CONSTRUCTION VEHICLE NAVIGATION AND AUTOMATION

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ABSTRACT

The U.S. Army Topographic Engineering Center (TEC) and Caterpillar Inc. have cooperated in the joint research and development of a system to position, track, and maneuver construction and other equipment during their normal construction activities. The two main components of this research focus are the positioning system needed for navigation and the Computer Aided Drafting and Design (CADD) interface for automation. The positioning system is based on software developed by TEC that utilizes the Global Positioning System (GPS). It is called the On-the-Fly (OTF) Differential GPS system. Several repeatability tests were conducted to test the accuracy and precision of the OTF software. The results proved that the OTF system can provide an accuracy of 3 centimeters in a robust manner. The positioning system software has been integrated with Caterpillar developed software tools to automate construction activities and increase productivity and safety in the project area. This software allows the construction vehicle to perform its operations and provide real time as-built drawings in the process. This joint effort has produced an autonomous construction vehicle navigation and automation system that has been demonstrated on a Track-Type Tractor (dozer) and will be adapted to various other construction vehicle platforms, which include an off-highway truck and a motor grader. CADD tools based on the envisioned vehicle navigation system have been integrated, offering the user highly accurate and responsive production, planning and monitoring tools that were previously unavailable.

INTRODUCTION

Most construction activities require some form of earth movement, whether it be grading, clearing, cutting and/or filling. Before, during and after these construction activities, site surveys are performed to verify that the project area is consistent with the engineering design. In years past, these designs were drafted by hand and interpreted by surveyors in the field as to whether the proper quantities of soil were being excavated and/or deposited. With the improved performance of Computer Aided Design and Drafting (CADD) and other automated surveying means, users are able to accurately and efficiently design and construct in the virtual world of computers. Until now that automation stopped when moved from the office computer to the project site. In other words, earth moving equipment operators relied on experience and wooden stakes accurately placed by surveyors to communicate the proper design surface.

In April 1993, the U.S. Army Topographic Engineering Center (TEC) and Caterpillar Inc. signed a three-year Construction Productivity Advancement Research Program Cooperative Research and Development Agreement (CPAR-CRDA) to develop a Global Positioning System (GPS) based construction vehicle positioning and navigation system that could be adapted to various construction equipment platforms. The final system combined the latest GPS technology with a variety of CADD tools. This combination offers the equipment user computer-generated views to display and continuously update the topography during normal construction activities. The system also produces as-built drawings of the construction site that can be electronically transferred back to the design engineer for verification.

Automation of any earth moving activity requires continuous tracking of the equipment's position in relation to the project area. This information must also be graphically relayed to the equipment operator and to the field office for monitoring the machine's progress (see **Figure #1**). Therefore, for the CPAR-CRDA to be considered successful and result in a marketable product, the positioning system and the CADD interface must operate without failure and be economically feasible in a construction environment.

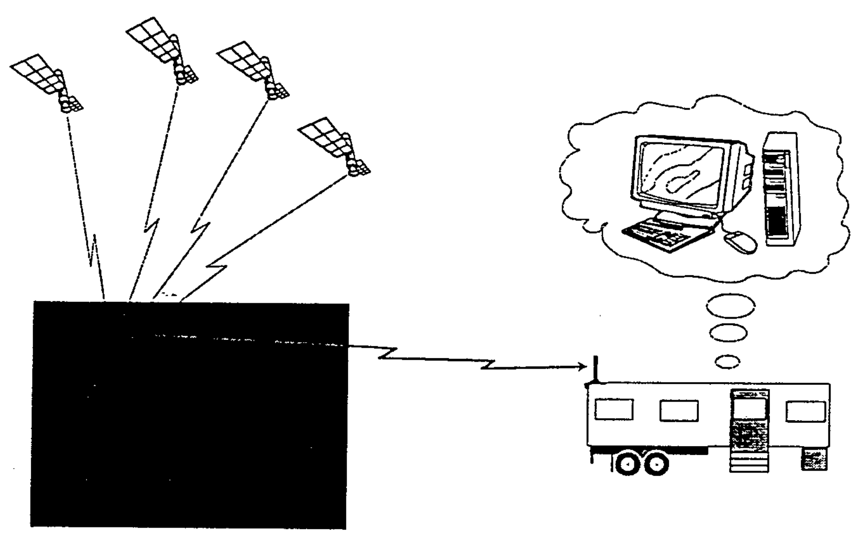

Figure 1. Schematic of Automated System

POSITIONING SYSTEM

The system developed in this CPAR project provides the equipment operator with positioning information based on GPS. NAVSTAR GPS is an all-weather, 24-hour, worldwide, three-dimensional (3-D) satellite-based positioning system developed by the Department of Defense (DoD). Each satellite broadcasts coded messages (the P-code and C/A code) on two frequencies, L1 and L2. Both the carrier frequency and their coded messages are used to obtain positioning information.

The primary purpose of GPS is to provide a Precise Positioning Service (PPS) to the U.S. military and its allies. GPS also provides the Standard Positioning Service (SPS), a service available to civilians with the purchase of necessary equipment. These services are affected by the transmission from the satellites of time-coded signals unique to each satellite and information on satellite timing and positions. By measuring the arrival time of these coded signals, the GPS receiver estimates the range to each of the GPS satellites in view and then, using the satellite positions, is able to compute its own position and clock offset. When using one GPS receiver, the 3-D absolute accuracy is approximately 16 meters for PPS and 100 meters for SPS.

Differential GPS (DGPS) techniques process signals from two GPS receivers operating simultaneously and determines the 3-D vector between them. This technique can be used with the code phase information transmitted by the GPS satellites to obtain meter accuracy or the carrier information to obtain an accuracy to a few millimeters.

In the past, a significant restriction to using GPS technology has been the ability to position accurately in real time. Until recently, the ability to position a moving platform with DGPS (to a few centimeters) required very strict operational constraints and procedures that were not feasible in a construction environment. In 1988, under funding from the U.S. Army Corps of Engineers (USACE) Dredging Research Program (DRP), TEC began developing a real time GPS-based positioning system capable of delivering 3-D positions accurate to a few centimeters over a range of approximately 20 kilometers. To obtain "centimeter" level positions in real time, the integer ambiguities (whole number of integer wavelengths) between the receiver and the observed satellites must be solved while one receiver is in motion (termed On-The-Fly (OTF)) and another is located over a known control point. For every common epoch (one measurement of GPS carrier phase data) measured by the receivers, a 3-D vector is calculated between them establishing the position of the moving receiver relative to the reference receiver.

The OTF real-time system requires dual frequency (L1/L2) geodetic GPS receivers capable of receiving full wavelength carrier phase measurements during Anti-Spoofing (AS). AS is the encryption of the P-Code on the GPS signal. A base/reference receiver is placed over a known control monument. The raw carrier phase measurements are formatted using a computer and broadcast over a telemetry link to the roving unit or moving platform. The rover setup requires a telemetry link (to receive reference station measurements), a computer, and a GPS receiver. The raw carrier phase measurements from both the reference and rover receivers combined with the OTF algorithms are used to compute the rover's position in real time.

The high-precision positioning is available from the OTF system once integer ambiguities are resolved by the software. Before initialization can occur both the user and reference station must be tracking five common satellites in which the L1 and L2 carrier signals are being measured. As long as both the reference and rover receivers remain locked on at least four common satellites, real-time "centimeter" level positioning in three dimensions will continue to be available at the rover.

Under this CPAR-CRDA, the OTF system was extensively tested and modified to work with Leica SR399 GPS receivers. Many tests of the OTF system have occurred since August 1993. The results of these tests have shown that the OTF system can provide a horizontal and vertical accuracy of approximately 3 centimeters in a robust manner. The OTF system offers a very powerful tool to position accurately in real-time which results in reduced costs of construction and earth moving projects for USACE and the private sector.

CADD INTERFACE

Caterpillar Site Data Processor (SDP)

Caterpillar has developed and demonstrated in-house, an on-the-machine dynamic construction site database. The SDP accepts site data design information from third-party site design tools, e.g. Intergraph CADD, AutoCad, LandCAD, AGTEK Edge, PAYDIRT, etc. and translates the design file into a data file compatible with the machine system. The site data file is transferred to the machine by either a PCMCIA flash drive or a direct radio link.

Computer Aided Earthmoving System (CAES)

The Caterpillar CAES uses high-accuracy GPS receivers in conjunction with computers and displays mounted on earthmoving equipment to provide machine operators and site managers with a variety of real-time information regarding the execution of the earthmoving task. On-board information systems provide the machine operator the information he needs to correctly and accurately accomplish the earthmoving task. Generally, the information includes the engineering plan, the current status of the job, the machine location, the job site, and specific information for controlling the machine's working tool, i.e., the blade, bucket, etc. As the machine accomplishes the tasks, the on-board information system records that accomplishment for later transmission to site management and engineering facilities.

FIELD TESTING

Several experiments tested the effectiveness and feasibility of the positioning system and CADD interface. Practical tests were performed to test the integrated GPS/CADD system under typical construction conditions. Repeatability tests were also performed to test the validity of the OTF positioning system with different types of GPS receivers.

Practical Tests

Test #1. The first practical test was performed in December 1993 at Caterpillar's Peoria Proving Grounds in Peoria, Illinois. The objective of this test was to combine TEC's positioning software with Caterpillar's SDP/CAES and test its functionality on board a Track-Type Tractor (dozer). A second objective was to determine the best possible location on the dozer to mount the GPS antenna, on the cab or on the blade.

The equipment used for this test included two Trimble 4000SSE GPS Receivers with dual frequency geodetic antennas, three notebook computers, two Trimble TrimTalk radios with antennas and a fixed height two-meter range pole. The base station GPS antenna was mounted on the two-meter range pole and set-up on a hill overlooking the project site. The other GPS antenna was first mounted on top of the dozer cab and later during the testing it was moved and mounted on the dozer blade.

The machine (dozer) operator prepared a section of a highway construction site without grade stakes or a survey crew, relying only on the geographical display on the machine. Simultaneously, the dynamic construction site data was broadcast via a radio link to a remote location (in this case a notebook computer at the project site) to provide a current topographic model of the site. The cab appeared to be the optimal location for the antenna, until a process can be developed to prevent modification of the as-built (terrain model) caused by raising the blade and moving to different sites.

Test #2. The second practical test of the joint system was to evaluate the static and dynamic performance of the positioning hardware and software with the CADD interface. Acquisition, reacquisition and repeatability were evaluated under simulated "deep open pit mining" conditions where satellites were intermittently shaded. A reference antenna was mounted on the roof of the maintenance shop at Caterpillar's Peoria Proving Grounds. Signal splitters were used to route the satellite signals to several GPS receivers simultaneously, and each system broadcasted their reference data independently to a corresponding receiver on the mobile rover (Machine). The machine, a Caterpillar Belted Agricultural, was similarly equipped. A single GPS antenna and signal splitters provided the satellite signal to the various GPS receivers mounted on the Tractor. Each GPS system received its reference information separately, and independently computed a position. The Tractor operated for a period of two weeks in various conditions, including areas with few obstructions and low multipath environment, as well as areas with partial to total satellite blockage with high multipath environment. The most challenging environment for the receivers was generated when the Tractor was driven through a metal shed which provided total satellite blockage and a high multipath environment before and after the transition. The position computations of the various receivers agreed within the constraints imposed on the solution when each receiver system had resolved its ambiguities. The reacquisition and ambiguity resolution times varied from system to system, and needs to be shortened for acceptability in the commercial arena. However, the amount of time when high accuracy kinematic solutions are available, and can be used in the performance of a precision task, was lower than expected.

Repeatability Tests

Three repeatability tests were performed at Caterpillar Inc. Technical Center, Peoria, Illinois. These tests were performed in December 1993, March 1994 and March 1996. The objective of this testing was to determine the repeatability of the OTF positioning software over known baselines using different manufacture's GPS receivers. These tests were conducted on a known test course (see **Figure #2**) with each point repeatedly observed during different

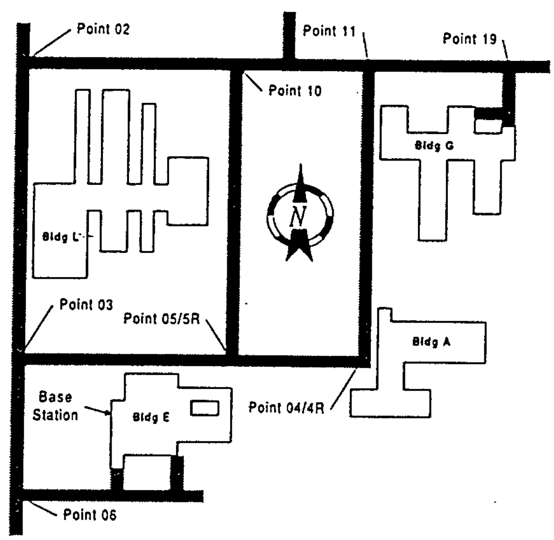

Figure 2. Caterpillar Technical Center

GPS satellite constellations. During each of the three tests the OTF system was operated within 2 kilometers of the reference station providing positions at one second intervals. The initialization time was set to attempt a solution after 15 epochs had been recorded of L1 and L2 data for 5 satellites.

The equipment for the first test consisted of two Trimble 4000SSE GPS receivers with geodetic and kinematic antennas, two notebook computers, two Trimble TrimTalk radio/modems, a two-meter fixed height tripod and a bipod. The base station was set-up on Point 5 of the test course using the two meter fixed height tripod. The position of this point had been established by a local surveyor using traditional surveying procedures (non-GPS). The roving antenna was mounted on the bipod which attached to a roof mount of TEC's Chevy Suburban (**Figure** #3). During this initial repeatability test, observations were made on a few of the established marks around the test course. Although the results from the OTF solution were consistently within one decimeter, the test was marred by constant radio/modem and GPS signal loss at several points. The radio and GPS signal loss was due to shading as the vehicle passed close to high buildings where satellite obstruction angles as high as 68 degrees were not uncommon. In an open pit mining operation, the high walls could reach 60 degree mask angles and are to be accommodated in the system development. Therefore, a fast reacquisition and ambiguity resolution is mandatory for commercial mining and construction applications. A follow-up repeatability test was scheduled for March 1994.

Figure 3. Repeatability Testing

The equipment, reference station and procedures used for the second test was identical to the equipment used for the first. However, there were only a few radio/modem losses observed which did not impact the test. To demonstrate the repeatability of the OTF solution, two testing sessions were scheduled. The first session was conducted on 14 March 1994 between 19:52 and 21:47 (UTC) observing seven stations around the test course. For each station, the known position was computed by averaging the OTF solutions obtained during the first occupation. This averaged position served as the baseline for comparison of all subsequent observations in both sessions. The second session was conducted on 15 March 1994 between 14:19 and 17:01 (UTC) observing three stations which were observed the previous day.

The equipment used for the third test consisted of two Leica SR399 GPS receivers, two notebook computers and a two-meter fixed height tripod. The base station was set-up on the roof of Building E of the Technical Center. The roving GPS antenna was mounted with a quick release on a two-meter fixed height tripod and transported from point to point via a Caterpillar construction van. This test was conducted on 28 March 1996 between 19:17 and 21:37 (UTC) observing eight stations around the test course. The known positions of the reference and test course stations were established by GPS static surveying procedures.

The performance of the OTF system yielded a positional (horizontal and vertical) difference of 0.0183 m $\pm$ 0.0101 (95% confidence interval). These repeatability tests demonstrate the positional accuracy and precision of the OTF system.

CONCLUSIONS AND RECOMMENDATIONS

Today, most of the engineering design work is being done in a CADD environment. However, some benefits of CADD design work are lost when drawings are plotted and taken to the field as 2-D sheets. Extending this electronic automation (CADD) to the field allows the equipment operator to view and update the design/terrain information during normal construction activities. This automation eliminates the need for grade stakes on the construction site. Combining OTF positioning and CADD demonstrates the viability of bringing this construction navigation and positioning system to a truly production level system. CAES improves the quantity, quality and frequency of the information that flows to and from the office and field. This information is available , upon demand, from either the field or the office.

Based on the test results from the OTF positioning system combined with the CAES, an on-machine dynamic data base coupled with GPS provides the machine operator instantaneous feedback of his performance and provides management timely progress information during site development. In addition, site design information can be reliably transmitted to the machine and presented to the machine operator on a daylight readable color screen. Also, the position of the machine tool can continuously be measured and compared to the spatial coordinates of the site to generate and maintain as-built site data files. The machine, using geodetic quality GPS equipment, continuously performs the surveying operation while simultaneously shaping the site to conform with the planned design.

The results achieved under this CPAR-CRDA support the continued development of the OTF positioning software utilizing commercial suppliers of GPS hardware to provide enhancements for evolving commercial and military products. The further development of the CAES technology will allow the smooth transition from the current terrain to the site design. This scenario creates an optimal relationship between the machine operator, the work site and technology.

REFERENCES

Deloach, S.R. (1995). *GPS Tides: A project to Determine Tidal Datums with the Global Positioning System.* U.S. Army Corps of Engineers Topographic Engineering Center, Alexandria, VA, USA.

Leick, Alfred (1995). *GPS Satellite Surveying. Second Edition.* John Wiley and Sons, Inc. New York, USA.

Gudat, A and Walker, J. (1994). *Caterpillar and TEC Joint Research Project Construction Vehicle Navigation and Automation.* Proceedings of the U.S. Army Corps of Engineers 1994 Training Symposium, New Orleans, LA, USA.

Walker, J. and Garster, J., "Differential GPS: Revolutionizing Corps Applications", Sea Technology, March 1995, Volume 36, No.3.

U.S. Army Corps of Engineers. (1994) *NAVSTAR Global Positioning System Surveying.* Engineer Manual No. 1110-1-1003, U.S. Army Corps of Engineers, Washington, DC, USA.