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Waterways Experiment
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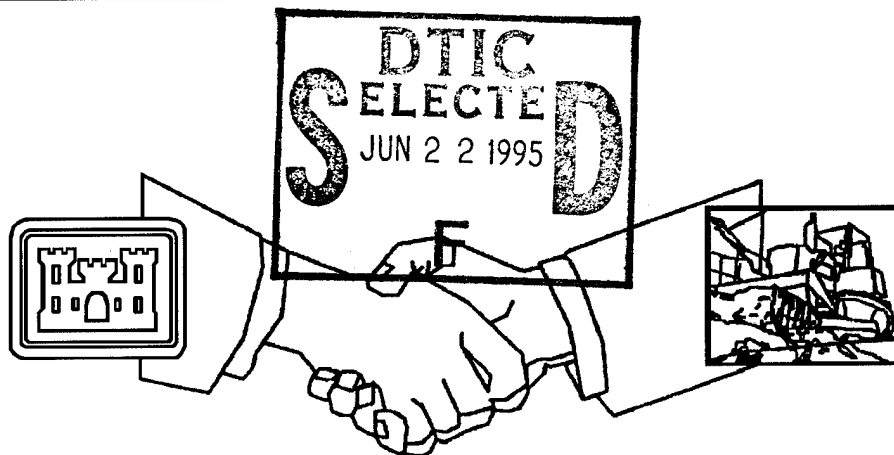
CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Crucial Links for Construction Site Productivity: Real-Time
Construction Layout and As-Built Plans

by

Yvan J. Beliveau, Jerry King, Carl Magnell,
Glen Weathers, J. Michael Williams, Harold L. Smith

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**A Corps/Industry Partnership to Advance
Construction Productivity and Reduce Costs**

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Crucial Links for Construction Site Productivity: Real-Time Construction Layout and As-Built Plans

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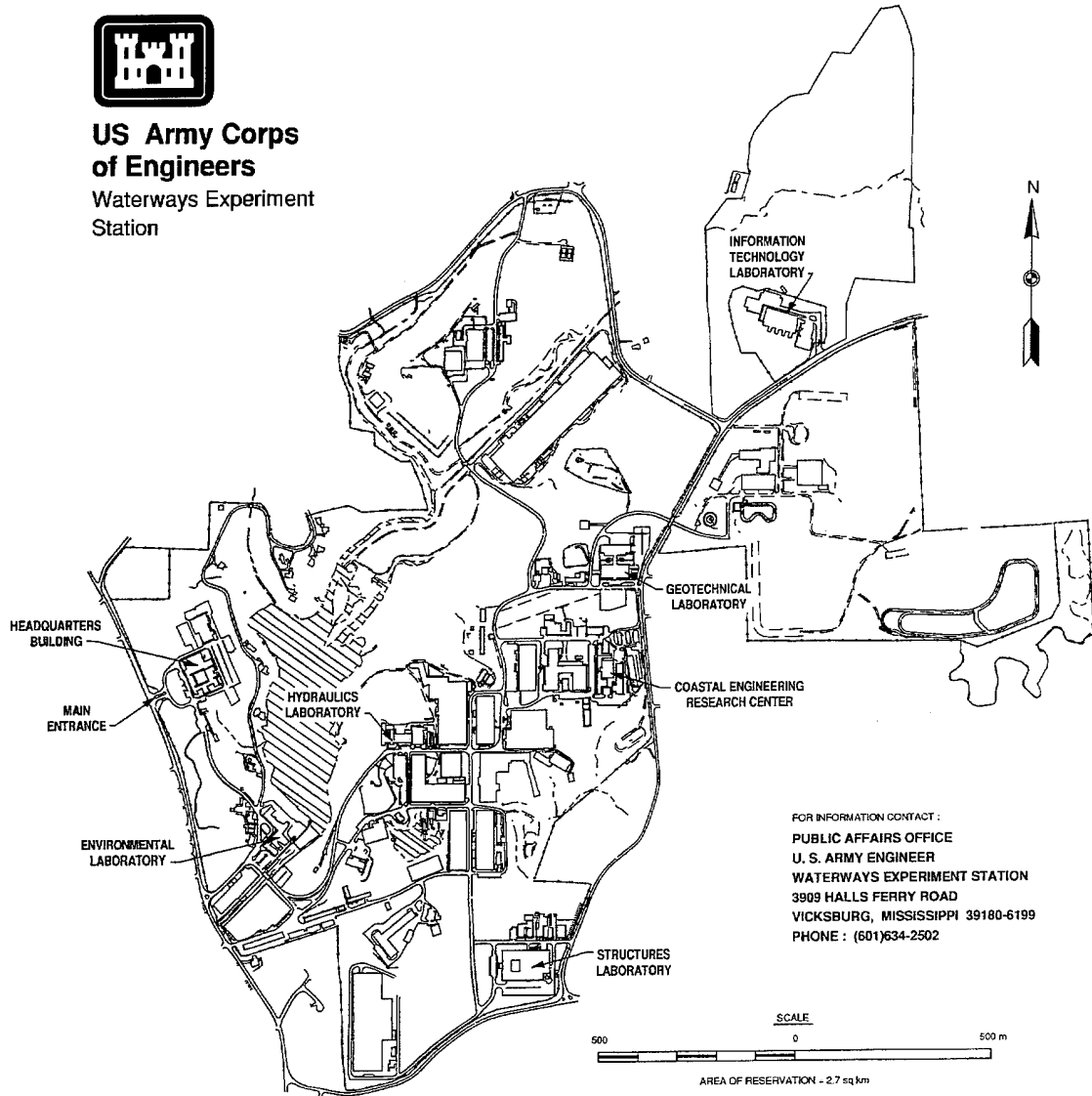
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Contents

Preface	vi
1—Introduction	1
Background	1
Formation of Consortium	2
CPAR/CRDA Proposal and Award	2
Study on Protocols	3
Initial System Test	4
Field Tests/Demonstrations of RtCLADS	5
Evolution of CAPS Terminology: A Necessary Comment	6
2—Validation Tests, Demonstrations, and Test Results	7
Field Tests	7
Total Station Link to CAD	12
Global Positioning Systems Integrated with Intergraph GeoCAD	15
Geodimeter Robotic Total Station Interfaced to Intergraph GeoCAD	23
RtCLADS and GeoCAD	23
RtPM Link to CAD	25
RtPM Link to JSpace™	30
3—Advantages and Limitation	32
Total Stations	32
Global Positioning Systems (GPS)	34
ODYSSEY™	35
Combined Capabilities of RtCLADS	38
Potential Benefits for USACE	39
4—Commercialization and Technology Transfer	45
Commercialization Status	45
Enhancements	47
Technology Transfer	51
5—Conclusions and Recommendations	52

References	54
Bibliography	55
Appendix A: Contributors	A1
Appendix B: Computer-Aided-Design (CAD) Communication Protocol Overview	B1
Appendix C: Real-Time Position Measurement Integrated with CAD: A Survey of Technology and Protocols	C1
Appendix D: Real-Time Positioning Technology: Development and Application	D1
Appendix E: SPSi ODYSSEY™ Position Measurement System Product Specifications	E1
Appendix F: Consortium for Advanced Positioning Systems (CAPS) Field Demonstrations	F1
Appendix G: Jacobus Technology, Inc., Product Specifications	G1
Appendix H: A Real-Time Laser-Based System for Collecting Construction Site Positioning Data	H1
Appendix I: Collaborative Applied Research: An R&D Case Study of the Development of a New Site Positioning Technology	I1
Appendix J: Real-Time Positioning Applications for Retrofit Projects	J1
Appendix K: Notation	K1
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List of Figures

Figure 1. CAPS participants	3
Figure 2. RtCLADS architecture	4
Figure 3. CAPS representatives at Blacksburg, August 1994	8
Figure 4. Schematic of RtPM system	8
Figure 5. CAPS representatives with RtPM system	9
Figure 6. Manchester Street Station Power Plant	10
Figure 7. Collecting field data at Manchester	10
Figure 8. Indoor workstation	11
Figure 9. Nikon DTM-750 total station	12
Figure 10. Plan view of Tinker test site	14

Figure 11. Microstation design file data plot	17
Figure 12. MDL-generated panels	18
Figure 13. Scatter diagram	19
Figure 14. GeoCAD panel	20
Figure 15. Terrain modeling	21
Figure 16. Triangle network plan view	22
Figure 17. Tinker groundwater pipeline	24
Figure 18. Geodimeter real-time tracking	25
Figure 19. GPC hardware	26
Figure 20. FPS receiver, mounted	26
Figure 21. Outdoor work area RtPM data	27
Figure 22. Plating shop RtPM as-built components	28
Figure 23. Merged data from total station, GPS, and RtPM	30

Preface

This report documents the results of a 2-year research and development effort under the Construction Productivity Advancement Research (CPAR) Program, U.S. Army Corps of Engineers (USACE). It was prepared by the Consortium for Advanced Positioning Systems (CAPS) for the Civil Engineering Research Foundation (CERF), the research affiliate of the American Society of Civil Engineers (ASCE). The USACE Technical Monitors were Messrs. B. Bergen, G. Hughes, and W. Norko. Mr. William F. McCleese, U.S. Army Engineer Waterways Experiment Station (WES), was the WES point of contact. Mr. Harold L. Smith was the WES principal investigator.

The report details an extraordinary “odyssey” wherein the common motivation to bring innovation to the construction site enabled the collective expertise, insights, and capabilities of industry, academia, and the public sector to merge in an effort that could not have been accomplished in the same time or with the same resources by any of these sectors acting alone. As such, CAPS and its partner, USACE, have demonstrated a process that, if broadly implemented in appropriate applications, augers well for the continued introduction of needed innovation into the construction sector. It represents an opportunity that the construction sector can ill afford to ignore. The productive relationship between CAPS members and USACE representatives is especially noteworthy.

Messrs. Yvan Beliveau, Spatial Positioning Systems, Inc.; Jerry King, Jacobus Technology, Inc.; Carl Magnell, CERF; Glen Weathers, Intergraph, Corp.; Mike Williams, Bechtel, Corp.; and Harold Smith, WES, are the principal authors of this report. They have been assisted by the critical review, supervision, and suggestions provided by the management of CERF and WES.

WES personnel involved in the study included Messrs. Sandy Stephens and Harold Smith, Tri-Service CADD/GIS Technology Center, Information Technology Laboratory (ITL), WES, and Dr. N. Radhakrishnan, Director, ITL. Mr. Thomas Logsdon of the USACE Tulsa District's Tinker Air Force Base office provided support and assistance.

At the time of the publication of this report, Dr. Robert W. Whalin was Director of WES. Commander was COL Bruce K. Howard, EN.

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1 Introduction

Background

Technology has cut a wide swatch across American industry in these latter decades of the 20th Century. In many sectors, continuous innovation determines industry survivors. Advances in productivity have been measured not in single-digit percentages but in many-fold gains. Computers are perhaps the outstanding example. In the construction sector, the impact of technology has made itself felt in many applications, but gains in productivity have proven elusive. Many reasons are posited for this, among them lack of adequate research and development, lack of recognized research priorities, and significant institutional barriers. Inadequate research and development has been widely documented, most recently in 1993, when construction industry research and development was estimated at 0.5 percent of industry annual volume, or a mere one-seventh of the average for industries in the United States. The issue of priorities was addressed in 1991 by the Civil Engineering Research Foundation (CERF¹); a significant priority emerging from this national forum was the need for improved automation on the construction site. Finally, barriers continue as pervasive challenges, especially to individual organizations seeking to introduce innovation. These factors underlie and influence the process and the technology that is the focus of this report.

Unlike many facets of construction, surveying has benefitted from advances in electronics. Today's surveying tools, such as theodolites and electronic levels, have improved accuracy and power and thus, productivity. Even so, they are not as yet capable of real-time data gathering. Moreover, even the most sophisticated surveying technologies have not been linked in real-time to one of the most powerful tools in the construction industry's "tool kit": three-dimensional computer-aided design (3D-CAD).

¹ For convenience, symbols and abbreviations are listed in the notation (Appendix K).

The belief that real-time surveying not only was technically feasible but could help create an even more powerful construction site tool if linked in real-time to 3D-CAD brought together four organizations which were diverse in size, focus, and expertise but linked in a common conviction that, by working together, real technological innovation could not only be achieved but could be successfully commercialized. A brief 2 years later, this belief has materialized; in contrast with the industry average of over 10 years to bring a product into the marketplace, only 2 years has been required to introduce the integration of real-time site positioning and 3D-CAD into actual construction practice. This report documents the process and results of this seminal effort.

Formation of Consortium

The Consortium for Advanced Positioning Systems (CAPS) was created in 1992; original members included CERF, the research affiliate of the American Society for Civil Engineers (ASCE); the Bechtel Group; Jacobus Technology, Inc., of Gaithersburg, MD; and Spatial Positioning Systems, Inc. (SPSi), of Blacksburg, VA. In 1993, CAPS added two new members: Intergraph Corporation and Du Pont. In addition, CAPS benefitted from both the interest and resource assistance provided by other leading institutions, including Amoco, Bentley Systems, the Virginia Center for Innovative Technology, Motorola, and the National Science Foundation. The CAPS organizational structure is depicted in Figure 1. See Appendix A for a list of contributors.

CPAR/CRDA Proposal and Award

From the beginning, CAPS members recognized that leveraging of public sector interest and resources would not only enhance the prospects for success but would, in all likelihood, help resolve major public sector needs. After analysis of available options, CERF concluded and recommended that the CAPS seek to partner with the U.S. Army Corps of Engineers (USACE) through the Corps' Construction Productivity Advancement Research (CPAR) Program. Discussions were initiated with the U.S. Army Engineer Waterways Experiment Station (WES) in early 1992, and a CPAR proposal was developed that garnered the necessary approvals. The Consortium was notified in June 1992 that its proposal had been accepted. Further development of a Cooperative Research and Development Agreement (CRDA) between USACE and CERF culminated in the signing of an official 2-year CRDA agreement on 27 November 1992. In accordance with specific USACE guidance, the object of the research undertaken was directed towards the creation and field testing of a system that:

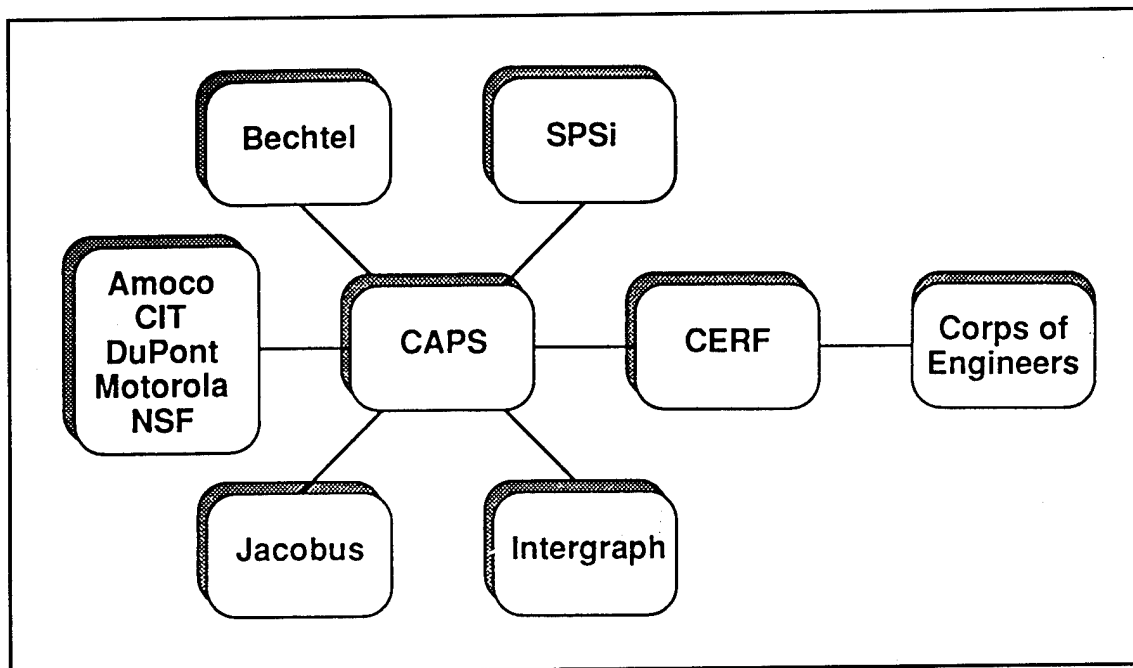


Figure 1. CAPS Participants

improves quality, speed and accuracy of construction layout and generates real-time as-builts....to integrate RtPM [Real-Time Positioning Measurement], and existing devices including total stations and GPS [Global Positioning Systems] with existing CAD/CAE [Computer-Aided Design/Computer-Aided Engineering] systems to form a Real-Time Construction and As-Built Development System (RtCLADS)

The schematic depiction of the RtCLADS design is shown in Figure 2.

Study on Protocols

The CRDA was further defined as encompassing two phases. The first phase called for a definition of the data exchange protocols for three site position technologies: global positioning, total stations, and SPSi's proprietary technology, RtPM. This research was designed to ensure that these site-positioning options would form the separate component capabilities of RtCLADS. This phase of the CRDA was completed and provided to USACE in October 1993 (see Appendixes B, C, and D).

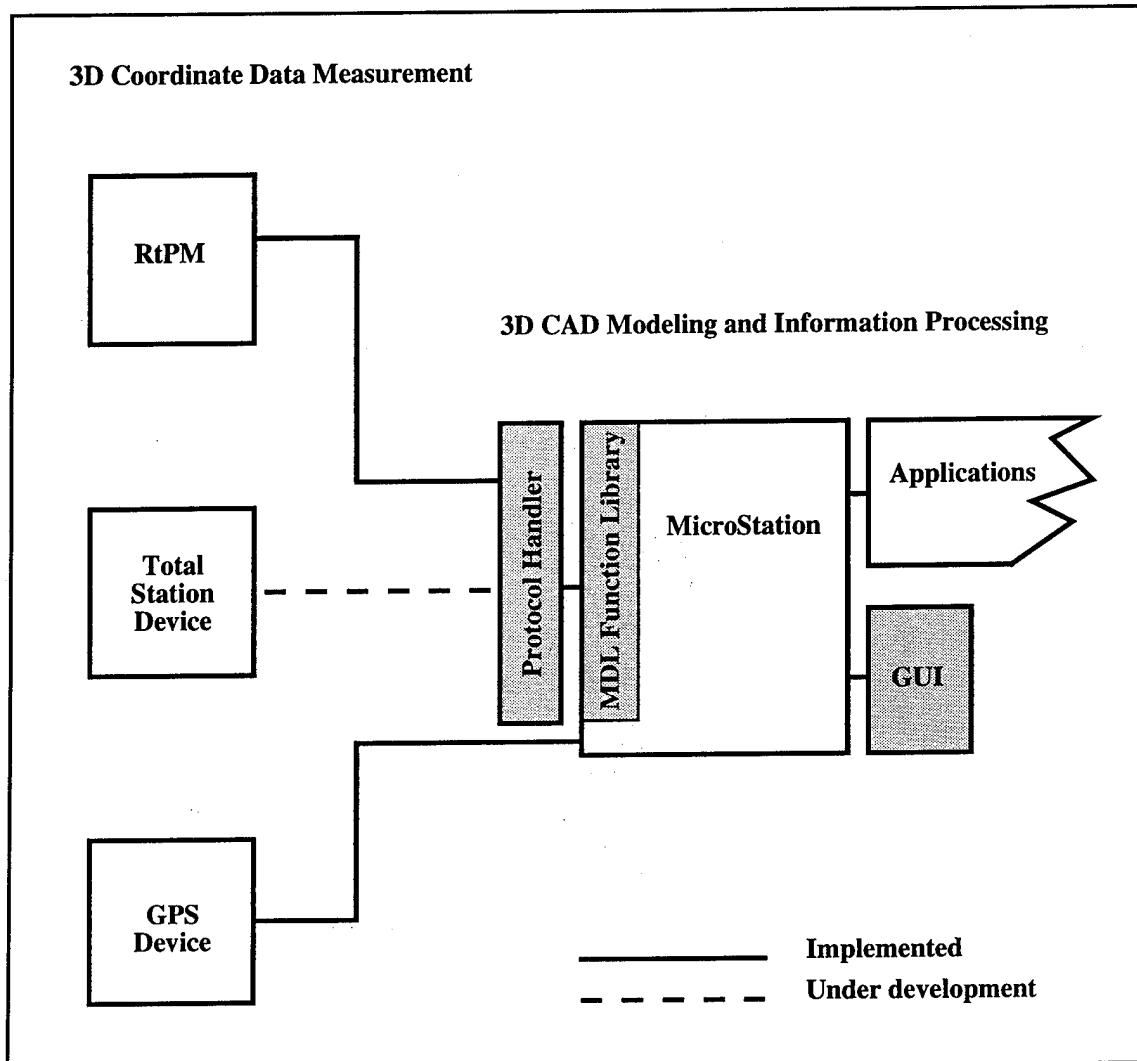


Figure 2. RtCLADS Architecture

Initial System Test

An important CAPS milestone was reached in 26-27 August 1994: the demonstration of the "prototype" RtPM system by SPSi in Blacksburg, VA. For the first time, the real-time link between site positioning and 3D-CAD was achieved and as-built data were captured. Successful results from this test enabled CAPS to conclude that an actual demonstration at an active construction site could be undertaken in less than 1 month.

Field Tests/Demonstrations of RtCLADS

Although CAPS has demonstrated and lectured on the development of RtCLADS in numerous fora (documented in Chapter 2), two field tests/demonstrations comprise the second phase of the CRDA agreement. These tests/demonstrations were undertaken as follows:

- September 1993: Providence, RI
- August 1994: Tinker Air Force Base, Oklahoma City, OK

The Providence demonstration provided an opportunity to illustrate “proof of concept” at an early stage in the development of RtCLADS. The site chosen for this demonstration, the Manchester Street Station facility of the Narragansett Electric and New England Power Company, provided the challenge of a complex Bechtel repowering project as a vehicle for exposing the technology to actual field personnel interaction. The demonstration tasks reflected actual work tasks and were designed to highlight system capabilities, including both layout and as-built activities. The results of this demonstration provided both encouraging results and identified areas requiring additional research and development.

The Tinker Air Force Base (AFB) demonstration (August 1994) served CAPS as the venue for demonstrating the results of the CPAR effort to key members of USACE, the other Department of Defense (DoD) services, the construction industry, and the media. Complex tasks were defined, including inside data capture in a base-plating shop and varied outdoor tasks, including capture of as-builts for a sensitive environmental restoration project. The demonstration also served to showcase the full RtCLADS complement of site positioning technologies.

Evolution of CAPS Terminology: A Necessary Comment

Lest the reader be confused in perusing this report, comments on the terminology appearing in the report are in order. As the research and development progressed from concept towards commercial application, conceptual terminology has been translated into marketplace labels for both hardware and software. Specifically,

- a. The concept term “real-time positioning measurement (RtPM)” is commercialized as the ODYSSEY™ system¹ (see Appendix E).

¹ ODYSSEY is a trademark of Spatial Positioning Systems, Inc.

- b.* SpaceStation™¹ is the commercial embodiment of the RtCLADS concept. Furthermore, SpaceStation™ is a MicroStation Development Language (MDL) application on Bentley System's MicroStation™² platform.

¹ SpaceStation is a trademark of Spatial Positioning Systems, Inc.
² MicroStation is a trademark of Bentley Systems, Inc.

2 Validation Tests, Demonstrations, and Test Results

As part of the ongoing development and testing process, CAPS members performed a number of field tests of system components and the integrated positioning system. Several tests stand out as milestone events during this process. These three field tests, identified by the location at which they were performed, are Blacksburg, Manchester, and Tinker. Numerous other field tests and demonstrations were performed by CAPS. A comprehensive list of demonstrations is presented in Appendix F.

Field Tests

Blacksburg - generating 3-D position data with RtPM

The first major CAPS demonstration took place on 26-27 August 1993. This demonstration was held at the SPSi offices and laboratory in Blacksburg, VA. Representatives from each CAPS member organization (Figure 3) and USACE participated.

The primary goal of this field test was to demonstrate the generation of real-time coordinate data using SPSi's RtPM system and the integration of these data into the MicroStation™ modeling environment.

This was the first successful integration of real-time position data into a Computer-Aided Design (CAD) model. This system is represented schematically in Figure 4. The specific components that were tested included SPSi hardware and software (Appendix E), Jacobus Technology CAPS communications protocol (Appendices B and G), Intergraph application software and MicroStation™ portable Microslate pen-based computer as a CAD platform, and Motorola RF modems for data transmission between the RtPM system and the computer.



Figure 3. CAPS representatives at Blacksburg, August 1994

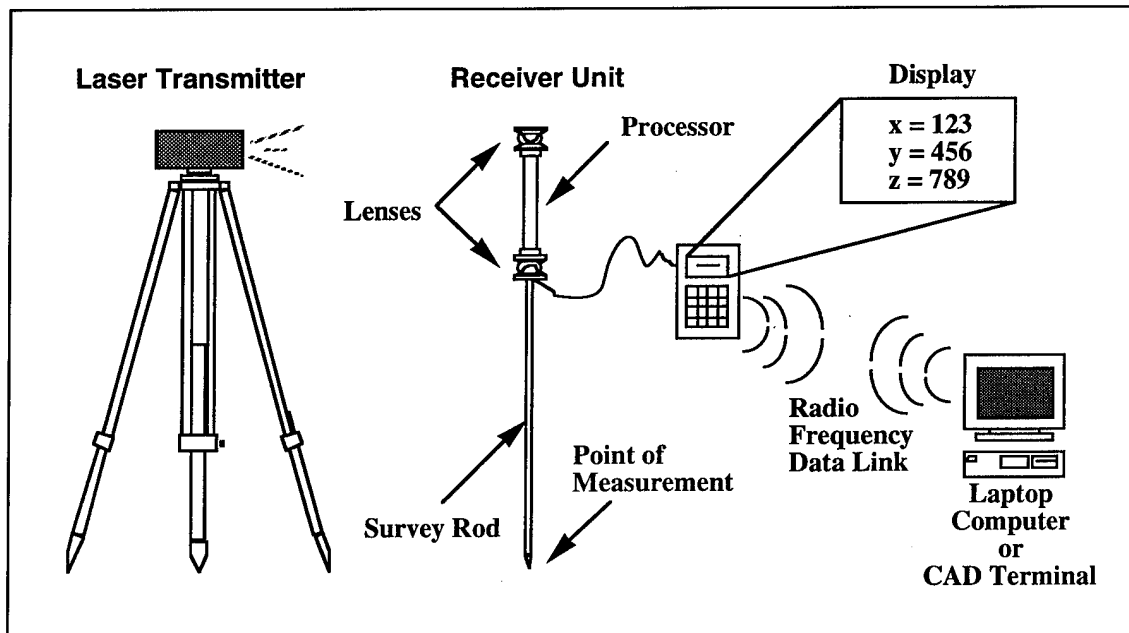


Figure 4. Schematic of the RtPM system

Figure 5 is a photograph of the system, which illustrates the two laser transmitters, the long-range outdoor receiver, and the Microslate pen-based computer. All the components were tested individually and as part of the integrated real-time positioning system. CAPS members demonstrated for the first time that the integration of the various systems was indeed feasible (Appendixes D, H, I, and K).



Figure 5. CAPS representatives with RtPM system at Blacksburg field test

Manchester - performing construction layout and as-built

The CAPS RtPM System was demonstrated at a Bechtel power project during September 1993 (Appendix I). The Manchester Street Station Repowering Project (MSSRP) is located in Providence, RI, and is shown with CAPS members in Figure 6. The plant owners, Narragansett Electric and New England Power Company, selected Bechtel to convert the oil-fired facility to natural gas and install three state-of-the-art combustion turbines. Along with the heat-recovery steam generators (HRSGs) and new steam turbines connected to them, the three new combined cycle turbine trains helped triple plant capacity, from 132 megawatts to around 489 megawatts.

Working closely with Bechtel field personnel, CAPS members identified a series of initial demonstration tasks that reflect actual work tasks. These demonstration tasks also illustrate the capabilities of the system, including both layout and as-built activities. Figure 7 shows the use of the system at the Manchester site, collecting underground pipe as-built location data.



Figure 6. Manchester Street Station Power Plant, Providence, RI

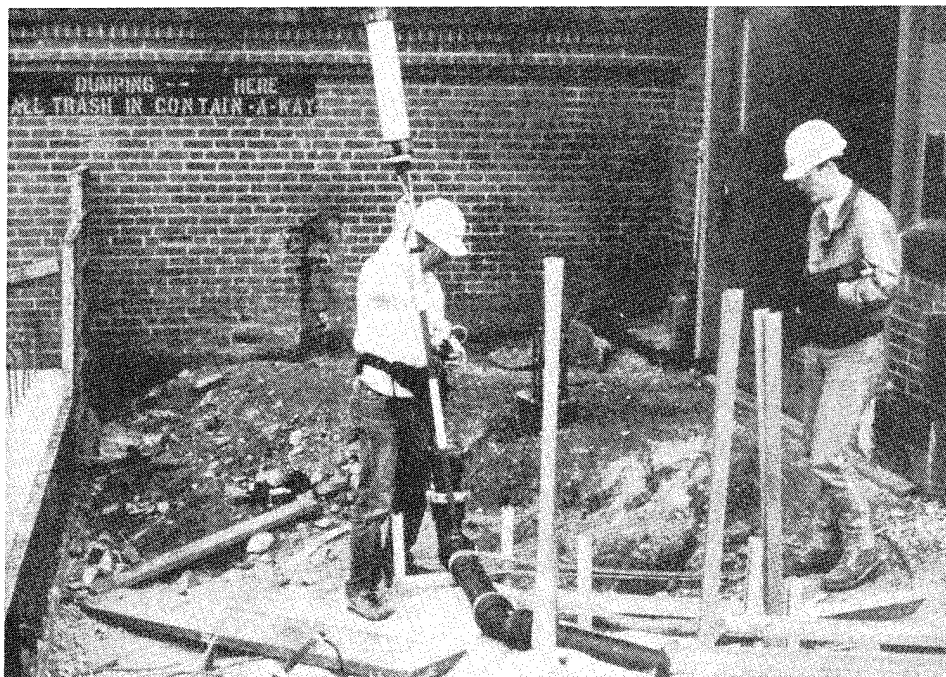


Figure 7. Collecting field data at Manchester

Although the SPSi/CAPS system has potential applications through the life of a construction project, the initial demonstration tasks were related to site civil work. These tasks were defined in order to take advantage of the project phase at the time of the demonstration. The demonstration tasks included:

- a.* Step-taper piles as-builts.
- b.* HRSG embedded plate as-builts.
- c.* Combustion turbine pedestal sleeves and blockouts as-builts.
- d.* Underground pipe as-builts.
- e.* H-pile as-builts.
- f.* General layout, or “guide-to-a-point” capability.

The principal CAD platform used was the portable Microslate pen-based machine. This small computer was typically carried by one person who directed the measurement activity and worked in close proximity with another person who actually made the field measurement.

However, the site demonstration also illustrated the feasibility of using the RF modems to send data to workstations located in the field office. Figure 8 is a photograph of an Intergraph TD-1 workstation inside a building overlooking the test site. It was used to run MicroStation™ and to model plant components based on data transmitted from the positioning system outside in the field.



Figure 8. Indoor workstation used to collect data directly from the RtPM

Tinker - demonstrating RtCLADS integration

The third major field demonstration took place at Tinker Air Force Base (AFB), Oklahoma City, OK, during August 1994. The objective was "the effective, real-time transmission of captured data to CAD files." This goal was met by demonstrating the real-time integration of data generated by three different positioning technologies: RtPM, GPS, and Total Station, with the CAD modeling environment.

The site selected for the demonstration consisted of two work areas. The first was an outdoor area consisting of relatively level ground bordered by a drainage ditch along an abandoned taxiway. This area contained a concrete slab over a series of underground waste fuel storage tanks with associated pipes and pumps, and a series of well inspection stations for monitoring and collection of contaminated groundwater. The second work area consisted of a working plating shop. This indoor environment contained concrete slab floors, floor grating, vats, stairs, structural steel, piping, and other mechanical components.

CAPS members worked closely with representatives from USACE to define appropriate and representative tasks for each positioning system. The tasks that were identified and performed were selected to take advantage of the unique capabilities of each of the three positioning technologies. These tasks are described in detail in the subsequent portions of this section, which focus on each positioning technology.

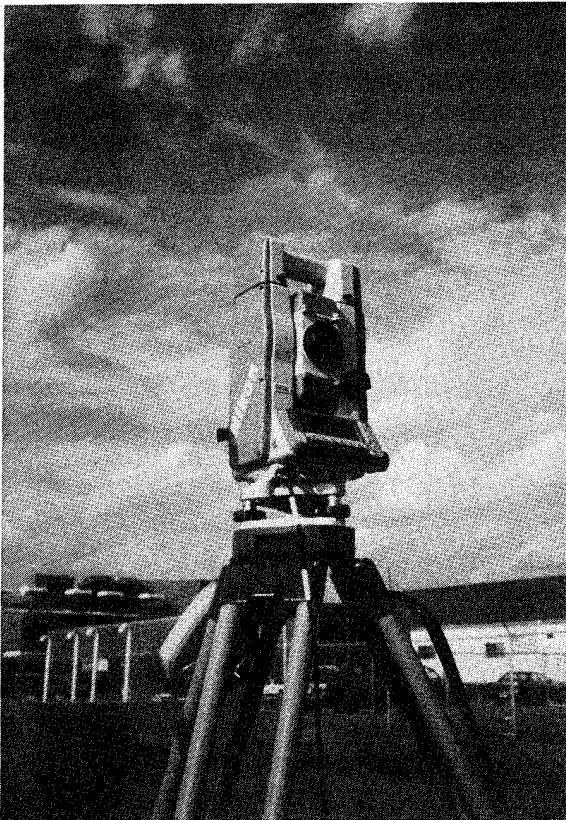


Figure 9. Nikon DTM-750 total station

Total Station Link to CAD

When CAPS members began to plan for the integration of total station data, it became apparent that each total station manufacturer used a different protocol to generate and display data.

CAPS members agreed to direct their efforts towards building an interface for one specific model of total station, the Nikon DTM-750 instrument (Figure 9). The Nikon gun was selected for several reasons. Bechtel had recently standardized on this instrument for use on its projects and was able to provide expertise in its use. This instrument is also the top of the line Nikon product and had superior data processing capabilities. Finally, Nikon agreed to provide

technical support in modifying its onboard software and provided an instrument on loan for use in CAPS activities.

This instrument uses two PCMCIA cards during operation. One card contains program instructions, and the other is used for data collection. Nikon engineers created a modified program card that computed an X,Y,Z coordinate for each data point as it was measured and then exported the data to the RS-232 serial data port.

The CAPS Communication protocol created earlier in the CAPS effort was modified by SPSi into its SpaceStation™ product. The SpaceStation™ software read the X,Y,Z data from the Nikon instrument and delivered it as a series of data points to the laptop computer. The computer operator then was able to use MicroStation™ commands to represent the Nikon Total Station data graphically in the CAD model.

CAPS representatives and USACE worked together to define a series of appropriate tasks for each of the three positioning technologies involved in the Tinker field test. Two field tasks were identified for the total station.

Total Station Task 1

Total Station Task 1 was to extend survey control from existing plant monuments and establish control at the entrance to the plating shop, so that the RtPM indoor survey task can be registered to the standard grid coordinate system used at Tinker. This task was the first priority upon arrival at Tinker AFB. The total station field team consisted of representatives from Nikon and Bechtel, who immediately began to establish references for subsequent use by the RtPM and the GPS teams. Figure 10 shows a plan view of the work area and the relative location of the plating shop, the outdoor test area, and the references that were established.

Total Station Task 2

Total Station Task 2 was to survey the contaminated water piping run defined as RtPM Task 1. This task was accomplished during the first and second day at the field test site. The total station team surveyed the contaminated groundwater monitoring and collection system. Measurements were made at the inspection ports for the monitoring system and at the concrete vaults for the collection system.

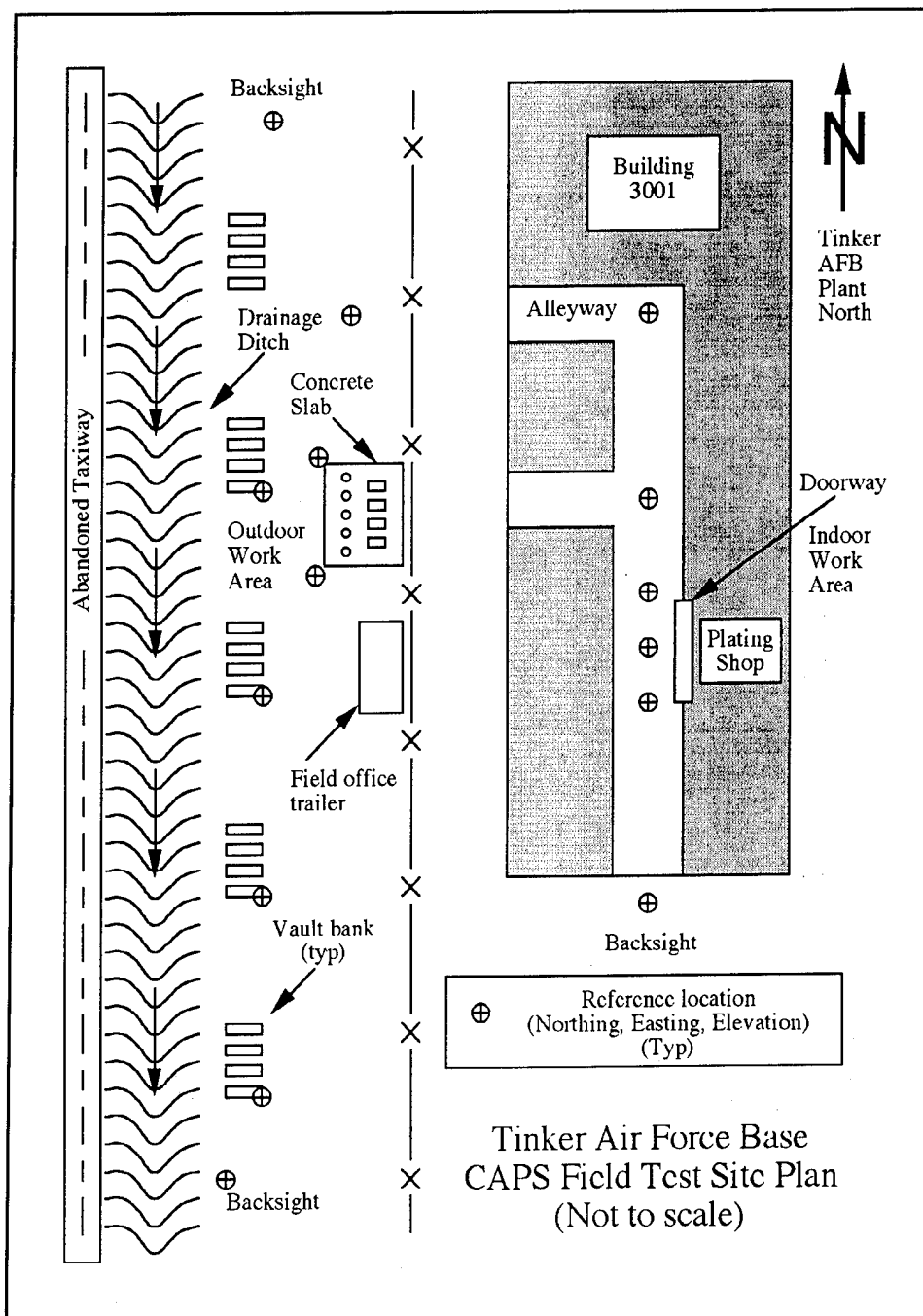


Figure 10. Plan view of Tinker field test site

Global Positioning Systems Integrated with Intergraph GeoCAD

As part of the activities of CAPS, Intergraph Corporation has developed a prototype software package called GeoCAD, which had as its design objectives:

- a.* The ability to demonstrate the benefits of integrating a graphical CAD package with advanced position-measuring systems for field application.
- b.* The ability to serve as a test-bed for investigating and refining field workflows using the integrated CAD software field application with new electronic position measurement technology.

The GeoCAD application software package is based upon MicroStation™ and includes facilities for interfacing with:

- a.* GPS receivers, including On-the-Fly/Global Positioning Systems (OTF/GPS) from the Topographic Engineering Center (TEC) (TEC 1993).
- b.* Advanced Robotic Total Stations manufactured by Geodimeter.
- c.* Advanced positioning measurement systems manufactured by SPSi.
- d.* Highly portable field “vector” measurement device manufactured by Criterion.

Each of these position measurement technologies have advantages for certain survey tasks and require slightly different workflow support from the field software for maximum efficiency.

The GPS includes a constellation of satellites which support the determination of position. The GPS was developed and is maintained by the Department of Defense. It was primarily intended for military users, but has been exploited by civil engineers for survey purposes. A number of vendors offer GPS receivers in a wide range of price and capability. For the activities sponsored by CAPS, Intergraph worked closely with USACE/TEC. TEC developed a method of providing accurate (centimeter level) GPS position measurement in real-time using differential correction and carrier phase tracking and error correction. This system provides a very convenient means of making accurate survey measurements outdoors.

The particular considerations that favor a GPS-based position measurement includes:

- a.* Outdoor survey application.

- b. Wide area being surveyed.
- c. Limited local survey benchmarks for control.

Differential correction for GPS has been a well-known technique for some time, and the TEC's OTF technique uses the reference station and differential correction approach, so that in effect, survey control is established by the reference GPS receiver being positioned at a known location.

Intergraph's prototype application software, GeoCAD, designed to work with the OTF/GPS in the field and is an evolution of Intergraph software designed to collect field GPS data. The major functions supported by GeoCAD, as the GPS-CAD Interface software, include:

- a. Use of GPS data to register a map or aerial photograph to a true set of coordinates.
- b. Guidance to a selected point in the registered design file.
- c. Collection of position data of features with the ability to add attribution.
- d. Ability to locate particular objects based upon a feature/attribute search combined with a spatial qualification.

One of the most important findings from operation with GPS for field spatial data collection and field data graphical interaction by the user is the necessity to combine the ability to receive real-time position data with the ability to perform "queries" based upon either non-spatial attribute data, spatial data, or a combination of the two. For example, the user might wish to find all of the construction elements manufactured by a particular vendor or made of a certain grade steel. The user likewise might wish to locate all of the foundation "block-outs" deeper than 1 ft and within 30 ft of an arbitrary center line. Or, the user might wish to combine searches, such as all the anchor bolts of a certain type within a given geometric area and also installed between two selected dates.

The user interface must support the generation of these queries in simple manner in the field, but still allow the user the freedom and power to compose the interactive information access requests and present the results in context with the real-time position data available. As an example, the user might wish to locate all of the construction elements of a certain type within 100 ft of the sensor's (GPS antenna's) current position. The graphical presentation of results of queries can include vector directions from the present real-time position to a particular object, or a graphical highlighting of objects that meet a given criterion.

The following conclusion has been reached: for many applications integrating computer data with a real time-spatial position measurement source in the field, a significant subset of the capabilities of a Geographic

Information System, combining graphical representations of spatial relationships as well as a database of non-graphical attribute data, is required. The challenge is to provide the user all of these capabilities without an overly complex interface so that he can work efficiently in the field using a platform such as a pen-based portable computer. GeoCAD was designed to investigate the required features of a user interface for efficient support of real in-field workflows.

At the CAPS demonstration at Tinker AFB in August 1994, Intergraph interfaced GeoCAD to the TEC's OTF/GPS system to collect data on the location of elements of the groundwater remediation facility as a demonstration of the capabilities of the system.

The specific tasks were:

- a. *Task 1.* Collect terrain data at an open field location.
- b. *Task 2.* Operate over several known benchmarks to verify GPS accuracy.
- c. *Task 3.* Survey the same contaminated water piping run defined as RtPM Task 1.
- d. *Task 4.* Survey the boundary of a large constructed facility, for example, a runway boundary.

Figure 11 illustrates a plot from a MicroStation™ design file of data collected at the site. In the figure, AP stands for "access port" and the X-Y location of the access port is indicated, as well as a "depth" attribute, which is the depth below the surface of the access port to the top of the underground pipe. Figure 12 shows two of the MicroStation™ MDL-generated panels for providing the required field user's interface with the GPS equipment. One of the panels is used to control the electronic interface to the GPS unit. The second panel, labeled "GIS FM" for Geographic Information System for Facility Management, shows the interface whereby the user can tag a collected pipeline or conduit as being for water, sewer, gas, electrical, or fuel.

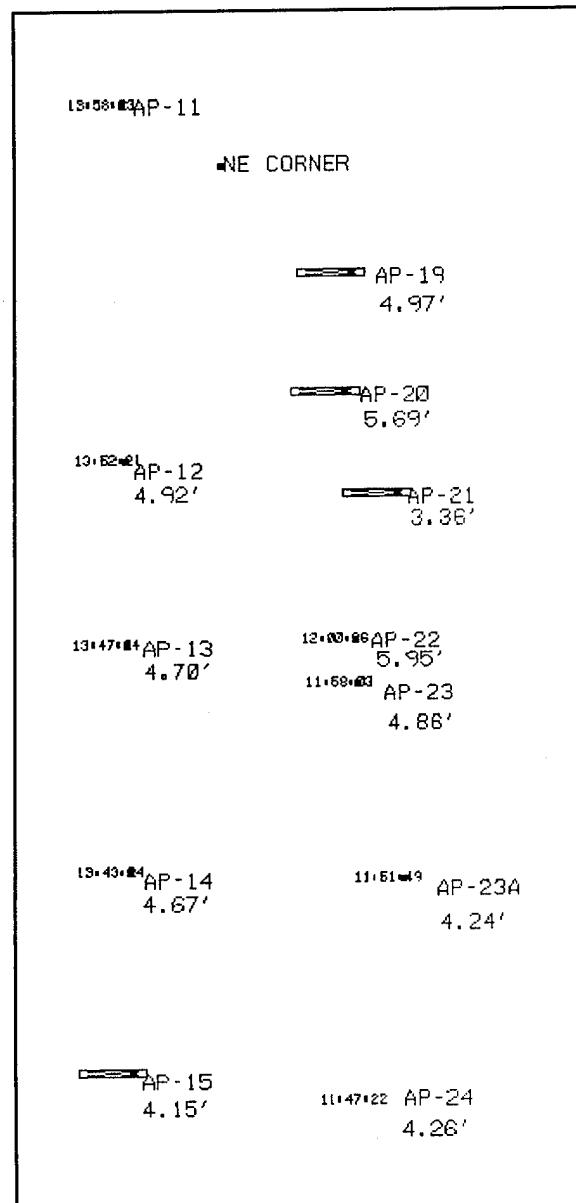


Figure 11. Microstation design file data plot

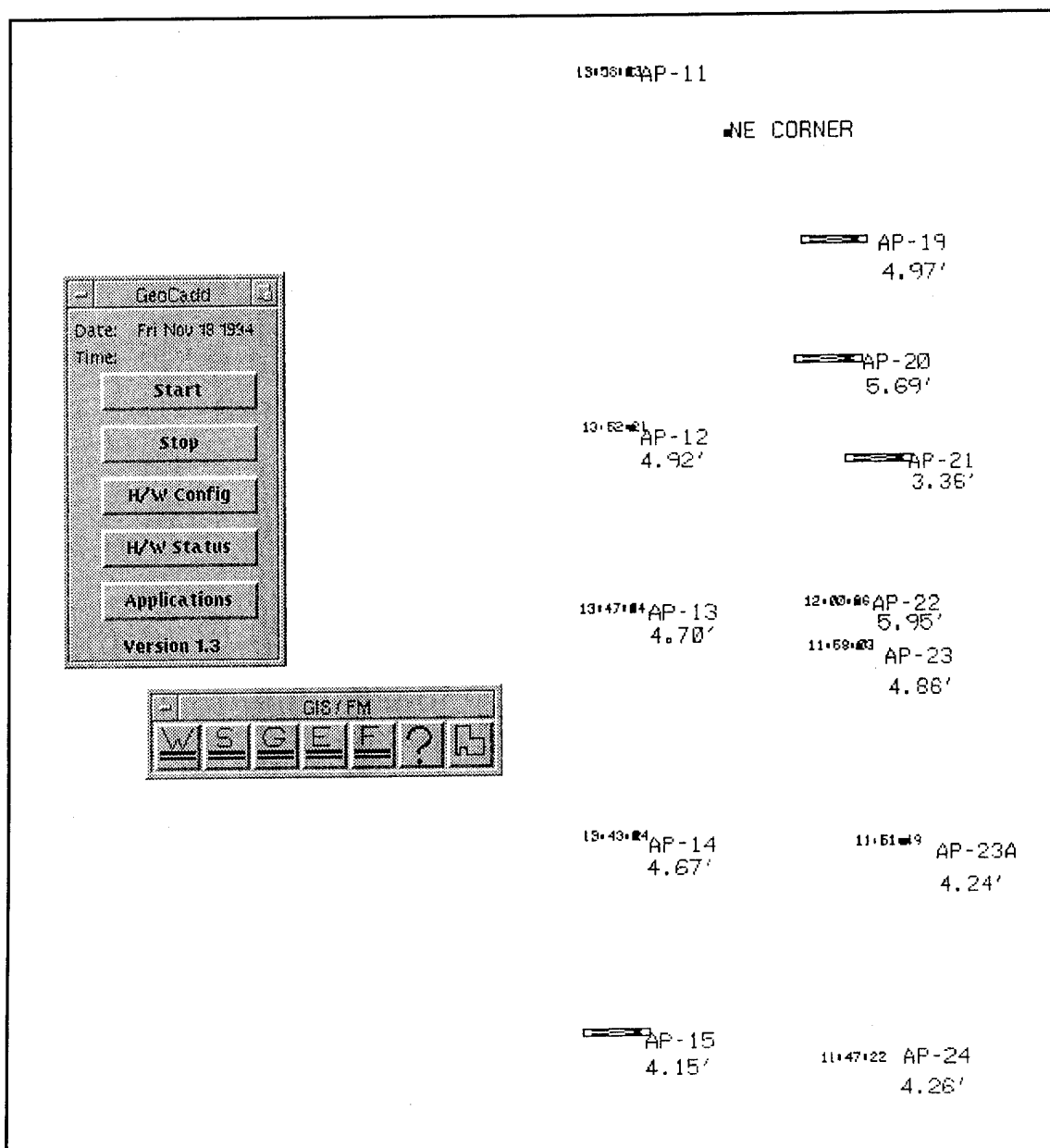


Figure 12. MDL-generated panels

Figure 13 illustrates the advantage of basing the field collection software on a full-featured CAD package such as MicroStation™. Here, the standard measurement facilities of MicroStation™ are used to evaluate the results of an accuracy experiment with the GPS instrument. A scatter diagram was collected with the GPS receiver at a set location, and the stability of the resulting position reports are illustrated by plotting the collected position data and measuring the resulting scatter diameter using the standard capabilities of MicroStation™. In this case, it was not necessary to design a special user interface panel; the standard capabilities of MicroStation™ provided the required capability in the field.

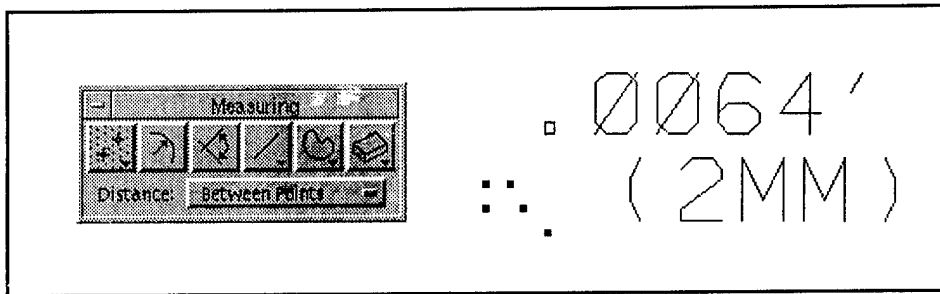


Figure 13. Scatter diagram

Figure 14 illustrates the GeoCAD panel for selecting the particular application from the options of Navigation, Trails/Playback, Overbank Data, GIS/FM, Baseline Layout, and Accuracy Analysis. In this case, the Trails/Playback mode has been selected, and the results of a data collection exercise to collect terrain data are illustrated. A vehicle with the GPS receiver and portable field computer hosting GeoCAD was driven over approximately 5 acres (20,234 m²) of land on Tinker AFB. The figure shows the trail for data collection, as well as a numerical printout of the collected elevation data. Figure 15 illustrates the terrain-modeling function of GeoCAD, allowing the surface to be modeled as a network of triangles. Figure 16 shows a plan view of the resulting triangle network that models the terrain collected. The exercise of collecting the data and creating the terrain model required only approximately 15 min. The operator could interact with the data as they were being collected by observing a graphical map of the trails and could model the terrain, look at a rendered perspective view, and judge the quality of the resulting data collection, all at the site, in a matter of minutes.

Another important feature of GeoCAD is its ability to handle various map projections and realistic grid coordinate systems. For example, for the Tinker AFB demonstration, the Base Facility Engineer was able to provide a digital base map in Intergraph format as a design file. These data in the Oklahoma state plane coordinate system were registered to the GPS data (received as Latitude, Longitude, NAD83). GeoCAD's map coordinate transformation capability allowed these data to be transformed in real-time to the Oklahoma State Plane Projection coordinates in NAD27.

Another important feature of GeoCAD is its ability, based upon the capabilities of MicroStation™, to import graphical file formats from other popular CAD packages such as AutoCAD. This gives the user the ability to use in the field maps and plans developed on a wide range of systems in addition to those developed upon Intergraph systems.

As a direct result of the CAPS demonstration at Tinker AFB, Intergraph Corporation is now underway with an activity for the Tinker Base Facility Management/Civil Engineering Office to implement an Intergraph Modular Geographic Information System Based GPS data collection system, which will incorporate many of the lessons learned from the CAPS activity.

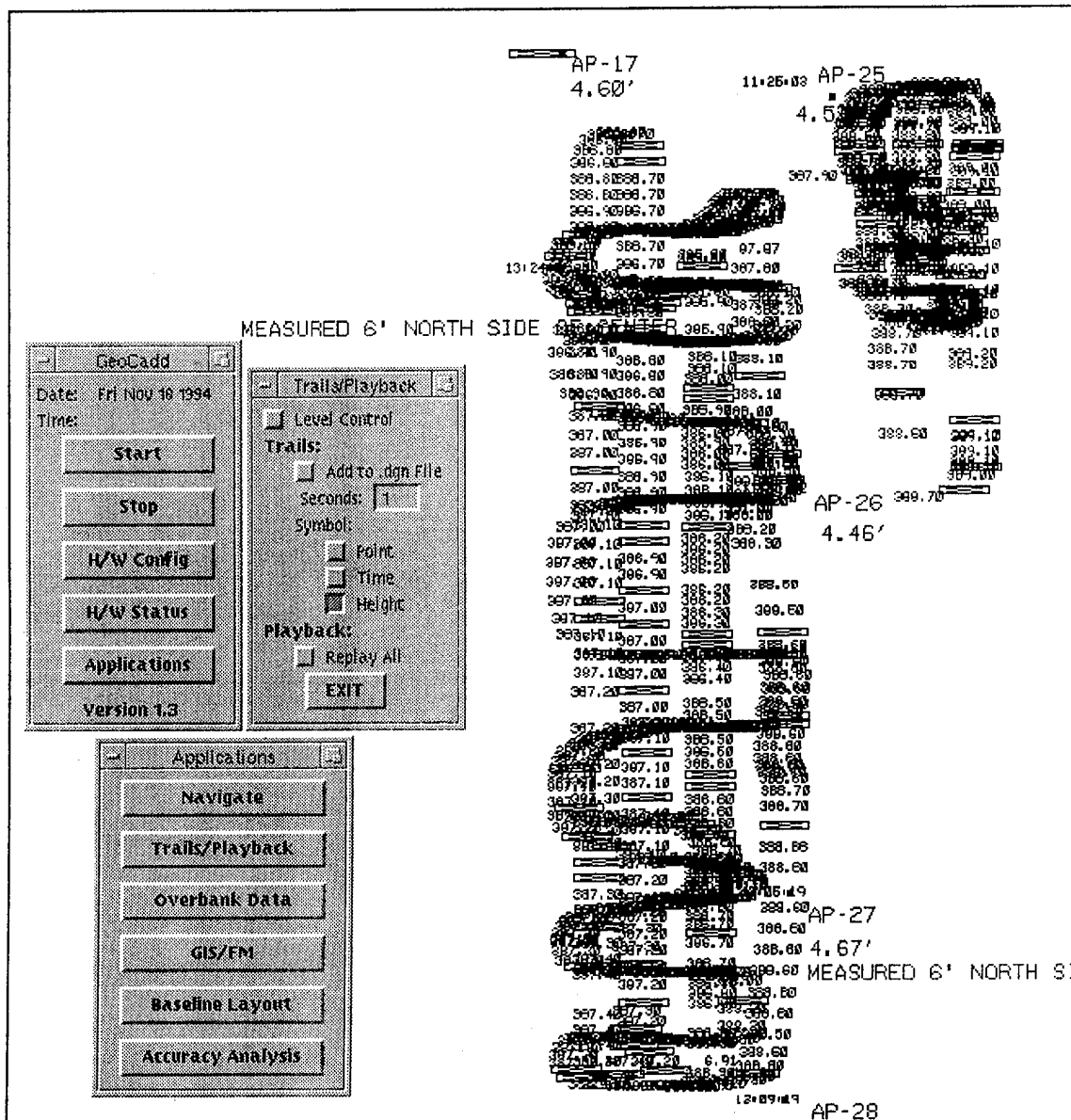


Figure 14. GeoCAD panel

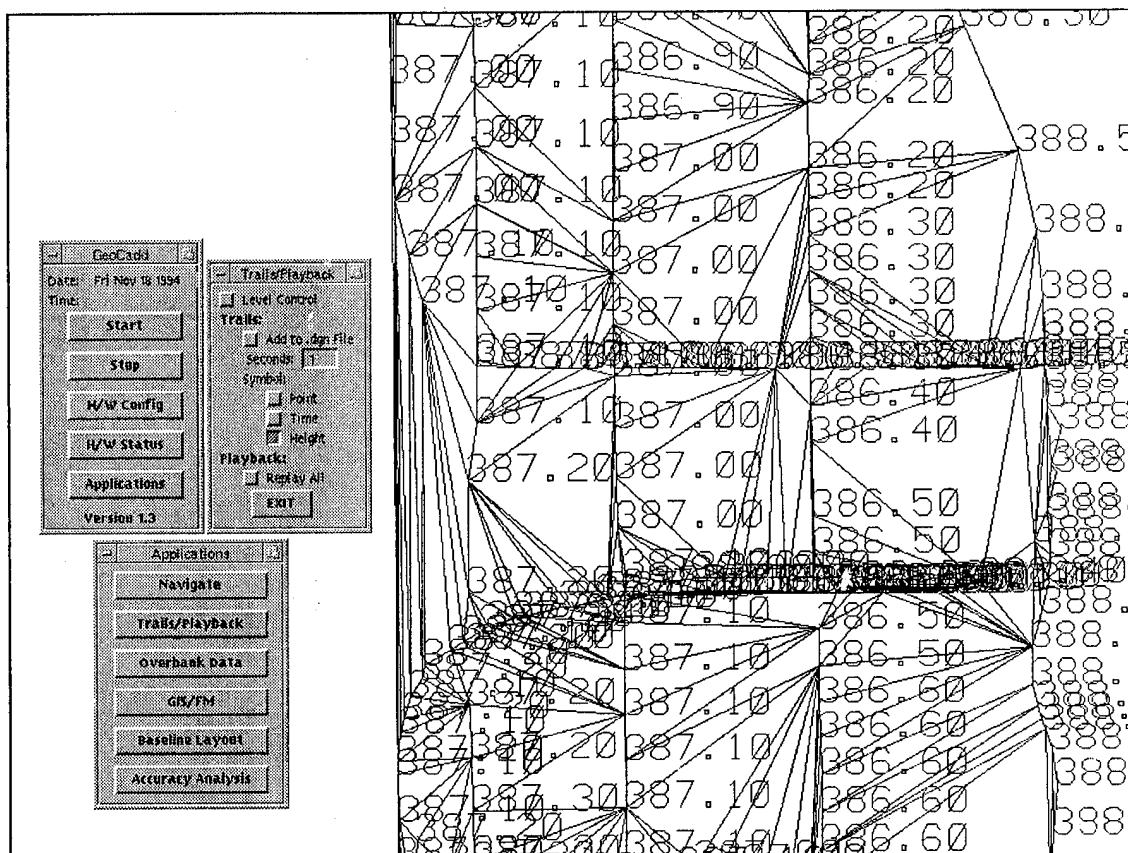


Figure 15. Terrain modeling

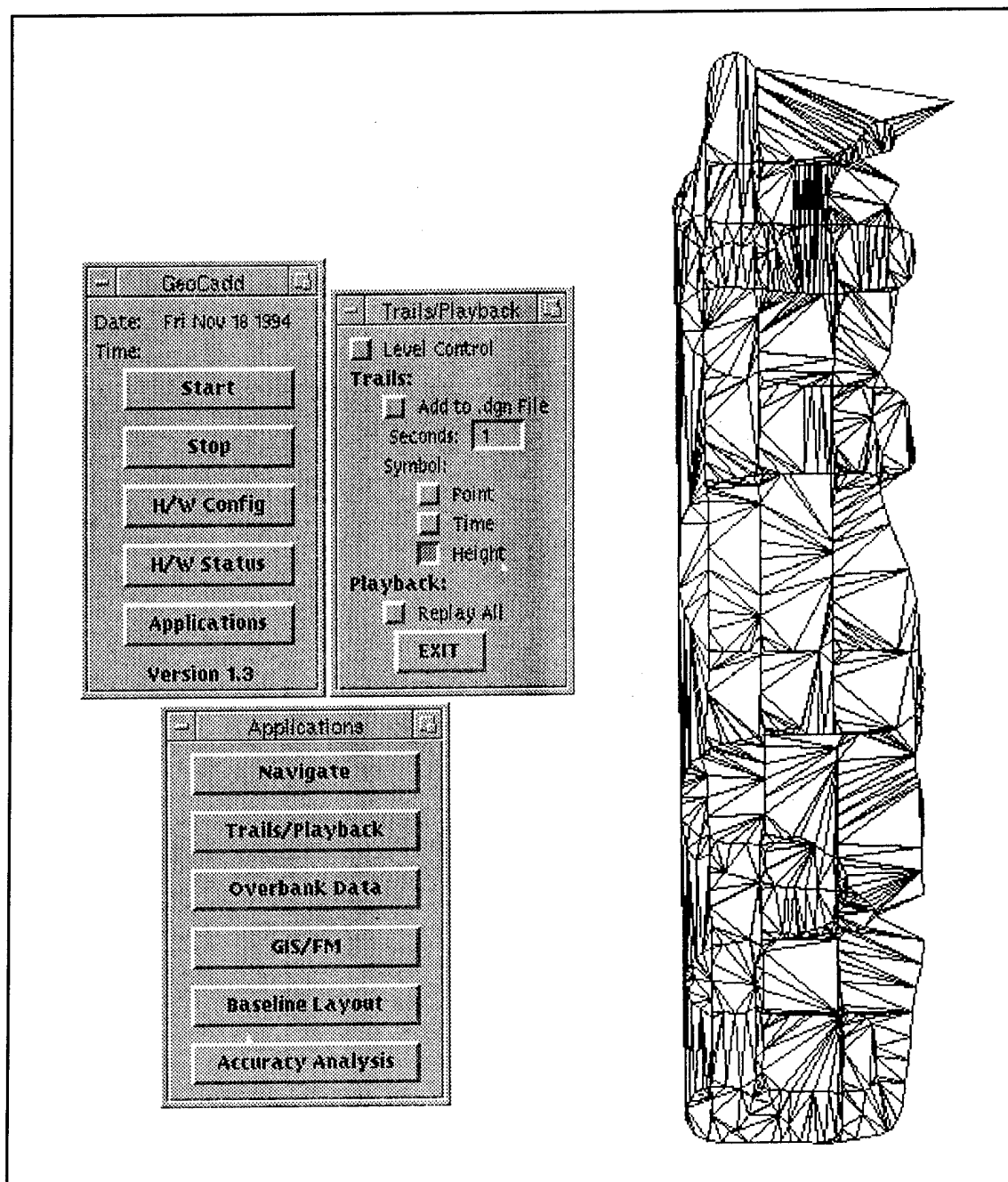


Figure 16. Triangle network plan view

Geodimeter Robotic Total Station Interfaced to Intergraph GeoCAD

In June 1994, as part of its CAPS activities, Intergraph, in corporation with the U.S. Army Engineer District, Louisville, demonstrated the interface of MicroStation™-based GeoCAD as a field collection and field interactive graphical workflow implementer with a robotic total station manufactured by Geodimeter. This Geodimeter total station features a one-man operation, with the measurement data available at the "pole" via radio link from the robotic station. Intergraph developed a real-time electronic interface to this device to support all of the GeoCAD features previously described. The field workflow for the Geodimeter total station is much like the SPSi Real-Time Position Measurement System (RtPM) described elsewhere in this report. The Geodimeter device provided the ability to perform rapid, accurate measurements over a long range with a minimum of setup time.

As a demonstration of the capabilities of GeoCAD in working with this instrument, the team surveyed the complete Tinker Groundwater Remediation Pipe-Line complex in a period of 1 work day. Figure 17 shows the complete pipeline, where data were collected at each access panel along the pipeline. All data were collected by GeoCAD as a demonstration of an as-building task. During the collection process, the data were available in the field in graphical form, along with a real-time indication of the current pose position. The advantage of this capability as a quality control tool is evident. The GeoCAD panel in Figure 17 shows the capability of MicroStation™ to support the development, using MDL, of custom user interfaces, in this case tools for collecting as-builts of particular types of objects such as piping, structural members, shapes, and plates.

As an illustration of the Geodimeter's ability to track in real time, the pole was mounted on a vehicle and driven over the ramp area near a hanger on Tinker AFB. Figure 18 shows the track overlaid on the Tinker base map provided by the base Civil Engineer's Office. This illustrates that this position measurement instrument has the ability to dynamically collect data very rapidly over an extended area and a surface model of the ramp could be generated using the data collected by this means.

RtCLADS and GeoCAD

The GeoCAD MicroStation™-based application meets the basic objectives stated by USACE for a RtCLADS. GeoCAD interfaces to Geodimeter, Criterion, general GPS receivers via the NMEA format, and TEC's OTF/GPS. In addition, through an interface to a program external to MicroStation™ written by Jacobus, it interfaces with SPSi's RtPM system. GeoCAD includes the capability to manage nongraphical attribute data as well as spatial data with a user interface in the familiar MicroStation™

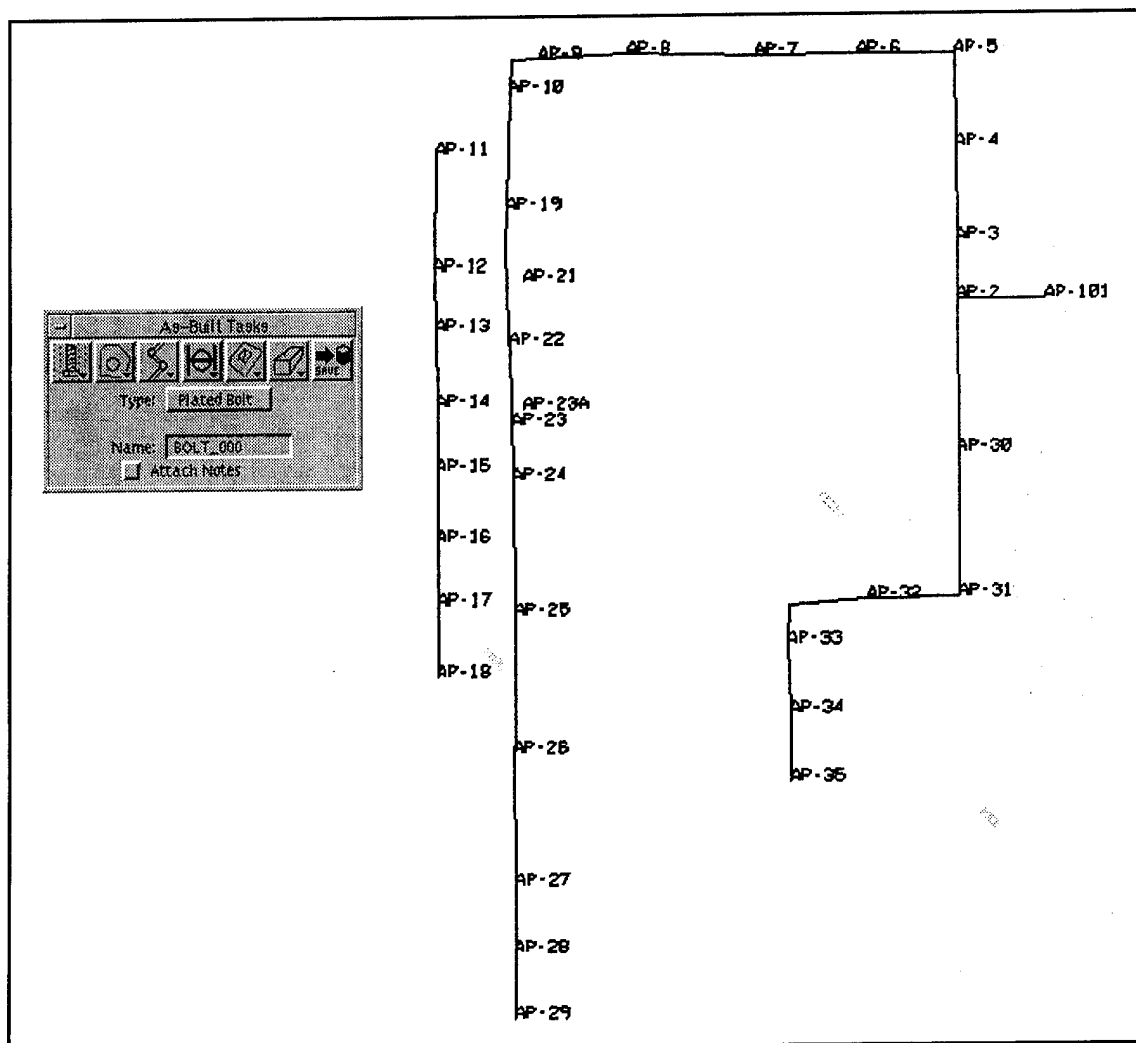


Figure 17. Tinker groundwater pipeline

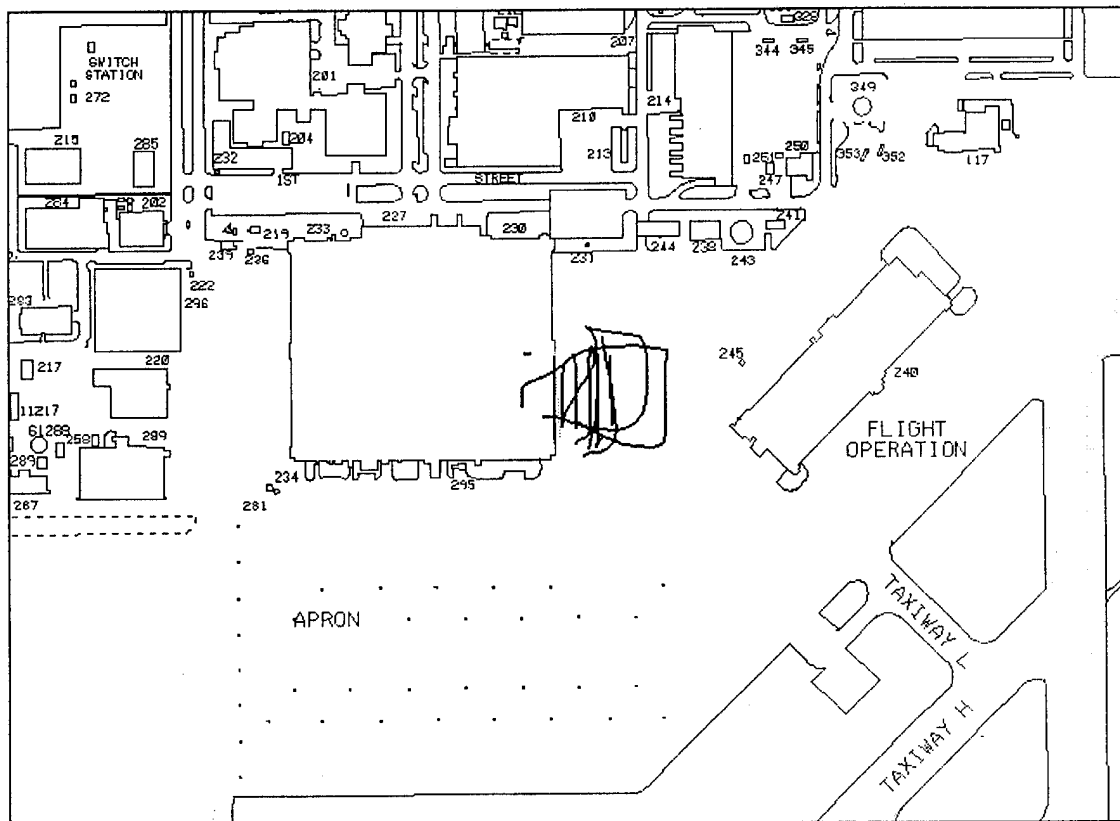


Figure 18. Geodimeter real-time tracking

environment. With the continued efforts with Tinker AFB, GeoCAD will provide a field front-end to the Intergraph MGE Geographic Information System. GeoCAD will support a GIS database schema in compliance with the Spatial Data Standard developed by the Tri-Service CAD/GIS Center, WES, and will allow data collection and layout using GPS, RtPM, Geodimeter total stations, and, in the future, other appropriate real-time position-measurement instruments as required by the survey community.

Figures 19 and 20 show some of the GPS hardware, as well as a mounted GPS receiver.

RtPM Link to CAD

The RtPM-CAD linkage was successfully demonstrated during the Tinker AFB demonstration using SPSi's SpaceStation™ product. SpaceStation™ provides a direct real-time link between the ODYSSEY™ system and MicroStation™ and facilitates recording coordinate data graphically in the CAD model.

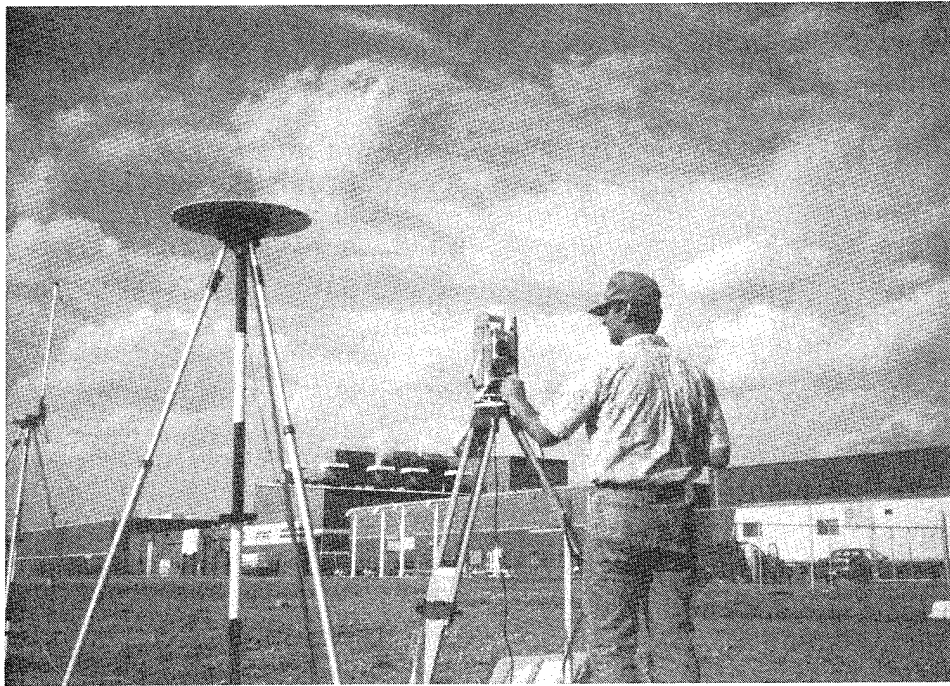


Figure 19. GPC hardware



Figure 20. FPS receiver, mounted

By using two different receivers, an indoor model and an outdoor model, the ODYSSEY™ system was able to collect data in the indoor environment in the plating shop and also in the outdoor work area. These data were recorded in two separate CAD files. Figure 21 shows the data collected in the outdoor work area, and Figure 22 illustrates the components that were modeled at the plating shop.

RtPM tasks

Five RtPM tasks were identified by CAPS and USACE representatives. These were also prioritized so that the more important tasks could be performed first. The CAPS team accomplished all of the tasks identified during the Tinker field test.

- a. *Task 1 (priority 1).* Capture an as-built of the piping run that transports contaminated water from the wells to the treatment plant. Task consists of capturing the pipe elevation and X,Y position at a number of access points through inspection shafts.

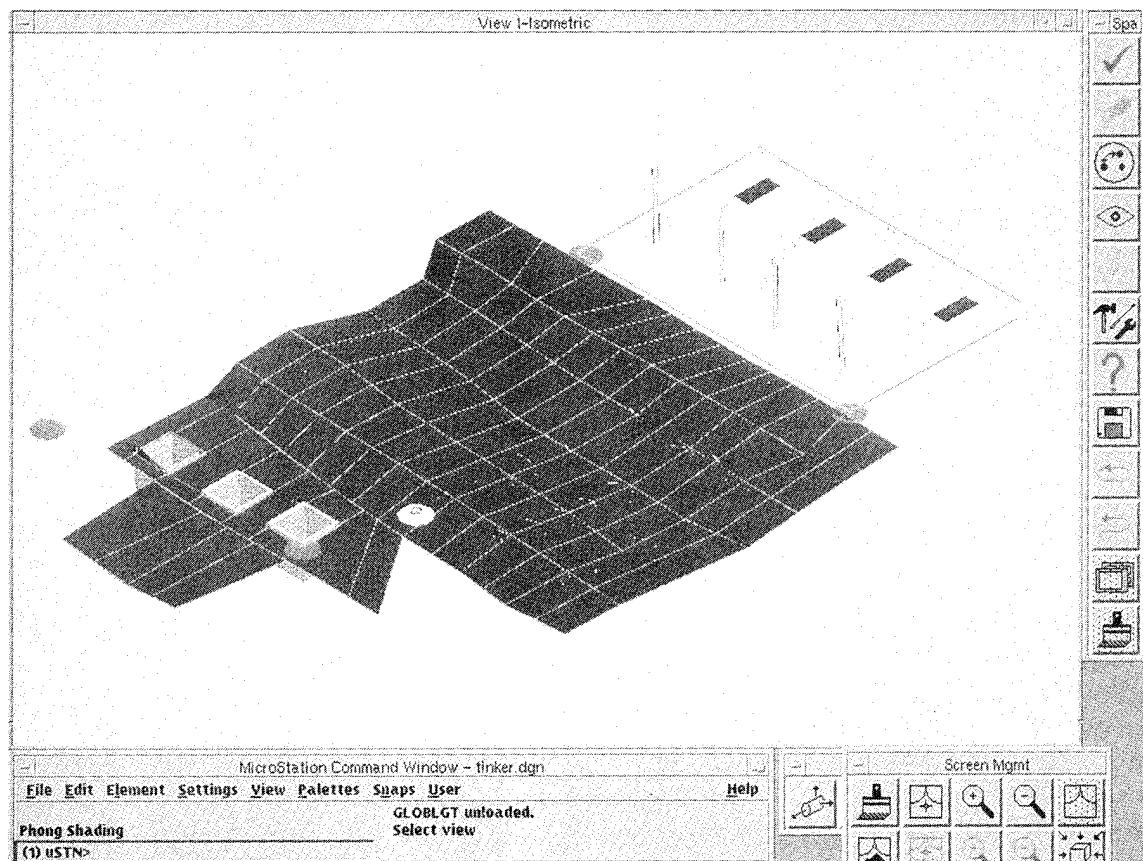


Figure 21. Outdoor work area RtPM data

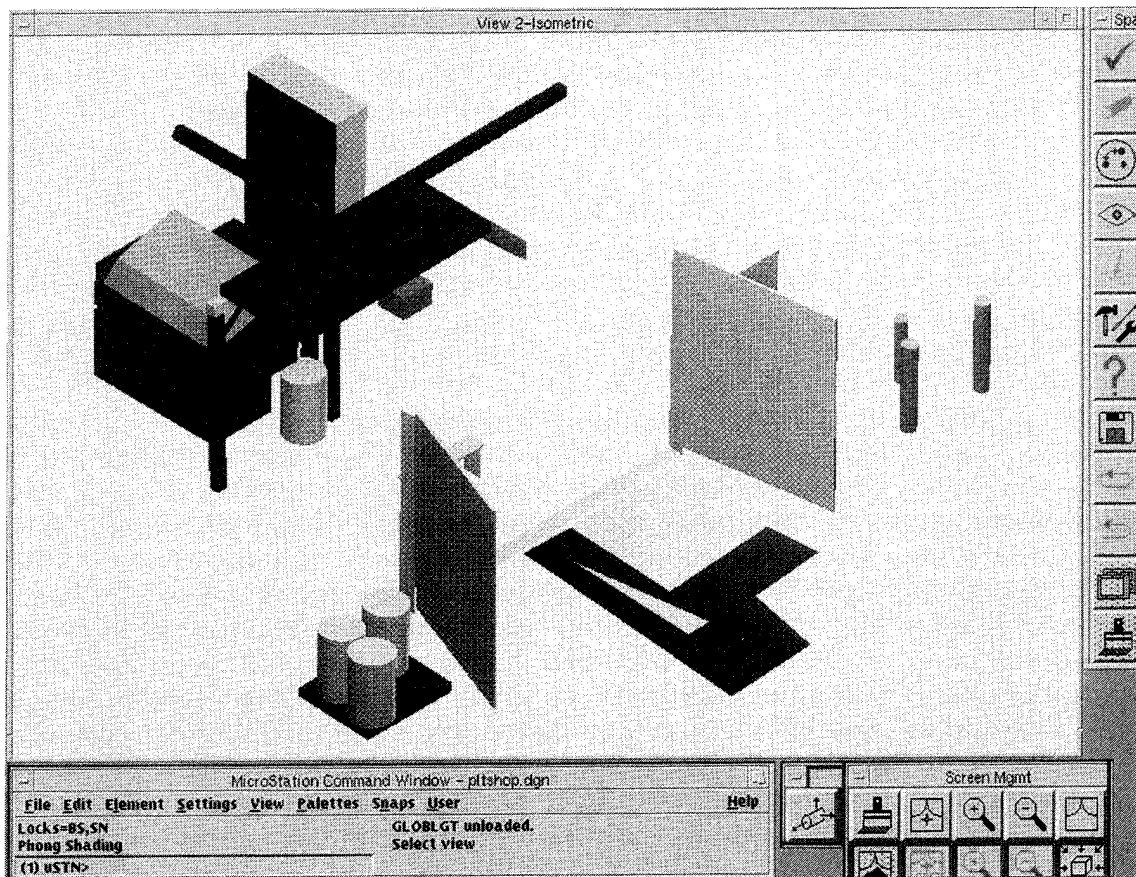


Figure 22. Plating shop RtPM as-built components

- b. *Task 2 (priority 3).* Lay out a construction project such as a parking lot. Stake the lot using the guidance to a point function, and indicate the elevation cut at each stake.
- c. *Task 3 (priority 2).* Capture 3-D items inside the indoor plating shop, including modeling of pipes, vats, and other objects.
- d. *Task 4 (priority 5).* Capture outdoor 3-D objects near the entrance to the plating shop.
- e. *Task 5 (priority 4).* Surface modeling, for example, a parking lot.

Task explanations

- a. *Tasks 1 and 5.* The RtPM system was used to capture the as-built condition of the area west of the plating shop and near some construction trailers. The equipment used was the SPSi ODYSSEY™ outdoor system. The computing hardware was an IBM Thinkpad. The software used was MicroStation™ 5.0 (by Bentley Systems) and SpaceStation™ 1.0 (by SPSi). The as-built information collected included a concrete slab, several stand pipes

on the slab, access doors on the slab, three access vaults, one pipe stand, several other objects found in the area, and the surface topography of the area between the access vaults and the concrete slab (Task 5). This work was done by a two-person crew on the evening of August 29 between 10:00 p.m. and 1:00 a.m. The resultant 3D-CAD model was demonstrated during the CAPS presentation on Wednesday, August 31, and is available as a MicroStation™ CAD file. Figure 21 is a representation of this CAD model.

- b. *Tasks 3 and 4.* The RtPM system was used to collect a significant number of outside objects near the entrance to the plating shop. A significant number of objects were also collected inside the plating shop. The objects collected included pipes; steel beams, columns, and other steel structure; doors; vats; electrical switchgear; storage drums; and other objects. The equipment, hardware, and software utilized was the same as that employed outdoors, except that an indoor receiver was used. The work to collect the 3D-CAD as-built data was done by a two-person crew on the evening of August 30 between the hours of 6:00 p.m. and 8:00 p.m. The result of this effort was a 3D-CAD model which was demonstrated during the CAPS presentation on August 31 and is available as a CAD file. Figure 22 is a representation of this CAD model.
- c. *Task 2.* After the collection of the as-built data near the entrance of the plating shop, a test was conducted to demonstrate layout of a predefined surface and shape. The area selected was small with several changes in directions. The overall size at the extreme edges was about 3 by 2 m. The guide to a point function was used to lay out the site, which consisted of 16 points. This work took two people 30 min to do. Stakes were not set, nor were elevation cuts indicated due to the hard surface on which the work was done. The design of this layout effort is shown at the front of the doors of the plating shop and is available as a CAD file.

At the completion of site data collection activities at Tinker, the CAPS team had collected field data using three positioning systems, total station, GPS, and RtPM. These data were merged by referencing the associated files so that all data could be viewed simultaneously. Figure 23 shows the combined Tinker field data.

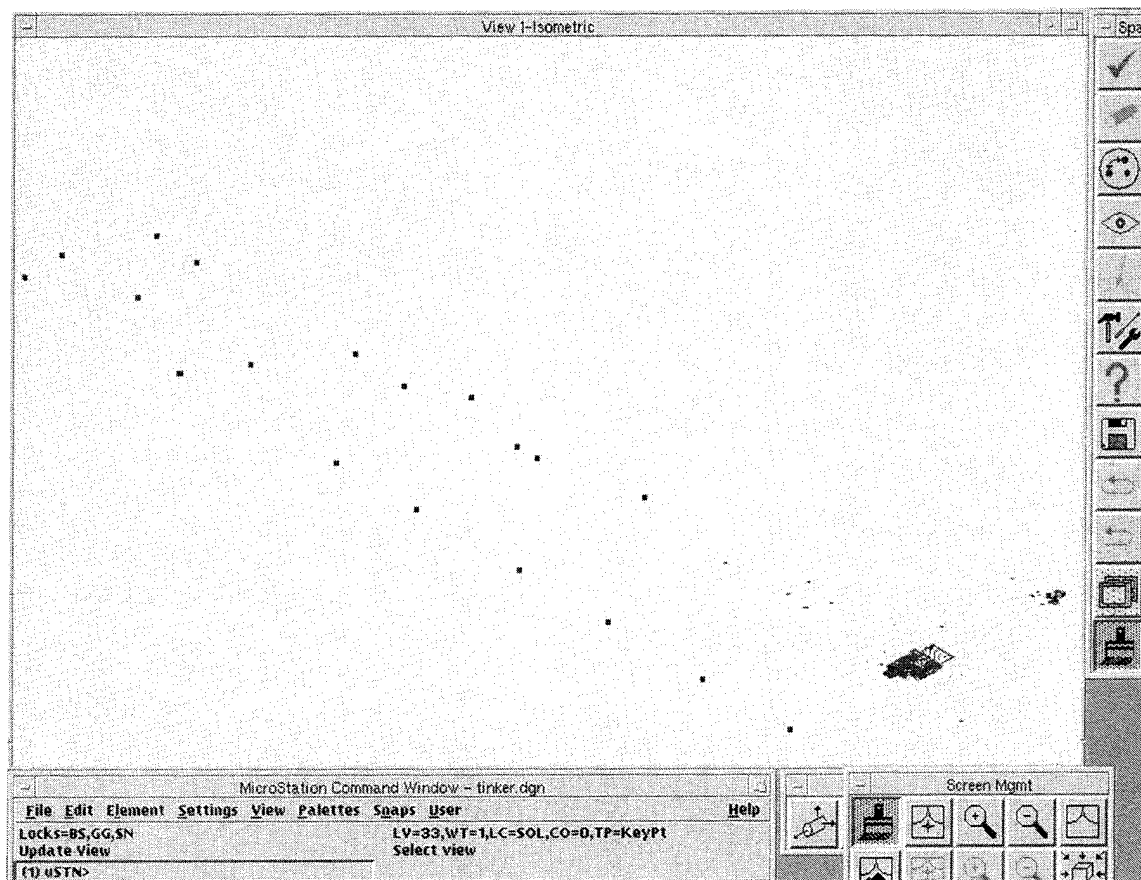


Figure 23. Merged data from total station, GPS, and RtPM

RtPM Link to JSpace™¹

One additional part of the RtCLADS system is a software link between the ODYSSEY™ system from SPSi and JSpace™ visualization software from Jacobus Technology, Inc. This software developed under the CRDA allows real-time communication of X,Y,Z coordinate data from the ODYSSEY™ system to the JSpace Viewer™.

The software link was developed in prototype form early in the CRDA schedule to help validate and test the communication protocol which was developed in the initial CRDA tasks and described in the Phase I report delivered in October 1993. The testing of the prototype software was conducted in November 1992 at a demonstration performed at the offices of SPSi in Blacksburg, VA. At that time, the prototype version of ODYSSEY™ hardware was being used. The ODYSSEY™ to JSpace™ software link was later updated and further demonstrated at the August 1994 demonstration conducted at Tinker AFB.

¹ JSpace and JSpace Viewer are trademarks of Jacobus Technology, Inc.

The ODYSSEY™ link to the JSpace Viewer™ visualization software provides three modes of operation. The first mode is always active and provides a dynamic display of the measured point (the tip of the ODYSSEY™ measuring device) represented as a 3-D cursor. The cursor tracks within each of the windows of the JSpace viewer™, showing the location of the measured point with each position update transmitted by ODYSSEY™. The second mode of operation permits the view position of one of the JSpace Viewer™ 3-D view windows to be controlled in real-time by the measured coordinates transmitted by the ODYSSEY™ system. In this mode, the position or vantage point from which the 3-D view is generated is the position of the measured point. The orientation of the view is controlled by the user, independent of the view position, which is controlled by ODYSSEY™. The third mode of operation allows the JSpace Viewer™ to instance JSpace™ objects into the 3-D model using coordinate data transmitted by ODYSSEY™. For example, at the November 1992 prototype demonstration, several 3-D boxes were instanced into the model by “touching” with the ODYSSEY™ measuring device two diagonally opposite corners on the base of the box and one corner on the top of the box. The first two measured points define the length and width of the box, and the third point defines the height of the box. Any JSpace™ object class can be instanced in this way.

The first two modes of operation were also demonstrated at the August 1994 demonstration at Tinker AFB. The 3-D model data collected by the Odyssey system of the plating shop was transferred into the JSpace Viewer™. As the demonstration was being conducted, the position of the ODYSSEY™ measuring device was being transmitted to both a notebook PC running MicroStation™ and SpaceStation™ software and to a Silicon Graphics workstation running the JSpace Viewer™ software. The position of the measuring device was displayed in real-time on both machines simultaneously and was also used to dynamically control one of the JSpace Viewer™ windows. Together, these tests demonstrated each of the required features outlined in the description the RtCLADS system related to interfacing JSpace™ and ODYSSEY™.

3 Advantages and Limitations

The three technologies studied for this CRDA include total stations, GPS, and ODYSSEY™ (RtPM). Each of these technologies has specialized capabilities that provide specific advantages in certain tasks. Also, each has specific limitations which will limit its capabilities. This section reviews these three technologies and provides a view of their advantages in certain markets and some limitations.

Total Stations

Total stations are a proven existing technology and are fast becoming the mainstay of the survey and measurement industry. A total station includes a mechanism for measuring distance (commonly called an electronic distance measuring device (EDM)), a vertical and horizontal measuring device (commonly called a theodolite), and an onboard processor to automatically measure each of the resulting measurements. The onboard processor can have onboard memory or can be linked to a data logger in order to keep track of the day's activities. The EDM portion of the total station transmits an infrared beam that is modulated at several frequencies. Each of these frequencies are usually less than 15 MHz. The transmitted signal is received by a retro-reflector and redirected to the EDM, where the signal is interpreted through phase measurements and the distance is determined.

Total stations are an established technology and are the advanced tool of choice for surveying and construction layout. Whereas transits are still prominent in the industry, any firm wishing to do measurements of many points is quickly outpaced in production and cost. Total stations will become more dominant in the overall measurement industry as theodolites become more functionally obsolete and the price of total stations continues to become more competitive. Theodolites will continue to be used by small and large surveyors and contractors who do not perceive a need to measure many points but rather continue to set a few points and than

calculate and measure offsets to required components. Levels will continue to be used in conjunction with theodolites to determine elevations. Levels will also continue to be used in conjunction with total stations when critical elevation determination and control are required.

Total stations are used extensively for the placement of critical equipment and components for mechanical assemblies. This work is similar to construction surveying. However, this process requires set-points, or fiducials, to be established on equipment as references to aid in correctly positioning the component. The integration of RtCLADS will help to extract dimensional information for the set-points/fiducials directly from the CAD model. The functionality of RtCLADS is discussed in the section on "Advantage of Combined Capabilities of RtCLADS."

The primary limitation of total station technology is the time required to make a measurement. The time required to take each individual measurement makes the total station an excellent tool for land boundary surveying and control point determination for construction as well as other measurement processes. However, the use of total stations in real-time control of operations and equipment is limited to operations that require position update rates which are in line with the crew and/or equipment capability (i.e., hydrographic survey boats are controlled in real-time on a daily basis). The integration of CAD with total stations can reach a high level of functionality. However, batch type data transfer will remain the primary operating paradigm.

New, one-person total stations have been developed whereby the total station can track a user with a retro-reflector. These systems use servo motors to control the horizontal and vertical rotation of the total station. A dedicated total station is required for each retro-reflector making measurements.

The ultimate accuracy of information generated by a total station relies heavily on the skills of the crew and the physical limits of the users. For example, when sighting over long distances, it becomes difficult to precisely align the reticule with the center of the retro-reflector, contributing to measurement inaccuracy. The better the skill level of each member of the crew, the better the overall measurement.

The accuracy of the total station in x and y dimensions has established it as the standard within the survey and construction industry. However, due to inaccuracies in making vertical measurements, most practitioners continue to rely on high-end levels and standard leveling techniques to achieve highly accurate elevation control (Kirby 1992).

Global Positioning Systems (GPS)

GPS is a passive, one-way satellite-based positioning system operated and maintained by DoD. At the end of 1993, a 24-hr window was available for users in most locations of the world that provided (3-D) positions of latitude (ϕ), longitude (λ), and geodetic height (h).

GPS data are broadcast from the satellites on two carrier frequencies: L1 at 1575.42 MHz and L2 at 1227.60 MHz. Two pseudo-random codes are modulated onto these carrier frequencies: the Coarse Acquisition (C/A) and the Precise (P) codes. A receiver processes the satellite data to determine ranges to the satellites, and with simple geometry, to determine the receiver's position. Positioning methods use various combinations of these signals, with varying position accuracies and operational constraints.

GPS system performance is a function of the mode of operation and the type of equipment used. Absolute point positioning and differential point positioning (including kinematic GPS) are the two common modes of operation.

GPS is currently experiencing tremendous growth in sea, land, and air navigation. Absolute positioning receivers can cost under \$500 and are used on a variety of vessels, from oil tankers to fishing vessels to recreational boats. GPS is also being used for tracking in fleet operations, such as trucking, police, fire, and rescue operations. The Federal Aviation Administration is considering the use of digital global positioning system (DGPS) in aircraft approach and landing operations.

In real-time positioning, DGPS has tremendous capabilities and promise where ± 1 and ± 0.1 m are needed. Some of these markets include:

- a. *Equipment control.* Given a need for ± 0.1 -m accuracy for operations such as rough grading, mining, earth moving, etc. By mounting antennas at unique locations on pieces of equipment, the relative location of the blade, bucket, or edge can be determined. This will allow for automated control of the active edge of the equipment.
- b. *Topologic feature data collection.* Both ± 1 - and ± 0.1 -m accuracies provide unique opportunities to characterize features by simply driving a vehicle randomly over the site. This would also be used to determine the amount of excavation or fill accomplished over a given time period.
- c. *Hydrographic survey and control.* This has been shown on revetment placement on the Mississippi River. The integration of electronic data with position data should provide understandable graphical information to better guide work or movements within constricted areas.

- d. *Measurements for object placement and as-built creation.* The user could select the point of interest within the electronic data (CAD file) and watch the position of the receiver on an interactive screen as it moves toward the ultimate destination. This can be accomplished using the GeoCAD software discussed earlier. As objects are placed, an as-built is recorded.

The dominant limitation of GPS is that it must have line-of-sight to the satellites in order to achieve better than 1-m accuracy. The system therefore will not produce accurate results in enclosed areas, such as buildings or underground. Interruption of the satellite signals is also commonly encountered when any object passes between a satellite and the observer. For example, trees, bridges, towers, etc., can cause interruption to the positioning service. To a lesser extent, multi-path, or the reflection of satellite signals off surfaces, can cause sudden position shifts. This problem was more common with the initial user equipment that was available, although advanced algorithms and antenna design have minimized these occurrences.

ODYSSEY™

ODYSSEY™ is a new technology that can provide accurate real-time 3-D position measurement information about points or objects. ODYSSEY™ will be able to fundamentally alter the tolerances currently achieved in the construction environment. The first ODYSSEY™ system has been developed and demonstrated. This system provides 3-D measurement information over a 130-m range with millimeter accuracy at a 5-Hz data rate. The next generation RtPM system will be capable of millimeter accuracy over 200+ m with a 10- to 20-Hz data rate.

Longer ranges and higher update rates are anticipated in the near future. There are two primary components in an ODYSSEY™ system: transmitters and receivers. The system requires a minimum of two transmitters. More transmitters would cover a larger area of space and would allow for redundant position determination to be made as each pair of transmitters provides a position measurement. The number of receivers is up to the user since, once the transmitters are set up, any number of receivers can collect positioning signals.

Each transmitter is set on a tripod with a front face plate such that light can be scattered about the site. A battery is used to power the unit, and each 12-v battery will operate a transmitter for 30 hr. The system can also be directly wired to a standard outlet with the addition of an AC to DC converter.

The setup of the transmitters can be very quick and imprecise. The transmitters can be set up at unknown points with the face plate generally aimed at the site. This can be thought of as setting up a spotlight which is

generally aimed at the site to be illuminated. However, the energy source is infrared, which will allow only the receivers to “see” the “light.”

The site would require several known points to be established within the area of the site to be used to back-calculate the position of the transmitters. The current effort is dedicated to the development of the software and hardware to allow for setup with points within the area of the site and using a calibration algorithm to determine the location and orientation of the transmitter.

The receiver is composed of a computer and screen, two optical lenses mounted on a pole, a battery mounted on the pole, and a data entry and retrieval system. The two optical lenses form a line. The position of the lenses and the known geometry of the pole allow the point of position definition to be projected to the end of the pole. Therefore, the position of any point that the user touches with the device is accurately and “instantly” captured. Note that the position of the tip of the pole does not change if the pole is slanted, rotated, upside down, or sideways.

It is expected that ODYSSEY™ will work in many markets alongside current measurement equipment as an added tool in the overall measurement toolkit. In addition to this concurrent utilization, ODYSSEY™ has unique characteristics which provide unique capabilities.

The rapid update rate mentioned previously allows for true integration with electronic data. This integration provides tremendous potential markets within and outside the construction environment.

- a. Measurements for object placement and as-built creation.* These measurements would be quite different from today’s methods as batter boards, lines, plumb bobs, tapes, levels, and transits would not be needed. Instead, the user would select the point of interest within the electronic data and watch the position of the receiver on an interactive screen as it moves towards the ultimate destination. These measurements would be done by surveyors, construction layout personnel, and craftspeople. These measurements can also be done for object placement and to record the as-built environment.
- b. Control of equipment.* Two points make a line on the current receiver shown in Figure 2, and three points provide full dimensional and rotational information. Therefore, by mounting three receiver optics at unique locations on pieces of equipment, the relative location of the blade, bucket, or edge can be determined. This will allow for automated control of the active edge of the equipment as that edge relates to the electronic database. For example, a paver would have received optics mounted at a known location above each screw. As the paver moves about a parking lot, the exact surface geometry previously entered into the electronic data would allow for real-time control of the paver.

- c. *Robotics or remotely operated vehicle control.* Again, if one can control automatically active edges of equipment, the control of robots or vehicles either automatically or remotely is possible. This would require full integration with the electronic data and proper control systems to be developed.
- d. *Modeling of surfaces.* A close range system can provide extremely rapid update rates and extremely tight accuracies. Given these capabilities, the receiver could be traced over a surface at random to output a real-time electronic depiction of that surface. This would be useful for machining and parts assembly. Further, this would be valuable for large-scale surface modeling to determine if the pavement will pond water, how much fill has been placed in a given time period, or where the current surface profile is such that the next day's work can be planned.

There are many other potential markets; however, these four give a flavor of the overall market potential within the construction industry. A further description of potential markets is presented in the Chapter 4.

Where the system will work is also of interest. ODYSSEY™ will work indoors, outdoors, under obstacles, in urban environments, underwater, on land, in the dark, and in space. Several of these capabilities provide unique market potential.

The dominant limitations of ODYSSEY™ are the distance and the accuracy achieved. In the short term, the distance achieved can be overcome by adding cascading areas of control. This will allow individuals to move from one part of a large site to another, and a continuity of measurement would take place. However, the logistics and time required for such moves can be detrimental to success on large sites. Also this capability does not presently exist. As sensor and laser technology matures in areas of visible light and other light frequencies, ultimate distance will increase. The accuracy achieved by the system will also improve over time as the software matures. Current accuracy of one part in 10,000 at 130-meter range will improve to somewhere around one part in 100,000.

ODYSSEY™ does not need to maintain lock onto transmitters. That is to say that as soon as a receiver "sees" two or more transmitters, the position is determined instantaneously. As a final note, ODYSSEY™ is not affected by changes in temperature or humidity nor by human sighting error. ODYSSEY™ range is presently affected by visible light. Independent performance and accuracy testing is recommended before use of ODYSSEY™ on USACE projects. This should greatly reduce human error prevalent in current measurement techniques.

Combined Capabilities of RtCLADS

The CRDA envisioned a capability which was given the acronym RtCLADS (Real-Time Construction Layout and As-Built Development System). RtCLADS was envisioned as a tool to simplify the process of creating and accessing coordinate information to and from 3D-CAD models.

The fundamental idea behind RtCLADS was the motivation to allow productive work to be done by non-engineers with limited training. The goals as encompassed in the RtCLADS acronym are (a) the use of CAD data to deliver position information to craftspeople to produce a real-time construction layout capability and (b) the generation of as-built drawings with attribute tagging capability.

A further goal of RtCLADS was to allow multiple measurement devices to feed position data directly to the CAD model. Specifically, the intent was incorporating protocol exchange with the RtPM system, a total station, and the USACE's on-the-fly DGPS (OTF DGPS) system.

In order to make these goals possible, a software product, SpaceStation™, was developed by SPSI. This product was field tested during the Tinker AFB demonstration. SpaceStation™ is an MDL application built on top of MicroStation™ 5.0. A driver has also been created that allows multiple positioning devices to interact with the CAD data. This driver is the key to having the positioning devices react with the CAD data as if they were individual mouse controls similar to a current mouse driver which allows for tracking and data entry directly in a MicroStation™ design file.

The delivery of position information directly from the CAD data to craftspeople without outputting drawing or sketches will certainly enhance the layout function for construction. An individual's position can be shown interactively within the CAD model with appropriate notes about his current position with relation to his required position. SpaceStation™ has been designed to make this possible. SpaceStation™ allows access of dimensional data directly from the CAD model. The user simply selects a point of interest (such as the top corner of a footing) and then observes the position of the measurement device as it moves towards the selected point of interest. Significant performance improvement will be achieved for the measurement and layout process. A significant reduction in transcribe and taping errors will also be obtained as the raw data will be the true data for the project.

The generation of as-built drawings with attribute data is of significance to the construction industry. This need extends throughout the construction industry and includes existing facilities and new facilities. Many existing facilities have poor or no existing as-builts. Before design or construction can start, as-builts are needed. SpaceStation™ has been

designed to allow the creation of smart CAD files. "Smart CAD files" simply means files with geometric information with appropriate classification information and level structures. This will allow designers to easily expand the collected data into their design without needing new information. During construction of a project, it would certainly be beneficial to collect as-built data such that the exact status of the project is captured for the understanding of current job status and to help in the future with the various changes, operations, and maintenance issues. SpaceStation™ is designed to do this work in an interactive, easy-to-do fashion that does not require CAD training. This product is available from SPSi and is further detailed in Chapter 4. A second product, GeoCAD, is available from Intergraph Corp. for customized applications.

An additional look at potential benefits of RtCLADS is given in the following sections, where the benefits of the integration of real-time position measurement and CAD are further developed.

Potential Benefits for USACE

The USACE builds, maintains, and rehabilitates many projects and facilities in the United States and throughout the world. These projects and facilities can achieve tremendous advantages in improved quality and reduced cost. These savings are available given the utilization of RtCLADS with the ODYSSEY™ system, total stations, and GPS. The facilities for which the USACE has responsibility can be made better by the benefits of the individual measurement technologies mentioned previously. A review of some specific benefits are detailed in the following, given the integration of positioning technologies and CAD. Real-time 3-D positioning measurement provides unique benefits via this positioning/CAD link. Therefore, the benefits outlined concentrate on future benefits given this capability.

The ability to produce very accurate position data very quickly in three dimensions provides significant benefits to the surveying and measurement industry. However, the integration of position measurement information with a CAD environment provides the potential for a revolution to the construction industry.

Real-time 3-D position measurement integrated with CAD provides the necessary link of the database to the end users. These end users include surveyors, inspectors, managers, operators, and craftspeople. This capability measurement provides a link from the virtual world (the CAD database) to the real world (the project). Real-time 3-D position measurement supports information dissemination to people and control of equipment and processes within that real world.

The potential benefits to the construction industry rely on adopting 3D-CAD as the managing entity of data for electronic data interchange within all aspects of the Architect-Engineer Construction community. If this is done, the added benefit of having accurate “living” data about the facility will allow the owner to use this living database for such life-cycle activities as operations, maintenance, retrofit, renovation, rebuild, and demolition. The use of real-time position measurement to update the living project database makes possible the creation of as-builts quickly, easily, and inexpensively.

The benefits to the USACE and the construction industry fall into several categories. These include quicker and higher quality layout surveying, quicker and higher quality characterization of existing facilities, improved craftspeople performance, improved surveyor and craftspeople status, reduced rework, improved modular construction, improved as-builts, equipment performance and quality improvement, control potential for robots or autonomous vehicle, and improved overall construction control.

Quicker and higher quality layout surveying

Layout and control surveying currently account for about 1 percent of construction cost. This process typically does not rely on electronic interface of data to the real-world. Instead, this process typically relies on error-prone hand calculations and on-the-fly recalibration and adjustments.

Although the current use of total stations, transits, levels, and tapes will continue even after significant adoption of RtPM, and/or OTF DGPS, these new technologies are an addition to the overall toolkit of measurement instruments. The addition of RtPM and OTF DGPS with their speed and data access opportunities will significantly improve the overall process several-fold for a net reduction of the overall construction cost of, at a minimum, one-half to three-quarters of a percent.

As the design industry begins to design to the process of construction that best supports the use of a tool like RtPM, these overall savings are likely to improve. As the process more fully adapts to utilizing RtPM, more measurements will be made, and people with the skills to interface with the database will be required. These people with their added skills and job status will more fully interface with the CAD data and the design professionals.

Quicker and higher quality characterization of existing facilities

Many projects today include renovation, modernization, or retrofit of existing facilities. These projects account for about 40 percent of all construction dollars spent (Ichniowski 1993, *Building Design and Construction* 1986). These projects also require extensive cataloging and

characterization of existing components and their locations in order to properly plan for the work and the shut-down of the facility.

Retrofit projects require significantly more surveying and measurement than greenfield projects. The cost of this work can run 7 to 10 percent of the construction budget. ODYSSEY™ offers a tremendous advantage over current measurement devices. The target performance is to have the ability to collect data that are structured in such a format that a 3-D model can be generated directly from the built condition without reference or with limited reference to original drawings. This will eliminate the need to interpret and convert existing drawings to dimensional information to prepare a CAD file and then have to verify the CAD data to see if things are in the location that is required. With ODYSSEY™ communicating directly with a CAD modeler, the primary source of information about location and objects can be directly collected and transmitted to the CAD modeler, and objects can be placed directly into the CAD file. With better and more thorough data about the project, the project will run more quickly, more smoothly, and with fewer overall problems.

Improved craft performance

It has been estimated that only 40 percent of construction labor's time is spent doing productive work, with antiquated methods accounting for 20 percent of the lost time, administrative delays an additional 20 percent, work restrictions 15 percent, and personal time accounting for the remaining 5 percent (Tucker 1988). RtCLADS will have dramatic impact on the 20 percent lost due to antiquated methods and the 20 percent due to administrative delays.

Giving the craftspeople and the surveyors direct access to the database, whereby they can easily and graphically interface with the design data, will provide immediate productivity gains to the user. These users will not rely on someone else for information but will access the design database directly.

Once the data are accessed, they will not make transcribe errors or errors such as left side, right side, or center line of wall. The data delivery system will be designed such that people can interface with the design world with maximum advantage and minimum confusion.

Improved surveyor and craftspeople status

The idea that surveyors and craftspeople will be working directly with the design data provides tremendous opportunity for career enhancement and personal status growth for people involved with the construction industry. The interface with data that is presented and accessed through easily understood graphical formats will provide for much better communication and overall commitment to the task. More efficient communication

of the design intent and more effective interaction with the design database support the goals and objectives of many firms' total quality management programs. Although this benefit is difficult to quantify, it is one of the key issues that will define the overall construction industry culture of the future.

Reduced rework

The construction industry has long had tremendous rework. Classically, this rework has been identified as 12 percent of total construction cost. For nine fast tract projects, Burati, Farrington, and Ledbetter (1992) concluded that 12.4 percent of total construction cost went to fix deviations. *Business Week* (1982) placed the cost due to mistakes at 15 to 20 percent of construction. The reasons that rework occurs are varied and can be classified into five categories: owner changes, errors, and omissions; design changes, errors, and omissions; construction changes, errors, and omissions; vendor changes, errors, and omissions; and shipping errors and omissions. The first two (owner and design changes, errors, and omissions) account about equally for about 78 percent of the rework. Construction and vendor changes, errors, and omissions account again equally for about 16 percent of the rework (Burati, Farrington, and Ledbetter 1992).

This rework could be reduced substantially using a "living" electronic database which can be built, maintained, augmented, and redistributed as the overall construction process evolves. The ability in real-time to manage, use, change, and redistribute positioning data to all parties would be key to the overall reduction in rework.

Improved modular construction

The construction industry's increased reliance on modular assemblies will continue. The construction industry will build large assemblies off-site or at controlled locations onsite. The manufacture and the mating of these modules become more and more complex as assemblies grow in quantity, complexity, and size. RtCLADS provides the ability to interact with electronic data and to easily determine if surfaces, volumes, and interfaces are acceptable. This will provide for improved module-to-module fit, improved manufacturing processes, and increased support of modular construction.

Improved as-builts

The construction industry typically produces very poor as-builts. The reason for this is the difficulty, cost, and time required to produce the as-built. The cost to characterize existing facilities properly is often so prohibitive that contractors fall far short of proper characterization. The real

impact of incomplete as-builts is to the owner who must contract or perform future work without adequate data.

Using RtCLADS, the cost and time to generate as-built position data for plant components would drop substantially. As components are installed, their precise position can be captured and recorded directly in a CAD model for future reference.

Equipment performance and quality improvement

RtCLADS can interface with equipment to provide graphical real-time data to the operator. The operators could see equipment's active edges of their equipment (blade, auger, screed, etc.) superimposed onto the CAD design data. This will allow operators to do their tasks without requesting information and references from the survey crew. This will significantly improve equipment performance, improve operator learning, reduce the demand for support personnel, and improve the overall quality as errors in data transfer will be all but eliminated. Further, automated equipment will eventually evolve to the point where the active edge of the equipment is automatically controlled autonomously using the position information generated in real-time.

Control potential for robots or autonomous vehicle

The idea of assisting operators to perform their tasks more efficiently as outlined previously has dramatic implications to the control of robots and autonomous vehicles. A robot could move about in 3-D space and receive continuous feedback of its position (including the position and orientation of arms or appendages) within the design environment. As work is accomplished by one autonomous device, information about changes in the geometry of the work environment is sent to all other robots. This is done by updating the "living" database that continually reflects the site changes as work is accomplished. The database continuously gets updates about the current project topology as well. This allows for determination of work achieved as well as for the planning of subsequent work.

Improved overall construction control

The ability to have a database that interacts, grows, and changes with the daily changes of the construction project offers unique opportunities to the construction industry. As an example, assume a certain section of pipe is installed. By locating preestablished set-points, the user identifies the exact location of the installed component. This information is transmitted to the project database.

The database determines if the object has been installed within acceptable tolerances or if it is not within tolerances. If it is not acceptable, the database can request that the object be reworked now before future errors arise or that downstream components be modified to accept the misplaced object. The database distributes change data to all users and verifies that all users accept this changed data.

If the pipe spool is acceptable, the system catalogues the installation event. Over time, the database catalogues production achieved because as each piece or section of pipe is located and sent, a record of achieved production is available. Unit production information, as well as unit cost data would be available. Daily output and changes could be used to plan the subsequent day's activities. This integrated systems approach will drive a construction process that resembles a just-in-time manufacturing process.

4 Commercialization and Technology Transfer

Commercialization Status

This CRDA effort has contributed to the development and market introduction of several products. These products include the ODYSSEY™ system and SpaceStation™ by SPSi and the JSpace Viewer™ interface to ODYSSEY™ by Jacobus Technologies, Inc. The commercialization efforts will continue into the future to produce software and hardware products for the construction industry. A review of these commercialized products is presented in the following sections, followed by a look at future enhancements and product development.

ODYSSEY™ system

ODYSSEY™ is the name of the product developed by SPSi and described as RtPM in the CRDA and the text of this report. ODYSSEY™ is a laser-based system that is best described in the product literature appended to this report (Appendix E). Pertinent facts include a current outdoor range of 130 m and an indoor range of 130 m as well. Outdoor optical receivers are about 35 mm cubed and indoor receivers are 11 mm cubed. The system provides accuracies of 1 part in 10,000. The receivers can be configured with any number of receivers, and the base ODYSSEY™ system includes two receivers mounted in line with the point of the measurement “wand” or “pole.”

The first commercial product was delivered to Bechtel Corporation in August 1994. This system marks a major milestone in the product commercialization cycle and demonstrates the clear advantages of partnering arrangements available through consortia and CRDA. A second system has been contracted and delivery of that system will be about January 1995.

SPSi is currently able to deliver systems on a 60-day notice. SPsi will be gearing up its production and marketing staff to move from one-at-a-time manufacturing to larger scale lots. This will allow better price performance and future viability of ODYSSEY™ in the construction market.

SpaceStation™

SpaceStation™ is the name of the product envisioned in the CRDA as RtCLADS. SpaceStation™ was started in June 1994 and is ready for delivery. The first system was delivered to Bechtel Corporation in August 1994. SpaceStation™ currently can accept position data from a Nikon 700 series total station, the USACE OTF DGPS, and the ODYSSEY™ system.

SpaceStation™ was designed to allow interaction with any positioning device and the 3D-CAD model. SpaceStation™'s design utilized extensive studies of what users would need if position and CAD data could be integrated. Further, SpaceStation™ was designed for the capability of real-time position information interacting with the CAD model.

In order to accomplish these functionalities, significant prototyping and testing were done during the execution of the CRDA. User responses were obtained from project personnel, onsite personnel, members of CAPS, and student-run experiments at Virginia Tech. From this user input, SPsi developed the product.

The key to SpaceStation™ is the dynamic interaction of a positioning device moving about the 3D-CAD model. As the positioning device moves, its motions and position are tracked. A user can capture 3-D coordinates at any time a particular function is active, thus allowing quick capture of accurate 3-D data without converting to hard copy or data loggers. Again, the issue is to capture this geometric data, tag the data with appropriate notes, and record the data into various model levels consistent with design desires, thus making the data captures a true 3-D model with intelligence which can then be used for future work.

The dynamic interaction in SpaceStation™ also allows the selection of dimensional information directly from the CAD model. Once these data are selected, the user can see their position on screen as it relates to the selected object. Appropriate menus are brought up to help the user see how their position is doing relative to the selected object.

In order for this to happen, 3-D electronic project data had to be separated into a series of functions which identify all objects or components of objects in a model. Further, the project data had to be in a format such that the process of collecting information matched the process of creating or extracting objects. For example, in normal design the CAD designer inputs a pipe into the model between its center line and the radius. However, in the actual condition onsite, the user cannot measure the center line of the pipe and must settle for measuring the outside of the pipe. This

process of collecting data, therefore, had to be revised to match the real field conditions. This example and several like it lead to a separation into several palettes of object definition and functional operations on those objects.

SpaceStation™ is currently available for sale in several forms. The first is called SpaceStation™ Link™¹ which is intended for current CAD users who do not need simplified palettes to improve their performance. SpaceStation™ Link has palettes that support the specialized functions described previously. All other functions are normal MicroStation™ commands.

The second product is simply called SpaceStation™ and is intended for the non-CAD user who would like to do productive work with minimal training in the area of as-built generation and automated data extraction for component installation. SpaceStation™ allows the creation of an intelligent database which will need additional massaging by a CAD user later.

The third product is called SpaceStation™ Pro™². SpaceStation™ Pro allows full SpaceStation™ functionality, a few specialized additional functions and all MicroStation™ commands. This product is intended for the user who has a CAD background and who would like to walk away at the end of the data-collecting process with a fully defined 3D-CAD model.

JSpace Viewer™

The JSpace Viewer™ is currently available with an interface option to permit the JSpace Viewer™ to receive X,Y,Z coordinate data from ODYSSEY™. The information in Appendix g provides an overview of JSpace™ and more information on the features of the JSpace Viewer™.

Enhancements

The various products described in the previous sections are the first of their kind. As such, they provide significant functionality and capabilities to satisfy their goal of improved performance for the construction industry. These products will experience tremendous change and growth in the future as more is learned about their use and how to best apply them.

In addition to normal growth and changes through time, there are several areas or future enhancements which are currently targeted. These areas of future enhancements have been defined from the work done by CAPS in fulfillment of the CRDA.

¹ SpaceStation Link is a trademark of Spatial Positioning Systems, Inc.

² SpaceStation Pro is a trademark of Spatial Positioning Systems, Inc.

Technology enhancements

- a. *Add drivers for other measurements to SpaceStation™ software.* A significant area of future enhancements is to provide drivers for many other total stations and GPS systems. The work for CRDA allowed proof of concept for one total station and for the USACE OTF DGPS system. These products have specialized individual protocols, and each must be tailored to the interface protocol for SpaceStation™.
- b. *Disposable optics for receivers.* For several operations, it would be beneficial to have optics that can be installed on components as they are moved in space. These components could be motorized equipment, equipment for a facility, or the measurement “wands” or “poles.” Because of their exposure during normal use, it would be advisable to have replacement optics to quickly get back on-line without having to ship the optics back for repair or refit.
- c. *Increased range.* The current system was designed to achieve distances of about 100 m. There has been a significant demand for longer range optical receivers. SPSi has been developing and testing various optical designs and is confident that ranges greater than 400 m can be obtained. This increased range program will continue through time with new products moving towards longer distances in the future.
- d. *Multiple transmitters and receivers.* The current ODYSSEY™ system is configured to work with two transmitters, and the current receiver system is configured to work with two optical receivers. There is a need to allow cascading measurement areas whereby differing transmitters can be used by the various receivers. Further, there is a need to have more than two receivers working together to provide full 6 deg of motion (pitch; roll; yaw; X,Y,Z information) at one time for equipment control. Also the application of multiple receivers for paving equipment with multiple screws is of interest.
- e. *Specialized process support.* The current software and hardware has been designed to work as a generic system with many applications. As time goes by, specialized software will need to be developed to support specialized processes. These could be areas such as software for tool alignment, equipment control for pavers, equipment control for backhoes, and automated control for cranes.

Additional construction applications

- a. *Mining applications.* Mining operations, both open pit and below ground, have a need to manage the critical excavation of layers of ore and the equipment as materials are moved about. DGPS and ODYSSEY™ both provide opportunities to track equipment on open

pit mines as work progresses. The integration of SpaceStation™ can provide immediate feedback from the predefined surface layers identified within the CAD or GIS data. Automated control of the excavation equipment can allow the equipment to very accurately excavate to the desired level. Intelligent systems can also be developed to track progress and make decisions on haul road locations and equipment mix. The Odyssey system can be used for below-ground mining. This would provide for significant production gains by better planning excavation of layers of ore.

- b. Environmental cleanup.* Environmental cleanup requires the removal of contaminated materials to very specific layers. This is similar to the layer of ore problem mentioned previously. With SpaceStation™ and systems such as ODYSSEY™ or DGPS, automated control of equipment could be done whereby the active edge of the equipment is controlled to match the specified layer of removal. The location of critical contaminants could also be done when found by recording exact position, therefore, providing an additional functionality of characterizing contaminated sites.
- c. Underwater applications.* The ODYSSEY™ system was conceived and built to withstand pressure. The ODYSSEY™ transmitters can be configured to be placed underwater with little modification. A redesign of the receiver and receiver processor would be required, but this should be fairly straightforward. Range for underwater applications would be somewhat restrictive; however, laser safety issues can be relaxed, and overall range should be able to achieve better than 100 m. Underwater applications could include repair of drill rigs, quantification and repair of ships, and any other underwater construction or measurement process.
- d. Safety envelope.* During construction, objects are moved about through material handling equipment such as cranes. The objects being moved as well as the crane can be configured with optical sensors such that as they move through the 3-D space, their position, orientation, and movements can be tracked and projected on a 3-D model. Safety envelopes can be electronically defined. With online interference detection of the crane, object, and safety envelope between the existing project objects, warnings can be sounded as potential collisions or encroachment occurs. This same idea can be used for safety envelopes about underground utilities to provide warnings as equipment come into close proximity. A further extension would be to have automatic shut down or collision evidence if collision is imminent.
- e. Virtual reality.* The ODYSSEY™ system receivers can be built into very small packages. Currently, the indoor receiver is 11 mm cubed and weighs 3 g. Multiple receivers (at least three) can be mounted on a helmet and will be used as a position and orientation measurement system. By wearing stereo goggles, the user could

then move about a large area to view full scale (or to scale) 3-D models. This can be viewed as untethered virtual reality without user's sitting in one area, but rather, having the opportunity to move about freely and get a view based on how the individual maneuvers about the specific 3-D model.

A further area of use in shipbuilding is to put several optical sensors at various locations of the ship. As temperature changes cause dimensional fluctuations, variations can be interpreted and compensated. This will allow the assembling of components as they change dimensions. This is much like having a measuring stick that changes its length to match existing conditions.

Non-construction applications

- a. Medical.* During operating procedures, there is a need to view the position and orientation of the surgical tools superimposed on the electronic image of the area of surgery. This can be done with very small sensors located on the surgical tools to provide direction and/or orientation as the surgical process is done. This would be helpful for areas such as brain surgery or intricate operations to vital organs.
- b. Integration with fleet monitoring and management.* There is a need to monitor and manage equipment fleets on projects as the projects progress. The issue is to gather queuing and cycle information as the operations are progressing. In order to do this, position information would need to be gathered from DGPS or ODYSSEY™. This position information from multiple positioning systems and different pieces of equipment can be input into SpaceStation™. The location of each piece of equipment can be viewed as they move throughout the site. Information about duration in queue time and cycle time can be processed in real time to better manage the overall equipment mix as various project issues change.
- c. Manufacturing robots.* Current robots install components under the assumption that no deflection occurs in the various links of the manipulators. For large lifts as experienced in construction, this "no-deflection" assumption will not work. ODYSSEY™ can have several optical receivers on various components of the manipulator such that trajectory realignment can be done under differing loads.
- d. Integration with GIS.* GIS's provide electronic data about projects. These data are structured in layers or levels, usually depicting individual geographical features. The integration of DGPS, total station, and ODYSSEY™ position information directly into these GIS's can allow for rapid data collection and retrieval of items such as various underground utilities, surface features, and facilities themselves.

- e. *Shipbuilding.* Shipbuilding today is done by constructing large-scale modules apart from one another. These modules are then brought together for final assembly. This fitting together of modules requires that each interface be built to receive and append to another interface. The ability to measure and electronically match these interfaces will minimize full-scale model building and the necessary rework as modules are assembled.

Technology Transfer

This technology was demonstrated to the Corps of Engineers and the industry at two construction sites where real world projects were in progress. These demonstrations are further discussed on page 5. Numerous other demonstrations were conducted at various government and industry trade shows, SAME meetings, symposiums, and conferences. The system has also been presented and discussed at all Corps and Tri-Service working group meetings with interest in integrating positioning techniques with CADD technology. Various articles and papers have been published in trade magazines and journals, some of which are reproduced in this report at the appendices. An article will be published in the Tri-Service CADD/GIS Technology Center's *CADD/GIS Bulletin* to coincide with the publication and distribution of this document. The *CADD/GIS Bulletin* has Tri-Service and industry distribution. This report will be distributed to all Corps construction and engineering components as well as similar functional areas within the Army, Navy, and Air Force.

5 Conclusions and Recommendations

This report documents the successful development and commercialization of an innovative technology that promises to significantly impact the productivity of the U.S. construction industry and, hence, its competitiveness both at home and in the global arena. Significant conclusions and recommendations derive from this significant 2-year CPAR effort.

First, the CPAR Program is invaluable for the advancement of construction-related innovation. The ability of industry to leverage its own limited resources with those of a premier Federal agency ensures that more substantive research and development can be undertaken. Moreover, the expertise of USACE professionals is an invaluable adjunct to the expertise resident in industry and academia. When combined, as in this effort, the results auger well for the U.S. construction industry.

This CPAR effort has been a successful demonstration of the intended research results of the CPAR Program. The consortium has been able to fulfill all the expectations outlined in the CRDA. In sum, the intent of both phases has been realized. The consortium has created and field tested a system that greatly improves quality, speed, and accuracy of construction layout and generates real-time as-builts. Moreover, software has been developed that successfully integrates various positioning devices with existing CAD/CAE systems. It is the belief of CAPS members that the consortium approach has strong advantages for CPAR-type efforts; the broad-based expertise and resources inherent in a consortium add valuable leverage to inherently scarce CPAR resources.

The results of this CPAR effort fulfill the ultimate intent of the CPAR charter, namely to advance the productivity and competitiveness of the U.S. construction sector. The advantages inherent in the integration of real-time site positioning and 3D-CAD have been outlined elsewhere in this report (see Chapter 3). In addition, the technology has many cross-cutting applications, in fields as diverse as medicine and space; these have likewise been identified elsewhere in the report.

The completion of this CPAR-CRDA relationship has resulted in a commercially available set of products. There remains ample opportunity for additional research and development to further enhance the capabilities of RtCLADS. For example, RtCLADS will emerge as a more powerful construction site tool if additional focus is placed upon identifying metrics for improvements in productivity, cost savings, work processes, etc. The CAPS consortium therefore recommends that a future CPAR effort be developed that addresses these issues, among others.

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Appendix A

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Appendix B

Computer-Aided Design (CAD)

Communication Protocol

Overview

Consortium for Advanced Positioning Systems CAD Communications Protocol

1. Introduction

The intent of the CAD communications protocol is to provide a standard way in which positioning data from a variety of 3D measurement devices can be integrated with computer-aided design (CAD) systems. In this sense, CAD is also intended to encompass the use of CAD data to display positioning information graphically, such as real-time 3D displays.

1.1 Objectives

In addition to supporting multiple measurement devices, the protocol is intended to satisfy a number of other objectives:

- Allow for bi-directional communication between the 3D measurement device and the CAD systems.
- Provide capabilities for both real-time and batch transmission of coordinate data.
- Allow for both single point coordinates and continuous streams of coordinates.
- Allow for asynchronous communication between the measurement device and the CAD system.
- Support the communication of both commands and data, either from the measurement devices or the CAD system.
- Provide a framework which is extensible, i.e., the protocol is easily extended to include new commands or new data types.

1.2 Approach

The basic mechanism by which the CAD system and the measurement system communicate is via "messages." Messages may contain commands or measured data. Messages may also flow in both directions. For batch collection of data, or for batch transmission of commands, the syntax of the messages will be the same.

2. Syntax and Content

The syntax and content for the proposed protocol is defined using the Backus-Naur Form (BNF). In the convention used here, the concepts being defined are enclosed by <>. Literal values are shown without <>. The ::= symbol signifies 'defined as.' The vertical bar, |, signifies OR. For simplicity, this definition of the protocol does not include and separators, e.g., commas or blank spaces.

```
<message> ::= <begin message code>
               <message header> <message item> <check sum>
               <end message code>
```

A message is the fundamental unit of communication. Any information or commands transmitted is included within a command.

```
<message header> ::= <origin> <destination> <time stamp>
                    <message text> <acknowledge code>
```

The message header defines basic information about the message being transmitted.

```
<message item> ::= <command item> | <data item> | <NULL>
```

The message item represents the information being communicated by the message. It is either a command item or a data item.

```
<command item> ::= <command item code>
                   <command name> <command arguments>
                   <command text> <end item code>
```

A command item transmits a command to be executed by the receiving device. Arguments may be transmitted with the command.

```
<command arguments> ::= <open list code> <argument list> <close list code>
<argument list>      ::= <argument string> | <argument string> <argument list>
```

The command arguments are sent in a list whose length varies with the specific command.

```
<data item> ::= <data item code> <coordinate code> <delta code>
                <type code> <units code> <data ID> <data text>
                <open list code> <value list> <close list code>
                <end item code>
```

```
<value list> ::= <value vector> | <value vector> <value list>
```

A data item transmits either position, velocity, or acceleration vectors (including rotation). A data item may include a list of vectors. The definition of the coordinate system, type of vector, units of measure, and whether the vector is being given in absolute coordinates or relative to the last vector is contained within the data item. A unique identifier may be assigned to a data item.

<value vector> ::= <value> <value> <value> <value> <value> <value>
<time stamp> <value ID>

The value vector contains the actual data for the vector. Provisions are made to allow the vector to be assigned a unique ID if desired.

<begin message code> ::= MESSAGE
<end message code> ::= END_MESSAGE
<command item code> ::= COMMAND
<data item code> ::= DATA
<end item code> ::= END_ITEM
<open list code> ::= [
<close list code> ::=]

The various codes are used to signify the beginning and end of the message and sub-parts of the message. These literal strings could be reduced to single character control codes to reduce message size.

<origin> ::= <character string>
<destination> ::= <character string>

The origin and destination are node names assigned to the measurement device and the CAD system.

<time stamp> ::= <character string>

A time stamp indicates the time at which a message was sent or when a value vector was measured.

<argument string> ::= <character string>

An argument string is a character string with the value of a specific command argument.

<message text> ::= <character string>
<command text> ::= <character string>
<message text> ::= <character string>

These are character strings which may be optionally used to transmit text to be displayed or interpreted by the receiving system.

<command name> ::= SEND_COORDINATE | SEND_VELOCITY | SEND_ACCELERATION |
TRACE_LINE | TRACE_LINestring | TRACE_POLYGON |
etc.

This is the name of the command to executed by the receiving system.

<coordinate code>	::=	CARTESIAN POLAR etc.
<delta code>	::=	ABSOLUTE RELATIVE
<type code>	::=	POSITION VELOCITY ACCELERATION
<units code>	::=	FEET METERS CUBITS etc.

These codes define the conventions used when transmitting a value list.

<data ID>	::=	<character string>
<value ID>	::=	<character string>

These are unique identifiers for data items and value vectors. These would be optional in many cases.

<value>	::=	<floating point number>
---------	-----	-------------------------

This is the value for an individual component of a value vector.

<character string>	::=	"<literal string>"
<NULL>	::=	

3. Examples of Communications

3.1 Request and receive coordinate value:

```
MESSAGE
"PC01" "RtPM01" "10:15:00"
"REQUESTING POINT"
COMMAND
  REQUEST_COORDINATE ["C1"]
  "SEND CURRENT POSITION"
END_ITEM
END_MESSAGE
```

```
MESSAGE
"RtPM01" "PC01" "10:15:10 "
"SENDING POINT"
DATA
  CARTESIAN ABSOLUTE POSITION FEET
  "C1" "I AM HERE"
  [
    15.5 23.45 3.68 0.0 0.0 0.0
    "10:15:09" "C1"
  ]
END_ITEM
END_MESSAGE
```

Request and receive polygon:

```
MESSAGE
"PC01" "RtPM01" "10:15:00"
"REQUESTING POLYGON"
COMMAND
  TRACE_POLYGON ["P1"]
  "SEND BUILDING OUTLINE"
END_ITEM
END_MESSAGE
```

```
MESSAGE
"RtPM01" "PC01" "10:15:10"
"SENDING POLYGON VERTICES"
DATA
  CARTESIAN ABSOLUTE POSITION FEET
  "P1" "POLYGON VERTICES"
  [
    5.0 2.0 1.5 0.0 0.0 0.0
    "10:08:11" "P1.1"
    10.5 2.0 1.7 0.0 0.0 0.0
    "10:10:35" "P1.2"
    10.5 27.3 1.7 0.0 0.0 0.0
    "10:14:43" "P1.3"
  ]
END_ITEM
END_MESSAGE
```

```
MESSAGE
"RtPM01" "PC01" "10:22:10"
"POLYGON COMPLETE"
COMMAND
  CLOSE_POLYGON ["P1"]
  "I AM FINISHED"
END_ITEM
END_MESSAGE
```

3.2 RtPM initiates creates multiple line strings:

MESSAGE

```
"RtPM01" "PC01" "10:20:15"  
"TRACING LINE STRING"  
COMMAND  
  CREATE_LINestring [ "S1" ]  
  "CREATING FIRST STRING"  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"RtPM01" "PC01" "10:27:20" ""  
DATA  
  CARTESIAN ABSOLUTE POSITION FEET  
  "S1" ""  
  [  
    105.67 213.14 4.67 0.0 0.0 0.0  
    "10:20:21" "S1.1"  
    114.45 220.06 5.73 0.0 0.0 0.0  
    "10:22:14" "S1.2"  
    136.14 230.34 5.70 0.0 0.0 0.0  
    "10:26:56" "S1.3"  
  ]  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"RtPM01" "PC01" "10:28:12"  
"TRACING LINE STRING"  
COMMAND  
  CREATE_LINestring [ "S2" ]  
  "CREATING SECOND STRING"  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"RtPM01" "PC01" "10:39:20" ""  
DATA  
  CARTESIAN ABSOLUTE POSITION FEET  
  "S2" ""  
  [  
    215.67 213.14 4.67 0.0 0.0 0.0  
    "10:31:21" "S2.1"  
    224.45 220.06 5.73 0.0 0.0 0.0  
    "10:35:14" "S2.2"  
    245.14 230.34 5.70 0.0 0.0 0.0  
    "10:38:56" "S2.3"  
  ]  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"RtPM01" "PC01" "10:39:45"  
"END LINE STRING"  
COMMAND  
  END_LINSTRING [ "S2" ]  
  "LINE STRING 2 COMPLETE"  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"RtPM01" "PC01" "10:48:20" ""  
DATA  
  CARTESIAN ABSOLUTE POSITION FEET  
  "S1" ""  
  [  
    145.67 243.14  4.67 0.0 0.0 0.0  
    "10:40.21" "S1.4"  
    154.45 250.06  5.73 0.0 0.0 0.0  
    "10:42.14" "S1.5"  
    166.14 270.34  5.70 0.0 0.0 0.0  
    "10:46.56" "S1.6"  
  ]  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"RtPM01" "PC01" "10:49:45"  
"END LINE STRING"  
COMMAND  
  END_LINSTRING [ "S1" ]  
  "LINE STRING 1 COMPLETE"  
END_ITEM  
END_MESSAGE
```

3.3 Initialize construction equipment transmitter:

MESSAGE

```
"SGI01" "TRUCK01" "11:36:45"  
"INITIALIZING TRUCK 1"  
COMMAND  
  SET_POSITION  
  [  
    210.45 103.05 14.56 0.0 0.0 34.1  
    CARTESIAN FEET  
  ]  
  "CALIBRATING POSITION"  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"SGI01" "TRUCK01" "11:36:45"  
"SETTING UPDATE RATE - TRUCK 1"  
COMMAND  
  UPDATE_POSITION [ 10.0 DELTA ]  
  "UPDATE EVERY 10 SECONDS"  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"TRUCK01" "SGI01" "11:37:00" ""  
DATA  
  CARTESIAN DELTA POSITION FEET "" ""  
  [ 10.7 15.4 3.6 0.0 0.0 3.5 ]  
  "11:37:00" ""  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"TRUCK01" "SGI01" "11:37:10" ""  
DATA  
  CARTESIAN DELTA POSITION FEET "" ""  
  [ 11.3 1.5 5.7 0.5 0.0 0.5 ]  
  "11:37:10" ""  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"TRUCK01" "SGI01" "11:37:20" ""  
DATA  
  CARTESIAN DELTA POSITION FEET "" ""  
  [ 11.1 2.5 0.7 0.0 0.0 0.0 ]  
  "11:37:20" ""  
END_ITEM  
END_MESSAGE
```

MESSAGE

```
"TRUCK01" "SGI01" "11:37:30" ""  
DATA  
  CARTESIAN DELTA POSITION FEET "" ""  
  [ 11.1 2.5 0.7 0.0 0.0 0.0 ]  
  "11:37:30" ""  
END_ITEM  
END_MESSAGE
```

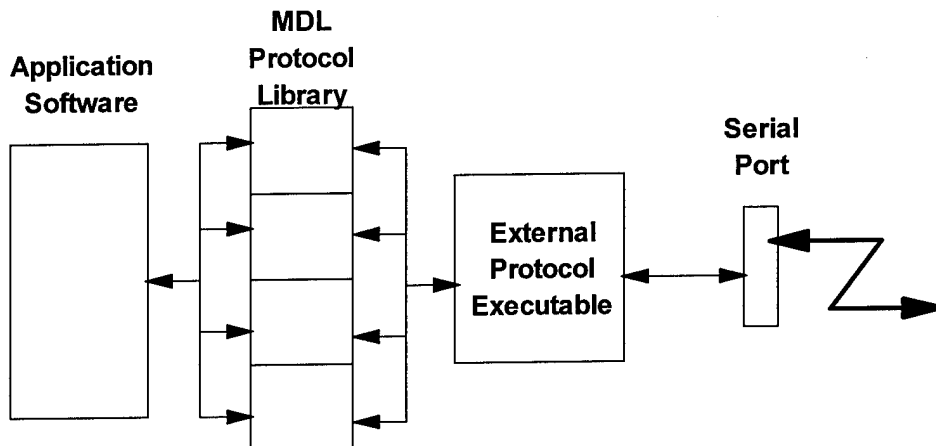
MESSAGE

4. MicroStation Interface

In order to facilitate the integration of positioning devices, which support this protocol, with applications software, a standard library of software will be established to be used by applications developers. This library will consist of a subroutine library for the MicroStation Development Language (MDL). The library is referred to as the MDL Protocol Library. This will include MDL-callable routines as well as an external program communicating with the MDL software. This implementation will make it much easier for applications developers to implement new software.

4.1 Basic Functions

The protocol library will handle functions such as communicating with the serial port, parsing incoming protocol messages, formatting outgoing protocol messages, and directing the output to a file for batch data collection. Commands and message data will be communicated via C data structures which the application software will send to and receive from the MDL Protocol Library. The basic architecture of the MDL Protocol Library and its integration with application software is shown in the figure below:



The basic functions performed by the MDL Protocol Library are described in the following paragraphs.

- Initialize serial port.

This function will set the various parameters of the local serial port, such as baud rate, data bits, parity checking, etc.

- Open serial port

This function will enable the serial port to send and receive data.

- Close serial port

This function will disable the serial port and suspend communications with other workstations.

- Open file

This function will open a file to contain messages generated by the application program. This will allow batch collection or batch processing of protocol messages.

- Close file

This function will close the file being used in lieu of the serial port.

- Send protocol message

This function will send a protocol message via the serial port. The calling application program will define the message content via a C data structure (see Section 4.2) and pass this structure to this function. The calling program can pass an array of these C structures which will be transmitted sequentially. Alternatively, the calling program can specify that the messages are to be written to a text file rather than the serial port. This option will provide the capability for batch collection of data.

- Receive protocol message

This function will retrieve incoming protocol message(s) from the serial port and parse the message(s) into the same C data structure used to transmit messages. The calling program can instruct the function to retrieve the last, next, or all of the messages received. Alternatively, the calling program can specify that the messages are to be retrieved from an open text file rather than the serial port. This option will provide the capability for processing data generated in a batch mode.

4.2 Data Structures

The basic data structures to be used in passing messages between the application program and the MDL Protocol Library is defined below:

```

/*****
This header file defines the various C data structures and
codes associated with the MDL Communications Protocol for the
Consortium for Advanced Positioning Systems (CAPS).
*****/

#ifndef __JIOPROTO__
#define __JIOPROTO__

enum Jp_COMMAND_NAME {Jp_SEND COORDINATE, Jp_SEND VELOCITY};
enum Jp_ITEM_TYPE {Jp_COMMAND, Jp_DATA, Jp_NULL};
enum Jp_COORDINATE_CODE {Jp_CARTESIAN, Jp_POLAR};
enum Jp_DELTA_CODE {Jp_ABSOLUTE, Jp_RELATIVE};
enum Jp_TYPE_CODE {Jp_POSITION, Jp_VELOCITY};
enum Jp_UNITS_CODE {Jp_FEET, Jp_METERS};

typedef struct
{
    int id;
    char *date;
    double *value;
    int length;
} JP_VALUE_VECTOR;

typedef struct
{
    Jp_COORDINATE_CODE coord;
    Jp_DELTA_CODE delta;
    Jp_TYPE_CODE type;
    Jp_UNITS_CODE units;
    char *id;
    char *descrip;
    JP_VALUE_VECTOR *vector;
    int count;
} JP_DATA_ITEM;

typedef struct
{
    Jp_COMMAND_NAME name;
    char *descrip;
    char **argv;
    int argc;
} JP_COMMAND_ITEM

```

```
typedef struct
{
    char          *origin;
    char          *destination;
    char          *date;
    char          *descrip;
    int           notify;
    Jp_ITEM_TYPE  type;

    union
    {
        JP_COMMAND_ITEM  command;
        JP_DATA_ITEM     data;
    };
} JP_MESSAGE_ITEM;
```

Appendix C

Real-Time Position Measurement Integrated with CAD: A Survey of Technology and Protocols

Real-Time Position Measurement Integrated With CAD:

A Survey Of Technology And Protocols

by Yvan J. Beliveau¹ , J. Michael Williams² , M. Gerald King³ , Anthony R. Niles⁴

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Abstract

The Consortium for Advanced Positioning System (CAPS) was formed in December 1992. The purpose of CAPS is to assist CERF with the CRDA. Towards this endeavor CAPS will field and test a new real-time laser based technology, real-time DGPS, and total stations to determine areas of functionality and how to best integrate these measurement devices towards the goal of improving the work process and as-building capabilities.

The founding members of CAPS are Bechtel Corporation, Spatial Positioning Systems, Inc., Jacobus Technology, Inc., and the Civil Engineering Research Foundation (CERF).

The US Army Corps of Engineers (Corps) is participating in CAPS through a Cooperative Research and Development Agreement (CRDA) with CERF. The objective of the CRDA is to create and field test a system that improves quality, speed, and accuracy of construction layout and generates real time as-builts. This effort encompasses the integration of the above mentioned new laser-based positioning system, total stations, and DGPS with CAD/CAE systems to form a Real-time Construction Layout and As-built Development System (RiCLADS).

The founding members of CAPS along with a new member (Intergraph Corporation) are supporting the goals and tasks specified in the CRDA. This report is a product of the group and a deliverable under the terms of the CRDA.

Executive Summary

Construction is inherently and ultimately a field activity. The various components that comprise a building, a process facility or a power plant have one thing in common: they must be located accurately in their designed position. The field positioning of construction components is one of the most fundamental and pervasive of all construction activities.

There are a number of new positioning technologies available today. These new systems can provide digital position data using local or global coordinate systems, with varying degrees of accuracy. In order to fully utilize these systems, we are challenged to reassess the way that design information is developed and communicated to the field and the way that field personnel use that data to physically locate components.

However, obtaining 3D coordinate data is only one half of the implementation equation. The field data that is generated by the new generation of positioning technologies must be easily reduced to usable information about the location of specific components or control points at the construction site.

The full power of real-time positioning systems is only realized when the systems are linked to project CAD and database applications so that the data generated can be effectively transformed into useful information to guide project activities.

The integration of real-time positioning with CAD provides the opportunity for Real-time Construction Layout and As-built Development System (RtCLADS) to be created and demonstrated. RtCLADS provides a critical link between CAD design/construction and operations/maintenance. The utilization of Geographic Information Systems (GIS) is also increasing in the construction industry; or more realistically, CAD 3-D capabilities are approaching the needed functionality to provide GIS capability directly without going to a specialized GIS system. This utilization of GIS will allow for layering of system information throughout a facility and to maintain needed data throughout the operations, maintenance, retrofit, and decommissioning of the systems and facility.

This report first describes CAPS, an industry consortium dedicated to the development and demonstration of a new positioning system. It then describes three of the most important positioning technologies: the new laser based positioning system by SPSi, Total Stations, and differential applications of the Global Positioning System (DGPS). It also provides a brief description of several other emerging positioning technologies. The report provides an overview of existing communication protocols and issues to data exchange for an integrated RtCLADS. Finally, the report addresses benefits and issues related to project implementation of real-time positioning systems.

This paper serves as a report for a Cooperative Research and Development Agreement (CRDA) between the Civil Engineering Research Foundation and the US Army Corps of Engineers.

1.0 Introduction

One of the fundamental construction operations is that of locating and positioning components in the field. These activities are typically performed by surveyors and inspectors using equipment such as theodolites, levels, total stations, and chains or tapes. These methods provide the required degree of accuracy and precision for the construction industry. These methods are laborious, time consuming, expensive and susceptible to errors in collecting, transcribing and reducing data.

There are a number of alternative positioning technologies that provide three dimensional (3D) coordinate data. These technologies are evolving rapidly. Data accuracy and processing power are increasing, while implementation costs are decreasing.

In December of 1992, an industry consortium was formed to address the issue of developing and demonstrating a new real-time laser-based positioning system. The purpose of the Consortium for Advanced Positioning Technologies (CAPS) is to develop and demonstrate new positioning technologies. CAPS's objectives include the fielding of a new generation, state-of-the-art laser-based positioning system; developing the software that allows the system to communicate with CAD environments; demonstrating the capabilities and effectiveness of the system through on-site tests at a construction project; and reporting the results of the project.

The founding members of the consortium, Spatial Positioning Systems, Inc. (SPSi), Jacobus Technology, Inc., Bechtel Corporation, and the Civil Engineering Research Foundation (CERF) formally initiated the consortium in December 1992. Intergraph Corporation joined CAPS in June of 1993.

The positioning system is based on hardware developed and patented by Spatial Positioning Systems, Inc. SPsi's system consists of multiple laser-based transmitters and portable receivers that can be maneuvered through the work space to provide real-time, digital position data. The primary capabilities include rapid update rates (at least 10 times per second) of positioning data in three dimensions with accuracies that meet or exceed current requirements for construction operations.

Jacobus Technology has created a powerful object-oriented programming and modeling environment called JSpaceTM ¹. JSpace can interpret signals from the positioning receiver and convert them into a CAD model of the object being measured. JSpace can also send data to the positioning device, enabling the user to locate components or set reference points that have been modeled in the CAD environment.

Bechtel is funding a portion of the development costs and is contributing field expertise from a user perspective. Bechtel will also manage a series of system demonstrations on Bechtel projects under actual field conditions.

Intergraph Corporation is developing software to integrate the CAD data with the positioning technology. Graphical screens have been developed such that users can select points or surfaces of interest from the CAD model and direct the positioning device to the selected points or surfaces. Further the work allows for immediate capture of measured points which can be recorded and transmitted to other users and directly to the CAD model.

In December 1992, the Civil Engineering Research Foundation entered into a Cooperative Research and Development Agreement (CRDA) with the US. Army Corps of Engineers. CERF performs CAPS management functions, such as arranging and chairing meetings and making distributions of reports to members. The Corps of Engineers is contributing both matching funds and in-kind services to the CAPS development effort. The primary objectives of the CRDA is consistent with the goals of CAPS and goes further to seek a Real-time Construction Layout and

¹JSpace is a trademark of Jacobus Technology, Inc.

As-built Development System (RtCLADS) which can be used with SPSi's laser based 3D positioning technology, total stations, and DGPS.

RtCLADS is envisioned as a system operating at a large construction site with an interactive data access and retrieval system with multiple users utilizing multiple measurement devices. These measurement devices are interacting with the overall project data base and possibly with one another. RtCLADS requires several bits of hardware and software to operate efficiently. The first major bit of hardware and software required is a central CAD platform which run the selected CAD package and has data links to the various positioning devices working concurrently over the site. For this to work effectively, each positioning device would need some data logging capability which would search for a time slot to interact with the central CAD data base. For these various devices to work concurrently, the protocol that will be generated during this effort must be designed to work with multiple devices attempting to access and deliver data. The software and hardware at some of the devices may also need to interact with the CAD data on a real-time basis. This will require that interactive capabilities be developed between the CAD data and the positioning devices. The data transmission from the various positioning systems (to the central data base, to their own data base, or to each other) will have to be sent by hardwire or RF modems. Using hardwire is good for some applications but on a dirty construction site with equipment running around there is a need for RF modems as the primary data transmission capability. Given these capabilities and the various pieces of hardware and software to run each of the positioning devices, the full intent of RtCLADS will be realized.

As the first product of this unique collaborative effort, this report focuses on three positioning technologies: Total Stations, DGPS, and a new state-of-the-art laser-based system. It then offers a brief description of several other emerging positioning technologies, provides a look at data communication protocols for RtCLADS, and closes with a discussion of implementation issues. Before starting with the review of the three technologies a brief look at the topographic survey control requirements for the US Army Corps of Engineers (USACE) is provided.

2.0 USACE Survey Standards

The USACE is producing an engineer manual for topographic surveying (Department of the Army, 1993c) which identifies the various levels of surveying accuracies expected for differing USACE processes. A quick overview of this report is presented below.

The USACE has a set of classification and point closure standards for horizontal control surveys. There are five survey classifications and each has a point closure standard which is given as a ratio. These are as follows: 1) Second Order Class I --- 1:50,000, 2) Second Order Class II --- 1:20,000, 3) Third Order Class I --- 1:10,000, 4) Third Order Class II --- 1:5,000, 5) 4th Order-Construction layout --- 1:2,500 to 1:20,000.

The USACE has point closure standards for vertical control surveys as well. There are four classifications for vertical control surveys with a differing point closure standard for each given in feet. This point survey closure standard is a function of the total distance in miles of the line of circuit. A factor times the square root of the distance in miles (shown as $\sqrt{M}$ below) is given as the standard for each classification. These standards are as follow: 1) Second Order Class I --- $0.025\sqrt{M}$ feet, 2) Second Order Class II --- $0.035\sqrt{M}$ feet, 3) Third Order --- $0.50\sqrt{M}$ feet, 4) 4th Order-Construction --- $0.100\sqrt{M}$ feet.

The manual (Department of the Army, 1993c) also provides a table (Table 2-1) of accuracies and tolerances of various USACE surveying and mapping requirements for military construction, civil works, operations, maintenance, real estate, and hazardous and toxic waste projects (HTW). General observations from the table showed that higher order surveys requiring relative line accuracies exceeding 1:50,000 are rare for USACE applications (The table showed only two entries where Second Order Class I was required.). Further, surveys requiring first-order

(1:100,000) or better were not within the scope of the table. There are 49 different types of projects or activities in Table 2-1. Only six of these entries require accuracies of better than third order. The reader should refer to the report for more specific information on the various accuracies required by the USACE.

The three positioning technologies developed below (Total Stations, GPS, and RtPM™) can or expected to meet many of the accuracies mentioned above. A brief look at each of these technologies vis-a-vis the closure standards given above will be explained to a limited degree below.

Most total stations are advertised as being able to meet first, second, third and fourth order of both horizontal and vertical control. Some doubt is cast on achieving first and second order vertical control (Kirby, 1992); however, no doubt is cast on horizontal control except for first order control requirements with some less accurate total stations. For more information, refer to (Reilly, 1993).

DGPS used in static mode, where a point is occupied for an hour or more, can provide accuracies sufficient for even first order 3-D control. However, for dynamic, real-time applications, which is the context of this report, current DGPS systems can provide accuracies in the one meter range and would not provide accuracies consistent with the control survey requirements of USACE. Current development efforts will enable centimeter-level real-time accuracy (discussed further in this report). Therefore, DGPS could eventually be applied to various real-time control surveying applications.

RtPM™ (Real-time Position Measurement) technology has the promise to achieve all orders of horizontal and vertical control. However, for the short term, accuracies of 1:20,000 are the targeted capability. This means that RtPM™ technology should achieve up to second order class II in horizontal and vertical control surveys early on in its product development. Long term theoretical accuracies promise accuracies exceeding first order control requirements.

3.0 Total Stations

Total Stations are a proven existing technology which are fast becoming the mainstay of the survey and measurement industry. A total station includes a mechanism for measuring distance (commonly called an electronic distance measuring device or an EDM), a vertical and horizontal measuring device (commonly called a theodolite), and an on-board processor to automatically measure each of the resulting measurements. The on-board processor can have on-board memory or can be linked to a data logger in order to keep track of the days activities. EDM's and theodolites have been utilized since the late 1960's. They were initially used without integration and electronic recording of measurements. However, today most of these devices have been integrated to form the total station.

The EDM portion of the total station transmits an infrared beam that is modulated at several frequencies. Each of these frequencies are usually less than 15 MHz. The transmitted signal is received by a retroreflector and redirected to the EDM where the signal is interpreted through phase measurements and the distance is determined.

3.1 Total Station Performance

Total stations come with various performance characteristics. These characteristics usually include the range, the vertical angle accuracy, the horizontal angle accuracy, and the distance accuracy. The measurement time is also usually given.

The maximum effective ranges of total stations vary from 800 meters to 9000 meters (Department of the Army, 1993a). The maximum effective ranges given above are achieved by increasing the number of retroreflector prisms that can be grouped together. This increases the amount of infrared signal that can be redirected back to the EDM. Some total stations have specifications that claim distances of 40,000 to 50,000 meters (Reilly, 1993). Measurements in these ranges would have

very little applicability for most construction sites. The use of such long baselines would also stress the limits of the angular accuracies of total stations and provide for excessive errors in the position coordinates. The price goes up dramatically for these long range systems and only two systems reported that they achieved distances in this range.

Distance accuracies also vary. Accuracies range from ± 1 mm and 1 ppm to ± 300 mm and 3 ppm for longer range total stations, with a typical working accuracy of about ± 3 mm and 3 ppm. The vertical and horizontal angle measurements have accuracies which range from a low of one second to a high of 10 seconds with a median of about three seconds.

Various other errors internal to the total stations will add an additional error in the ultimate accuracy of the system. These errors will typically add 25 to 100 % to the reported vertical and horizontal errors. The measurement time for the total stations reported ranged from a low of 1.5 seconds to 5 seconds once visual alignments and acceptable fix of the retroreflector were completed.

3.2 Total Station Update Rates

Total stations update rates are more a function of the crew utilizing the equipment rather than the limitation of the total station itself. The setup procedure described below can take between 5 and 15 minutes depending on the size of the site, accessibility to points, and the skill of the crew. Once setup, the total station can rapidly obtain position information related to specific points. Each measurement will typically take from 30 seconds to 2 minutes. Setting points requires repetitive trial and error and can take from 2 minutes to 5 or more minutes for each point, excluding setup time. The set-up procedure is given below.

3.3 Total Station Setup

Total stations can obtain position information related to any random point. Conversely, they can be used to set points at specific coordinates. Setting a random point is generally easier than setting a point at a specific coordinate location.

For setting a random point, a survey crew must set a monument or some other fixed marker, then hold a retroreflector plumb above the point in question and oriented in the direction of the total station.

Before "shooting" this point, the total station would need to be in a known location and known orientation. The total station location is determined in one of two ways. If the total station is set above a known point, the user simply needs to know how high above the known point the total station is set and then do an alignment to another known point. If the user is set up above a random point, the user must back sight to two known points and determine distance, horizontal angle, and vertical angles to both points. Once this is done the total station can calculate where it is and its orientation.

The user is now ready to take a measurement. The user would then sight in the retroreflector being held plumb above the point to be measured, activate the EDM and the total station would identify the position of the fixed point. This overall process of determining position of a random point will take several minutes for the first measurement. However, measuring additional points will only require that the crew member with the retroreflector walk to the next point and hold the retroreflector plumb above this point. The crew member at the total station will sight this point, activate the EDM and determine its position in rapid order with typical position determination taking under one minute.

The process of setting a specific point would require everything mentioned above except that the crew member at the total station would need to turn a specific horizontal and vertical angle. These horizontal and vertical angles are determined with reference to the current total station position and orientation. Calculations can be done remotely or at the total station using an additional hand held computational device appended to the total station. The crew member at the total station can then use verbal commands (i.e., shouting or radio link) or hand signals to direct the crew member with

the retroreflector to a desired alignment. The total station is used to measure distance and repeated adjustments are done by redirecting the crew member with the retroreflector to new and sequentially more precise points approaching the required specific point. The operation of measuring vertical and horizontal angles can be done concurrently or can be separated to simplify the operation. This would require another operation to determine the elevation of the point when the x and y locations have been determined.

3.4 Total Station Markets

Total stations are an established technology and are the advanced tool of choice for surveying and construction layout. Whereas transits are still prominent in the industry, any firm wishing to do measurements of many points is quickly outpaced in production and cost. Total stations will become more dominant in the overall measurement industry as theodolites become more functionally obsolete and the price of total stations continues to become more competitive. Theodolites will continue to be used by small and large surveyors and contractors who do not perceive a need to measure many points but rather continue to set a few points and then calculate and measure offsets to required components. Levels will continue to be used in conjunction with theodolites to determine elevations. Levels will also continue to be used in conjunction with total stations when critical elevation determination and control is required.

Total stations are used extensively for the placement of critical equipment and components for mechanical assemblies. This work is similar to construction surveying. However, this process requires set-points, or fiducials, to be established on equipment as references to aid in correctly positioning the component.

3.5 Total Station Limitations

The primary limitation of total station technology is the time required to make a measurement. The time required to take each individual measurement makes the total station an excellent tool for measurement for land boundary surveying and control point determination for construction as well as other measurement processes. However, the use of total stations in real-time control of operations and equipment is limited to operations that require position update rates which are in line with the crew and/or equipment capability. (i.e. Hydrographic survey boats are controlled in real-time on a daily basis.) The integration of CAD with total stations can reach a high level of functionality. However, batch type data transfer will remain the primary operating paradigm.

New, one-person total stations are being developed whereby the total station can track a user with a retroreflector. These systems utilize servo motors to control the horizontal and vertical rotation of the total station. A dedicated total station is required for each retroreflector making measurements.

The ultimate accuracy of information generated by a total station relies heavily on the skills of the crew and the physical limits of the users. For example, when sighting over long distances, it becomes difficult to precisely align the reticule with the center of the retroreflector, contributing to measurement inaccuracy. The better the skill level of each member of the crew, the better the overall measurement.

The accuracy of the total station in x and y dimensions has established it as the standard within the survey and construction industry. However, due to inaccuracies in making vertical measurements, most practitioners continue to rely on high-end levels and standard leveling techniques to achieve highly accurate elevation control (Kirby, 1992).

4.0 Global Positioning System (GPS)

GPS is a passive, one-way satellite-based positioning system operated and maintained by the Department of Defense (DOD). At the end of 1992, a 24-hour window was available for users in most locations of the world that provided two-dimensional (2D) positions of latitude (ϕ) and

longitude (λ); three-dimensional (3D) positions of ϕ , λ , and geodetic height (h) could also be obtained but at more limited times. The full constellation will consist of 24 satellites. As of 12 June 1993, 23 satellites were available for positioning service. Three of these satellites are Block I, or first generation space vehicles which have exceeded their life spans and could be deactivated at any time. However, with additional launches of newer satellites, the system is expected to provide 24-hour 3D coverage by the end of 1993.

GPS data is broadcast from the satellites on two carrier frequencies; L1 at 1575.42 MHz and L2 at 1227.60 MHz. Two pseudo random codes are modulated onto these carrier frequencies; the Coarse Acquisition (C/A) and the Precise (P) codes. A receiver processes the satellite data to determine ranges to the satellites, and with simple geometry, determine the receiver's position. Positioning methods use various combinations of these signals, with varying position accuracies and operational constraints.

4.1 GPS Performance

GPS system performance is a function of the mode of operation. Absolute point positioning and differential point positioning (including kinematic GPS) are the two common modes of operation.

Absolute Point Positioning

Absolute point positioning refers to the positioning of a point by a single receiver. The position accuracies attainable are dependent on the user's ability to access the commonly available Standard Positioning Service (SPS) or the restricted Precise Positioning Service (PPS). In a process known as Selective Availability, DOD intentionally degrades time and satellite position information to SPS users, thereby reducing position accuracy. The real-time absolute position accuracy that the different GPS users can expect are as follows:

PPS users 16 meters SEP

SPS users 100 meters 2 DRMS with Selective Availability turned on

Note that Selective Availability is not always activated, and SPS users may be able to achieve accuracies as low as 30 meters. However, since the schedule of Selective Availability is unknown to users, 100 meters accuracy should be assumed.

GPS equipment provides positions on WGS84 in geodetic coordinates (ϕ , λ , h) to the levels stated above. WGS84 is an earth-centered earth-fixed coordinate reference system. If WGS84 positions are not desired, then transformations must be performed to obtain information on another desired datum. Most surveying and engineering applications require greater accuracy than can be provided by real-time absolute mode GPS. For applications requiring greater accuracy, relative survey methods are employed.

Relative Survey Methods (Differential Point Positioning)

Differential GPS (DGPS) surveying is the positioning of one point relative to another. Relative positioning is achieved by setting up satellite receiver antenna sets on at least two points and obtaining satellite data simultaneously. One receiver occupies a point with known coordinates, which means that ranges to the satellites are also known. Using the true ranges, corrections to the computed ranges can be determined. Either these range corrections or adjustments to the position coordinates are then applied to the receiver at the unknown point to improve the accuracy of the computed position. This mode can be implemented in either a static mode or a mobile mode.

Surveys using the L1 and L2 carrier phases can be performed to routinely achieve centimeter (cm) accuracy using the static mode of operation. With careful observations and under favorable conditions, millimeters accuracy can be achieved. In this mode, satellite data is logged and post-processed to achieve a statistically refined precise vector between the known and unknown points.

This 3-D vector can be as accurate as 1-5 parts per million (ppm) of the separation distance between the stations.

DGPS results can be obtained in real-time through the use of a data link between the reference and remote stations to transmit the range or position corrections. Since no statistical refinement is possible, accuracies are not as high as in the static mode described above. Initialization and signal recovery procedures also make use of the carrier phase signals for real-time applications currently impossible or non-feasible. Currently available systems utilize the pseudo-random code on the L1 signal to obtain position accuracies of 5-20 meters. Some newer receivers utilizing both L1 and L2 signals enable 0.5 to 3 meters accuracy.

Some commercial manufacturers are reportedly developing systems that will enable use of the more accurate carrier-phase signals with little or no initialization and that can recover from signal loss. These systems are projected to be available by late 1993 or 1994. The USACE's Topographic Engineering Center (TEC) has recently developed and demonstrated a real-time system that uses the L1 and L2 carrier phases and determines high-accuracy position "on-the-fly"; That is, no static initialization or signal loss recovery procedures are needed. This system, which is capable of 20-50 mm accuracy, has been demonstrated in a hydrographic survey application. This system will be applied to various other uses.

4.2 Set-Up

For the purpose of this section of the paper, the discussion will be limited to real-time positioning applications. Real-time operations can currently be done at 100 meter accuracy given absolute GPS and one meter accuracy given DGPS. A third level of accuracy will soon be possible with the real-time carrier-phase systems discussed above. This third level will provide ± 0.1 meter.

1. 100 Meter Accuracies—These accuracies can be achieved with any standard GPS receiver currently available. Upon turning on the receiver, positions are shown on the receiver display or are output through a data port, at a rate of one per 0.1 second to 5 seconds.
2. $\pm$ One Meter Accuracies—A reference DGPS receiver is positioned over a known point and a data radio and modem are interfaced to the receiver. With a properly functioning receiver and radio link, position corrections are obtained and transmitted almost instantly. A typical set-up time for the reference station is approximately twenty minutes.

The remote DGPS receiver also has an interfaced radio and modem to receive the transmitted corrections. The receiver will typically recognize the transmitted data and begin computing corrected positions in less than one minute after turn-on. Corrected positions will continue to be computed as long as there is no interruption in the satellite signals or the transmitted data. If a problem does occur with reference station data, the remote receiver typically reverts to absolute positioning with the corresponding degraded accuracy. Differential positioning resumes when the transmitted data is restored.

Note that the distance between the reference and remote stations can be several hundred kilometers with minimal degradation of accuracy. The distance is therefore usually limited by the radio link.

3. ± 0.1 Meter Accuracies—Real-time carrier-phase systems that will soon be available will be operated essentially the same way as current meter-level systems. Reference and remote station set-up will similarly require interfaced radio and modem, although a higher data transmission rate will be required. The maximum range between stations will also be lower; approximately 20 kilometers, although future developments may enable longer ranges.

4.3 Markets

GPS is currently experiencing tremendous growth in sea, land, and air navigation. Absolute positioning receivers can cost under \$2,000, and are used on a variety of vessels, from oil tankers

to fishing vessels to recreational boats. GPS is also being used for tracking in fleet operations, such as trucking, police, fire, and rescue operations. The Federal Aviation Administration is considering the use of DGPS in aircraft approach and landing operations.

In real-time positioning, DGPS has tremendous capabilities and promise where $\pm$ one meter and ± 0.1 meter are needed. Some of these markets include:

1. Equipment Control—Given a need for ± 0.1 meter accuracies for operations such as rough grading, mining, earth moving, etc., it is expected that GPS will provide tremendous opportunities for equipment automation and control.
2. Topologic Feature Data Collection— $\pm$ One meter and ± 0.1 meter accuracies both provide unique opportunities to characterize features by simply driving a vehicle randomly over the site. This would also be used to determine the amount of excavation or fill accomplished over a given time period.
3. Hydrographic Survey and Control—This has been shown on revetment placement on the Mississippi River. The integration of electronic data with position data should provide understandable graphical information to better guide work or movements within constricted areas.

4.4 Limitations

The dominant limitation of GPS is that it must have line-of-sight to the satellites. The system therefore will not work in enclosed areas, such as buildings or under ground. Interruption of the satellite signals is also commonly encountered when any object passes between a satellite and the observer. For example, trees, bridges, towers, etc. can cause interruption to the positioning service. To a lesser extent, multipath, or the reflection of satellite signals off surfaces, can cause sudden position shifts. This problem was more common with the initial user equipment that was available, although advanced algorithms and antenna design have minimized these occurrences. Multipath is observed less frequently in GPS applications than in other land-based electronic positioning systems.

5.0 RtPM™

Real-time Position Measurement (RtPM™²) is a new technology that can provide accurate real-time three dimensional position measurement information about points or objects. RtPM will be able to fundamentally alter the tolerances currently achieved in the construction environment. The first RtPM system has been developed and demonstrated. This system provides three-dimensional position measurement information over a 50 meter range with centimeter accuracy at a 5 Hz data rate. The next generation RtPM system will be capable of millimeter accuracy over 200 meters with a 10 to 20 Hz data rate. Longer ranges and higher update rates are anticipated. This report addresses performance and implementation issues as they are envisioned for the next generation RtPM system.

The next generation system is being developed. All information given on accuracies, update rates, and capability is based on theoretical and practical limitations. Actual accuracies, update rates, and overall capabilities will be part of the testing envisioned during the execution of the CAPS initiative and the CRDA tasks. Further, overall accuracy of the system is a function of the relative orientation of the transmitters to the particular receiver. Better geometry provides better accuracy. The best geometry is achieved when the receiver is at right angles to any two transmitters. Degradation curves for various angles of intercept will be quantified and incorporated into product literature as testing progresses through the execution of the CAPS effort.

² RtPM is a trademark of Spatial Positioning Systems, Inc.

There are two primary components in an RtPM system; transmitters and receivers. A conceptual representation of a transmitter and a receiver are given in Figures 1 and 2. The system requires a minimum of two transmitters. More transmitters would cover a larger area of space and would allow for redundant position determination to be made as each pair of transmitters provides a position measurement. The number of receivers is up to the user since once the transmitters are set up any number of receivers can collect positioning signals.

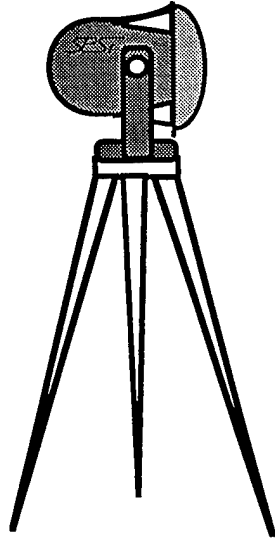


Figure 1

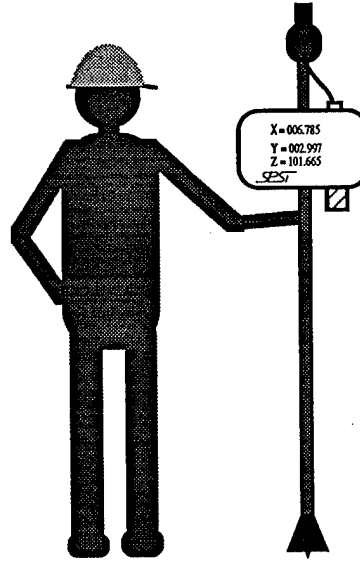


Figure 2

Each transmitter is set on a tripod with a front face plate such that light can be scattered about the site. A battery is used to power the unit, and each 12 volt battery should be able to operate a transmitter for approximately 30 hours. The system can also be directly wired to a standard outlet with the addition of an AC to DC converter.

The set-up of the transmitters can be very quick and imprecise. The transmitters can be set up at unknown points with the face plate generally aimed at the site. This can be thought of as setting up a spotlight which is generally aimed at the site to be illuminated. However, the energy source is infra-red which will allow only the receivers to "see" the "light".

The site would require several known points to be established within the area of the site to be used to back-calculate the position of the transmitters. The current effort is dedicated to the development of the software and hardware to allow for set-up with points within the area of the site and using a calibration algorithm to determine the location and orientation of the transmitter.

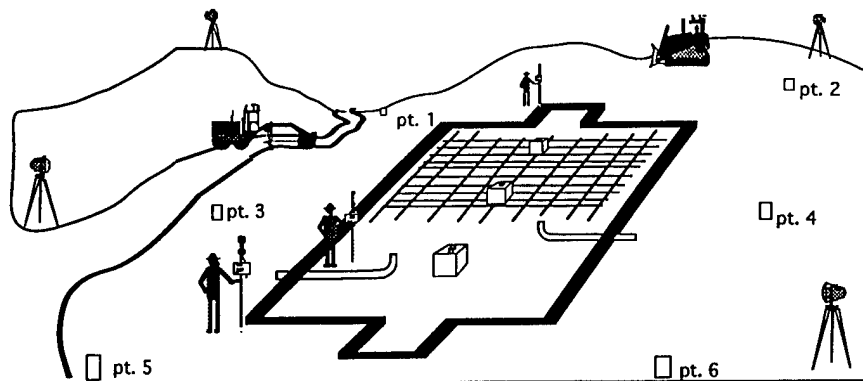


Figure 3

The receiver is comprised of a computer and screen, two optical lenses mounted on a pole, a battery which is mounted on the pole, and a data entry and retrieval system. The two optical lenses form a line. The position of the lenses and the known geometry of the pole allow the point of position definition to be projected to the end of the pole. Therefore, the position of any point that the user touches with the device is accurately and "instantly" captured. Note that the position of the tip of the pole does not change if the pole is slanted, rotated, upside down or sideways.

Figure 3 is a conceptual view of a site using RtPM. The figure represents a series of control points 1 through 6 that would be used to calibrate the transmitters. The figure also shows many users of the receiver including surveyors, craftspeople, and equipment operators each of whom is working concurrently and using the positioning system to capture accurate real-time position information about the work environment. These various users are working from the same set of transmitters. Each user can determine their position if they can "see" any two transmitters. "Seeing" more than two transmitters provide redundant position information.

5.1 Performance

RtPM is expected to provide capabilities which cannot be achieved by other systems. These performance characteristics are accuracy, update rates, and a reduced set-up requirement. These characteristics in turn provide unique new markets and overall improvement of current markets within the construction industry where measurements are continually required.

The basic issue that determines the ultimate accuracy of the system is the rotational stability of the motors that are found in the transmitters. There are several other components of the system that will contribute to ultimate accuracies. Each of these in time will be characterized and quantified such that over time the unique transmission characteristics of each transmitter will be communicated to the receivers so that increasing accuracies will be achieved.

The motor stability for the system being built for CAPS will be better than one part in 100,000 with a potential of achieving one part in 1,000,000. This means that if a point is at right angles to two transmitters its ultimate accuracy will be the distance away from the transmitter divided by a factor between 1,000,000 and 100,000. This assumes that signals from each transmitter will arrive at 50 Hz and that averaging takes place such that output will be between 10 and 20 times per second.

If higher accuracies were required, staying steady over a point for a longer period of time, such as 1/2 of a second, would significantly improve the achieved accuracy. As an example, at a distance of 250 meters the theoretical accuracy will be between 250/1,000,000 to 250/100,000 or between 0.25 mm and 2.5 mm. If the distance goes down to 100 meters, the accuracies would be between 0.1 mm and 1 mm, and if the distance was down to 10 meters the accuracies would be between .01 mm and 0.1 mm.

These accuracies will not be achieved at the start of the demonstration project. Maturing of the software and full characterization of the hardware will occur over time. It is expected that at the beginning of the demonstration project, limits in manufacturing, and the current projected limits in motor stability will combine to provide an overall accuracy of the system of somewhere between one part in 50,000 to one part in 10,000. This would equate to an accuracy at a distance of 250 meters of 5 mm to 25 mm, at 100 meters an accuracy of 2 mm to 10 mm, and at 10 meters an accuracy of 0.2 mm to 1.0 mm.

5.2 Update Rates

The data rate or the frequency at which the system can provide position measurements is of critical issue to RtPM and its potential markets. The current prototype updates position measurement at 5 times per second. The RtPM system being built for the CAPS project will update at 10 to 20 times per second. The current limitation is due to several issues including physical limitation, hardware limitation, and software maturity.

The number of updates per second is a function of the number of times each transmitter passes its energy across a site. This in turn is limited by the energy density at a receiver which brings into play the ultimate distance achieved by the overall system. In other words, the slower the transmitter passes energy across a site, the greater the distance at which the system will operate. However, physical limitations and eye safety enter into the overall process. Therefore, for short distances, the update rates could be significantly increased to say 100 to 200 times per second.

Also, as the software matures and begins to "learn" from previous signals from transmitters at the receiver, a new point of information is gathered. With proper mathematical algorithms, the system should be able to update position on a particular strike from any transmitter at each signal. Update rates may increase up to 200 times per second with no modification to the transmitters. Averaging several signals as is currently done will considerably improve the ultimate accuracy achieved.

5.3 Set-up

The set-up of the transmitters and the overall RtPM system can be done by one person once internal control points are established. There are several ways to set-up the system, each of these set-up methods having advantages and disadvantages. The set-up method to be implemented for the CAPS project is described below. (Refer to Figure 3.)

The laser based system depicted in Figure 3 requires two transmitters and one receiver at a minimum. Additional transmitters allow for redundancy and also help receivers maintain a direct view (link) to a minimum of two transmitters. Once the transmitters are set up, any number of receivers can calculate position information using line of sight to any two transmitters. The laser system would work as follows:

1. Transmitters are set up at random points with the front face generally aimed at the site. Transmitters do not have to be level. They only have to be set securely on tripods with the front face of the transmitter generally aimed at the site.
2. To calibrate the system, a set of preestablished points are needed. The location of these points is entered into the computer on the receiver. The receiver, in turn, is set on four of the known points. The receiver then calculates the position and orientation of each transmitter. This information can be shared via RF modems, serial ports, or direct data transfer to all other users. A check of the four points used for calibrating the system of transmitters is done by

setting over a fifth point. This setting over a fifth point will determine if consistent answers are being obtained (i.e. If answers are inconsistent, the system would say that one of the points used is in error.). If the user sets the receiver on a sixth point, the system would determine which of the five points was in error and it would also calculate its correct position. Setting over more points would allow the system to adjust all points via standard least-square adjustments in order to provide an added level of accuracy.

3. Information is available at the receiver via graphical displays, or sound (beeps of varying pitches) to guide the user to the desired location. The user's location is juxtapositioned within the electronic presentation of the data (i.e. A CAD model). Once components are installed, the exact position of the components is recorded and fed back to the as-built data base. The users of the information are equipment operators, construction surveyors, and craftspeople.

There are alternative ways to set-up the system besides the one described above. Each of these set-up procedures would require additional software development and a potential for hardware development as well.

5.4 Markets

It is expected that RtPM will work in many markets alongside current measurement equipment as an added tool in the overall measurement toolkit. In addition to this concurrent utilization, RtPM has unique characteristics which provide unique capabilities.

The rapid update rate mentioned above allows for true integration with electronic data. This integration provides tremendous potential markets within and outside the construction environment.

Measurements for object placement and as-built creation

These measurements would be quite different from today's methods as batter boards, lines, plumb bobs, tapes, levels and transits would not be needed. Instead, the user would select the point of interest within the electronic data and watch the position of the receiver as it moves towards the ultimate destination. These measurements would be done by surveyors, construction layout personnel, and craftspeople. These measurements can also be done for object placement and to record the as-built environment.

Control of equipment

Two points make a line on the current receiver shown in Figure 2, and three points provide full dimensional and rotational information. Therefore, by mounting three receiver optics at unique locations on pieces of equipment, the relative location of the blade, bucket, or edge can be determined. This will allow for automated control of the active edge of the equipment as that edge relates to the electronic data base (e.g. a paver would have receive optics mounted at a known location above each screw. As the paver moves about a parking lot, the exact surface geometry previously entered into the electronic data would allow for real-time control of the paver.)

Robotics or remotely operated vehicle control

Again, if one can control automatically active edges of equipment, the control of robots or vehicles either automatically or remotely is possible. This would require full integration with the electronic data and proper control systems to be developed.

Modeling of surfaces

A close range system can provide extremely rapid update rates and extremely tight accuracies. Given these capabilities, the receiver could be traced over a surface at random to output a real-time electronic depiction of that surface. This would be useful for machining and parts assembly. Further, this would be valuable for large scale surface modeling to determine if the pavement will

pond water, or to determine how much fill has been placed in a given time period, or to determine where our current surface profile is such that the next day's work can be planned.

There are many other potential markets; however, the four mentioned above give a flavor of the overall market potential within the construction industry.

Where the system will work is also of interest. RtPM will work indoors, outdoors, under obstacles, in urban environments, under water, on land, in the dark, and in space. Several of these capabilities provide unique market potential.

5.5 Limitation

The dominant limitation will be the distance achieved. This can be partially negated by adding cascading areas of control. This will allow individuals to move from one part of a large site to another, and a continuity of measurement would take place. As sensor and laser technology matures in areas of visible light and other light frequencies, ultimate distance will grow dramatically. The ability to achieve a distance of one kilometer should be possible within a two year horizon.

RtPM does not need to maintain lock onto transmitters. That is to say that as soon as a receiver "sees" two or more transmitters, the position is determined instantaneously. As a final note, RtPM is not affected by changes in temperature or humidity nor by human sighting error. This should greatly reduce human error prevalent in current measurement techniques.

6.0 Other Positioning Systems

Total Stations, Global Positioning Systems, and RtPM are the three measurement technologies that are of the greatest current interest to CAPS members and provide the focus for this report. However, there are a number of other technologies available for capturing 3-D coordinate information. These technologies are not generally as appropriate for making measurements in the construction environment at this time. Reasons for this lack of viability are distances required, accuracy required, speed of data required, and maturity of the technologies. A general overview of several of these technologies is provided below.

6.1 LORAN

LORAN positioning technology uses a series of fixed transmitters that cover wide areas, on the order of hundreds of miles. Portable Loran receivers, typically used for marine or aircraft navigation, determine their position by measuring the time difference between signals received from multiple transmitters. Since LORAN is principally a navigation system, it works in units of latitude and longitude, and it can provide accuracies of about 30 meters.

6.2 Laser range finding/scanning lasers

Laser range finding technology measures distances in one of two ways. One method is to measure the time-of-flight of a laser pulse. The other is to measure the phase shift in the reflected pulse. Due to the high speed at which light travels, the accuracy of the technology is dependent on the ability to measure phase shifts and short time durations. Laser technology have been available for several years. Their cost and data manipulation and storage requirement cause severe limitations in the measurement requirement of the construction industry.

6.3 Radio frequency devices

These would be positioning devices that use RF but not the GPS systems mentioned above. Radio frequency (RF) technology uses multiple RF beacons that transmit signals to one or more receivers. The receivers measure the phase delay in the beacon signals, from which the receiver position can be calculated. Some systems use coded signals and an active, or transmitting, mobile

unit to correlate the transmitted and received signals. Accuracy of the systems vary. Most systems provide accuracies at more than 50 meters and under local area controls can approach accuracies of one meter.

6.4 Ultrasonic ranging

Ultrasonic range-finding technology measures distances by measuring the time it takes for a sonic impulse to travel from a sound generator to one or more receivers (microphones). The location of the source is triangulated from the position of the receivers. For 2D digitizing, two receivers are required; for 3D digitizing, a minimum of three receivers are required. Accuracies of ultrasonic ranging can be very precise in the centimeter arena. However, significant issues limit consistent accuracies, primary of these is the speed of sound through differing temperature air. This differing temperature air or thermal layering consistently would degrade accuracy such that the measurement would not be reliable.

6.5 Electromagnetic field sensing

Electromagnetic field (EMF) sensing technology employs a set of electromagnetic coils that generate electromagnetic fields. These are used to calculate the position and orientation of a receiver unit. The transmitter contains three orthogonal EMF coils which pulse in a phased sequence. The receiver also contains a set of three orthogonal coils that sense the intensity of the generated field from each pulse, which can be deduced to provide coordinate data. This system requires significant receiver components with significant energy levels which make it impractical for measurements in the construction environment.

6.6 Dead reckoning systems

Dead reckoning systems utilize accelerometers and other methods to measure changes in direction. These systems can guide a vehicle moving from a point of origin, traveling about, and then determine when the vehicle comes back to its origin. These systems can also, given a current trajectory, maintain very accurate position determination from the current trajectory as it can measure changes in direction very accurately. These systems by themselves cannot help the construction environment; however, these systems linked to a system that can determine trajectory can provide continued guidance if the vehicle loses its source of data to determine its location. Accuracies are dependent on the quality of the accelerometers. Very inexpensive (= \$800) 3D accelerometers are currently available which can maintain millimeter accuracies for several meters.

6.7 Photogrammetry

Photogrammetry cannot do real-time measurements for the construction site. However, over time this technique will become a candidate for some sort of data gathering and equipment control. Photogrammetry uses multiple photographs and a photogrammetric plotter or digitizer to analyze photographs and create three-dimensional position information. The precision of the position information is dependent on a number of parameters, including the distance from which the photographs are taken. The process requires that several points with known positions appear in each set of photographs to be analyzed. Although the information contained in the photographs can be gathered rapidly in the field, significant effort is currently required to analyze and reduce the photogrammetric data into useful 3D information.

6.8 Digital cameras

Charged Coupled Device (CCD) and Charged Induction Device (CID) camera technology is similar to photogrammetry. Multiple images are captured of a given area from which 3D position can be determined. However, instead of using analog images (photosensitive emulsion film), the data is collected digitally by an array of photosensitive receptor cells. The accuracy of the measurements is dependent upon the resolution (density) of the photosensitive receptor cells. Digital cameras

currently cannot accomplish measurements accurately or timely enough to meet the current needs nor the projected needs (given R_iPM) of the construction industry. As image processing and analysis increases, digital cameras will play a part in the overall data gathering process of the construction industry.

7.0 Integration Protocol

Once three dimensional (3D) coordinate data is generated, it needs to be communicated to the CAD or other system that utilize the data. One of the tasks addressed here is the definition of a communications protocol for collecting as-built position data from any 3D measurement device and integrating that data with existing CAD systems.

The approach taken to investigate existing protocols used for Total Station and GPS systems included a survey of product literature for both Total Station and GPS products, review of published standards for GPS, and conversations with Total Station manufacturers and developers of surveying hardware and software products.

The areas of primary interest are the existence of such standards and the suitability of any existing protocols for use in the demonstration tasks to be performed under this CRDA. The following section summarizes the issues of the integration protocol required for the demonstration project.

7.1 Issues

The protocol developed for the integration of CAD and measurement technology must be able to address the following issues.

1. Support multiple 3D measurement devices - The protocol must provide the structure for even the simplest of measurement devices to communicate with a CAD system without limiting the effectiveness of more sophisticated measurement technologies, e.g., R_iPM.
2. Allow for bi-directional communication between the 3D measurement device and the CAD systems - The protocol must allow for bi-directional communication between the measurement device and the CAD system. Commands, coordinate information, attributes, etc. must be able to pass in both directions.
3. Provide capabilities for both real-time and batch transmission of coordinate data - The protocol must provide the flexibility to allow for the real-time, interactive transmission of data as well as the batch mode transmission of data that was collected off-line.
4. Allow for both single point coordinates and continuous streams of coordinates - In order to support the entire spectrum of measurement technologies as well as the envisioned spectrum of applications, the protocol must allow for both single point communication as well as continuous streams of coordinate data.
5. Asynchronous communication between the measurement device and the CAD system - The protocol, and its implementation, must be structured to allow for asynchronous communication between the CAD system and the measurement device. This is necessary to recover from errors, to modify the mode of data collection and transmission, etc.

7.2 Types of data

The protocol must be able to exchange the following types of data between the CAD system and the measurement device:

1. 3D coordinates - As-built coordinates or the position of the measurement device may be transmitted to the CAD system. Likewise, as-designed data may be transmitted from the CAD system to the measurement device.

2. Time of measurement and transmission - Data must be time-stamped to provide both an audit trail as well as support the integration of real-time position measurement with real-time applications such as animation or equipment control.
3. Attribute information to identify the type of coordinate - Attributes will be used to identify information regarding the points (e.g., end point of a line) and objects (e.g., door, anchor bolt) associated with the coordinate data.
4. Commands to direct either the measurement device or the CAD system to perform a certain function or enter a certain state - Commands may be passed in either direction. For example, to request the measurement device to transmit a single point or stream of points. The measurement device may also request an as-designed point from the CAD system.
5. Status data defining the current state of either the measurement device or the CAD system. - In response to command request, either the CAD system or the measurement device will transmit its current status, e.g., ready, computing, off-line, etc.

7.3 Findings on Protocols

Given the issues and data requirements for the integration protocol, the existing protocols in use for Total Station and GPS systems do not fully meet the requirements of the demonstration project, but certain aspects of these existing communication protocols can be used to help model the protocol for integration of RtPM and CAD.

While protocols are in use for communication within Total Station and GPS systems, standards have only been established for use in Differential GPS, while each Total Station manufacturer utilizes a different communication protocol, even amongst different products from the same manufacturer. None of the protocols were found to support the type of tasks to be performed under this CRDA.

7.4 Total Stations Data Protocols

The configuration of Total Station systems varies widely from one system to another and for different applications. Typically, a Total Station has the ability to display and store survey data as it is collected. There is a limit to the amount of data which can be collected before it must be downloaded from the total station to a data collector or personal computer.

It is also common to attach a hand-held data collector (programmable calculator or palm-top computer) to the total station to process, display and store the survey data as it is collected. It is most common to collect the data in a batch mode, creating a data file, and then upload the data to a desktop PC or laptop PC for further processing. No interface is currently available for real-time data transfer to another software process, i.e., a CAD software package. The communication protocol used to upload or download data is different for each Total Station manufacturer. The more common brands used include SOKKIA, Leica, Topcon, Geodimeter, Nikon, Pentax, Zeiss, and Cubic Precision.

Another option is to connect a personal computer directly to the Total Station, although it is less common to carry a PC or laptop into the field.

Total Station systems can communicate bi-directionally, between the theodolite and the data collector or PC. However, this is currently only available in a batch, or file transfer, mode.

Jacobus Technology has some limited experience with interfacing Total Stations directly to a CAD system. Jacobus offers a software product, TeleMetriX³, which provides a means for capturing

³ TeleMetriX is a trademark of Jacobus Technology, Inc.

3D geometry data within MicroStation™ 4 4.0. An interface was designed between TeleMetriX and the SOKKIA NET2 3D station, allowing coordinate information to be passed from the total station to MicroStation and vice-versa. The communication protocol was unique to this application and did not conform to any other manufacturer's communication method. This protocol was also very simplistic, only passing coordinate data.

7.5 GPS Data Protocols

A communication protocol standard has been established for use in Differential GPS systems. This standard is published by the Radio Technical Commission for Maritime Services and includes specific grammar for allowable messages. Communication from the GPS system to a host computer is one-way, although there is two-way communication between GPS receivers and the GPS base station when a Differential GPS configuration is utilized.

7.6 RtPM Data Protocols

A number of software development and testing tasks have been completed relative to the integration of the real-time positioning system, RtPM, and computer-aided design, CAD. Each of these activities have been carried out to demonstrate the feasibility and effectiveness of the integration of real-time position measurement with CAD.

Integration with MicroStation

The first test of this integration was in developing and testing software which allowed RtPM to be integrated directly with the MicroStation CAD software. In this test, RtPM was set up to transmit x, y, z coordinate data over an RS232 connection. RtPM was connected, via the RS232 link, to a personal computer running the MicroStation software. An interface was written using the MicroStation Development Language (MDL) and C. The communication protocol was unique to this test application.

The interface was established such that 3D coordinates could be retrieved from the RS232 port while within any MicroStation command. When a 3D point was required from RtPM, the user could press a function key and the interface would 'listen' to the RS232 port on the personal computer until a 3D coordinate was received from RtPM. The interface would then send the coordinate to MicroStation. MicroStation processes the coordinate point as if the point had been input via the digitizer or mouse. During this test, it was possible to accurately 'digitize' the features of physical objects in a large open field.

This test provided the initial demonstration of the feasibility of the integration of RtPM with CAD. This test demonstrated that RtPM could serve as a '3D cursor' within a CAD system and be used to collect coordinate data in an interactive mode with the CAD system.

Integration with JSpace (Phase 1)

The second test was to confirm that integration could also be achieved between RtPM and 3D, real-time animation software. In this test, RtPM was also configured to deliver 3D coordinate information over an RS232 connection. An interface was developed with the JSpace Viewer™ 5 software to accept coordinate data over the RS232 connection. In this case, the coordinate data retrieved from the RS232 port was mapped to the viewer coordinates in one of the JSpace view ports. With this type of interface, the viewer coordinates of a 3D view would change as the position of the RtPM device moved. Thus the view displayed in the 3D port corresponded with what the RtPM device 'saw.'

⁴MicroStation is a trademark of Intergraph Corporation

⁵JSpace Viewer is a trademark of Jacobus Technology, Inc.

This test provided confirmation that, in addition to providing integration between RtPM and CAD for single point input, as in the first test, RtPM and CAD could also be integrated such that a continuous stream of 3D coordinate points could be received and processed within the CAD system.

Integration with JSpace (Phase 2)

A final test was conducted to demonstrate that both single points and streams of points could be computed and transmitted by RtPM and be received and processed by the CAD system. As in the previous tests, RtPM was set up to transmit 3D coordinate points via an RS232 connection. However, in this test, unlike the previous tests, the data was transmitted to the CAD workstation via Radio Frequency (RF) modems. This meant that RtPM can be physically de-coupled from the CAD system.

The first part of the test was to demonstrate the use of RtPM for collecting as-built data. A simple application was implemented in JSpace to place boxes and simple piping layouts. RtPM was then used as the '3D cursor' to locate key points (e.g., corners of the box, ends of piping runs). These key points were used by the JSpace application to interactively place 3D objects into the computer model. A box was located and modeled by touching two points on the box and immediately transmitting the coordinates to the CAD workstation. These points were used by the JSpace application to place a box of the appropriate size and position (i.e., as-built) within the model. Next, RtPM was used to locate the changes in direction for a simple piping layout created for the test. As each point was located with RtPM a piping object appeared in the model at the appropriate location.

As part of the same test, the coordinates transmitted by RtPM were mapped to a simplified model of the RtPM device. Thus, as RtPM was moved within the test area, its movement could be tracked by watching its motion in the 3D view port.

7.7 Recommendations and Conclusions for Protocol Adoption

The software prototyping and testing activities performed between RtPM and MicroStation and JSpace demonstrated convincingly that the use of RtPM interactively with a CAD system was indeed practical and effective. The next step in the process, before implementing the production version of the interface software is to develop a communications protocol for integrating multiple measurement devices with CAD in a generic and flexible manner.

The available protocol standards for Differential GPS are well-defined but operate in one-way communication only. Total Station protocols can operate in two-way communication, but do not fully satisfy the requirements of the demonstration project for real-time communication. There is no industry-wide standard for communication protocols between data collection devices (Total Station and GPS receivers) and host computers running application software. Therefore, it is reasonable to proceed to design a protocol which is appropriate for the demonstration project, utilizing existing protocol components where appropriate.

8.0 RtPM Benefits

The ability to produce very accurate position data very quickly in three dimensions provides significant benefits to the surveying and measurement industry. However, the integration of position measurement information with a CAD environment provides the potential for a revolution to the construction industry.

RtPM integrated with CAD provides the necessary link of the data base to the end users. These end users include surveyors, inspectors, managers, operators, and craftspeople. RtPM provides a link from the virtual world (the CAD data base) to the real world (the project). RtPM supports information dissemination to people and control of equipment and processes within that real world.

The potential benefits to the construction industry rely on adopting 3D CAD as the managing entity of data for electronic data interchange within all aspects of the AEC industry. If this is done, the added benefit of having good "living" data about the facility will allow the owner to utilize this living data base for such life cycle activities as operations, maintenance, retrofit, renovation, rebuild, and demolition. The use of RtPM to update the living project data base makes possible the creation of as-builts quickly, easily and inexpensively.

The benefits to the construction industry fall into several categories. This include: quicker and higher quality layout surveying, quicker and higher quality characterization of existing facilities, improved craftspeople performance, improved surveyor and craftspeople status, reduced rework, improved modular construction, improved as-builts, equipment performance and quality improvement, control potential for robots or autonomous vehicle, and improved overall construction control.

8.1 Quicker and higher quality layout surveying

Layout and control surveying currently account for about one percent of construction cost. This process typically does not rely on electronic interface of data to the real-world. Instead, this process typically relies on error prone hand calculations and on-the-fly recalibration and adjustments.

Although the current use of total stations, transits, levels, and tapes will continue even after significant adoption of RtPM, the new technology is an addition to the overall toolkit of measurement instruments. The addition of RtPM with its speed and data access opportunities will significantly improve the overall process several-fold for a net reduction of the overall construction cost of, at a minimum, one half to three quarters of a percent.

As the design industry begins to design to the process of construction that best supports the use of a tool like RtPM, these overall savings are likely to improve. As the process more fully adapts to utilizing RtPM, more measurements will be made and people with the skills to interface with the data base will be required. These people with their added skills and job status will more fully interface with the CAD data and the design professionals.

8.2 Quicker and higher quality characterization of existing facilities

Many projects today include renovation, modernization, or retrofit of existing facilities. These projects account for about 40% of all construction dollars spent (Ichniowski, 1993), (Trends and Statistics, 1986). These projects also require extensive cataloging and characterization of existing components and their locations in order to properly plan for the work and the shut-down of the facility.

Retrofit projects require significantly more surveying and measurement than greenfield projects. The cost of this work can run 7% to 10% of the construction budget. RtPM offers a tremendous advantage over current measurement devices. The target performance is to have the ability to collect data which is structured in such a format that a 3-D model can be generated directly from the built condition without reference or with limited reference to original drawings. This will eliminate the need to interpret and convert existing drawings to dimensional information to prepare a CAD file and then having to go verify the CAD data to see if things are in the location that is required. With RtPM communicating directly with a CAD modeler, the primary source of information about location and objects can be directly collected and transmitted to the CAD modeler and objects can be placed directly into the CAD file. With better and more thorough data about the project, the project will run more quickly, more smoothly, and with fewer overall problems.

8.3 Improved craft performance

It has been estimated that only 40% of construction labors' time is spent doing productive work, with antiquated methods accounting for 20% of the lost time, administrative delays an additional

20%, work restrictions 15% and personal time accounting for the remaining 5% (Tucker, R., 1988). RiCLADS will have dramatic impact on the 20% lost due to antiquated methods and the 20% due to administrative delays.

Giving the craftspeople and the surveyors direct access to the data base, whereby they can easily and graphically interface with the design data, will provide immediate productivity gains to the user. These users will not rely on someone else for information but will access the design database directly.

Once the data is accessed they will not make transcribe errors or errors such as left side, right side, or center line of wall. The data delivery system will be designed such that people can interface with the design world with maximum advantage and minimum confusion.

8.4 Improved surveyor and craftspeople status

The idea that surveyors and craftspeople will be working directly with the design data provides tremendous opportunity for career enhancement and personal status growth for people involved with the construction industry. The interface with data that is presented and accessed through easily understood graphical formats will provide for much better communication and overall commitment to the task. More efficient communication of the design intent and more effective interaction with the design data base support the goals and objectives of many firms total quality management programs. Although this benefit is difficult to quantify, it is one of the key issues that will define the overall construction industry culture of the future.

8.5 Reduced rework

The construction industry has long had tremendous rework. Classically this rework has been identified as 12% of total construction cost. For nine fast tract projects, a paper (Burati, et. al., 1992) concluded that 12.4% of total construction cost went to fix deviations. A 1982 report (Quality, 1982) placed the cost due to mistakes at 15 to 20% of construction. The reasons that rework occurs are varied and can be classified into five categories: owner changes, errors, and omissions; design changes, errors, and omissions; construction changes, errors, and omissions; vendor changes, errors, and omissions; and shipping errors and omissions. The first two (owner and design changes, errors, and omissions) account about equally for about 78% of the rework. Construction and vendor changes, errors, and omissions account again equally for about 16% of the rework (Burati, et. al., 1992).

This rework could be reduced substantially using a "living" electronic data base which can be built, maintained, augmented, and redistributed as the overall construction process evolves. The ability in real-time to manage, use, change, and redistribute positioning data to all parties would be key to the overall reduction in rework.

8.6 Improves modular construction

The construction industry's increased reliance on modular assemblies will continue. The construction industry will build large assemblies off-site or at controlled locations on site. The manufacture and the mating of these modules becomes more and more complex as assemblies grow in quantity, complexity, and size. RiCLADS provides the ability to interact with electronic data and to easily determine if surfaces, volumes, and interfaces are acceptable. This will provide for improved module to module fit, improved manufacturing processes, and increased support of modular construction.

8.7 Improved as-builts

The construction industry typically produces very poor as-builts. The reason for this is the difficulty, cost, and time required to produce the as-built. The cost to characterize existing facilities properly is often so prohibitive that contractors fall far short of proper characterization. The real

impact of incomplete as-builts is to the owner who must contract or perform future work without adequate data.

Using RiCLADS, the cost and time to generate as-built position data for plant components would drop substantially. As components are installed, their precise position can be captured and recorded directly in a CAD model for future reference.

8.8 Equipment performance and quality improvement

RiCLADS can interface with equipment to provide graphical real-time data to the operator. The operators could see their equipment's' active edges (the blade, the auger, the screed, etc.) superimposed onto the CAD design data. This will allow operators to do their tasks without requesting information and references from the survey crew.

This will significantly improve equipment performance, improve operator learning, reduce the demand for support personnel, and improve the overall quality as errors in data transfer will be all but eliminated. Further, automated equipment will eventually evolve to the point where the active edge of the equipment is automatically controlled autonomously using the position information generated in real-time.

8.9 Control potential for robots or autonomous vehicle

The idea of assisting operators to perform their tasks more efficiently as outlined above has dramatic implications to the control of robots and autonomous vehicles. A robot could move about in three dimensional space and receive continuous feedback of its position (including the position and orientation of arms or appendages) within the design environment. As work is accomplished by one autonomous device, information about changes in the geometry of the work environment is sent to all other robots. This is done by updating the "living" data base that continually reflects the site changes as work is accomplished. The data base continuously gets updates about the current project topology as well. This allows for determination of work achieved as well as for the planning of subsequent work.

8.10 Improved overall construction control

The ability to have a data base that interacts, grows, and changes with the daily changes of the construction project offers unique opportunities to the construction industry.

As an example, assume a certain section of pipe is installed. By locating preestablished set-points the user identifies the exact location of the installed component. This information is transmitted to the project data base.

The data base determines if the object has been installed within acceptable tolerances or if it is not within tolerances. If it is not acceptable, the data base can request that the object be reworked now before future errors arise or that downstream components be modified to accept the misplaced object. The data base distributes change data to all users and verifies that all users accept this changed data.

If the pipe spool is acceptable, the system catalogues the installation event. Over time the data base catalogues production achieved because as each piece or section of pipe is located and sent a record of achieved production is available. Unit production information, as well as unit cost data would be available. Daily output and changes could be utilized to plan the subsequent day's activities. This integrated systems approach will drive a construction process that resembles a just-in-time manufacturing process.

9.0 Project Implications of Advanced Positioning Technologies

Advanced Positioning Technologies offer the promise of real time collection of highly accurate three dimensional position data. The use of these data will impact projects in a number of different ways, particularly in engineering and construction.

9.1 Engineering

In order to utilize 3D position data, components will have to be located using the concept of set-points associated 3D position data. Each component is traditionally located through the use of three independent measures, an X offset, a Y offset, and a Z elevation. These data are represented as linear offset distances, and in the field each is traditionally established independently. If 3D coordinate data is used to physically locate components, then the traditional offset and elevation data given on drawings must be transformed to coordinates in the reference coordinate system. In addition, the set point, or point at which the coordinates are specified, must also be determined and represented.

The set point must be a physical point that can be easily located and measured in the field. This is straightforward in the case of an anchor bolt; the center of the top of bolt is a convenient place to both compute coordinates and collect position data. This is somewhat more complicated in the case of components such as pumps that typically use a centerline of inlet or outlet as a reference line. In this case, set points might include the invert of the inlet or the top of the base plate at a specified location. The conversion of offset data into 3D XYZ coordinate data and the identification of set points are new activities that must be performed to support RtPM field applications, and create a new set of design deliverables.

9.2 Construction

There are several obvious benefits to using RtPM for plant layout. The use of RtPM can save substantial time in performing field layout and inspection activities. By blanketing an area with a laser signal, the position of any component within the area of coverage can be determined in as short a time as it takes to place the receiver on the component and either read or transmit the coordinate data.

When compared to the conventional process of running control points into the proximity of the component, calculating the XY position from the offset lines, running a level loop into the area to measure elevation (the Z coordinate), and field reducing the level data, the savings are substantial.

The anticipated initial crew size for an RtPM crew is two people. One person will handle the notebook computer and one person will handle the position sensor. This is a significant reduction from the conventional survey crew of at least three people, including a crew chief, instrument person, rod and chain person and often, one or more laborers. The combined effects of increased speed and smaller crew size lead to significant increases in productivity for both layout and inspection activities.

RtPM will reduce computation time and errors, and will also reduce data transcription errors. Many survey calculations are still performed manually in the field as required. Data and computations are entered into field books and then uploaded into computers or onto drawings in the field or home office. Since data is transferred electronically from design files to the RtPM system, and collected electronically from one field measurement, computation times are greatly reduced and the possibility of transcription errors is essentially eliminated.

However, despite these clear cut benefits, use of RtPM methods will require a re-orientation in the traditional manner of thinking about layout and inspection activities. Instead of thinking in terms of running control loops into an area, a system of plant monuments could be used to calibrate a system of transmitters with relatively few control, or turning points, required.

Technology training and acceptance should be relatively easy since the intended initial users of the system are surveyors and field engineers, who are already trained in the use of relatively sophisticated tools such as levels, total stations, theodolites, electronic distance measurement (EDM) equipment, and one dimensional and two dimensional lasers systems. They are also accustomed to performing data reduction in the field book or in the field office using calculators and microcomputers. Therefore, although training and learning effects are real and can create cost impacts and implementation barriers, these impacts are mitigated by the fact that surveyors should prove to be both more accepting of new technological tools and more easily trained in their use.

RtPM systems are not envisioned as displacing conventional survey techniques or tools. They are complementary and form an addition to the surveyor's tool box.

10.0 Summary and Conclusions

This report has provided a look at advanced positioning systems that when integrated with CAD has the potential to significantly alter the way we do business. Specifically the paper has presented integration of total stations, DGPS and RtPM with CAD data to form RtCLADS. Each of these three technologies has been presented with a look at performance issues, update rate, set-up issues, market potential, and limitations. A brief look at additional measurement systems that are currently available or on the horizon has also been presented.

The RtPM system presented in this report offers unique capabilities that set it apart from more traditional measurement systems. RtPM offers real-time modeling capabilities, real-time as-building capabilities, real-time data dissemination, real-time interaction with the design environment for craftspeople and surveyors, and real-time control of equipment as they relate to their design environment. These capabilities are fundamentally different to today and they are where the real benefits will be realized for the construction industry.

RtPM, total stations, and DGPS integrated together with access to the central project CAD data will provide the missing link for a real-time construction layout and as-built development system (RtCLADS). RtCLADS is a product of the CRDA between CERF and USACE. RtCLADS is critical to the integrated project where design/construction information passes and grows through operations/maintenance.

The report presents issues as they relate to communicating between measurement devices and CAD data. A review of existing communication protocols is presented along with issues of a more robust protocol which will be needed to support integration of real-time positioning capabilities.

The report finally presents expected general benefits of the systems and some specific project benefits that are expected to be achieved in the short term. The overall benefits to the construction industry are expected to be profound. The direct utilization of the dimensionally correct CAD data as the source and form of information presented to all participants of the construction process is revolutionary. The ability to collect object data from the built environment and to create as-builts directly without interpreting old, out-of-date drawings is of tremendous advantage to retrofitting and rebuilding processes. Lastly, the ability to utilize the CAD electronic data as the source of control for equipment will rewrite how design is currently envisioned and how the construction process is currently done.

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Appendix D

Real-Time Positioning

Technology: Development and

Application

**Real-Time Positioning Technology:
Development and Application**

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Abstract

Bechtel Corporation maintains a large in-house Research and Development organization that is unique among American Engineering and Construction firms. One division of this organization has been active in an industry collaboration, the Consortium for Advanced Positioning Systems, CAPS. This group of firms has developed and fielded a new laser-based positioning system with integrated CAD capabilities that allows the user to capture and record real time as-built data. This paper describes the Bechtel R&D organization, the CAPS consortium, and the development and application of the real-time positioning system.

Introduction

In keeping with a longstanding tradition of innovation and technology leadership, Bechtel maintains an active Research and Development organization that is unique among American Engineering and Construction firms. The R&D organization is composed of six functional divisions, one of which is Engineering and Construction Technologies (E&CT).

In December of 1992, the Consortium for Advanced Technologies (CAPS) was formed to develop and demonstrate new positioning technologies, and E&CT represented Bechtel as a founding member of CAPS. Spatial Positioning Systems, inc., another founding member of CAPS, developed a patented laser-based positioning system that generates real-time 3-D coordinate data. The CAPS group has developed an integrated CAD link that allows real-time data collection and modeling in the CAD environment. Bechtel is in the process of fielding the first of these new generation field as-building systems.

This paper describes the Bechtel R&D organization, the CAPS consortium, and the development and application of the real-time positioning system.

Bechtel Research and Development

Bechtel Corporation recognizes the importance of developing and implementing new technologies in its rapidly evolving and highly competitive industry. The Bechtel Research and Development organization group is a major corporate resource that supports Bechtel's Regional Offices and projects worldwide.

Bechtel's Research and Development – the largest in-house research and development organization in the U.S. engineering and construction industry – is a prime source of many of the innovative technologies Bechtel uses to execute projects around the globe.

In the last 35 years, Bechtel has investigated some 200 different technology areas, ranging from fundamental research into the nuclear fuel cycle to commercial development of waste-to-energy systems. Bechtel scientists and engineers hold patents across a wide spectrum of technologies, including seawater desalination, solar thermal, hazardous waste containment, flue gas desulfurization, and mineral and hydrocarbon recovery processes. Bechtel R&D is active in other scientific and applied technology fields such as superconducting magnetic energy storage, biomass energy production, fuel cell technology, and magnetically levitated transportation systems.

The Research and Development organization works closely with Bechtel functional groups as well as with Bechtel clients and projects to provide a wide range of support services. It is a large and diverse group of over 150 people, most of whom are located in Bechtel's corporate headquarters in San Francisco, California.

The R&D organization is composed of six groups: Applied Physics and Civil Programs, Energy Programs, Process Programs, Commercial Development, International Technology and Resources, and Engineering and Construction Technologies. (See Figure 1)

Applied Physics and Civil Programs (APCP)

The APCP group focuses on space and telecommunications technologies as well as working in the areas of advanced civil and applied physics.

APCP represents R&D on a multi-company team that proposes to develop an Automated Highway System as part of the United States Intelligent Vehicle Highway System. Bechtel responsibilities would include cost and schedule implication studies for alternative designs,

infrastructure cost estimates and schedule sequences for a test facility, existing roadway retrofit studies, and prototype track construction management.

Energy Programs (EP)

The Energy Programs group works with technologies related to energy storage, nuclear systems, and renewable energy. EP also worked on the design and development of Superconducting Magnetic Energy Storage (SMES) technology.

EP recently completed an assessment of two biomass power plant options for the Pacific International Center for High Technology Research. In addition to plant performance and economic analyses, EP prepared specifications, flow diagrams, construction schedules, plot plans, a plant O&M plan, and a plant performance summary.

Process Programs (PP)

PP addresses technologies related to advance power generation systems, advanced process systems, coal conversion, emission control, and solid fuels. Recent activities include studies on thermal desorption, mixed waste treatment technologies, and soil washing and incineration of hazardous wastes.

Bechtel is active in the area of molten carbonate fuel cell technology. The PP group is working on system optimization, balance-of-plant component development, and engineer and construction of a MW-class demonstration plant.

PP is also participating in the development of a conceptual design for an "organic sponge" system. The sponge uses organic material, rather than activated carbon, to remove chlorinated volatile organic compounds from the air emissions of typical groundwater air stripping and soil vapor extraction facilities.

Commercial Development (CD)

The CD group focuses on major projects, marketing and business development, and technology commercialization. CD recently participated in the completion of a lump sum project to engineer, procure, and construct two photovoltaic power systems that are situated atop the new Solar Energy Research Facility at the National Renewable Energy Laboratory in Golden, Colorado.

Earlier this year, CD worked on the license arrangements for Bechtel's patented seawater scrubber system, a technology that uses seawater to remove over 95 percent of the sulfur dioxide from the flue gas of a power plant.

It is also the home of Bechtel Software, which develops and supports a large number of engineering and project management related products. Bechtel Software, Inc., a subsidiary of Bechtel Group, Inc., is engaged in commercialization of Bechtel software applications worldwide. The organization provides numerous services, including licensing Bechtel proprietary software, value added hardware and software resales, training, consulting, and application software support and development.

International Technology and Resources Programs (ITRP)

In response to the rapidly changing structure of the oil, gas, and power industries, Bechtel has established a consulting arm called International Technology and Resources Programs. ITRP provides a complete range of technical assistance and planning services by drawing on Bechtel's expertise and resources. It identifies and recommends innovative technologies that use indigenous resources in a cost-effective and environmentally sound manner.

ITRP provides specific technical expertise in: energy planning; energy efficiency and conservation; power system planning; oil and gas systems; privatization; environmental services; regional planning; and surface transportation.

Engineering and Construction Technologies (E&CT)

E&CT's charter is to identify, develop and implement new technologies that directly enhance the engineering and construction work processes. Recent development efforts have addressed technologies related to integrating engineering and design technologies with field execution methods.

E&CT also acts as an external interface between Bechtel and numerous entities in the academic, industry and government sectors. Collaborative development efforts, such as the creation of consortia, are increasingly common mechanisms for leveraging research and development investment and technological expertise. E&CT represents Bechtel in the Consortium for Advanced Positioning Systems (CAPS), and has worked closely with Jacobus Technology, Spatial Positioning Systems, inc., and the other CAPS members to develop a real-time, integrated, CAD-based positioning system.

CAPS, the Consortium for Advanced Positioning Systems

One approach to leveraging the resources of individual firms is to create consortia that share in the costs and benefits of the research and development process. The Consortium for Advanced Positioning Systems (CAPS) is such a collaborative effort, created to develop and implement a revolutionary new site positioning technology.

The Consortium for Advanced Positioning Systems was formally organized in December of 1992. The CAPS structure is illustrated in Figure 2. The founding members of CAPS include Bechtel Corporation, Jacobus Technology, Spatial Positioning Systems, inc., and the Civil Engineering Research Foundation (CERF).

Spatial Positioning Systems, inc. has developed a proprietary and patented laser-based position measurement technology that provides a significant increase in performance and capability over current methods. SPSi's ODYSSEY™ system has a wide range of applications in the construction, manufacturing, space, defense, environmental, and medical fields. The system uses a series of fixed laser transmitters to generate signals that are beamed throughout a work area. Small, portable receivers that are carried through the work space receive the laser signals, and either process the information on-board or transmit the position data to an external processor. The result is the real time, three dimensional location of the desired point.

Jacobus Technology, Inc. created JSpace™, a general purpose object-oriented environment for creating and interacting with the large and complex sets of data encountered in AEC projects. This environment is created by the effective integration of object-oriented concepts, real-time animation and integration of project data and users. JSpace™ is a very flexible and extensible environment that provides both immediate usability and sophisticated development tools that can be used to process 3D position data and create graphical as-built representations of field components.

Intergraph Corporation joined CAPS as a full member during the second quarter of 1993. Intergraph is a leading supplier of CAD related hardware and software, and is providing software development expertise to CAPS using the MicroStation and MicroStation Review products.

CERF is a non-profit affiliate of the American Society of Civil Engineers. CERF's mission is to promote research that benefits the AEC industry in general. The United States Government has recently made funds available for infusion into the private sector as a stimulus for research and development activity, through the Construction Productivity Advancement Research program.

These funds are administered through a mechanism known as a Cooperative Research and Development Agreement, or CRDA. The **United States Army Corps of Engineers** is participating in the CAPS consortium through a CRDA agreement with the Civil Engineering Research Foundation.

Additional CAPS participants include the Amoco Oil Company, the Center for Innovative Technology, DuPont, Motorola Corporation, and the National Science Foundation.

CAPS Mission

The long term goal of CAPS is to combine the resources and experience base of industry, academia, and government to identify, develop, integrate and implement new positioning technologies for the common benefit of consortium members and the U.S. construction industry.

Recent tasks include supporting the development of the new generation, state-of-the-art laser-based positioning system developed by SPSi; developing the software that allows the system to communicate directly with CAD modeling systems; and demonstrating the capabilities and effectiveness of the system through on-site tests at construction projects.

The CAPS Positioning Technology

The positioning system under development by CAPS is comprised of several distinct components that have been integrated into a functional system. The core of the system is the SPSi laser-based positioning device called Odyssey.TM

There are two primary components in the Odyssey system, transmitters and receivers. At least two transmitters are required to provide positioning signals to a receiver. However, any number of receivers can utilize the positioning signals simultaneously.

The transmitters can be set up at convenient locations and generally aimed at the work site. This is analogous to setting up a spotlight that is pointed towards the site to be illuminated. However, the infra-red energy source is selective and only the tuned receivers can "see" the "light."

Existing plant benchmarks are used to calibrate the system using any local coordinate system. Alternatively, any convenient consistent reference system, such as a series of quickly established triangles on an operating floor, can be used to create a temporary, local frame of reference that is then used to capture relative position data, which can later be tied into an existing coordinate system.

Each receiver is composed of two lenses mounted on a pole, a processor, a data entry and retrieval system, and a power supply. The two lenses form a line, and the position of the lenses and the known geometry of the pole allow the point of position measurement to be projected to the end of the pole. Since the position of the tip of the pole does not change if the pole is slanted, rotated, turned upside down or sideways, the position of any point that the user touches with the receiver is accurately and "instantly" measured.

The Odyssey system provides basic coordinate measurement capability even with no direct integration with CAD. SPSi system software will provide basic functions such as distance between two points, areas, volumes, or angles using a simple user interface. However, real-time position data linked directly with CAD modeling systems provides a powerful tool with unlimited field applications.

Odyssey Positioning System - CAD Integration

The integrated site positioning system combines real-time coordinate data from the Odyssey system with CAD design data. The combination of real-time coordinate measurement and CAD

representation allows field position data and graphical design data to be provided simultaneously to the user. A schematic representation of the CAPS system is shown in Figure 3.

Communication Protocol

In order for the positioning system to communicate with the CAD environment, Jacobus Technology used its object oriented modeling environment JSpace™ to develop a communications protocol called CAPSCOM.

The purpose of CAPSCOM is to provide a standard format for the integration of positioning data from a variety of 3D measurement devices with CAD systems. The CAPSCOM protocol:

- Allows for bi-directional communication between a 3D measurement device such as Odyssey and a CAD system such as Intergraph's MicroStation.
- Provides capabilities for both real-time and batch transmission of coordinate data.
- Allows for the transmission of both single point coordinates and continuous streams of coordinates.
- Supports asynchronous communication between the measurement device and the CAD system.
- Allows the communication of both commands and data, either from the measurement devices or the CAD system.
- Provides a framework that is extensible to include new commands or new data types.

Using the CAPS protocol, the SPSi positioning system can communicate directly with the CAD environment. This is physically accomplished by linking the positioning receiver to a computer, using either a hardwired connection or radio frequency (RF) modems. The initial CAPS system utilizes Motorola RNet 9600 RF modems to exchange coordinate data with a MicroSlate pen-based computer or an Intergraph TD-1 workstation running either MicroStation or MicroStation Review. However, many other hardware and software configurations are possible.

The CAD platform contains both design files and the CAD application software. The MicroStation application software running on the MicroSlate, for example, displays the location of the positioning receiver on the screen, relative to the other objects in the CAD file. As the receiver moves, so moves the receiver icon on the computer screen. The receiver icon can be used to initiate CAD commands or to provide a data input point.

The direct positioning system-CAD link allows the operator to download plant design files and use the design information as a basis for field layout activities. Application software developed by Intergraph allows the user to select a point in the CAD model, and then use the positioning system to guide to the point. The user can also collect as-built data directly from the field environment and upload it directly to the modeling environment, creating real-time as-builts.

Field Demonstration

The CAPS Positioning System was demonstrated at a Bechtel power project during September, 1993. The Manchester Street Station Repowering Project (MSSRP) is located in Providence, Rhode Island. The plant owners, Narragansett Electric and New England Power Company selected Bechtel to convert the oil-fired facility to natural gas and install three state-of-the-art combustion turbines. Three heat-recovery steam generators (HRSG's) collect the waste heat from the combustion turbine exhaust and feed three new steam turbines as well as three rebuilt existing steam turbines. The three new combined cycle turbine trains will help triple plant capacity, from 132 megawatts to around 489 megawatts.

Working closely with Bechtel field personnel, CAPS members identified a series of initial demonstration tasks that reflected actual work tasks. These work tasks also demonstrated the capabilities of the system, including both layout and as-built activities.

In order to take advantage of the project phase at the time of the demonstration, the initial demonstration tasks were related to site civil work. These tasks included:

1. Step-taper piles as-builts
2. HRSG embedded plate as-builts
3. Combustion Turbine pedestal sleeves and blockouts as-builts
4. Underground pipe as-builts
5. H-pile as-builts
6. General layout, or "guide-to-a-point" capability

The site demonstration also confirmed the feasibility of using RF modems to send data to workstations in the field office. An Intergraph TD-1 workstation was located inside a building overlooking the test site, where it was used to model plant components in the CAD model, based on data transmitted from the positioning system outside in the field.

Conclusion

Bechtel's Research and Development organization continues to lead the way in the development and implementation of new engineering and construction technologies. One effective mechanism for leveraging research and development resources is the consortium approach, such as demonstrated by the CAPS collaboration.

The ODYSSEY system's ability to generate accurate three dimensional position data, in real-time, is a significant benefit to construction and retrofit projects. Integrating this position information directly with sophisticated CAD systems provides a powerful tool for current and future projects. As further development and field testing of the integrated positioning system progresses, we face the challenge of creatively utilizing the tremendous potential of the system to perform our project work more efficiently.

Acknowledgments

The Bechtel R&D environment and the CAPS collaboration provide unique collaborative environments for the formulation and development of new ideas. Group members share freely of their thoughts and ideas. Consequently, papers presented by individuals often reflect collaborative thinking and describe joint activities. I would like to acknowledge the contributions of all the CAPS members, not only to the development effort itself, but also to the creation of the open and stimulating environment that made CAPS possible.

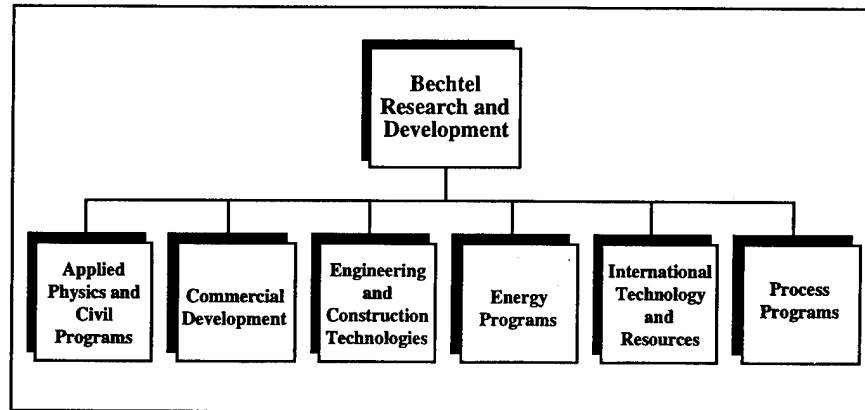


Figure 1 Bechtel Research and Development

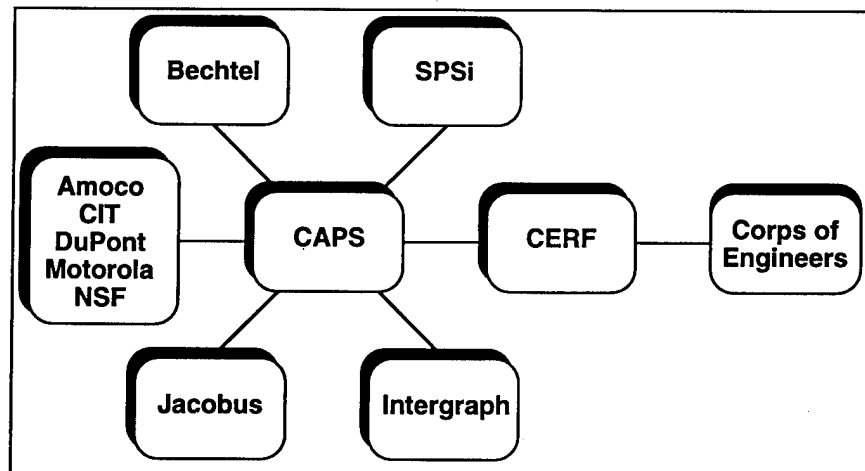


Figure 2 - CAPS Structure

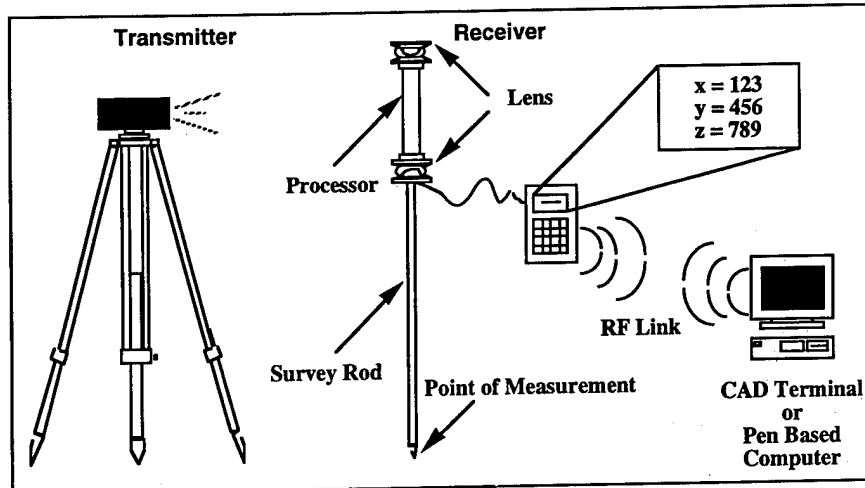


Figure 3 - CAPS System Schematic

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Appendix E

SPSi ODYSSEY™ Position

Measurement System Product

Specifications

SPSi ODYSSEY™ Position Measurement System

Performance

Range: 75 meters
Accuracy 1:10,000
Precision 1:50,000
Update Rate: 5Hz

Base As-Built Modeling Package:

Item 1 Laser Transmitter Model 10G (Quantity 2)

- Scan rate = 50 Hz
- Emission wavelength = 813 nm +/- 3nm
- Dimensions = 513 mm (L), 214 mm (W), 178 mm (H)
(20.2 in (L), 8.4 in (W), 7.0 in (H))
- Weight (est.) = 12 kg (26.4 lb.)
- 12 VDC, 3.0 A (max.), 1.5 A (steady-state)
- Class 1 CDRH laser safety specification
- 5/8"-11 x 3/4" mechanical interface (standard surveying interface)
- Transmitter Operation and Maintenance manual

Item 2 Portable Indoor As-built Modeling Receiver Package(Quantity 1)

- 1 SPsi Wand Receiver Model 120-1
 - 5 degrees of freedom point position measurement
 - indoor operation
- SPsi hand-held display w/ host processor Model 1401-1
 - 20 x 4 supertwist LCD w/ backlight
 - 24 key - keypad
 - RS232 Serial communications interface
- Construction ToolBox™ survey & construction layout software (version 2.0)
- 5/8"-11 x 3/4" mechanical interface

Item 3 Accessory Package

- Receiver pole extension w/ pole point (5 ft x 1.25 in (dia.))
- 2 - 8 hour Receiver battery pack (12V)
- 2 - Transmitter power supply
- SPsi 12V Battery Charger
- SPsi Communications Cable (*to link a graphical computer via RS232*)
- Training Tutorial
- Owners Manual

Optional Accessories

- SPsi SpaceStation "As-Built" Modeling software
- Bentley Microstation™ 5.0
- Motorola RNet 9600 baud RF modem (*to link a remote CAD computer*)
- SPsi Tripod - Model W-1A
- SPsi Tribrach - Model 2151
- SPsi Transmitter shipping/storage container - Model SCTX02
- SPsi Receiver shipping/storage container - Model SCR02

Spatial Positioning Systems, inc., 1800 Kraft Drive, Blacksburg, VA 24060 USA TEL: (703) 231-3145
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Appendix F

Consortium for Advanced Positioning Systems (CAPS) Field Demonstrations

Numerous presentations and field demonstrations were performed by the Consortium for Advanced Positioning Systems (CAPS) during 1993 and 1994.

Civil Engineering Research Foundation (CERF) Corporate Advisory Board

CAPS' third demonstration on 13 October 1993 was for the Corporate Advisory Board of the CERF in Washington, DC. As a member of CAPS, CERF invited the CAPS members to demonstrate progress to date. This demonstration used the Spatial Positioning Systems, Inc. (SPSi), calibration system and a smaller hand-held receiver. The smaller system performs indoors at ranges of up to 35 m and outdoors at ranges of up to 35 m with a range of 20 m on a bright sunny day. No accuracy tests were conducted. All systems performed well including RF modem, Jacobus' protocol, Intergraph's MicroStation™, and receiver interface with SPsi's hardware. The response from the people present was very good. SPsi will continue contact with several of these companies for future relationships and sales.

National Institute for Standards and Technology (NIST)

CAPS' fourth demonstration on 14-15 October 1993 was a demonstration at NIST in Gaithersburg, MD. This test was to quantify accuracy of the system as it existed at that time. Unfortunately, SPsi's calibration

algorithm seemed to go awry. Whereas the system had worked well in SPSi's laboratory environment, SPSi was unable to get the system calibrated at the NIST site. Therefore, no testing was done on accuracy. However, the demonstration did provide an opportunity to test the system for distances and various issues of the interface software by Intergraph. SPSi was able to calibrate the system by visual alignment, and meaningful work was done to determine utility and methods of use. CAPS also presented the technology to several representatives of Bechtel, Gaithersburg, and NIST. It is hoped that SPSi will go back to NIST or another site offered by the U.S. Army Corps of Engineers outside Fredericksburg to test the system for accuracy.

American Society for Civil Engineers (ASCE)

ASCE Board of Directors

CAPS' fifth demonstration on 23 October 1993 was to the ASCE Board of Directors in Dallas, TX. This was the first time that the SPSi system was used with a preconfigured calibration and preassembled space frame, which was used as a spacer to provide a known orientation and distance between transmitters. This proved to be an excellent way to demonstrate the system with a reduced set-up time and less reliance on the calibration system. The system worked well for indoor demonstrations with measurement distances up to 35 m.

ASCE National Convention

CAPS' sixth demonstration on 24-26 October 1993 was to the ASCE National Convention in Dallas, TX. This was the first public exhibition where CAPS' products were shown. Response was excellent from the attendees. The system performed well. SPSi learned that the system would work with a single battery charge for about 8 hr given the indoor small receiver. For 3 days, CAPS members were able to test the hardware and software interfaces. Real-time 3-D modeling of several objects was done. A 3-D model of a complex object was also done by collecting many 3-D points all about the surface of the object. This exhibition provided an excellent opportunity to learn about customer needs and how to best apply the smaller indoor receiver.

Military Engineers

The seventh demonstration on 28-29 October was given to the Military Engineers meeting in Memphis, TN. The system was the same setup that was used for the ASCE National Convention. The presentation was well-received by the audience.

Further field tests are planned during 1995. These include field work to be performed at the Manchester Street Station Repowering Project in Providence, RI, and a series of tests to be performed at the NIST Corbin site.

Other Field Tests and Demonstrations

August 1994	Tinker Air Force Base Oklahoma City, OK
October 1993	CERF Corporate Advisory Board Washington, DC
October 1993	NIST Gaithersburg, MD
October 1993	ASCE Board of Directors Dallas, TX
October 1993	ASCE National Convention Dallas, TX
September 1993	Manchester Street Station Repowering Project Providence, RI
August 1993	Blacksburg, VA

Additional CAPS Presentations

1993	Associated General Contractors' Annual Meeting University of British Columbia Vancouver, BC
	NIST CERF CAB, October 1993 Washington, DC

Beijing, China
EPRI Conference and paper

- 1994 University of British Columbia lecture for Tom Froese
NASA Ames Research Center
Dresden Nuclear Power Plant
SAME Oklahoma and OU Student Chapter
Retrofit Conference at Stanford University

Virginia Tech. Boiler Room
Spring Intergraph User's Group (IGUG)
Huntsville, AL

- 1994 Australia - Portland Smelter - Minenco - Western Mining

Australian IGUG

Corps CAD/GIS Conference
New Orleans, LA

TVA Watts Barr
Berkeley

Research and Development Technical Seminar
Bechtel Corporation
San Francisco, CA

ASCE Annual Convention
Atlanta, GA

University of Colorado

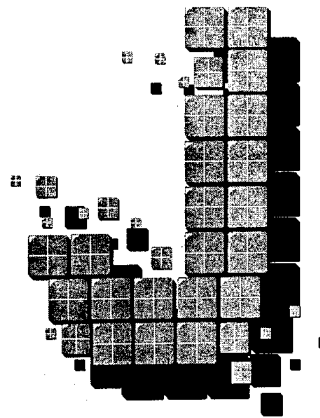
Appendix G

Jacobus Technology, Inc.,

Product Specifications

JSpaceTM

...an environment for objects



JSpace is a general purpose, object-oriented environment for creating and interacting with the large, and complex sets of data typical of projects in the architecture, engineering, and construction (AEC) industry. It is a flexible and extensible environment that provides both immediate usability and sophisticated development tools. *JSpace* is designed not only to provide the foundation for new applications, but to add value to the software and data already in use. The strength of the *JSpace* technology is that its architecture will allow diverse applications to share the same data and much of the same software.

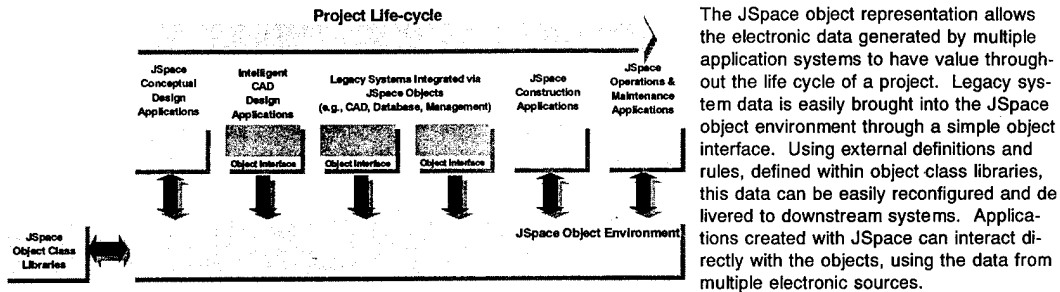
Modifying application software in order to respond to the rapid changes in technology, the introduction of new technology, and a changing business environment is becoming more critical every day. The challenges posed by a rapidly changing environment cannot be met by simply adding more programmers. It requires a software architecture that is *designed* to change and evolve. *JSpace* was specifically designed to meet this challenge and is an effective approach to implementing automation capabilities which recognizes that flexibility and extensibility are fundamental requirements for future automation systems within the AEC industry.

The *JSpace* technology can provide strategic new capabilities where solutions do not exist today, such as in conceptual design, construction support, and facility operations. It adds value to an organization's existing investment in automation, as represented by its legacy systems, by providing a flexible framework for delivering the data from those systems to new strategic applications. Through its visualization and multimedia capabilities, *JSpace* provides an extremely effective means of interacting with that data to support a wide range of applications. The *JSpace* object-oriented representation provides the robustness and flexibility required to enable the objects to be useful and evolve throughout a facility life cycle.

Jacobus Technology, Inc. offers a number of application modules as well as an end user development system. These modules can be applied to visualization, conceptual modeling, constraint checking, and information delivery tasks.

JSpace represents a new way to conceptualize, create, and apply both data and application software to tasks within the AEC industry.

 **Jacobus Technology, Inc.**



The JSpace object representation allows the electronic data generated by multiple application systems to have value throughout the life cycle of a project. Legacy system data is easily brought into the JSpace object environment through a simple object interface. Using external definitions and rules, defined within object class libraries, this data can be easily reconfigured and delivered to downstream systems. Applications created with JSpace can interact directly with the objects, using the data from multiple electronic sources.

JSpace Modules

Jacobus Technology offers a number of application modules created with JSpace. These systems can form the fundamental building blocks for sophisticated applications, relevant to many phases of the project life cycle.

JSpace Viewer. The *Viewer* provides the capability to visualize and interact with objects within the JSpace object environment. It provides 3D visualization and real-time animation capabilities as well as the ability to access non-graphic objects which are related to the graphical objects. The *Viewer* runs on multiple hardware platforms, including the Silicon Graphics workstations and workstations running Windows NT. The *Viewer* is the foundation upon which the JSpace Vantage and JSpace Vista systems, for intelligent design review and information query, were created.

JSpace Object Engine. The *Object Engine* is a general purpose object processor to manipulate objects within the JSpace object environment. For example, using the rules and relationships defined within external class libraries, objects from multiple sources can be automatically related and updated. The information from these related objects can then be used by other JSpace applications, such as the *Viewer*, or delivered into a database file. The *Object Engine* runs on virtually all hardware and operating system platforms.

JSpace Class Editor. The *Class Editor* is the tool for creating and maintaining object class libraries. These libraries are fundamental to the JSpace object environment. Objects, properties, creator rules, constraints, and relationship rules are all defined within the class libraries. The *Class Editor* employs a graphical user interface to make it very easy for a user to control the definition, creation, and behavior of the objects. It is available for Unix, Windows NT, and Windows.

JSpace Software Development Kit. The Software Development Kit (SDK) allows end user organizations to easily create their own object-oriented applications using the JSpace foundation. Users can extend the functionality of JSpace by simply adding new methods and functions within the JSpace environment. Likewise, users can create entirely new applications layered upon JSpace.

Why JSpace?

The areas where JSpace has the greatest potential are those where no significant applications exist today and where data from multiple, varied sources is required. Addressing these areas to-date has required significant investments in customized software development, out of the reach of most firms. JSpace is positioned to provide these types of capabilities very cost-effectively to companies of all sizes in the AEC market.



For more information about JSpace and our other products and services, please call or write:

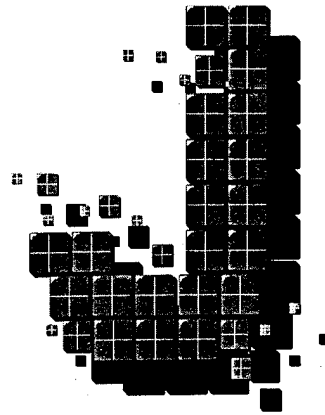
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JSpace ViewerTM

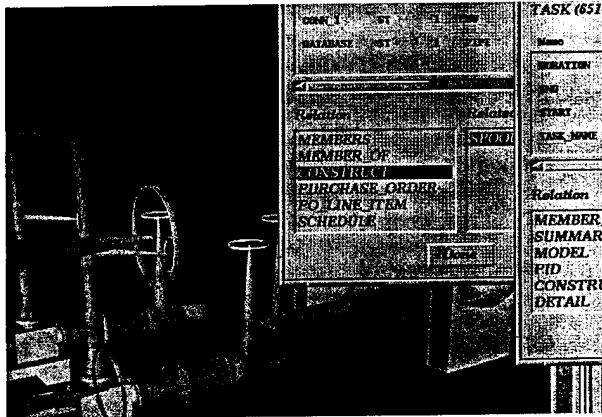
...adding value to information by making it visible



Built upon *JSpace*, Jacobus Technology's object-oriented environment, the *JSpace Viewer* provides a highly interactive and intuitive method for accessing project information, using the 3D graphics as the key into the project data environment.

The result of any project in the architecture, engineering, and construction (AEC) industry is always something that exists in 3D space—a building, refinery, power plant, etc. For this reason, 3D design and visualization has become very important for AEC projects. The *JSpace Viewer*, while providing high performance 3D animation, also provides a window into the multitude of data associated with the 3D objects. The *Viewer* is the means to visualize the complete data environment for the project.

The *Viewer* allows the user to graphically select a 3D object and then traverse through the network of information associated with that object—design data, purchasing status, schedule information, construction status. The *Viewer* can also support multimedia access to scanned images, such as vendor drawings, as well as digital audio and video, providing training information for example.



The 3D objects can be grouped and color-coded based on information from other sources through user-defined queries. These queries can also identify safety or logistical constraints violations.

The *JSpace Viewer* increases the value of your data in all forms by making it visible, supporting you in making the many critical decisions that inevitably arise during the project life-cycle.

JT *Jacobus Technology, Inc.*

The *JSpace Viewer* is a real-time, 3D animation system that allows you to view 3D model objects and their related data objects within the JSpace object environment. The Viewer is available under both Unix and Windows NT.

Viewer Functions

The *Viewer* provides a range of functions important for the effective interaction with complex 3D models and associated data.

Viewing. A full complement of view control and display functions are provided.

- Multiple graphical and non-graphical object models may be loaded simultaneously.
- Multiple, user-defined viewing windows.
- Wireframe, smooth-shaded, or mixed mode 3D, real-time animation display, independently controlled in each window.
- Viewer motion may be controlled by the mouse or by scroll bars.
- Display (On/Off) of individual objects, models or groups controlled independently for each open view window.
- Both orthographic and user-defined perspective modes are supported.
- Zoom in, zoom out, zoom all, zoom on object, and zoom on group functions are supported.

Annotation. Text annotation can be added to each of the active *Viewer* windows.

- User-defined text labels can be associated with selected objects.
- Text labels can be automatically formatted and displayed based on object properties using user-defined rules.
- Notes can be created, edited, and associated with selected graphical objects.
- Dimensions between points can be interactively defined and displayed.

Groups. Objects can be grouped and manipulated in a variety of ways within the *Viewer*.

- Objects can be grouped through interactive selection, either by individual selection or with a bounding box.
- Groups can be created by a user-defined query. The query can be based on the properties of the objects as well as those of related, perhaps non-graphical, objects.
- Groups can be assigned colors or display modes which override those of the individual objects in the group.
- Groups can be selectively turned on or off within each view window.
- Non-graphical properties can be assigned to group objects.

Object Query. Objects can be interactively queried for information.

- Distances between points and along a series of points can be measured.
- Minimum distance between two 3D objects can be computed.
- All the properties of a selected object can be displayed in an on-screen dialog box.
- The properties dialog box also displays a list of related objects. By double-clicking on the related object name, a properties dialog box will be displayed for the related object.

Standard Interfaces. The *Viewer* can import graphical data from 3D CAD systems as well as non-graphical data in a variety of formats.

- Computer-aided Design

<i>MicroStation (.dgn)</i>	<i>DXF</i>
<i>AutoCAD (.dwg)</i>	<i>IGES</i>
- Databases

<i>dBase</i>	<i>Oracle</i>	<i>Btrieve</i>
<i>Xbase</i>	<i>ODBC</i>	<i>Delimited ASCII</i>



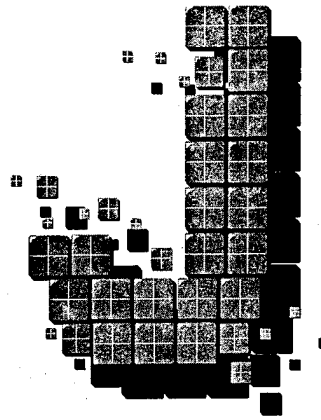
For more information about JSpace and our other products and services, please call or write:

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JSpace *Class Editor*TM

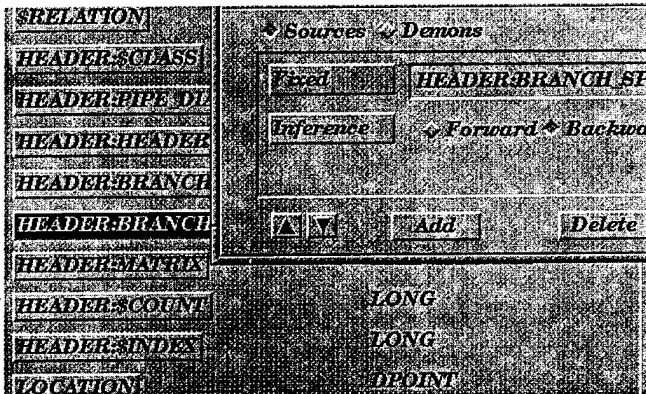


...applying your unique knowledge to your unique tasks

A fundamental principle in any object-oriented system is the concept of an object *class*. A class is the means by which an object is defined and serves as the template for creating new objects of that type. For many systems, the definition of the object types, i.e., the classes, are contained within the software itself, such as C++ classes.

The *JSpace* object-oriented approach maintains the class definitions *external* to the software itself. This allows developers as well as users to quickly adapt a *JSpace* application to incorporate new or modified object types, new functionality, or adapt to new data requirements. These external class libraries are created and maintained by the *JSpace Class Editor* software.

The *JSpace Class Editor* provides a graphical user interface (GUI) which allows complete control over the definition of object types. With the *Class Editor*, it is possible to define properties, constraints, methods, demons, relationships, and relationship rules for each class of object. *JSpace* supports the use of expert system rules for assigning property values.



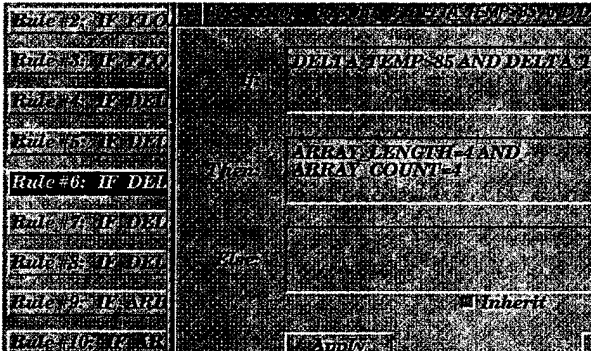
In an industry as diverse and dynamic as the architecture, engineering, and construction (AEC) industry, flexibility and extensibility of automation systems has become an absolute must. The object-oriented concepts, as implemented by the *JSpace* system are critical to achieving that goal. The *Class Editor* is the fundamental tool allowing applications to be adapted quickly and easily.

JT *Jacobus Technology, Inc.*

Object class definitions represent the fundamental structure around which the *JSpace* concepts are implemented. The *JSpace Class Editor* is the tool for creating and maintaining those class definitions, which are stored in an external class library. With the *Class Editor*, the following characteristics of new and existing classes can be defined and modified. The *Class Editor* is available under Unix, Windows NT, and Windows.

Properties. Each *JSpace* object may have one or more properties. Included in a property definition are such parameters as:

- The property type, such as integer, floating point, text, etc.
- The source of value for the property when the object is created. The source of value can be a user-defined expression, an external function, infer from a set of if-then-else rules defined for the class, or user input. Multiple sources of value may be defined which are evaluated based on their assigned priority.



- Complex constraints can be defined for each of the properties.
- Demons (software functions that execute automatically when a property value changes) can be assigned individually to properties.

Inference Rules. Expert system inference rules can be assigned to each class. These rules are expressed in an IF-THEN-ELSE format and can be defined via the *Class Editor*. These rules can be used to determine the values for object properties. The rules can be expressed in terms of the values of other properties of the object or values of related objects, e.g., CONNECTED. External functions may also be referenced by the inference rules assigned to a class.

Sub-objects. Any class may define that when an object of that class is created, objects of other classes are also to be created. The class and properties of the additional objects are determined by any of the *JSpace* sources of value, such as infer. This enables the implementation of knowledge-based design capabilities.

Methods. The function names associated with object methods are defined in the class library. The names of the functions are assigned to the various messages an object could receive, e.g., DRAW, RELATE, CREATE, etc. The names are determined from sources of value just as property values. In this way, method function names are sensitive to the context in which the object was created.

Relationships. Critical to many AEC applications is the ability to create and manipulate explicit relationships between objects. Any object within a project may be related to hundreds of other objects—connected, supported, purchased by, has status, etc. The *Class Editor* allows any user-defined relationship to be assigned to a class. In addition to defining the relationship names, rules for the relationships can also be defined. These rules are used both as constraints on the relationship as well as instructions to inform the object how to identify those other objects with which it has the defined relationship.



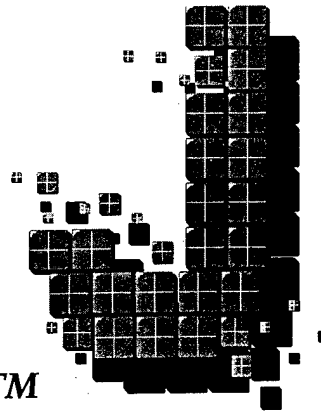
For more information about JSpace and our other products and services, please call or write:

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JSpace Object Engine™

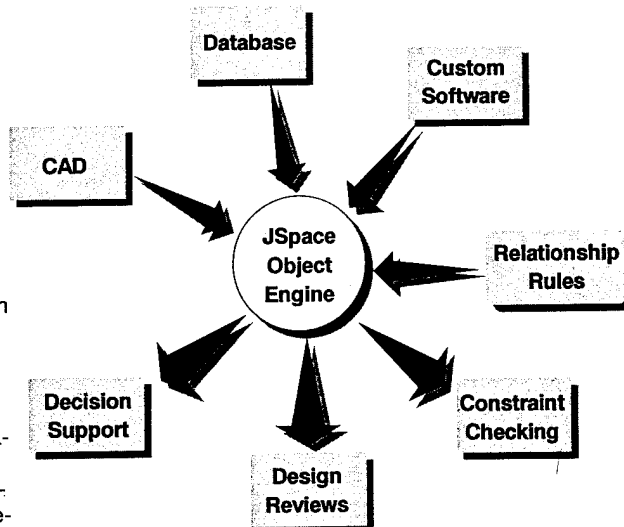
...delivering value by delivering information



Built upon Jacobus Technology's object-oriented system, *JSpace*, the *Object Engine* is designed to address the information delivery issues associated with architecture, engineering, and construction (AEC) projects and provide the flexibility required to easily adapt to the changing data needs on a project-by-project basis.

Delivering information across the many interfaces that exist in the AEC industry can be a daunting task. Each organization in a project has a necessarily different view of the world and thus a very different set of information requirements—different naming conventions, different scopes, different levels of detail. Simple data translations alone don't solve the problem. To make matters worse, seemingly every project has a different configuration of requirements for moving data throughout the multiple project organizations.

Through a simple software interface, nearly any application can be adapted to generate objects within the *JSpace* object environment. Using user-defined relationships and rules, the objects from multiple sources are automatically related to each



other. The objects can then be directed to configure and deliver the appropriate information into a scope and electronic form appropriate for the recipient of that information.

JT *Jacobus Technology, Inc.*

The *JSpace Object Engine* is a general purpose object processor. It operates using script files which issue commands to the *Object Engine*. The command set executed by the *Object Engine* can be extended with the *JSpace Software Development Kit (SDK)*. The *Object Engine* is available under DOS, Windows, and Windows NT, as well as multiple Unix workstations.

Standard Object Interfaces. For application software not originally based on the *JSpace* technology, an object interface is required in order to generate objects within the *JSpace* object environment. Interface development is very simple, even for complex applications. A number of standard interfaces to *JSpace* already exist:

- Databases

<i>dBase</i>	<i>Oracle</i>	<i>Btrieve</i>
<i>Xbase</i>	<i>ODBC</i>	<i>Delimited ASCII</i>
- Computer-aided Design

<i>MicroStation (.dgn)</i>	<i>DXF</i>
<i>AutoCAD (.dwg)</i>	<i>IGES</i>

For most applications, one or more of these standard interfaces can be used directly as the object interface for the application.

JSpace Class Libraries. A *JSpace* class library completely defines the configuration and behavior of *JSpace* objects. These libraries exist external to the *JSpace* software, allowing the behavior of the objects to be modified without modifying the software. Using the *JSpace Class Editor*, the class libraries can be created and updated by the end user to define object characteristics such as:

- Object properties and constraints.
- Rules for assigning values to properties.
- Functions to execute (methods) in response to commands (messages) to the object.
- Relationships that can exist between objects.
- Rules for establishing relationships.

These *Class Editor* functions enable a very high degree of flexibility and extensibility without requiring modifications to the software code.

Object Engine Functions. The *Object Engine* can perform a variety of functions on the *JSpace* objects. These functions allow the *Object Engine* to perform tasks such as:

- Automatically relate objects from different sources via the rules in the class library.
- Update an object's property values based on data contained in related objects.
- Generate more complex objects from simpler objects, i.e., increase level of detail.
- Create higher level objects from groups of existing objects, i.e., decrease level of detail.
- Generate database tables which combine information from multiple related objects, i.e., change scope of information.

These functions create a very robust tool for satisfying information delivery requirements.

Benefits. Using the *Object Engine* for information delivery provides a number of benefits:

- Allow applications to use data from multiple sources without requiring manual transposition or multiple point-to-point translators.
- Enable data from multiple sources to be verified for consistency and satisfaction of constraints, e.g., design, safety, OSHA.
- Easily reconfigure data (scope and level of detail) to be appropriate for the specific user.
- Enable a project to quickly adapt to new data requirements and new application software.

Most importantly, the *Object Engine* allows electronic data to be combined and then delivered in such a way that new, strategic applications can be implemented, enabling you to realize the full value of your electronic information.



For more information about JSpace and our other products and services, please call or write:

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Appendix H

A Real-Time Laser-Based System for Collecting Construction Site Positioning Data

Figures 1, 2, 3, and 4 are included in the main text as Figures 1, 3, 5, and 7, respectively.

**A Real-Time Laser-Based System for Collecting
Construction Site Positioning Data**

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Abstract

Locating components in the complex and changing construction site environment is a fundamental activity common to all construction projects. Conventional methods of surveying are labor intensive, expensive and time consuming. The authors describe the development of a new technology that uses laser signals to quickly and accurately generate real-time positioning data. The digital positioning data can then be fed directly to CAD systems to create "instant" as-built models. Conversely, positioning data can be downloaded from an existing CAD model for use in either locating or laying out points in space. This integration of real-time position measurement and CAD data lays a foundation for future construction field methods, including remote guidance, equipment automation, and virtual reality.

Introduction

Locating components in the complex and changing construction site environment is a fundamental activity common to all construction projects. Conventional methods of surveying are labor intensive, expensive and time consuming. This paper describes the development of a new technology that uses laser signals to quickly and accurately generate real-time positioning data. The digital positioning data can then be fed directly to CAD systems to create "instant" as-built models. Conversely, positioning data can be downloaded from an existing CAD model for use in either locating or laying out points in space.

This revolutionary technology is being developed and demonstrated by a group of firms that have formed the Consortium for Advanced Positioning Systems (CAPS). This unique group combines the resources and expertise of government and industry to field a new generation of CAD integrated positioning system technology.

This paper presents the firms represented by the authors, describes the CAPS organization, provides a description of the positioning system, and discusses the application of this technology at a Bechtel project site.

Bechtel Research and Development

Bechtel Corporation recognizes the importance of developing and implementing new technologies in our rapidly evolving and highly competitive industry. The Bechtel Technology Group is a major corporate division and contains four organizational groups: Geotechnical and Hydraulic Engineering Services, Materials and Quality Services, Bechtel Software, Inc., and Research and Development.

The Research and Development organization works closely with Bechtel functional groups as well as with Bechtel clients and projects to provide a wide range of support services. It is a large and diverse group of 150 people, who are primarily located in Bechtel's corporate headquarters in San Francisco.

The R&D organization is composed of six groups: Applied Physics and Advanced Civil, Commercial Programs, Energy Programs, International Technologies and Resources, Process Programs, and Engineering and Construction Technologies.

The mission of Engineering and Construction Technologies (E&CT) is to identify, develop and implement new technologies that directly enhance the engineering and construction work processes. E&CT also acts as an external interface between Bechtel and numerous entities in the academic, industry and government sectors. Collaborative development efforts, often through the creation of consortia, are increasingly common, and E&CT represents Bechtel in the Consortium for Advanced Positioning Systems.

Jacobus Technology

Jacobus Technology, Inc. is a Maryland-based company that provides automation products and services to the Architecture, Engineering and Construction (AEC) industry. Jacobus Technology offers both software products and technical services to the AEC industry. Their software products are focused on improving both quality and productivity throughout the design and construction cycle. Jacobus also provides consulting and technical services to the AEC industry,

A Real-Time Laser-Based System for Collecting Construction Site Positioning Data

and specializes in the area of computer-aided design, computer-aided engineering, and animation.

Jacobus Technology has created a 3D CAD modeling tool called JSpace™ that takes advantage of a powerful object oriented environment to process 3D position data and create graphical as-built representations of field components. JSpace™ is a general purpose object-oriented environment for creating and interacting with large and complex sets of data encountered in AEC projects. This environment is created by the effective integration of object-oriented concepts, real-time animation and integration of project data and users. The implementation of the object-oriented paradigm within JSpace™ is a very flexible and extensible environment that provides both immediate usability and sophisticated development tools.

JSpace is designed not only to provide the foundation for new applications, but to add value to the software and data already in use within the AEC industry. The strength of the JSpace technology is that its architecture will allow diverse applications to share the same data and much of the same software. The software architecture also makes it very easy to extend the systems to incorporate new features and data types.

Spatial Positioning Systems, Inc.

Spatial Positioning Technologies, inc., (SPSi) is a high technology firm that designs, creates, and supports three dimensional position measurement systems. SPsi was formed in June 1990 by three Virginia Tech scientists and inventors who recognized an industrial need for new position measurement capabilities. The company has developed a proprietary and patented laser-based position measurement technology that provides a significant increase in performance and capability over current methods. SPsi's EXPIRT™ (Exact Position in Real Time) technology has a wide range of applications in the construction, manufacturing, space, defense, environmental, and medical fields.

The system uses a series of fixed laser transmitters to generate signals that are beamed throughout a work area. Small, portable receivers that are carried through the work space receive the laser signals, and either process the information on-board or transmit the position data to an external processor. In either case, the result is the real time, three dimensional location of the desired point.

SPsi offers turn-key positioning measurement products for the AEC industry. These products are for use over a broad range of AEC applications including facility layout, "as-built" measurements, and automated equipment control. SPsi's advanced user friendly systems offer the AEC industry productivity improvement and cost savings over other surveying devices.

CAPS, the Consortium for Advanced Positioning Systems

One approach to leveraging the resources of individual firms such as Bechtel Corporation, Jacobus Technology, and Spatial Positioning Systems, inc. is to create consortia that share in the costs and benefits of the research and development process. The Consortium for Advanced Positioning Systems (CAPS) is just such a collaborative effort, created to develop and implement a revolutionary new site positioning technology.

The Consortium for Advanced Positioning Systems was formally organized in December of 1992. The CAPS structure is illustrated in Figure 1. The founding members of CAPS include Bechtel Corporation, Jacobus Technology, Spatial Positioning Systems, inc., and the Civil Engineering Research Foundation (CERF). CERF is a non-profit affiliate of the American

A Real-Time Laser-Based System for Collecting Construction Site Positioning Data

Society of Civil Engineers whose mission is to promote research that benefits the AEC industry in general.

The United States Government has recently made funds available for infusion into the private sector as a stimulus for research and development activity, through the Construction Productivity Advancement Research program. These funds are administered through a mechanism known as a Cooperative Research and Development Agreement, or CRDA. The United States Army Corps of Engineers is participating in the CAPS consortium through a CRDA agreement with the Civil Engineering Research Foundation.

Intergraph Corporation joined CAPS as a full member during the second quarter of 1993. Intergraph is a leading supplier of CAD related hardware and software, and is providing software development expertise to CAPS using the Microstation and Microstation Review products. Additional CAPS participants include the Amoco Oil Company, the Center for Innovative Technology, DuPont, Motorola Corporation, and the National Science Foundation.

CAPS Purpose Statement

The CAPS mission statement differentiates the long term goals of the consortium from the immediate objectives of the current development project described in this paper. The long term goal of CAPS is to combine the resources and experience base of industry, academia, and government to identify, develop, integrate and implement new positioning technologies for the common benefit of consortium members and the U.S. construction industry.

In order to accomplish this goal, CAPS members collectively:

- | | |
|------------------|--|
| Identify | new positioning technologies. |
| Establish | industry standards for the collection, transmission and processing of digital 3D positioning data. |
| Develop | promising new technologies. |
| Integrate | real-time positioning data with CAD systems. |
| Implement | new positioning technologies in industry working environments. |
| Report | the results of CAPS activities to member firms and the industry. |

With these long term objectives in mind, CAPS members are currently working on the development of a specific positioning technology, SPSi's system of real time positioning measurement, or RTPM. This laser based system generates accurate, digital, real-time positioning data. The initial project also demonstrates the capability of linking these data directly with a CAD modeling environment.

The SPSi Positioning Technology

The positioning system under development by CAPS is comprised of several distinct components that have been integrated into a functional system. The core of the system is the SPSi laser-based positioning device.

The SPSi positioning system is composed of a series of stationary laser transmitters, portable receivers and software that reduces the transmitter signals to coordinate information. These components are represented schematically in Figure 2.

The position measurement technology employed by SPSi is based on the geometric principle that the intersection of three planes defines a point in space. SPSi systems employ lasers in a unique

A Real-Time Laser-Based System for Collecting Construction Site Positioning Data

way to establish intersecting planes in space. These planes have specific temporal relationships for each intersection point in three dimensional space. The precise coordinate position of the portable receiver is determined through on-board analysis of precise time measurements of the signals received from the transmitters.

Each receiver requires line of site contact with at least two transmitters to generate coordinate data. Any number of receivers can operate independently from the same set of transmitters. Presently, receivers will work up to a range of 250 meters from any pair of laser transmitters. The predicted achievable measurement accuracy is 1:100,000 (e.g., 2.5 mm at 250 meters) with data rates as high as 10 Hz. The RiPM™ system is protected by U.S. patents. Other U.S. and foreign patents are allowed or pending.

The SPSi system can be packaged into a number of useful tools for construction personnel. The system can be configured to self-calibrate with no aiming or leveling necessary, thus reducing the potential for human error. Several people can work simultaneously in different areas of a site, independent of one another, from the same set of transmitters. SPSi's position measurement systems are designed so that one person can set up a system and then generate accurate position measurements as quickly as the user can move from point to point in the field.

Each receiver provides a combination of design data and position, or simple position at the instant that it is required. The display of information can be specialized to meet the specific needs of individual craftspeople such as carpenters, masons, or steel workers. Tools are being developed to be used across several construction applications, including surveying, building layout, "as-built" measurements, and on-site CAD/position integration and utilization.

A simple coordinate system interface is available when CAD data is not. This system provides basic coordinate measurement capability with no direct integration with CAD. Construction Toolbox™ software provides a simple interface for measurement functions including: distance, area, volume, and angle. This tool provides instantaneous numerical coordinate information for craftspeople using traditional design information such as blue prints, and existing construction techniques. However, the true power of the real-time positioning system is unleashed when it is integrated with a CAD modeling environment.

Positioning System - CAD Integration

In order for the positioning system to communicate with the CAD environment, CAPS members developed a communications protocol using Jacobus Technology's object oriented modeling environment JSpace™.

Communication Protocol

The intent of the CAD communications protocol is to provide a standard way that positioning data from a variety of 3D measurement devices can be integrated with computer aided design (CAD) systems. In this sense, CAD is also intended to encompass the use of CAD data to display positioning information graphically, such as real-time 3D displays.

In addition to supporting multiple measurement devices, the protocol satisfies a number of other objectives by:

- Allowing for bi-directional communication between a 3D measurement device and the CAD systems.
- Providing capabilities for both real-time and batch transmission of coordinate data.

A Real-Time Laser-Based System for Collecting Construction Site Positioning Data

- Allowing for both single point coordinates and continuous streams of coordinates.
- Allowing for asynchronous communication between the measurement device and the CAD system.
- Supporting the communication of both commands and data, either from the measurement devices or the CAD system.
- Providing a framework that is extensible to include new commands or new data types.

CAD Integration

Integrated systems combine real-time coordinate data from the RtPM system with CAD design data. The combination of real-time measurement and CAD representation allows both exact position and graphical design data to be provided simultaneously to an operator.

Using the JSpace protocol, the SPSi positioning system can communicate directly with the CAD environment. This is accomplished by linking the positioning receiver to a computer, using either a hardwired connection or radio frequency modems. The CAPS system utilizes RF modems to provide coordinate data to a MicroSlate pen-based computer provided by Intergraph Corporation. Figure 3 shows the system, including transmitters, receiver, and MicroSlate, in a field environment.

The pen-based computer contains both design files and the CAD application. The initial CAPS system uses Microstation Review provided by the Intergraph Corporation. The Microstation application software running on the MicroSlate displays the location of the positioning receiver on the screen. As the receiver moves, so moves the receiver icon. The receiver icon can be used to initiate CAD commands or to provide a data input point.

The direct positioning system-CAD link allows the operator to download plant design files and use the design information as a basis for field layout activities. Application software developed by Intergraph allows the user to select a point in the CAD model, and then use the positioning system to guide to the point. Conversely, The user can collect as-built data directly from the field environment and upload it directly to the modeling environment, creating real-time as-builts.

Bechtel/CAPS Field Demonstration

The CAPS Positioning System was demonstrated at a Bechtel power project during September, 1993. The Manchester Street Station Repowering Project (MSSRP) is located in Providence, Rhode Island. The plant owners, Narragansett Electric and New England Power Company selected Bechtel to convert the oil-fired facility to natural gas and install three state-of-the-art combustion turbines. Along with the heat-recovery steam generators (HRSG's) and new steam turbines connected to them, the three new combined cycle turbine trains will help triple plant capacity, from 132 megawatts to around 489 MW.

Working closely with Bechtel field personnel, CAPS members identified a series of initial demonstration tasks that reflect actual work tasks. These demonstration tasks also demonstrate the capabilities of the system, including both layout and as-built activities.

Although the SPSi/CAPS system has potential applications through the life of a construction project, the initial demonstration tasks were related to site civil work. Figure 4 illustrates the use of the system at the Manchester site. These tasks were defined in order to take advantage of the project phase at the time of the demonstration.

**A Real-Time Laser-Based System for Collecting
Construction Site Positioning Data**

The demonstration tasks included:

1. Step-taper piles as-builts
2. HRSR embedded plate as-builts
3. Combustion Turbine pedestal sleeves and blockouts as-builts
4. Underground pipe as-builts
5. H-pile as-builts
6. General layout, or "guide-to-a-point" capability

The CAPS group plans to continue working with the MSSRP as a beta-test site for the positioning technology. Future tasks will focus on mechanical as-builts as well as feeding real-time positioning information to project fabricators to support "just-in-time" component fabrication.

Conclusion

In conclusion, this paper describes the development and operation of a revolutionary new laser-based positioning system, the integration of positioning data with a CAD modeling environment using a sophisticated object-oriented protocol, and the demonstration of the system in a real construction project environment.

This integration of real-time position measurement and CAD data lays a foundation for future construction field methods. Field application opportunities for the integrated positioning system are limitless. However, we envision several initial categories of application in field construction. These include performing component layout, generating component as-builts, and controlling automated work systems such as heavy equipment operation for earthwork operations. Future applications might include fully autonomous earthmoving systems, "just-in-time" fabrication using actual field measurements and direct linked CNC machines, and new human-computer interfaces such as virtual reality applications.

Appendix I

Collaborative Applied Research: An R&D Case Study of the Development of a New Site Positioning Technology

ABSTRACT

Collaborative Applied Research: An R&D Case Study of the Development of a New Site Positioning Technology

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Abstract

This paper describes a revolution in site positioning activities and concepts that parallels the revolution in computer aided design tools. The first section of this paper describes the Consortium for Advanced Positioning Systems (CAPS), a collaborative effort to develop a revolutionary new site positioning technology. It includes descriptions of the structure and participants in CAPS.

The second portion of the paper describes the actual positioning system under development by the CAPS group. It is composed of a series of stationary laser transmitters, portable receivers and software that links the positioning device to a dynamic CAD environment.

The new positioning system underwent field tests on a Bechtel project in September 1993. The Manchester Street Station Repowering Project in Providence, Rhode Island hosted a series of demonstration activities designed to illustrate the functionality of the system. The third section of this paper presents a description of the project, the tests that were performed and outlines applications for further field implementation.

Collaborative Applied Research:
An R&D Case Study of the Development of a New Site Positioning Technology

Identify	new positioning technologies.
Establish	industry standards for the collection, transmission and processing of digital 3D positioning data.
Develop	promising new technologies.
Integrate	real-time positioning data with CAD systems.
Implement	new positioning technologies in industry working environments.
Report	the results of CAPS activities to member firms and the industry.

With these long term objectives in mind, CAPS members are currently working on the development of a specific positioning technology, the SPSi real time positioning measurement system, or RtPM™. This laser-based system generates accurate, digital, real-time positioning data. The initial project also demonstrates the capability of linking these data directly with a CAD modeling environment.

Civil Engineering Research Foundation

The Civil Engineering Research Foundation (CERF) was created by the American Society of Civil Engineers to provide a unique opportunity for industry coordinated and directed Research and Development. Working with the design and construction industry, CERF identifies research needs, coordinates research to meet those needs; and manages a program of research, development and demonstration filling gaps identified by the industry. CERF maintains a close association with the ASCE and the National Council on Civil Engineering Research (NCCER). NCCER involves over 40 governmental and private funding organizations who work together to coordinate research activities, leverage limited resources, and help transfer research into practice.

Bechtel Research and Development

Bechtel Corporation recognizes the importance of developing and implementing new technologies. Bechtel supports a large and diverse Research and Development organization in its San Francisco office. This organization includes a group called Engineering and Construction Technologies (E&CT) whose charter is to identify, develop, and implement new technologies in both the construction and engineering functional groups. E&CT also acts as an external interface between Bechtel and a number of entities in the academic, industry and government sectors. Collaborative development efforts, often through the creation of consortia, are increasingly common. Recent development efforts have addressed issues related to integrating engineering and design technologies with field execution methods.

Spatial Positioning Systems, inc. (SPSi)

Spatial Positioning Systems, inc. has developed a proprietary system that uses laser signals to accurately locate points in three dimensional space. The system uses a series of fixed laser transmitters to generate signals that are beamed throughout a work area. Small, portable receivers that are carried through the work space receive the laser signals, and either process the information on-board or transmit the position data to an external processor. In either case, the result is the real time, three dimensional location of the desired point.

Jacobus Technology, Inc.

Jacobus Technology has created a 3D CAD modeling tool called JSpace™ that takes advantage of a powerful object oriented environment to process 3D position data and create graphical as-built representations of field components. The JSpace environment is a general modeling tool with powerful capabilities. JSpace is being utilized to create "real-time" as-built models of field components using three dimensional positioning data from SPSi's positioning system. Conversely, positioning data can be downloaded from an existing CAD model for use in either

provides three-dimensional position measurement information over a 150 meter range with 2 two centimeter accuracy at a 10 Hz data rate. The actual performance of the system is now a function of the software used in the on board processor. The theoretical performance of the system predicts that sub-centimeter accuracy will be achievable at distances of around 200 meters.

A new generation of receiver has been demonstrated that has a theoretical accuracy of less than a millimeter at distances up to 25 meters. Longer ranges, higher update rates, and greater accuracy are expected as the processing software evolves.

The basic RtPM system provides basic coordinate measurement capability even with no direct integration with CAD. Associated SPSi software such as Construction Toolbox™ provides basic functions such as distance, area, volume, or angle using a simple interface. However, the true power of the real-time positioning system is unleashed when it is integrated with a CAD modeling environment.

RtPM/Cad Integration Protocol

In order for the positioning system to communicate with the CAD environment, CAPS members developed a communications protocol using Jacobus Technology's object oriented development environment JSpace.

The intent of the CAD communications protocol is to provide a standard way that positioning data from a variety of 3D measurement devices can be integrated with computer aided design (CAD) systems. In this sense, CAD is also intended to encompass the use of CAD data to display positioning information graphically, such as real-time 3D displays.

Protocol Issues

The protocol developed for the integration of CAD and measurement technologies addresses the following issues:

1. Support of multiple 3D measurement devices - The protocol provides the structure for even the simplest of measurement devices to communicate with a CAD system, without limiting the effectiveness of more sophisticated measurement technologies such as RtPM.
2. Bi-directional communication between 3D measurement devices and CAD systems - The protocol is structured to allow for bi-directional communication between the measurement device and the CAD system. Commands, coordinate information, attributes, etc. are designed to pass in both directions.
3. Real-time and batch transmission of coordinate data - The protocol provides the flexibility to allow for the real-time, interactive transmission of data as well as the batch mode transmission of data that was collected off-line.
4. Single point coordinates and continuous streams of coordinates - In order to support the entire spectrum of measurement technologies as well as the envisioned spectrum of applications, the protocol allows for single point communication as well as continuous streams of coordinate data.
5. Asynchronous communication between the measurement device and the CAD system - The protocol and its implementation are structured to allow for asynchronous communication between the CAD system and the measurement device. This is necessary to recover from errors, to modify the mode of data collection and transmission, etc.

Types of data

The protocol is designed to exchange the following types of data between CAD systems and positioning devices:

coordinate and graphical cues to help the user physically move to the desired point in space. As the user gets closer to the desired point, the scale of the figure changes, zooming in to provide greater detail. Additional buttons and pull down menus allow the user to navigate through the system.

In addition to the "guiding to a point," or layout function represented in this screen, the system can be used to collect information about the physical world that is then stored in the CAD system. These data can be used to instance components in the CAD model through parametric modeling of object libraries. For example, an anchor bolt schedule might be included in the model with all details of each anchor bolt type included. The user would then place the receiver on the anchor bolt in the field to capture the location of the top center of bolt, and enter an alphanumeric code identifying the type of bolt. The system would then update the model with a CAD object representing the anchor bolt in the as-built location.

Project Implications of Advanced Positioning Technologies

Advanced positioning technologies such as RtPM offer the promise of real time collection of highly accurate three dimensional position data. The use of these data will impact projects in a number of different ways, particularly in engineering and construction.

Engineering

In order to utilize 3D position data, components will have to be located using the concept of a set-point or fiducial and its associated 3D position data. Each component is traditionally located through the use of three independent measures, an X offset, a Y offset, and a Z elevation. These data are represented as linear offset distances, and in the field each is traditionally established independently. If 3D coordinate data is used to physically locate components, then the traditional offset and elevation data given on drawings must be transformed to coordinates in the reference coordinate system. In addition, the set point, or point at which the coordinates are specified, must also be determined and represented.

The set point must be a physical point that can be easily located and measured in the field. This is straightforward in the case of an anchor bolt; the center of the top of bolt is a convenient place to both compute coordinates and collect position data. This is somewhat more complicated in the case of components such as pumps that typically use a centerline of inlet or outlet as a reference line. In this case, set points might include the invert of the inlet or the top of the base plate at a specified location. The conversion of offset data into 3D XYZ coordinate data and the identification of set points are new activities that must be performed to support RtPM field applications, and create a new set of design deliverables.

Construction

There are several obvious benefits to using RtPM for plant layout. The use of RtPM can save substantial time in performing field layout and inspection activities. By blanketing an area with a laser signal, the position of any component within the area of coverage can be determined in as short a time as it takes to place the receiver on the component and either read or transmit the coordinate data.

When compared to the conventional process of running control points into the proximity of the component, calculating the XY position from the offset lines, running a level loop into the area to measure elevation (the Z coordinate), and field reducing the level data, the savings are substantial.

The anticipated initial crew size for an RtPM crew is two people. One person will handle the notebook computer and one person will handle the position sensor. The combined effects of increased speed and smaller crew size lead to significant increases in productivity for both layout and inspection activities.

There are numerous applications on fossil power projects that immediately present themselves, including:

- Real time As-Built
- Real-time sensing for setting steam drums
- Steam Turbine Replacement and Repair
- Boiler to Steam Drum Connector Spools
- Site Surveys of Existing Facilities
- Mapping and Locating Hidden Utilities
- Turbine Installation
- Retrofit and Rehabilitation

RtPM Benefits

The ability to produce very accurate position data very quickly in three dimensions provides significant benefits to the surveying and measurement industry. However, the integration of position measurement information with a CAD environment provides the potential for a revolution to the construction industry.

Real-time Position Measurement (RtPM) integrated with CAD provides the necessary link of the data base to the end users. These end users include surveyors, inspectors, managers, operators, and craftspeople. RtPM provides a link from the virtual world (the CAD data base) to the real world (the project). RtPM supports information dissemination to people and control of equipment and processes within that real world.

The potential benefits to the construction industry rely on adopting 3D CAD as the managing entity of data for electronic data interchange within all aspects of the AEC industry. If this is done, the added benefit of having good "living" data about the facility will allow the owner to utilize this living data base for such life cycle activities as operations, maintenance, retrofit, renovation, rebuild, and demolition. The use of RtPM to update the living project data base makes possible the creation of as-builts quickly, easily and inexpensively.

The benefits to the construction industry fall into several categories. This include: quicker and higher quality layout surveying, quicker and higher quality characterization of existing facilities, improved craftspeople performance, improved surveyor and craftspeople status, reduced rework, improved modular construction, improved as-builts, equipment performance and quality improvement, control potential for robots or autonomous vehicle, and improved overall construction control.

Quicker and higher quality layout surveying

Layout and control surveying currently account for about one percent of construction cost. This process typically does not rely on electronic interface of data to the real-world. Instead, this process often relies on error prone hand calculations and on-the-fly recalibration and adjustments. Although the current use of total stations, transits, levels, and tapes will continue even after significant adoption of RtPM, the new technology is an addition to the overall toolkit of measurement instruments.

Quicker and higher quality characterization of existing facilities

Many projects today include renovation, modernization, or retrofit of existing facilities. These projects also require extensive cataloging and characterization of existing components and their

Control potential for robots or autonomous vehicle

The idea of assisting operators to perform their tasks more efficiently has dramatic implications for the control of robots and autonomous vehicles. A robot could move about in three dimensional space and receive continuous feedback of its position, including the position and orientation of end effectors, within the design environment. As work is accomplished by one autonomous device, information about changes in the geometry of the work environment is sent to all other robots. This is done by updating the "living" data base that continually reflects the site changes as work is accomplished. The data base continuously gets updates about the current project topology as well. This allows for determination of work achieved as well as for the planning of subsequent work.

Conclusion

This paper describes the development of a revolutionary new laser-based positioning system, the integration of positioning data with a sophisticated CAD modeling environment, the successful demonstration of the system in a working construction environment, and presents applications and benefits for the technology on construction projects.

The use of a consortium approach to developing a new positioning technology has proven to be quite successful. Each participant brings unique resources and capabilities to bear on a issue fundamental to the construction industry, that of locating components quickly and accurately in the changing construction environment.

The success of the Consortium for Advanced Positioning Systems is due to the contributions of the people that formed the development team. These include not only the members of the site demonstration team shown in Figure 8, but the project owners, New England Power and Narragansett Electric Company, and the dedicated Bechtel Manchester Street Station construction team members who actively supported the demonstration.

The potential for application of the system is essentially unlimited, ranging from real-time as-builts to autonomous machine control. As further development and field testing of the integrated, laser-based positioning system progresses, we continue to learn more about how to apply the system to improve our construction work processes.

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Appendix J

Real-Time Positioning

Applications for Retrofit Projects

Figures 1 and 2 are included in the main text as Figures 1 and 4, respectively. The ODYSSEY™ system specifications (Table 1) are given in Appendix E.

Real-Time Positioning Applications for Retrofit Projects

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Abstract

In December of 1992, the Consortium for Advanced Technologies (CAPS) was formed to develop and demonstrate new positioning technologies. CAPS objectives include fielding a new generation, state-of-the-art laser-based positioning system; developing the software that allows the system to communicate directly with CAD environments; and demonstrating the capabilities and effectiveness of the system through on-site tests at construction projects.

This paper describes the positioning system developed by Spatial Positioning Systems, inc. and the CAPS members, and presents opportunities for applying this powerful technology on retrofit projects.

Introduction

In December of 1992, the Consortium for Advanced Technologies (CAPS) was formed to develop and demonstrate new positioning technologies. CAPS objectives include fielding a new generation, state-of-the-art laser-based positioning system; developing the software that allows the system to communicate directly with CAD environments; and demonstrating the capabilities and effectiveness of the system through on-site tests at construction projects.

This paper describes the positioning system developed by Spatial Positioning Systems, inc. and the CAPS members, and presents opportunities for applying this powerful technology on retrofit projects.

The Consortium for Advance Positioning Systems

There are five full CAPS members, each of whom brings a unique set of resources to the organization. Spatial Positioning Systems, inc. (SPSi), Jacobus Technology, Inc., Bechtel Corporation, and the Civil Engineering Research Foundation (CERF) formally initiated the consortium in December 1992. Intergraph Corporation joined CAPS in June of 1993.

The positioning system that is the focus of the consortium utilizes hardware developed and patented by Spatial Positioning Systems, inc. SPSi's system is composed of multiple, fixed laser-based transmitters and portable receivers that are manipulated throughout the work area. The system provides real-time, digital position data in three dimensions with accuracies that meet or exceed current requirements for typical construction operations.

Jacobus Technology created a powerful object-oriented programming and modeling environment called JSpace™. JSpace protocol code can interpret signals from the SPSi receiver and convert them to data that is represented graphically in a CAD model of the object being measured. JSpace can also send data to the positioning device, enabling the user to locate components or set reference points that have previously been modeled in the CAD environment.

Bechtel Corporation recognizes the strategic importance of developing and implementing new technologies on its projects. Bechtel supports a large and diverse Research and Development organization, which includes the Engineering and Construction Technologies Group (E&CT). Bechtel is funding a portion of the CAPS development costs and E&CT is contributing field expertise and product design input from a user perspective. Bechtel is also managing a series of system demonstrations on Bechtel projects under actual field conditions.

Intergraph Corporation developed application software to integrate the positioning technology with the MicroStation CAD modeling system. Users can select points of interest from the CAD model and direct the positioning device to the selected points in the physical world. Physical geometry data can also be captured, recorded and transmitted directly to the CAD model, allowing the user to create "instant as-builts."

In December 1992, the Civil Engineering Research Foundation entered into a Cooperative Research and Development Agreement (CRDA) with the U.S. Army Corps of Engineers. CERF performs CAPS management functions, such as arranging and chairing meetings and making distributions of reports to members. The Corps of Engineers is contributing both matching funds and in-kind services to the CAPS development effort. The primary objectives of the CRDA are consistent with the goals of CAPS and include further integration and demonstrations at Corps' sites.

In addition to these CAPS members, Amoco Oil Company, the Center for Innovative Technology, DuPont, Motorola Corporation, and the National Science Foundation have all contributed resources to the CAPS development effort.

The CAPS Positioning Technology

The positioning system under development by CAPS is comprised of several distinct components that have been integrated into a functional system. The core of the system is the SPSi laser-based positioning device called Odyssey.TM Product specifications for the Odyssey system are shown in Table 1.

There are two primary components in the system, transmitters and receivers. At least two transmitters are required to provide positioning signals to a receiver. However, any number of receivers can utilize the positioning signals simultaneously.

The transmitters can be set up at convenient locations and generally aimed at the work site. This is analogous to setting up a spotlight that is pointed towards the site to be illuminated. However, the infra-red energy source is selective and only the tuned receivers can "see" the "light."

Existing plant benchmarks are used to calibrate the system using any local coordinate system. Alternatively, any convenient consistent reference system, such as a series of quickly established triangles on an operating floor, can be used to create a temporary, local frame of reference that is then used to capture relative position data, which can later be tied into an existing coordinate system.

Each receiver is composed of two lenses mounted on a pole, a processor, a data entry and retrieval system, and a power supply. The two lenses form a line, and the position of the lenses and the known geometry of the pole allow the point of position measurement to be projected to the end of the pole. Since the position of the tip of the pole does not change if the pole is slanted, rotated, turned upside down or sideways, the position of any point that the user touches with the receiver is accurately and "instantly" measured.

The Odyssey system provides basic coordinate measurement capability even with no direct integration with CAD. SPSi system software will provide basic functions such as distance between two points, areas, volumes, or angles using a simple user interface. However, real-time position data linked directly with CAD modeling systems provides a powerful tool with unlimited field applications.

Odyssey Positioning System - CAD Integration

The integrated site positioning system combines real-time coordinate data from the Odyssey system with CAD design data. The combination of real-time coordinate measurement and CAD representation allows field position data and graphical design data to be provided simultaneously to the user. A schematic representation of the CAPS system is shown in Figure 2.

Communication Protocol

In order for the positioning system to communicate with the CAD environment, Jacobus Technology used its object oriented modeling environment JSpaceTM to develop a communications protocol called CAPSCOM.

The purpose of CAPSCOM is to provide a standard format for the integration of positioning data from a variety of 3D measurement devices with CAD systems. The CAPSCOM protocol:

- Allows for bi-directional communication between a 3D measurement device such as Odyssey and a CAD system such as Intergraph's MicroStation.

- Provides capabilities for both real-time and batch transmission of coordinate data.
- Allows for the transmission of both single point coordinates and continuous streams of coordinates.
- Supports asynchronous communication between the measurement device and the CAD system.
- Allows the communication of both commands and data, either from the measurement devices or the CAD system.
- Provides a framework that is extensible to include new commands or new data types.

Using the CAPS protocol, the SPSi positioning system can communicate directly with the CAD environment. This is physically accomplished by linking the positioning receiver to a computer, using either a hardwired connection or radio frequency (RF) modems. The initial CAPS system utilizes Motorola RNet 9600 RF modems to exchange coordinate data with a MicroSlate pen-based computer or an Intergraph TD-1 workstation running either MicroStation or MicroStation Review. However, many other hardware and software configurations are possible.

The CAD platform contains both design files and the CAD application software. The MicroStation application software running on the MicroSlate, for example, displays the location of the positioning receiver on the screen, relative to the other objects in the CAD file. As the receiver moves, so moves the receiver icon on the computer screen. The receiver icon can be used to initiate CAD commands or to provide a data input point.

The direct positioning system-CAD link allows the operator to download plant design files and use the design information as a basis for field layout activities. Application software developed by Intergraph allows the user to select a point in the CAD model, and then use the positioning system to guide to the point. The user can also collect as-built data directly from the field environment and upload it directly to the modeling environment, creating real-time as-builts.

Bechtel/CAPS Field Demonstration

The CAPS Positioning System was demonstrated at a Bechtel power project during September, 1993. The Manchester Street Station Repowering Project (MSSRP) is located in Providence, Rhode Island. The plant owners, Narragansett Electric and New England Power Company selected Bechtel to convert the oil-fired facility to natural gas and install three state-of-the-art combustion turbines. Three heat-recovery steam generators (HRSG's) collect the waste heat from the combustion turbine exhaust and feed three new steam turbines as well as three rebuilt existing steam turbines. The three new combined cycle turbine trains will help triple plant capacity, from 132 megawatts to around 489 megawatts.

Working closely with Bechtel field personnel, CAPS members identified a series of initial demonstration tasks that reflected actual work tasks. These work tasks also demonstrated the capabilities of the system, including both layout and as-built activities.

In order to take advantage of the project phase at the time of the demonstration, the initial demonstration tasks were related to site civil work. These tasks included:

1. Step-taper piles as-builts
2. HRSG embedded plate as-builts
3. Combustion Turbine pedestal sleeves and blockouts as-builts
4. Underground pipe as-builts
5. H-pile as-builts
6. General layout, or "guide-to-a-point" capability

The site demonstration also confirmed the feasibility of using RF modems to send data to workstations in the field office. An Intergraph TD-1 workstation was located inside a building overlooking the test site. It was used to model plant components in the CAD model, based on data transmitted from the positioning system outside in the field.

Real Time Positioning Applications on Retrofit Projects

The initial field system demonstration on a Bechtel repowering project illustrated several specific applications of the new integrated positioning system. As an increasing number of existing plants are being upgraded, modified or retrofitted, CAPS members and Bechtel are exploring additional opportunities to apply the technology in this growing market. These opportunities impact both project planning and project execution, and include facility characterization; outage planning and simulation; modular planning, fabrication and construction; consistent site control; real time position feedback for autonomous systems; and plant database baseline.

Facility characterization

Many projects today require renovation, modernization, or retrofit of existing facilities. These projects also require extensive cataloging and characterization of existing components and their locations in order to properly plan for the shut-down of the facility and subsequent work activities. This results in the creation and modification of a plant database. This living database contains not only component geometry and location, but other attribute data.

Data collection methods that use conventional survey techniques and technologies are slow, error prone and time consuming. Field measurements of angles, distances, and elevations are often recorded manually and later reduced and transcribed in the field or home office. The coordinate data that results is then use to produce as-built drawings or, less frequently, is loaded into a CAD graphical environment.

Since as-builts are difficult, costly, and time consuming to create using conventional data collection techniques, existing facilities are often facilities incompletely described in their as-built condition.

The contractors who propose to work in these uncertain plant environments must include substantial contingency in their proposals to cover unforeseen situations. Using an integrated CAD and real time position measurement system, the direct time and cost to create as-built position data for plant components will drop substantially. The indirect costs of contingency for working in uncertain plant environments with uncertain component geometry will decrease as well.

Outage planning and simulation

Once the plant environment in which an outage or shutdown will take place is well defined, task planning can begin. This may include such activities as crane placement, load definition, rigging analysis, component or module tie-in locations, spool dimensions, and other similar tasks.

Each of these tasks has a geometry component. For example, potential interferences to crane motion can only be determined if the location of the crane and existing structures are known. Waiting for observational data during field operations does not allow for a calm approach to evaluating options.

However, using real data to feed simulation and planning tools (such as Bechtel's ALPS™ system for rigging planning), project planners can incorporate actual plant geometry data when planning specific lifts. Each crane configuration is modeled in the system and combined with as-built data about the actual work environment, and each lift can be fully planned before the project moves to the field.

Modular planning, fabrication and construction

Modularization and other forms of preassembly are becoming standard practice for outage or shutdown work. Many plant components can be preassembled prior to the outage and installed as a unit during the time constrained shut down period. Real time positioning provides a number of benefits for the modular project.

One important aspect of modular work is physically interfacing different modules. Adjacent preassemblies may be fabricated in different shops or may mate with field fabricated sections. An integrated real time positioning system provides the ability to easily determine if interfaces surfaces are compatible. It also provides the same "electronic yardstick" for both the fabrication yard and the construction site. This results in consistent fabrication processes and improved module-to-module fit.

Once fabricated, modules and preassemblies must be moved into position. Once again, simulation tools using accurate as-built data can help path planners perform route surveys and ensure that the modules can navigate the selected path without interferences. The positioning receiver could also be mounted directly on a module in a known location relative to the module frame or other components. The actual progress of the module as it moves through space could then be tracked in real-time, as the unit is guided directly to the desired location using real-time positioning feedback.

Consistent site control

Using a common method of measurement provides a common "yardstick" for all project participants, with which they can control site work. Work done by one contractor will interface more easily with work performed by others. The piping fabricator's spools should fit the structural steel with no interferences and with fewer fit-up problems if they are both using the same measuring system.

For planned outages or scheduled shutdowns, the plant owner could provide the transmitters and the positioning signal would become a commodity shared by all crafts and all contractors. Several transmitters could provide positioning signal across the entire work area. Multiple receivers could be used by different crews simultaneously. Each crew could also access portions of the plant database to avoid conflicts during field routing operations.

Real time position feedback for autonomous systems

Remotely guided or autonomous systems are increasingly used for retrofit work, especially in hazardous or contaminated environments. One fundamental requirement of these systems is accurate and timely position updates.

Real time position measurement provides such a feedback mechanism. With a real time CAD link, the remote system not only knows where it is within a coordinate system, but also knows where other objects are located as well. This "knowledge" prevents collisions in real time 3-space.

Multiple units could work simultaneously using shared data. Collisions and near misses could be avoided by creating "forbidden zones" or volumes into which entry is prohibited. And as the remote vehicles mapped areas or installed components, their locations would be updated in the shared plant database to support planning and execution of subsequent work.

Plant database baseline

As constructors and inspectors use integrated real time positioning systems to install and verify the location and geometry of plant components, the plant database is updated in real time. The resulting data becomes not only an as-built record, but also a verification of pay quantities or pay tasks.

As each component is installed and each system is brought online, the system and component status can be directly input to the master plant or outage database. This provides status information as well as verification of installed configuration and geometry and an historical record for the next group who will perform maintenance or outage activities in the area at some future time.

The utilization of real time positioning data has now come full circle. The plant is accurately characterized in the living database and a baseline is provided for the next set of operations, maintenance or modification tasks.

Conclusion

The ability to generate accurate three dimensional position data in real time is a significant benefit to construction and retrofit projects. Integrating this position information directly with sophisticated CAD systems provides a revolutionary tool for current and future projects. There is essentially unlimited potential for the application of real time positioning devices and the integrated CAD modeling system.

As further development and field testing of the integrated positioning system progresses, we continue to learn more about how to apply the system to solve real world problems. Our challenge lies in matching the tremendous potential of the system with creative improvements in our construction work process.

Acknowledgments

The CAPS collaboration has provided a unique and synergistic environment for the formulation and development of new ideas. Throughout its existence, the group members have shared freely of their thoughts and ideas. Consequently, papers presented by individuals participating in the group often reflect thinking that developed interactively in this open environment.

I would like to acknowledge in particular the input and thinking of Yvan Beliveau and Eric Lundberg, from Spatial Positioning Systems, inc. and Jerry King, from Jacobus Technology, to the concepts contained in this paper.

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Appendix K

Notation

AFB	Air Force Base
ASCE	American Society of Civil Engineers
CAD	Computer-Aided Design
CAD/CAE	Computer-Aided Design/Computer-Aided Engineering
CAPS	Consortium for Advanced Positioning Systems
CERF	Civil Engineering Research Foundation
CIF	Construction Innovation Forum
CPAR	Construction Productivity Advancement Program
CRDA	Cooperative Research and Development Agreement
DGPS	Digital Global Positioning Systems
OTF DGPS	(On-the-Fly) Digital Global Positioning Systems
OTF/GPS	On-the-Fly Global Positioning Systems
DoD	Department of Defense
EDM	Electronic Distance Measuring Device
GIS FM	Geographic Information System for Facility Management
GPS	Global Positioning Systems
HRSG	Heat-Recovery Steam Generators
IGUG	Intergraph User's Group
MDL	MicroStation™ Development Language
MSSRP	Manchester Street Station Repowering Project
NIST	National Institute for Standards and Technology
NSF	National Science Foundation
RtCLADS	Real-Time Construction and As-Built Development System
RtPM	Real-Time Positioning Measurement
SPSi	Spatial Positioning Systems, Inc.
TEC	Topographic Engineering Center
USACE	U.S. Army Corps of Engineers
WES	U.S. Army Engineer Waterways Experiment Station

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