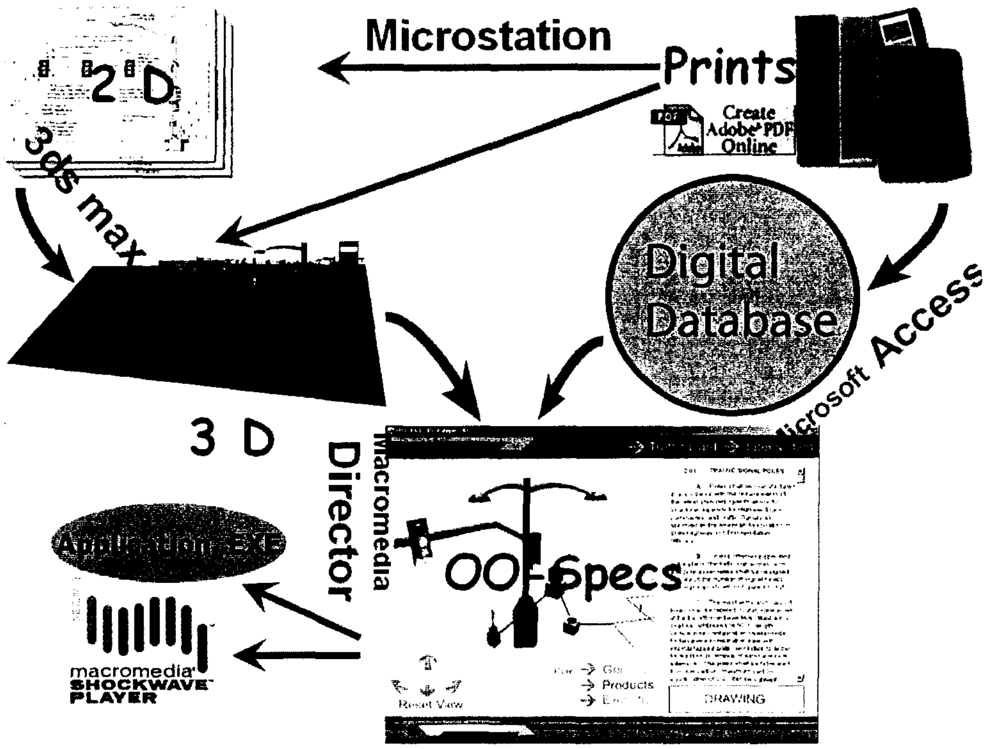

Figure 5-2 Software selection

Figure 5-3 Lincoln Way and Grand Avenue intersection, Ames, Iowa

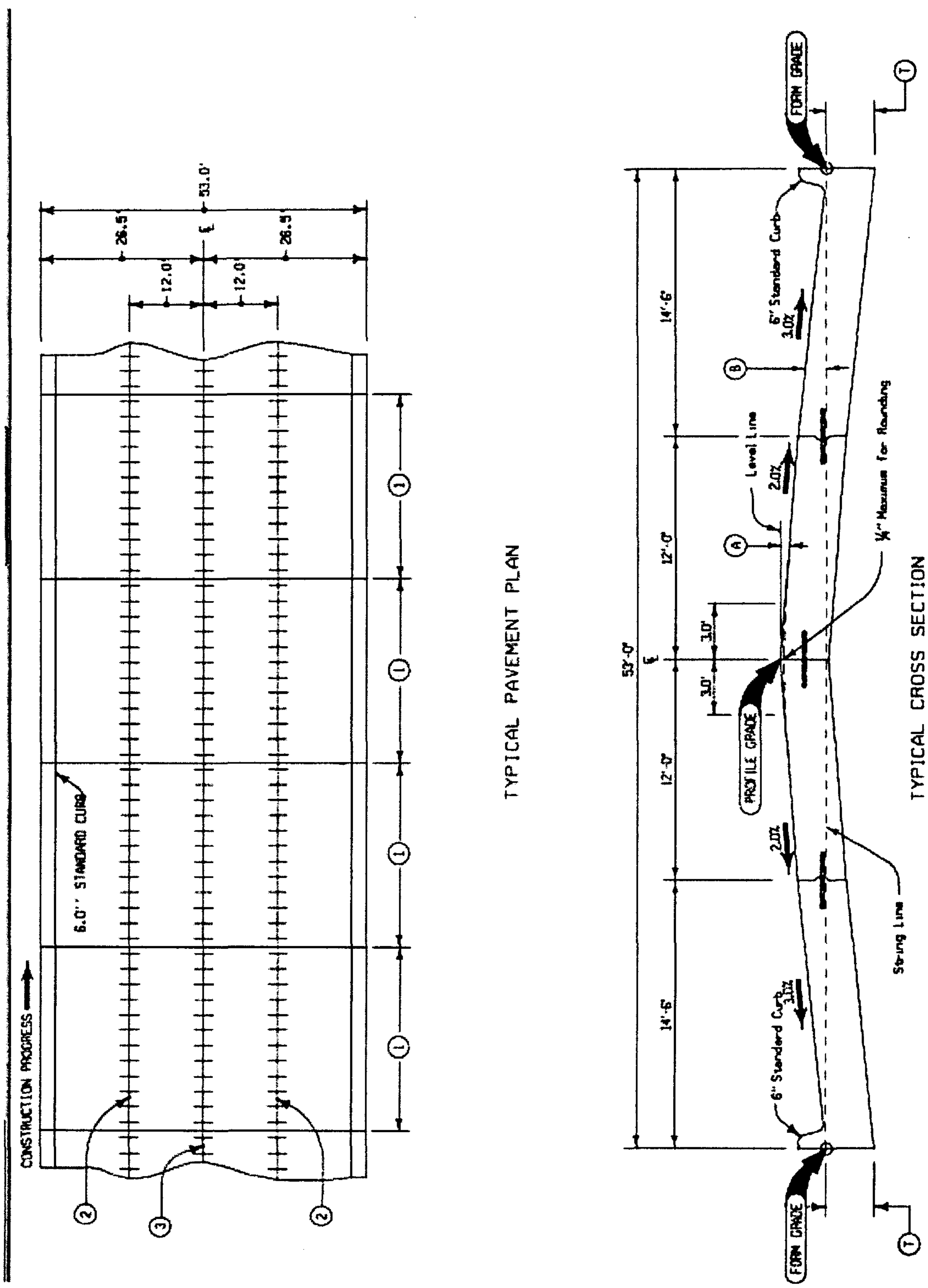

Figure 5-4 Portion of pavement plan from Iowa DOT standard drawing RH47b

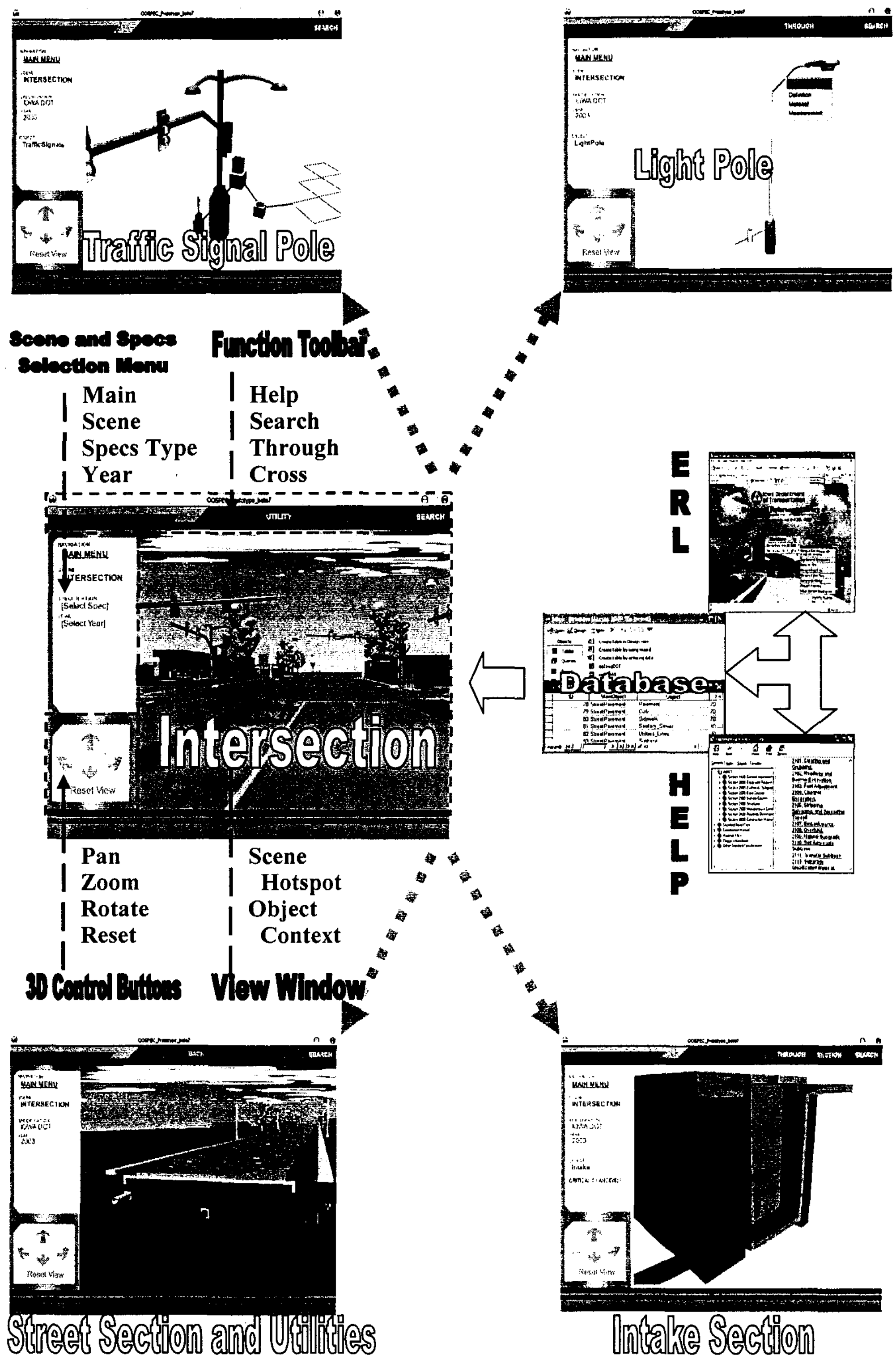

Figure 5-5 Overview of case study prototype

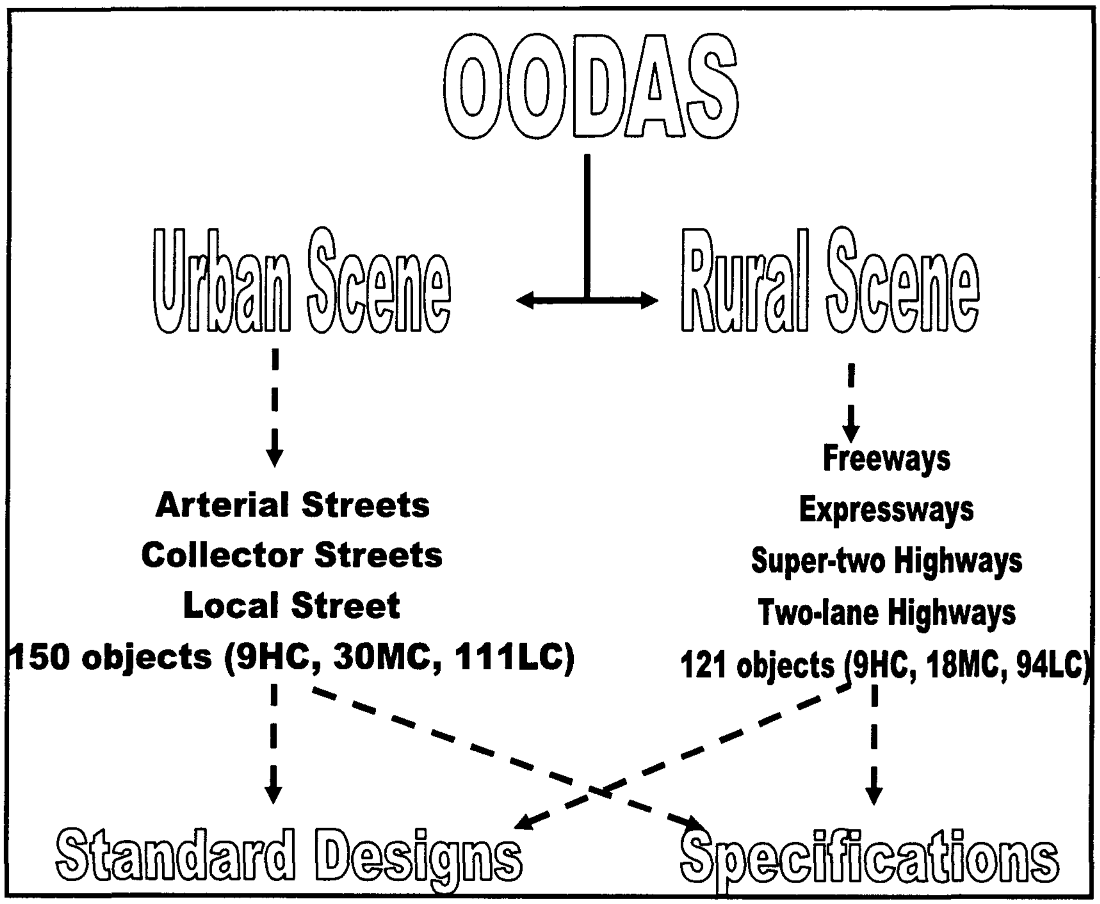

Figure 5-6 OODAS overall structure

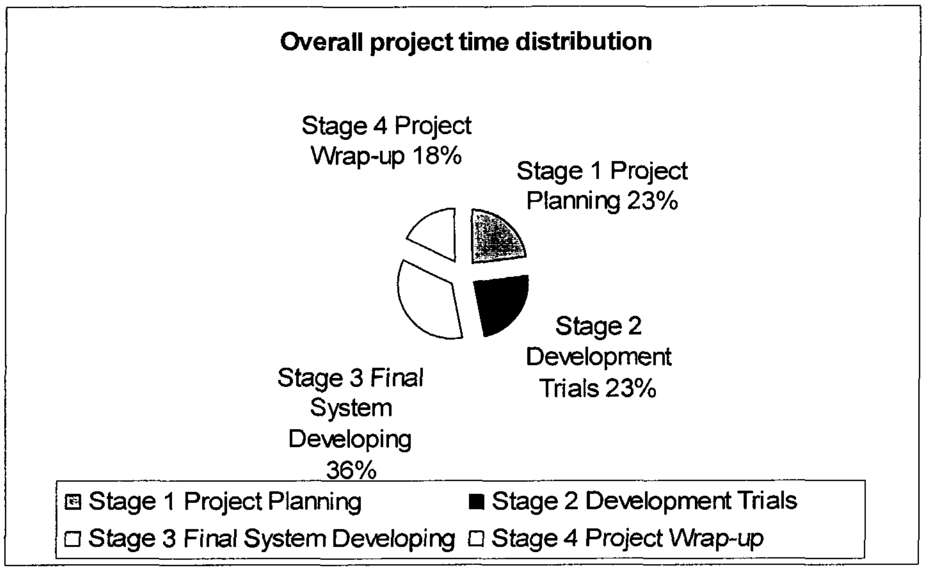

Figure 5-7 Overall project time distribution

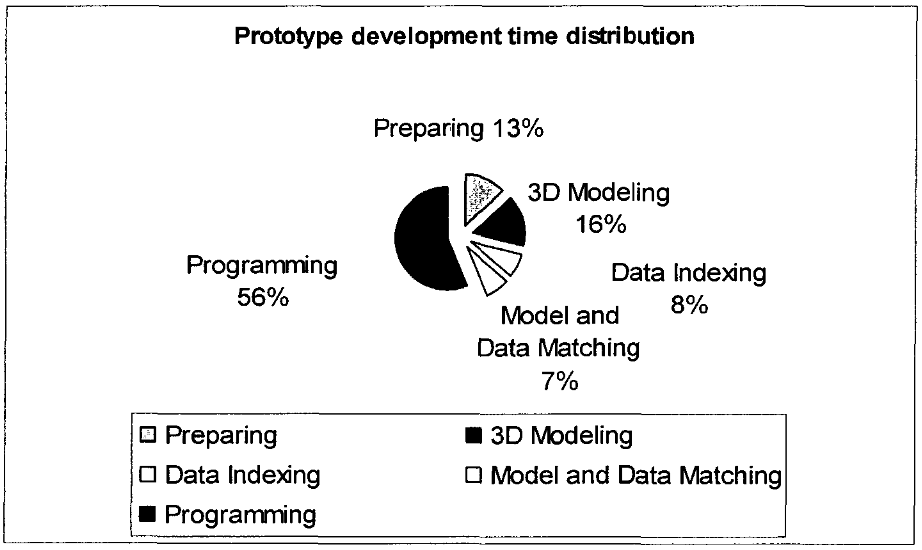

Figure 5-8 Prototype development time distribution

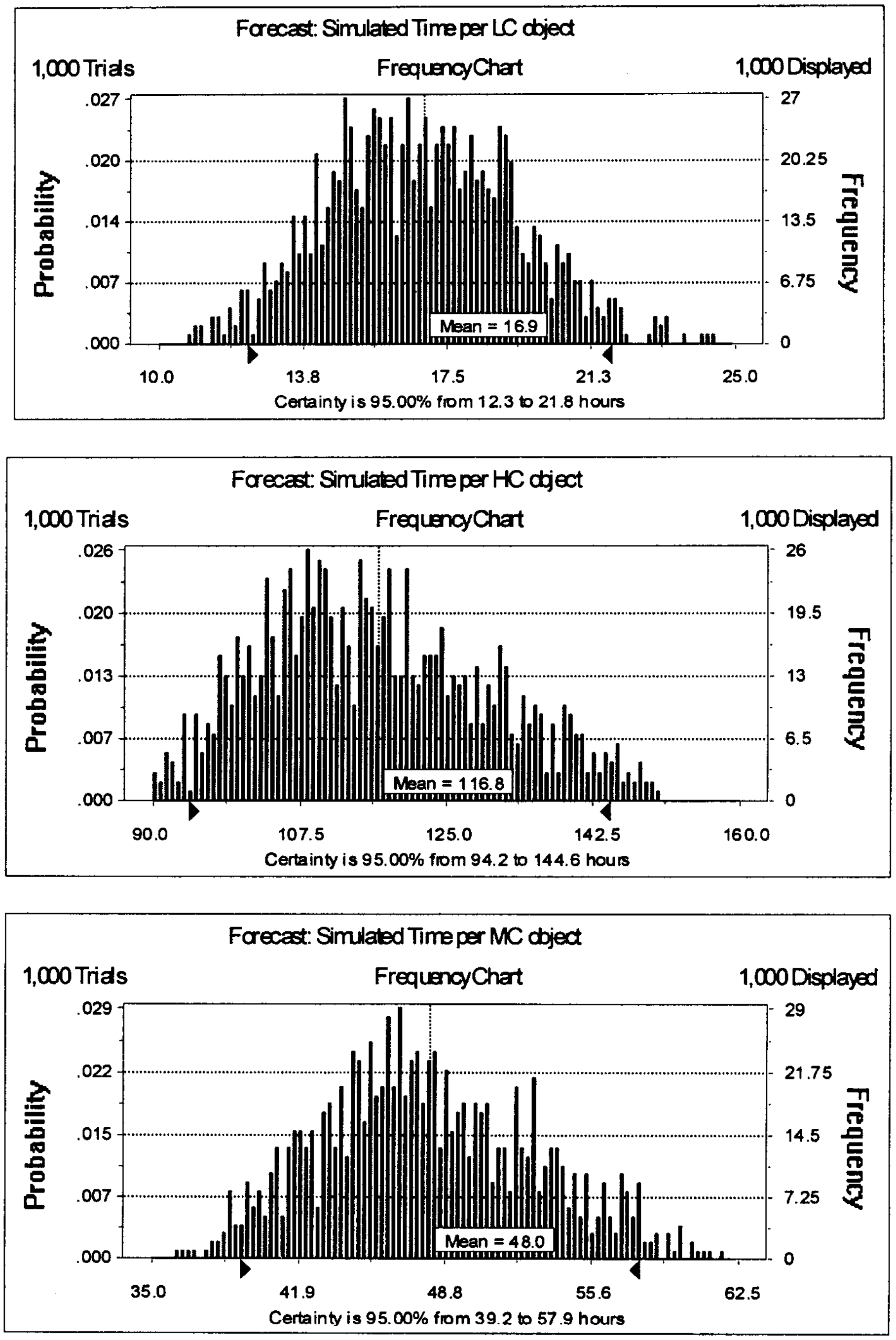

Figure 5-9 Crystal Ball simulated time range to develop an object of full system

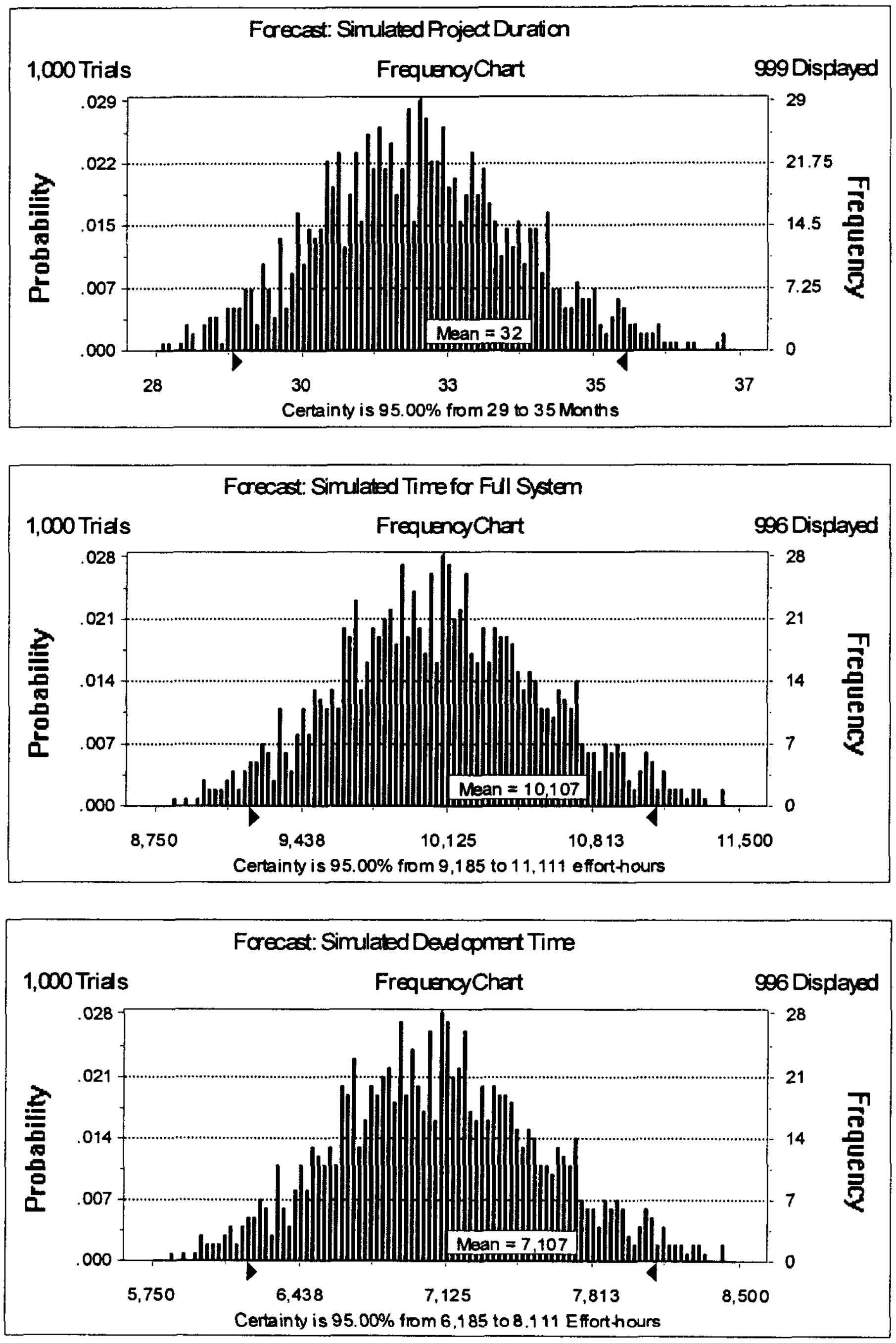

Figure 5-10 Crystal Ball simulated development time and project duration of full system

Table 5-1 Case objects and related design and specification information

Objects		Description		Materials		Methods		Drawings
Main (1)	Sub-Objects (2)	DOT (3)	SUDAS (4)	DOT (5)	SUDAS (6)	DOT (7)	SUDAS (8)	DOT (11)
Light Pole	Pole	2523.06		4185.02		2523.22		rm31
	Luminaries	2523.07		4185.03				rm31
	Conduit	2523.10		4185.10				rm34a
	Hand hole	2523.11		4185.08		2523.22		rm42
	Base	2523.05		4185.02				rm43
	Footing	2523.03		4101.01				rm39
	Cage	2523.03		4101.01				rm39
	Bolt	2523.15		4185.02				rm39
Drive Way	Sidewalk							
	Driveway							
	Curb	2301.17						
	Pavement	2301.01		4115.01				
Traffic Signals	Signal Head	2525.05		2525.01				
	Loop Detector	2525.04		2525.01				
	Pole	2525.06		2525.01				
	Push Button	2525.05		2525.01				
	Footing	2525.06		4101.01				
	Conduit	2525.02		2525.01				
	Cabinet	2525.03		2525.01				
Intake	Concrete Fillet		6030.1	4149.04	6030.2.01		6030.2.01	ra40
	Insert		6030.1	4149.04				ra40
	Access Cover		6030.1	4149.05				ra54
	Storm Sewer	2503.01	4020.1.02	4149.03	40202.01	2503.04	4020.2.01	ra50
	Backfill		3010		3010		3010	
	Frame		6030		6030		6030	
	Pavement							
Street	Pavement	2301.01	7010.1.02	4115.02	7010.2.02		7010.2.02	rh47b
	Curb	2512.01	7010.1.07	4101.01				
	Sidewalk	2511.01	7030.1.02	2511.02	7030.2.02		7030.2.02	
	Sanitary Sewer	2503.01	4010.1.02	4149.03	4010.2.01	2523.04	4010.2.01	
	Utilities Lines	1104.11	2010.1.06					
	Subbase	2110.01	2010.1.02	4122.02	2010.2.04		2010.2.04	
	Joint - Sealant	2542.01		4136.02	7010.2.02		7010.2.02	rh50
	Dirt	2102.01	2010.1.02	2102.04	2010.2.04		2010.2.04	
	Storm Sewer	2503.01	4020.1.02	4149.03	4020.2.01		4020.2.01	ra51

Table 5-2 Overall time spent on the project of case study

Project Stage (1)	(2)	(3)	Weeks (4)	Effort-hours (5)
Stage 1 Project Planning January - April 2003			17	816
Stage 2 Development Trials May - August 2003			17	816
Stage 3 Final System Development September - February 2004			26	1248
Preparation				158
3D Modeling	Sub-object	Polygons		200
Street Curb Curb Ramp Lane Marking Subbase Subgrade Pavement Median	7	6,390		80
Commercial Boxes	1	1,034		24
Traffic Signal Pole	9	1,530		24
Light Pole	5	1,536		18
Intake	9	461		30
Traffic Signs Stop Sign Speed Limit Sign Keep Right Sign	3	36		6
Utilities	5	3,252		18
Data Indexing				100
Model and Data Matching				90
Programming				700
Stage 4 Project Wrap-up March - May 2004			13	624
Total (17 months)			73	3504

Notes:

[1]Based on an assumption of 48 effort-hours per week (2 students at 20 hours/week and 2 faculties at 4 hours/week).

[2]Project planning time defines the time spent on getting ready for technical development to start, which includes the time for search related literature, determining methodology, selecting hardware and software, and define system feature requirements.

[3]Wrap-up time defines the time spent on reporting finding, developing future plan, and evaluating the research direction.

Table 5-2 (continued)

[4]System development time defines the time spent on technically developing the system, which includes time of preparing, 3D modeling, data indexing time, model and data matching, and programming.

[5]Preparation time includes time for reading and analyzing the design standards and specification, determining the objects with related drawings and specifications, and studying the required software.

[6]3D modeling time includes time for creating geometrics, assigning textures, and creating W3D files.

[7]Data indexing time includes time for clarifying or reorganizing (if necessary) the data files in existing ERL, creating an index, and establishing the database.

[8]Model and data matching time includes time for establishing relationships between 3D objects and data objects.

[9]Programming time includes writing required Lingo, C++, and html codes and creating a search function

Table 5-3 Time assumption for full system development based on case study

System Developing Activities		Developing Time (hours)			Suggested Simulation
		O	M	P	
(1)	(2)	(3)	(4)	(5)	(6)
Preparing		*6.4*	*9.5*	*15.0*	
	High Complexity	12.9	[redacted]	24.0	*Triangle*
	Moderate Complexity	3.9	[redacted]	12.0	
	Low Complexity	2.4	[redacted]	9.0	
3D modeling		*29.0*	*38.7*	*59.0*	
	High Complexity	60.0	[redacted]	120.0	*Triangle*
	Moderate Complexity	24.0	[redacted]	45.0	
	Low Complexity	3.0	[redacted]	12.0	
Data Indexing		*1.9*	*3.3*	*5.9*	
	High Complexity	2.4	[redacted]	7.5	*Triangle*
	Moderate Complexity	1.8	[redacted]	6.0	
	Low Complexity	1.5	[redacted]	4.2	
Model and Data Matching		*1.7*	*4.0*	*7.0*	
	High Complexity	3.0	[redacted]	12.0	*Triangle*
	Moderate Complexity	1.5	[redacted]	6.0	
	Low Complexity	0.6	[redacted]	3.0	
	Point Estimated	*39.0*	*55.5*	*86.9*	
	Time Per High Complexity Object	78.3	108.5	163.5	
	Time Per Moderate Complexity Object	31.2	43.5	69.0	
	Time Per Low Complexity Object	7.5	14.4	28.2	
	Crystal Simulation	Min	Mean	Max	
	Time Per High Complexity Object	95	117	145	*108.5*
	Time Per Moderate Complexity Object	40	48	58	*43.5*
	Time Per Low Complexity Object	13	17	22	*14.4*

Estimate Scenes in Full System		Typical Objects			Time
(7) (8)			(9)		(10)
Rural Objects Scene	Numbers	Min	Mean	Max	
High Complexity	9	848	1051	1302	977
Moderate Complexity	18	705	864	1043	783
Low Complexity	94	1156	1587	2047	1354
Subtotal	121	2979	3503	4079	3113
Urban Objects Scene					
High Complexity	9	848	1051	1302	977
Moderate Complexity	30	1175	1440	1738	1305
Low Complexity	38	467	642	828	547
Subtotal	*77 (of 150)*	2736	3133	3586	2829
	Programming				[redacted]
Development Time (effort-hours)		6185	7107	8111	6442
Extra Reporting Time (effort-hours)		1500	1500	1500	1500
Distribution and Maintenance (man hours)		1500	1500	1500	1500
Total Project Time (effort-hours)		9185	10107	11111	

Table 5-4 Estimated cost of OODAS full system development

Items (1)	Academic Price ($) (2)			Professional Price ($) (3)
Software Purchase	2,059			14,815
3ds Max	700			3,495
Macromedia Director MX	454			1,199
Microsoft Access Professional	0			229
SVG Maker	0			50
Adobe Acrobat	70			449
Adobe Photoshop	138			649
Bentley Microstation	400			4,450
AutoDesk AutoCAD	75			3,395
Macromedia 3D Studio	223			899
Hardware Purchase	4,759			4,759
Computer, Dual Monitors	3,381			3,381
Backup Drive	171			171
Laser Printer HP2300	630			630
Scanner HP5550C	251			251
Print Cartridges	207			207
Power Strips	66			66
Network Cable	18			18
Network Hub (Switch)	29			29
USB Cable	6			6
Design and Specification Standards	300			300
Subtotal of Facilities Cost	**7,119**			**19,874**
	Min	**Mean**	**Max**	
Salaries	193,000	219,000	232,500	
Two Principals	62,500	75,000	75,000	
Three Students	130,500	144,000	157,500	
Payroll Benefits	28,227	32,637	33,960	
Two Principals	15,438	18,525	18,525	
Three Students	12,789	14,112	15,435	
Travel		3,000		
Communication		2,000		
Printing		2,000		
Editorial		4,000		
Supplies		4,000		
Indirect Cost 26%	60,639	68,546	72,400	
Subtotal of Paid to Iowa Sate University	**296,865**	**335,183**	**353,860**	
Total Cost	**303,984**	**342,302**	**360,979**	

CHAPTER 6 – GENERAL CONCLUSION

Problems exist with using the current 2D drawings and specifications as well as the current standard way of gathering construction data. This study examined these problems and researches possible solutions. Various technologies (colored drawings, 3D laser scanning and 3D object-oriented design) can improve the drawings and specifications and to visualize the construction process. Although limitations still exist, the study results show that the new technologies can solve the two major concerns for the design and construction industry: (1) poor readability and inconsistency of drawings and specification, and (2) communication inefficiency in data access and acquisition.

There are several methods that can reasonably improve drawing quality and construction project communication. Colored drawings and improved design details are two improvements that could significantly reduce errors, maintain consistency, and improve overall drawing quality. However, there are more advanced technologies that may do a better job at improving quality of communication. 3D drawing will definitely help construction engineers overcome the challenging aspects of current drawings. With 3D drawings, the specification data can be accessed in an object-oriented way with the help of existing data management system. Laser scanning appears to be best suited for projects with a significant amount of construction details that need to be captured in a 3D environment and where 3D drawings need to be developed from existing transportation projects.

The problems specified in the previous chapters often result in less than optimal project cost, quality, and schedule. Thus, investigating solutions to these problems can enhance the design and construction documents, and therefore benefit the overall performance of design and construction. The study results show that it is feasible to visualize the design and construction standards and access the requirements in a more efficient way. Designers, field personnel, contractors, suppliers, and manufacturers can use a single source of data and to design and construct transportation projects.

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APPENDIX A – COLORED DRAWING QUESTIONNAIRE

Color Plan/Drawing Survey

RESPONDENT INFORMATION

Respondent's Name: ______________________ Title: ______________________

Telephone: ________________ Fax: ______________ E-mail: ________________

Organization Name:

____

Address:

____

____

GENERAL QUESTIONS

1. Your organization is primarily operating as a (please check one):

   Designer (e.g., DOT) ___ Contractor ___ Design-Build Contractor ___

   Other (Please specify)____

2. What kind of projects has your organization designed and/or built or renovated within the past year? (Please check all that apply)

   Highways ___ Bridges ___ Airports ___ Marine and Port Facilities ___

   Buildings ___ Mass Transit / Light Rail ___ Other(s) (Please specify)___________

3. Do you feel that the quality of the drawings used today to build projects could be improved? Yes ___ No ___

4. If the answer to question 3 is Yes, please explain how they can be improved to make the greatest impact.

QUESTIONS RELATED TO USE OF COLOR DRAWINGS

5. Do you have experience providing or using color drawings? Yes ___ No ___
   a. If yes, when did you start to use color drawings (provide approximate date)?

      ____

   b. If no, do you think they might be helpful? Yes ___ No ___ (Please go to Question 14)

6. Are you currently using color drawings? Yes ___ No ___
7. Approximately what percentages of your projects are using color to highlight certain features? ____________
8. Please check all of the types of projects for which you are currently using color drawings.
   Highways ___ Bridges ___ Airports ___ Marine and Port Facilities ___
   Buildings ___ Mass Transit / Light Rail ___ Other (Specify) ____________

9. Do you think color, generally, is important in improving the efficiency of drawings (1 = not important, 10 = very important)? __________
10. What were the reasons for using color drawings instead of conventional blue line or black and white drawings? (Please check all that apply).
    ___ Client/Partner requirement
    ___ Marketing challenges
    ___ Self-Motivation
    ___ Availability of high technology
    ___ Deficiency of the current drawings
    ___ Projects quality needs
    ___ Projects schedule needs
    ___ Other (Specify) ____

    ____

11. Based on your experience using color drawings, what, if any, are challenges to using this approach?

12. Do you have a set of color standards for elements of the drawings? Yes ___ No ___

    a. If yes, please briefly describe your major considerations and concerns of color standards. Please provide us a copy of your color standards and a sample color plan/drawing.

    b. If no, how are the colors used determined?

13. Please check the area(s) of a project that benefit from using color drawings.

    Quality ___ Cost ___ Schedule ___ Communication ___ other(s) (please specify)

    ____

    ____

    Please elaborate on any of the above or other benefits from using color drawings.

OTHER APPROACHES TO IMPROVE THE DRAWINGS

14. Besides the use of color, are there other approaches that you use to improve the quality and readability of the drawings (e.g., improving drawing layout)?

15. Do you have any other ideas (not currently implemented) that you feel might improve the drawing quality?

16. If you have written information on any of the approaches, please provide a copy for us. Please list the titles here and provide any necessary information that you have not included in the previous responses.

    a. ____

    b. ____

    c. ____

APPENDIX B – LASER SCANNING ANALYSIS PROCESS

The major procedures of data analysis of laser scanning include database setup, coordinate system, registration, image fitting and editing (data cleaning up), mesh editing, contouring, virtual surveyor, and 2D or 3D drawing (exportation). Not all of the projects needed all of the steps; it really depends on the purpose of analysis of the projects. Sometimes, special steps need to be added to meet the special requirements.

Database Setup

Database setup is a straightforward process that allows one to add a database for each of the pilot projects using a specific .imp file. Figure 0-1 shows an example that is the database of the I-235 project in the Navigator window of Cyclone. It includes all of the Scanworlds scanned in the field. Those data will remain unchanged during analysis of images. However, the outside file (*.imp) keeps updating if there is any modification.

Coordinate System

During scanning, spheres (globes) were introduced into the scene as registration objects and were scanned and surveyed to identify their actual x, y, and z coordinate location. A coordinate file from high quality survey control needs to be imported into the scanworld database before the registration process is begun. This operation happens in the Cyclone navigator window, which is the database manager of the program. Figure 0-2 shows the importing window of Stockpile coordinate file.

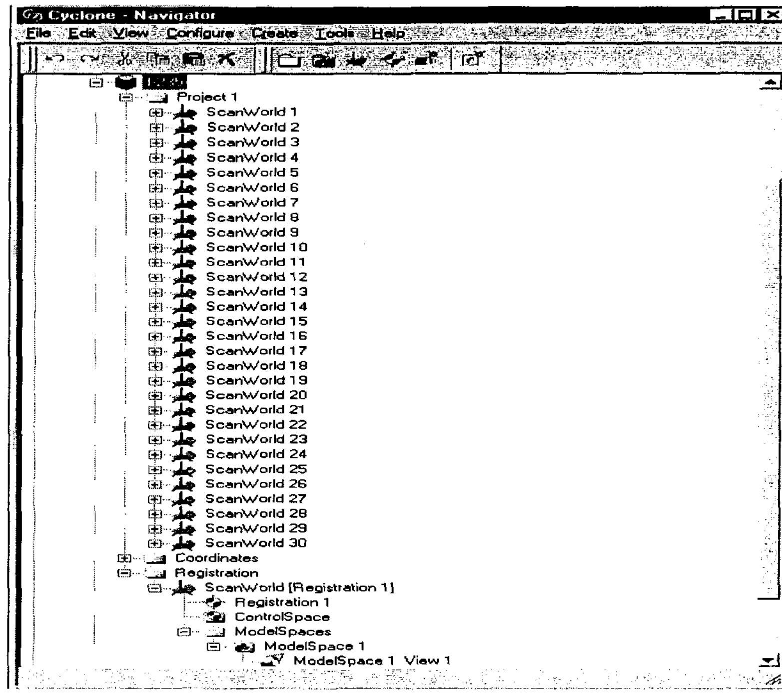

Figure 0-1 Navigator window of I-235 project database

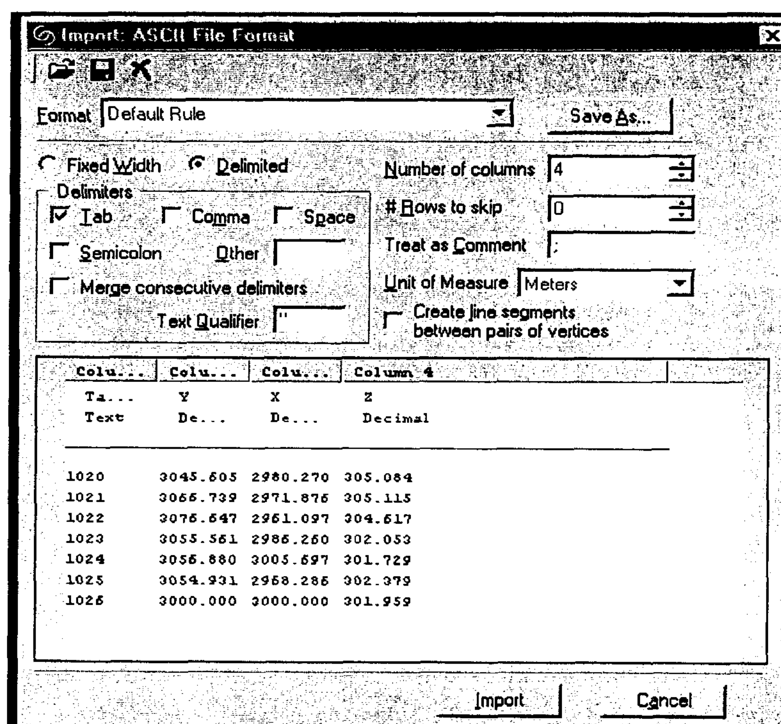

Figure 0-2 Importing coordinate system file of stockpile

In this step, the coordinate unit, three coordinate's values and coordinate file format must be chosen correctly; otherwise, it will result in a bad registration later. Figure 0-3 is one example of a poorly shaped stockpile, caused by coordinate errors (duplicated coordinates and wrong value format). In the figure one can clearly see that one of scanworld images doesn't match with other parts and shows gap between them.

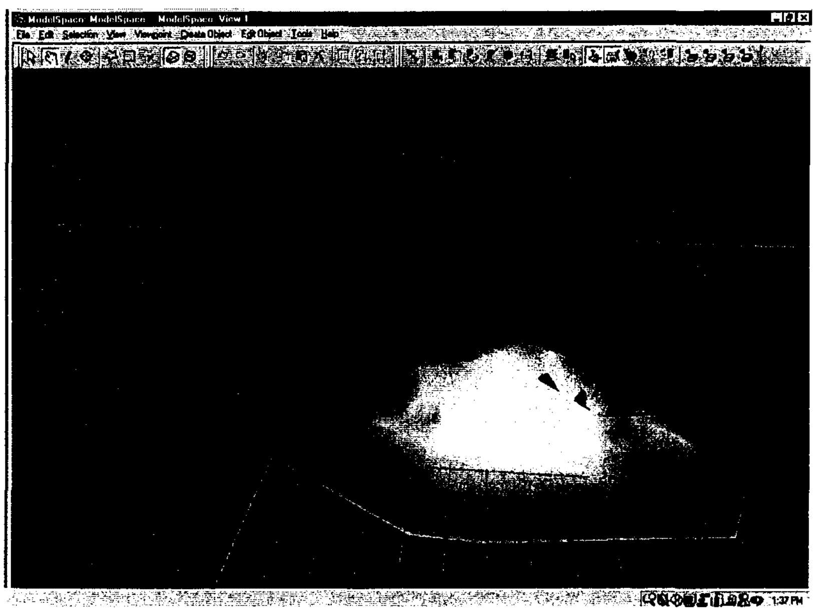

Figure 0-3 Poorly shaped stockpile mesh caused by wrong coordinates

Registration

Registration is an essential step that ties together all the individual scanworlds into a complete image of the scanned object. It is during this stage that errors are identified with the target numbering and coordinates assigned to the targets. Registration actually includes three steps. The first step is the registration of targets (spheres in this project) including the locations and labels (names) of targets, which is done in the field when the targets were acquired. Figure 0-4 shows an example of targets with labels in scanworld. The target in the scanworld should have the same label as the one in the control survey coordinate system.

The second step involves registration of the spheres to the survey data. This can be done by setting up and importing the coordinate system as described above. The third step involves registering all of the scanworlds together to generate the total 3-D image of the scene.

Figure 0-5 illustrates an I-235 registration window. During the final step above, all the errors of the first two steps must be detected and fixed in order to make the scanned data work correctly. Figure 0-6 shows an example of the control space for the I-235 project, which could be used to compare the scanworld control space (to check and fix errors).

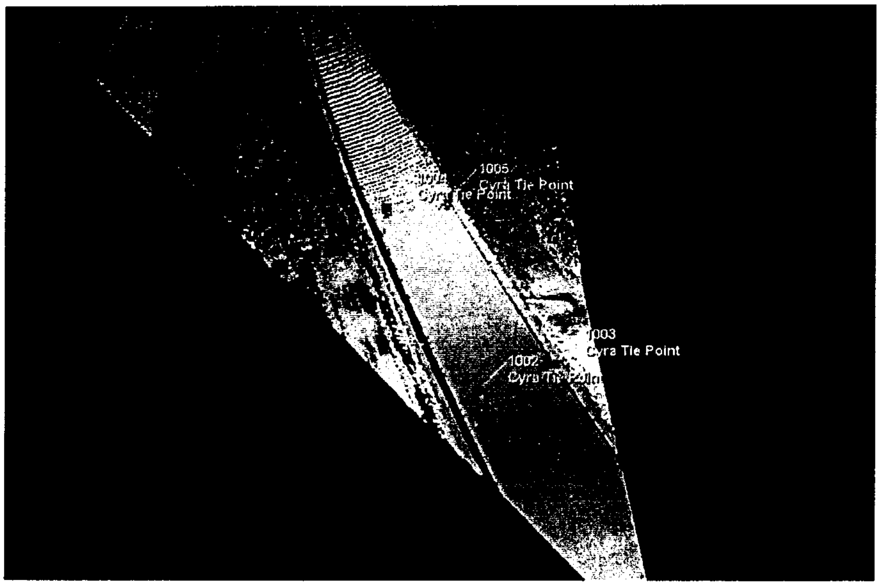

Figure 0-4 Targets with labels in one scanworld

In practice, in order to register the scanworlds correctly and fast, the targets, positions of targets, and even missed targets should be understood first. Without the coordinates, a scanworld to be registered must have common targets with its neighbors. In all cases, one scanworld must have at least three targets so that the registration can be tightened.

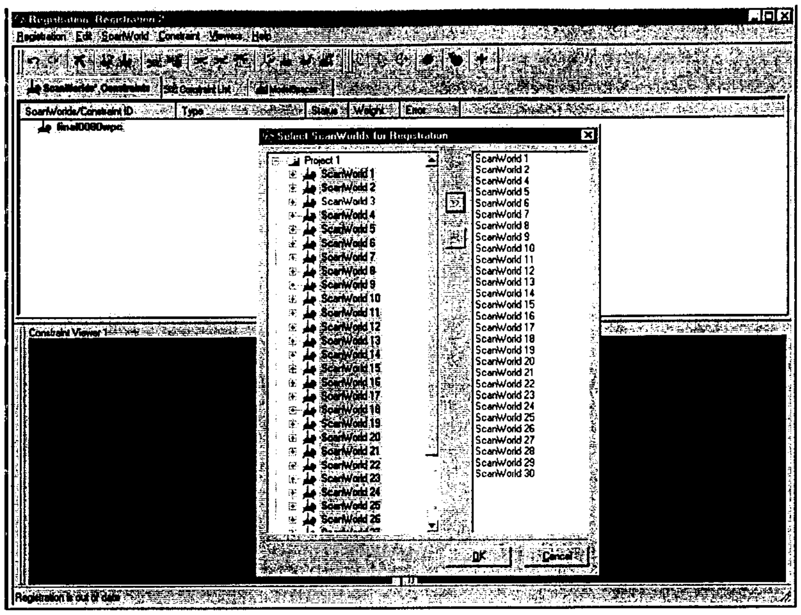

Figure 0-5 Registration window of I-235

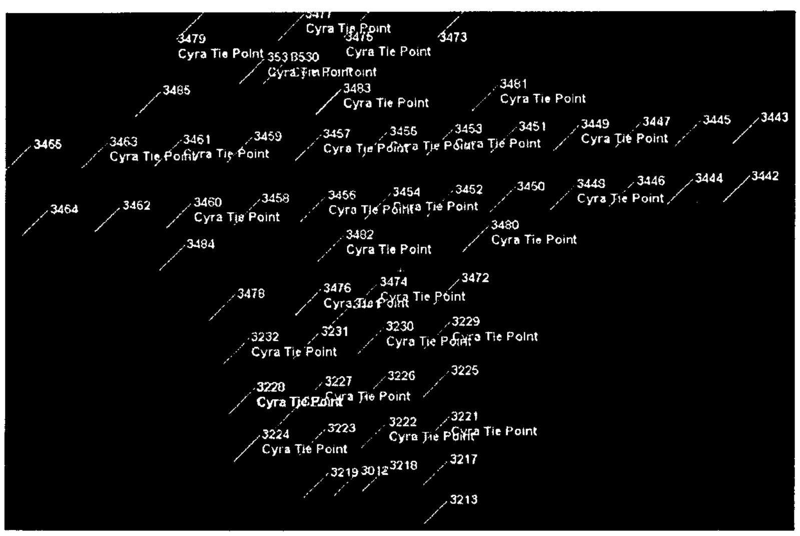

Figure 0-6 Control space of I-235 (Broadway Bridges)

Fitting and Editing

After registration is completed, a model space can be created for the registered scanworlds. However, scanned images may contain some noise that needs to be removed such as vertical lines representing traffic on the I-235 pilot test and grass in the ditches. The scanner even can scan some noise from the sky. Figure 0-7 through 0-9 show different noises in the original point clouds. This noise is not wanted in the final products and needs to be removed. The process of cleaning the noise and modifying the registered images is called fitting and editing.

The Cyclone software provides the capability to remove the superfluous data using segmenting, region growing, and other special editing tools. Segmenting is subdividing a point cloud (scanned image) into smaller subsets and modeling them. Segmenting involves cutting (draw a fence around the portion and cut by segment), fitting patches (deal with different types of objects in an image such as cylinder), and merging (merge the segments back to original point cloud). Region growing is modeling an object to the desired shape within a point cloud without segmenting. Region Growing involves fencing (not cutting) and growing (by it the unnecessary portion could be easily deleted). Figure 0-7 shows the noise that is generated by traffic in a laser scan as depicted by vertical lines. These lines can be easily removed using the region growing tool in the Cyclone software. Figure 0-10 shows a scanworld that is being region grown and Figure 0-11 is the result of region growing. During this process, one object can be merged, translated, resized and rotated in order to edit it optimally. Generally, 90% of the noise of one image can be cleaned by above method. The rest of the cleaning work can be continued in the meshing process.

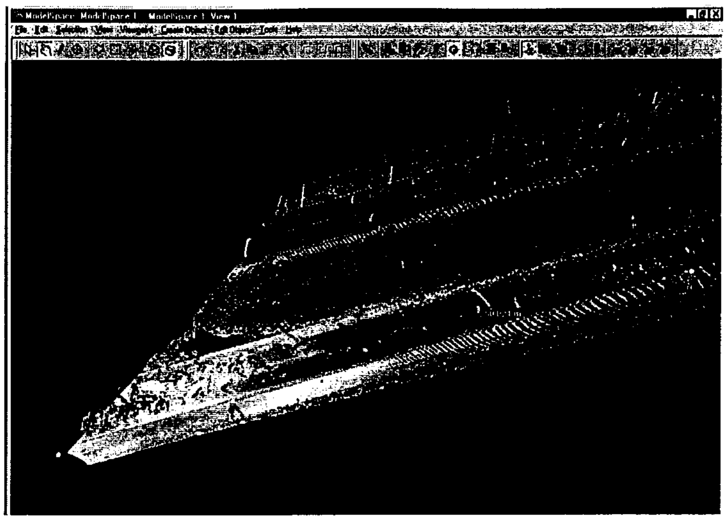

Figure 0-7 Traffic lines in point cloud of I-235 roadway

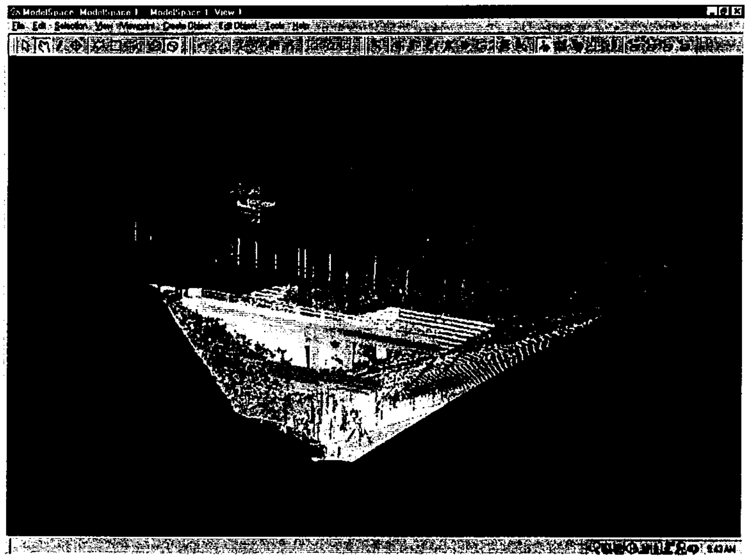

Figure 0-8 Surrounding noise in point cloud of I-235 Broadway Bridge

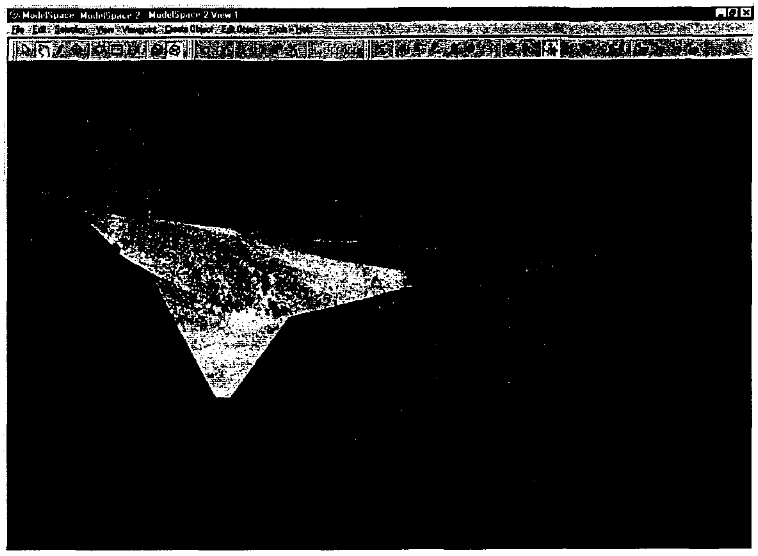

Figure 0-9 Unnecessary points in point cloud of Stockpile

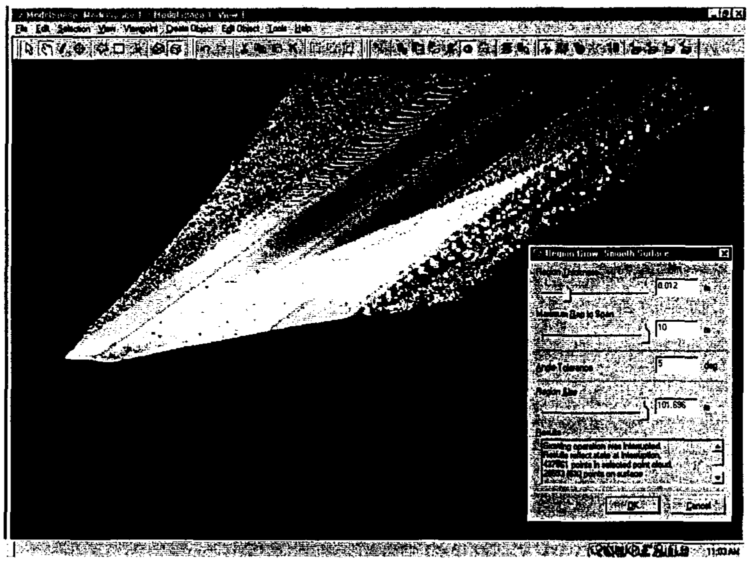

Figure 0-10 Region growing

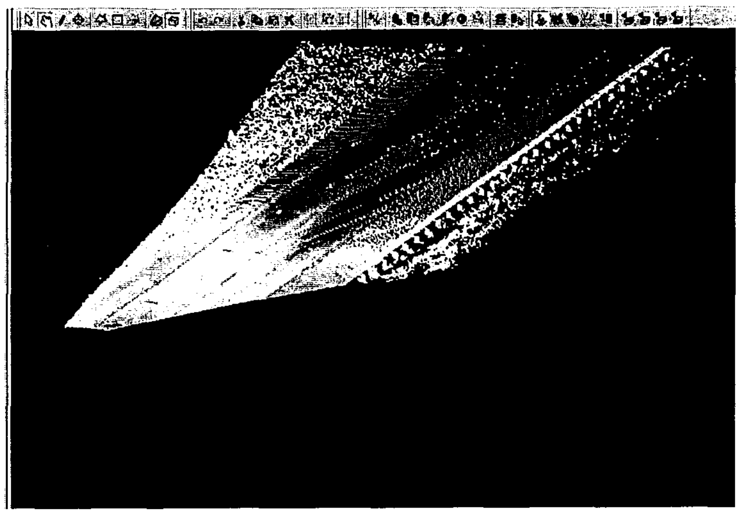

Figure 0-11 Result of region growing

Mesh Editing

To make a cleaned and edited point cloud more manageable in Cyclone or for further use by exporting to other CADD packages such as MicroStation, a mesh must be created on the cloud. There are different mesh styles to consider. In this pilot project, all of meshes are TIN meshes. The process of meshing includes mesh creation (including cloud points reducing), mesh editing (including edge and spikes clean up and break-line setup), and mesh decimation (to make the mesh work well on a specific computer). Figure 0-12 shows results of meshing in full range for the Stockpile project. Figure 0-13 shows a mesh in wire frame format for the I-235 Roadway project. The mesh illustrated in figure 0-14 is complex mesh of the Stockpile project, which gives a much better vision of image.

Figure 0-12 Full Range of Stockpile mesh

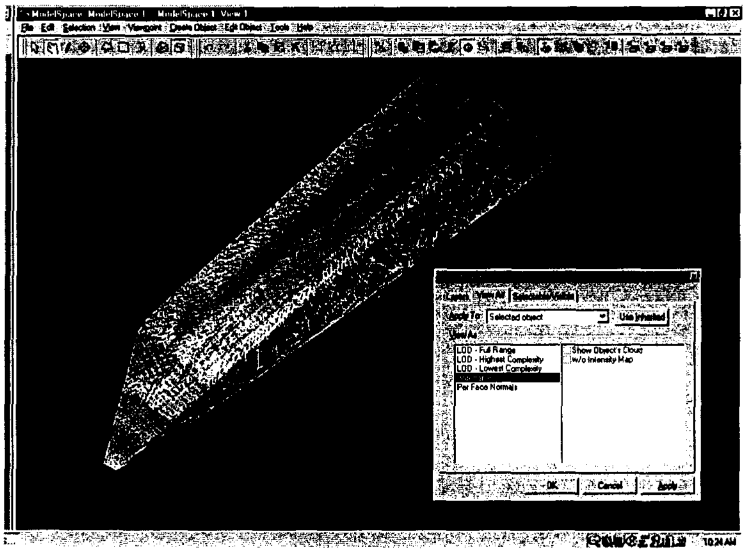

Figure 0-13 Wire Frame Mesh of One Scan of I-235 Roadway

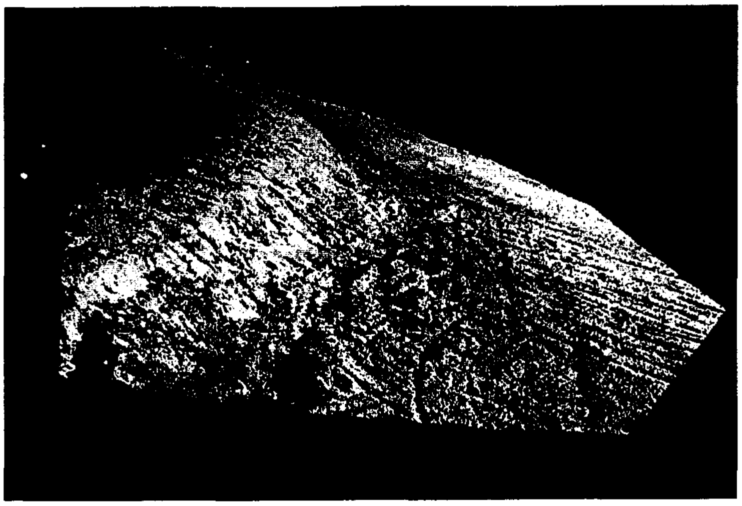

Figure 0-14 Complex mesh of part of Stockpile

Contours and Line Drawings

In order to measure the clouds and meshes and export the object to 2D drawing software packages, contour and line drawings must be created. A reference plane and a cut plane are useful with this process. The reference plane, which is an infinite two-dimensional plane, can be used as a reference for measuring a mesh volume, creating contour lines and orienting the cut plane. The contours can be drawn parallel to the current coordinate system or any other reference plane. The cut plane, which can be set up on either reference plane or objects on the point clouds, can facilitate exporting this data to MicroStation (or AutoCAD) or to draw 2D lines. Figure 0-15 and Figure 0-16 show the contours for the Stockpile project.

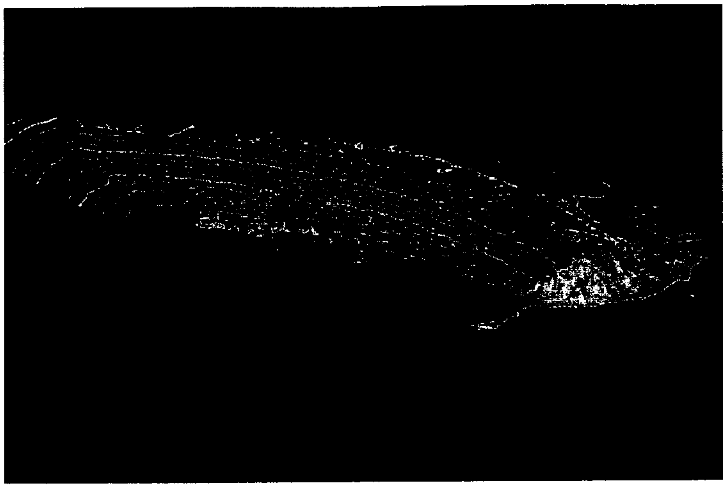

Figure 0-15 Contours with mesh of Stockpile

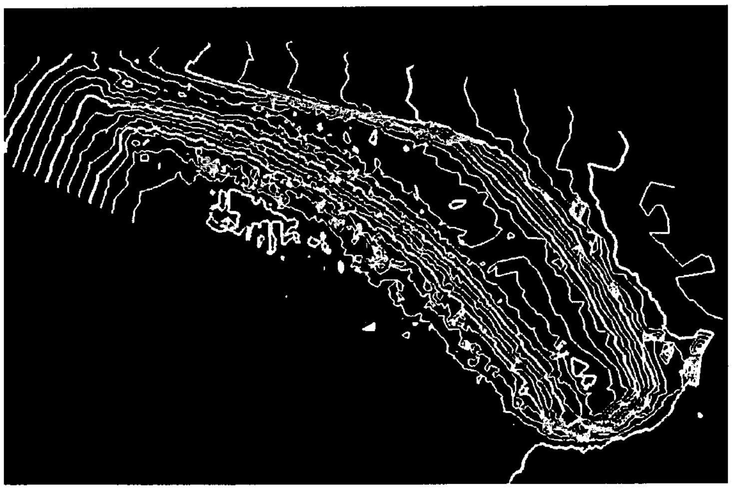

Figure 0-16 Top view of Stockpile contours

Virtual Surveyor

Virtual Surveyor is a useful tool in Cyclone to easily obtain information without physically being at the site. A surveyor can, with scanned data, easily pick coordinates, assign codes and notes, and export data to other applications. It is a separate process; one can do it either with the original image or meshed image. Figure 0-17 and Figure 0-18 show the examples of Virtual Surveyor for the I-235 and Hardin Bridge project, respectively.

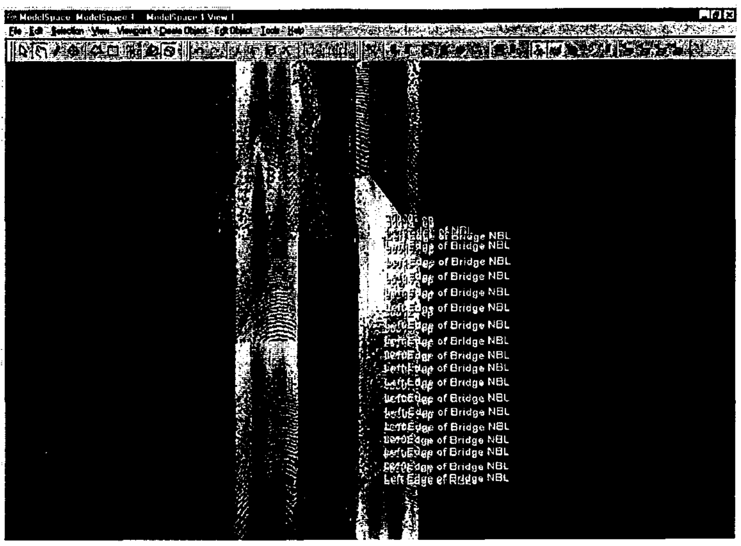

Figure 0-17 Virtual surveyor of I-235 roadway

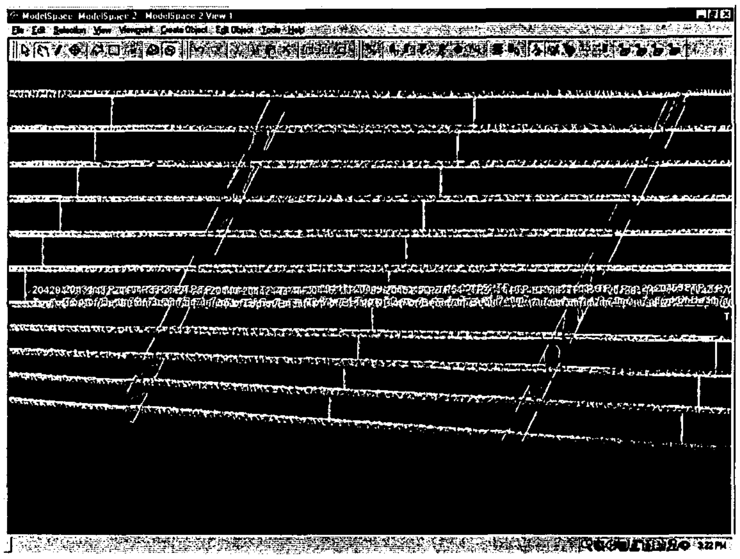

Figure 0-18 Virtual surveyor of Hardin Bridge beam camber

APPENDIX C – TYPICAL OBJECTS IN FULL OODAS SYSTEM

Table 0-1 Rural objects scene

Classification	Objects			Complexity Level		
				High	Moderate	Low
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Freeways/Expressways						
1	Typical four-lane PCC roadway			x		
		Lane Pavement and Shoulders				
			Segments			
			Joints			
			Dowel bars			
		Subbase				
		Subgrade				
		Treated Soil				
		Undisturbed Soil				
2	Subdrain				x	
		Longitudinal subdrain				
		Backslope subdrain				
		Foundation subdrain				
3	Median (depressed, closed)				x	
		Opening				
		Turnaround				
4	Ditches				x	
		Foreslopes				
		Backslopes				
5	Weigh station			x		
6	Rest area			x		
	Interchange					
	7	One-lane ramps and loops		x		
			Interstate system			
			Non-interstate system			
	8	Two-lane lamps		x		
	9	Accesses dikes			x	
	10	Safety dikes			x	
	11	Two-lane highway or country road		x		
	12	Bridge		x		
	Intersection					
	13	Right turn lanes			x	
	14	Left turn lanes			x	
	15	Median storage			x	
	16	Adding			x	
	17	Dropping			x	
	18	Redirecting			x	

Table 0-1 (continued)

Traffic control devices			
Pavement marking			
19 Lane lines			x
20 Edge lines			x
21 Centerlines			x
22 Pavement arrows			x
23 Word messages			x
24 Raised pavement markers			x
25 Delineators			x
Signs			
26 Regulatory signs (15)			x
41 Warning signs (8)			x
49 Guide signs (6)			x
55 Specific services signs (2)			x
57 Directional signs			x
58 Interest area signs			x
59 Emergency signs (3)			x
62 Channelizing devices			x
63 Warning lights			x
64 Floodlights			x
65 Arrow display			x
66 Changeable message			x
Super-two/Two-lane Highways			
67 Typical two-lane HMA roadway	x		
Lane Pavement and Shoulders			
Subbase			
Subgrade			
Treated Soil			
Undisturbed Soil			
68 Subdrain		x	
69 Median (painted)			x
70 Ditches		x	
Foreslopes			
Backslopes			
Intersection			
71 Major right turn lanes		x	
72 Minor right turn lanes		x	
73 Auxiliary left turn lanes		x	
74 Stop-sign islands		x	
75 Railway crossing	x		
76 Rumble strips		x	
Traffic control devices			

Table 0-1 (continued)

		Pavement marking				
		77 Lane lines				x
		78 Edge lines				x
		79 Centerlines				x
		80 Pavement arrows				x
		81 Word messages				x
		82 Raised pavement markers				x
		83 Delineators				x
		Signs				
		84 Regulatory signs (12)				x
		96 Warning signs (7)				x
		103 Guide signs (9)				x
		112 Signs at intersection				x
		113 Directional signs				x
		114 Interest area signs				x
		115 Emergency signs (2)				x
	117	Channelizing devices				x
	118	Warning lights				x
	119	Floodlights				x
	120	Arrow display				x
	121	Changeable message				x
Total	121			9	18	94

Table 0-2 Urban objects scene

Classification	Objects			Complexity Level		
				High	Moderate	Low
(1)	(2)	(3)	(4)	(5)	(6)	(7)
Arterial Streets						
1	Typical four-lane PCC roadway			x		
		Pavement				
			Segments			
			Joints			
			Dowel bars			
		Subbase				
		Subgrade				
		Treated Soil				
		Undisturbed Soil				
		Curb				
2	Subdrain				x	
3	Median (closed)				x	
4	Intake				x	
5	Storm sewer				x	
6	Sanitary sewer				x	
7	Traffic control poles			x		
8	Light poles				x	
9	Water mains				x	
	Interchange					
	10	Ramps and loops		x		
	11	Bridge		x		
	12	Right turn lanes			x	
	13	Left turn lanes			x	
	14	Median storage			x	
	15	Adding			x	
	16	Dropping			x	
	17	Redirecting			x	
	Traffic control devices					
		Pavement marking				
		18	Lane lines			x
		19	Edge lines			x
		20	Centerlines			x
		21	Pavement arrows			x
		22	Word messages			x
		23	Raised pavement markers			x
		24	Delineators			
		Signs				
		25	Regulatory signs (15)			x
		40	Warning signs (8)			x
		48	Guide signs (6)			x
		54	Specific services signs (2)			x

Table 0-2 (continued)

56	Directional signs			x
57	Channelizing devices			x
58	Warning lights			x
59	Arrow display			x
Collector Streets				
60	Typical two-lane HMA roadway	x		
	Pavement			
	Subbase			
	Subgrade			
	Treated Soil			
	Undisturbed Soil			
	Curb			
61	Subdrain		x	
62	Median (painted)		x	
63	Intake		x	
64	Storm sewer		x	
65	Sanitary sewer		x	
66	Traffic control poles	x		
67	Light poles		x	
68	Water mains		x	
	Intersection			
69	Major right turn lanes		x	
70	Minor right turn lanes		x	
71	Auxiliary left turn lanes		x	
	Traffic control devices			
	Pavement marking			
72	Lane lines			x
73	Edge lines			x
74	Centerlines			x
75	Pavement arrows			x
	Signs			
76	Regulatory signs (12)			x
88	Warning signs (7)			x
95	Guide signs (9)			x
104	Signs at intersection (5)			x
Local Streets				
109	Typical two-lane PCC roadway	x		
	Pavement			
	Segments			
	Joints			
	Dowel bars			
	Subbase			

Table 0-2 (continued)

	Subgrade			
	Treated Soil			
	Undisturbed Soil			
	Curb			
110	Typical two-lane HMA roadway	x		
	Pavement			
	Subbase			
	Subgrade			
	Treated Soil			
	Undisturbed Soil			
	Curb			
111	Intake		x	
112	Storm sewer		x	
113	Sanitary sewer		x	
114	Light poles		x	
115	Water mains		x	
	Intersection			
116	Major right turn lanes		x	
117	Minor right turn lanes		x	
118	Auxiliary left turn lanes		x	
119	Traffic control poles	x		
	Traffic control devices			
	Pavement marking			
120	Lane lines			x
121	Pavement arrows			x
122	Centerlines			x
	Signs			
123	Regulatory signs (12)			x
135	Warning signs (7)			x
142	Guide signs (9)			x
Total	150	9	30	111