PROTOTYPE IMPLEMENTATION OF AN AUTOMATED STRUCTURAL STEEL TRACKING SYSTEM[1]

by

Karen M. Furlani[2], DeWitt T. Latimer IV[3], David E. Gilsinn[4] and Alan M. Lytle[5]

ABSTRACT: This paper discusses the prototype implementation of a system developed by researchers at the National Institute of Standards and Technology (NIST) for the transfer of real-time on-site metrology and metrology-based data for tracking steel frame construction. The purpose of the implementation is to demonstrate the feasibility of automatically transferring information from the construction site to project management databases and associated applications, specifically for the identification and tracking of structural steel subsystems. The successful integration and implementation of the on-site field data collection system with a project information management system enables a field worker to identify and track a steel member's final position and orientation on the job site.

KEYWORDS: construction automation, 3-D coordinate measurement systems, project information management systems, communication protocols, coordinate frame transforms, position and orientation determination, steel tracking

1.0 INTRODUCTION

Many existing technologies that aid in the automation of construction component tracking systems are limited in their use by a lack of construction industry standards supporting interoperability between various hardware and software systems. In addition, to achieve the precise positioning of components to a level of accuracy sufficient for the placement of structural steel, standard methods are needed for the registration and calibration of 3-D coordinate measurement systems and for the determination of part position and orientation. To assist the construction industry in overcoming these obstacles and achieve a fully integrated and automated environment, the National Institute of Standards and Technology (NIST) has on-going research in several related areas. Researchers in the Construction Metrology and Automation Group (CMAG) are involved in the fundamental research and development of position/orientation tracking systems, sensor interface protocols for construction data telemetry and construction site simulation. The Computer Integrated Construction (CIC) group is doing research on the visual representation and simulation of construction and building related models, activities, and processes.

CMAG and CIC have collaborated on a joint implementation to demonstrate the feasibility of transferring information from the job site to project management databases and associated applications in a real-time and automated fashion. The purpose of the combined systems is to enable a field operator to identify, register and spatially visualize the final position and orientation of select structural steel members at the job site. Prior to the implementation, the Component Tracking (Comp-TRAK) system

---

[1] Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

[2] Former member of the NIST Construction Metrology & Automation Group (CMAG). Current address: 1201 Cutter Lane, Boulder, CO 80302, (303) 440-8433, karen@furlani.com

[3] Former NIST CMAG member. Current address: 4902 Forbes Ave, Box 114, Pittsburgh, PA 15213, (412) 901-0549, dl4s@andrew.cmu.edu

[4] Optimization and Computational Geometry Group member, NIST, 100 Bureau Dr., Gaithersburg, MD 20899, (301) 975-3491, david.gilsinn@nist.gov

[5] CMAG member, NIST, 100 Bureau Dr., Gaithersburg, MD 20899, (301) 975-6078, alan.lytle@nist.gov

functioned independently of the Project Information Management System (PIMS), relying on post-processing to achieve automated tracking of steel members at the construction site. Utilizing standard interface protocols to integrate the Comp-TRAK system with the PIMS enables seamless communication between the various system components.

2.0 SCOPE

In earlier work, CMAG proposed an overall system architecture [1] and developed a prototype system that experimentally demonstrated 3-D spatial tracking of discrete components in real-time and under controlled conditions to viewers at a remote location [2]. The prototype field data collection system was field tested at the Building 205 Emission Control System (ECS) Addition – a US$6 million project on the NIST, Gaithersburg campus [3].

Previous work in communications research investigated the applicability of IEEE 1278 as a protocol for exchanging information about changes to the construction site [4]. Since the IEEE 1278 standard is written for distributed interactive simulation, it does not contain all the features necessary to describe the results of building a world model from sensors. Earlier work focused on answering the data pedagogy questions, specifically, the "who, what, where, and when" criteria for the types of data to be communicated [5]. These previous projects cumulated in small prototypes that lead up to this project.

This paper discusses advances in the field data collection system, site registration method, coordinate transform routine, part locator routine and the project information management system, as well as the underlying communications that enable the various systems to function in a seamless fashion. The prototype implementation was limited to capturing the “as-built” status of structural steel members during the construction of the Tower #2 Wind Frame Assembly at the Building 205 ECS Addition.

3.0 SYSTEM ARCHITECTURE

Overviews of the system architecture and the flow of operations are provided in Figures 1 and 2, respectively. The following sections describe the function of the sub-systems.

3.1 Part Tracking Overview

Structural steel members scheduled for arrival on the Bldg. 205 ECS construction site are each tagged with a bar code at the galvanizing plant prior to shipment. Reference data for each tagged part is concurrently pre-loaded into the PIMS database. Steel member identification data are directly scanned into a rugged, wearable computer with wireless access to the PIMS database hosted on a remote server. A database query following the scan provides additional part-related information as well as a 3-D VRML (Virtual Reality Modeling Language) model of the steel member. User-friendly Web browsing software then guides the field worker through the process of measuring the position of key fiducial points with a long-range, laser-based 3-D coordinate measurement system. These fiducial points are pre-specified measurement locations defined at readily identifiable features of interest such as corners. Three fiducial points, of which two must be non-collinear, provide a sufficient set of locations to establish the position and orientation of the member in 3-D space. The measured points are transformed from the local coordinate frame to a globally referenced site coordinate system. In this implementation, the member’s site frame position and orientation (pose) is calculated via a Part Locator Routine hosted remotely. The steel member’s identification data and local fiducial measurements are wirelessly transmitted to this routine that updates the project database with the member’s site-frame pose. The same data are transmitted back to the field worker’s wearable computer to update the user’s visual display.

3.2 Field Data Systems User Interface

All operations conducted on the field data collection system employ a web-based interface. This includes user I/O and remote access to the part tracking routines and PIMS. This interface format was chosen over a proprietary application because it allowed inherent cross-platform compatibility and relatively simple page creation and modification.

3.3 Project Information Management System

The Project Information Management System (PIMS) allows information relating to structural steel members to be stored, accessed and modified. There are four essential parts of the PIMS system used during the implementation: an object-oriented database, a JAVA-based database server, a Common Object Request Broker Architecture (CORBA) compliant trading service, and a database administrative tool.

The database was developed based on a minimal physical schema derived from the CIMSteel Integration Standard (CIS) CIS/2 logical schema [6]. For the implementation, part definition data based on the CIS/2 representation of steel members was pre-loaded in the PIMS database via the administrative tool. This information is used to simulate structural steel parts in the ECS Tower #2 sub-assembly in VRML. The CORBA is used as the underlying communications infrastructure, allowing users to connect to the PIMS server and get information to and from the database.

4.0 POSE DETERMINATION

4.1 3-D Coordinate Measurement System

To successfully deploy the tracking system in the field, in-situ measurements of the steel frame members must be registered to a globally referenced site coordinate system for part pose determination. The field tracking system uses the Vulcan 3-D coordinate measurement system by ArcSecond Inc. to measure the local frame position of each target fiducial point on the part. This system uses two rotating laser transmitters and a receiving wand to calculate wand tip position via triangulation. The calibration method utilized for the implementation employs a proprietary variation of standard photogrammetry bundle techniques to calculate transmitter positions using the optical center of the first transmitter as the local origin. To register the coordinate measurement system to a globally referenced site frame, the locations of the transmitters must be known in the site frame.

4.2 Coordinate Frames & Transform

Two coordinate frames exist – a local frame defined by the location of the transmitters and a globally-reference site frame. To register the local frame to the site frame, the transmitters are placed on benchmarks surveyed in the Maryland State Plane Coordinate System of 1983 (MD SPCS) using the North American Datum 1983 (NAD83) as the horizontal datum and the North American Vertical Datum 1988 (NAVD88) as the vertical datum.

A transform matrix was developed to translate (move a point in space a finite distance along a given vector direction) and rotate the Cartesian points measured in the local frame to the Geodetic-Latitude-Longitude-Ellipsoid height of the site frame. Five points known in both the local and site frames are necessary to perform the transform: transmitter locations and three additional reference points. Figure 3 shows the relative location of the five points for a local frame, “Site Frame 1”, established for the implementation. K15 and K12 are used to establish a local X coordinate axis with positive direction from the origin transmitter K15 to the reference transmitter K12. The Y-axis is established perpendicular to the X-axis by using the right hand rule around the vertical Z-axis with positive direction upwards. Three other non-collinear points identified by K13, K16 and K19 serve as reference. These last three points must be non-collinear to provide a unique solution for the transform matrix. Refer to Figure 4 for a visual guide of the vector transform used for the implementation.

4.3 Part Locator Routine

A part locator routine was developed to visualize the final part position and orientation in the site frame. Developed in JAVA, the simple, robust part locator algorithm runs on the client-side and computes the part pose from the three measured fiducial point locations in the site frame. The algorithm takes the three inputs associated with a steel part from the transform routine and fixes the first point in the site frame, uses the second point to define the axis and the third point to define the plane. While this is not a precise method for determining the part pose, it does serve the purpose of enabling the visualization of the part within the site frame and for providing an estimate of the as-built location of a part's final pose.

5.0 INTEGRATION & COMMUNICATION

The key to successful development of the prototype implementation resides in seamless communication between the separate components. Component tracking data from both the ArcSecond measurement tool and the bar code scanner is captured, reformatted, and stored in the wearable computer's keyboard buffer via NIST-generated utilities on the wearable computer. These data are then displayed through a series of web pages and stateless CGI programs. The component-tracking library, linked through the CGI programs, queries the remotely hosted PIMS for related part information such as VRML models. Finally, CORBA-compliant communication routines provide the interface between the component-tracking library and the PIMS. Figure 5 illustrates the various communication methods developed for the implementation.

5.1 Wireless Communications

Running CAT-5 (Ethernet) cable across an active construction site is impractical so it is necessary to setup a wireless network. This allows users on the site to use untethered computers to communicate with other computers on or off the site. The Orinoco wireless networking hub and PC cards by Agere Systems were used to support TCP/IP networking to connect the wearable computer to the server.

6.0 CONCLUSIONS

The prototype implementation demonstrates the successful integration of various sub-systems and applications using standard interface protocols for the automated tracking of structural steel members at a job site. Enabling the transfer of real-time on-site metrology and metrology-based data from the job site to the appropriate applications and users supports operations that are dependent upon knowing and communicating the exact location and orientation of objects on the construction site.

Some areas for improvement and future work relating to the prototype system are discussed in the following two sections.

6.1 Accuracy of Reported Pose

The accuracy of the measured 3-D coordinate data supplied to the part locator routine should be quantified to provide an accuracy metric with the reported pose. This metric will enable a more precise determination of the accuracy of the reported pose for the part – a necessary component for the tracking system to be truly useful for operations such as the automated placement of structural steel members to within standard tolerances.

6.2 Communication

While the system communicated the essential information from the field to the project information management system, there are several areas to expand for error handling, error recovery, and extensions to the communications infrastructure.

As this was a prototype system, error handling and recovery were only minimally implemented. However, in real systems, error handling will need to handle users errors such as setup and registration of the coordinate measurement system, incorrect matching of field measurements to objects, and collection of collinear fiducial points. These are places where people interact with the system to provide information, and thus are potential sources of error that must be handled reliably.

The communication infrastructure, while complete for the given application, needs to be extended for future use. First, define a grammar for field measurements that can be common to all programs that use field measurements. Second, establish a communication protocol for coordinate system transforms since the exchange of the transforms between systems is not handled well in the prototype system. Third, express the system in as neutral a format as possible, so as to be extensible to future communication technologies.

7.0 REFERENCES

[1] Furlani, K.M., and Stone, W.C., “Architecture for Discrete Construction Component Tracking,” Proceedings, 16th IAARC/IFAC/IEEE International Symposium on Automation and Robotics in Construction, Madrid, Spain, September 22-24, 1999.

[2] Stone, W.C., Furlani, K., and Pfeffer, L., “Automated Part Tracking on the Construction Site,” Proceedings, 4th International Conference on Robotics for Challenging Situations and Environments (Robotics 2000), Albuquerque, NM, Feb 27 – Mar 2, 2000.

[3] Furlani, K.M., and Pfeffer, L.E., "Automated Tracking of Structural Steel Members at the Construction Site", Proceedings, 17th IAARC/IFAC/IEEE International Symposium on Automation and Robotics in Construction, Taipei, Taiwan, September 18-20, 2000.

[4] DeWitt Latimer IV, "Work Towards an Application Protocol to Support Interoperatbility of Sensors in Construction Metrology (LiveView)", National Institute of Technology Internal Report (NISTIR) 6867, National Institute for Standards and Technology, Gaithersburg, MD, USA, May 15, 2002.

[5] Pfeffer, L.E., and Latimer, D.T., "Toward Open Network Data-Exchange Protocols for Construction Metrology and Automation: *LiveView*," Proceedings, International Conference on Automation and Robotics in Construction (ISARC-99), Madrid, Spain, September 22-24, 1999.

[6] CIMSteel Integration Standards, Release 2, URL: http://www.cis2.org, The Steel Construction Institute, Ascot, Berkshire, UK, URL: http//www.steel-sci.org.

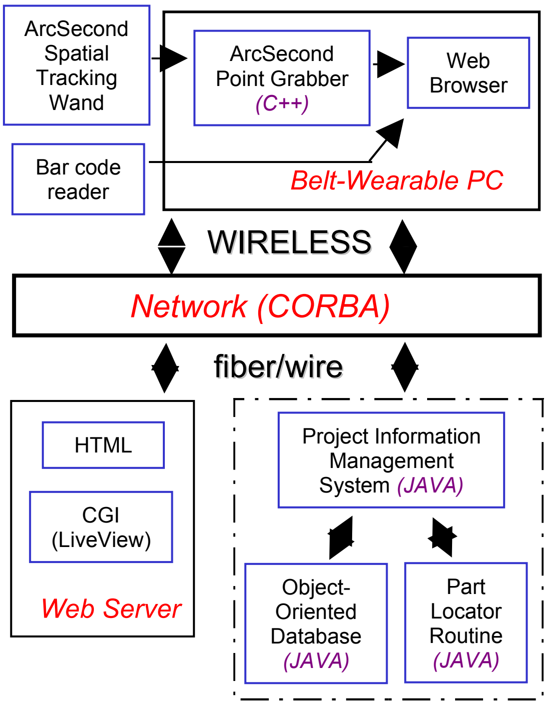

Figure 1. System architecture developed for the prototype implementation.

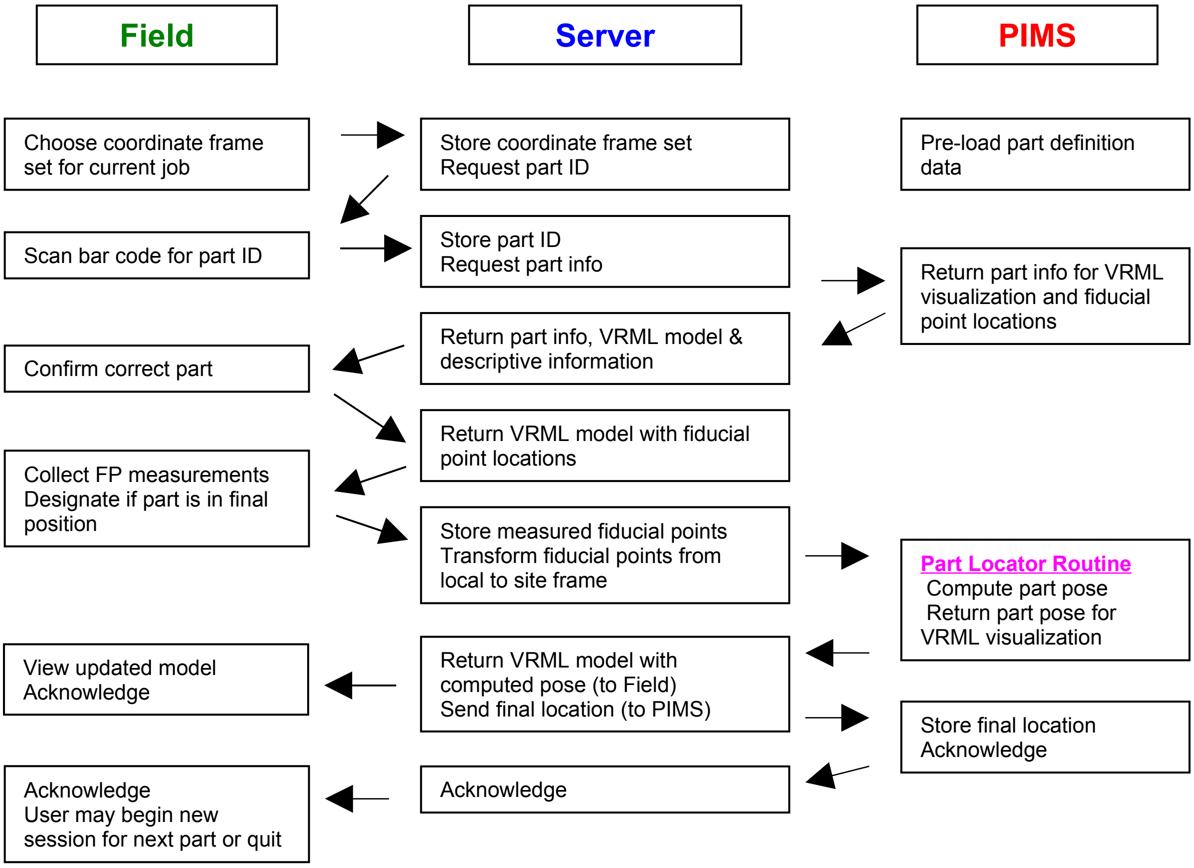

Figure 2. Operational flow chart outlining steps between the Field, Server and PIMS

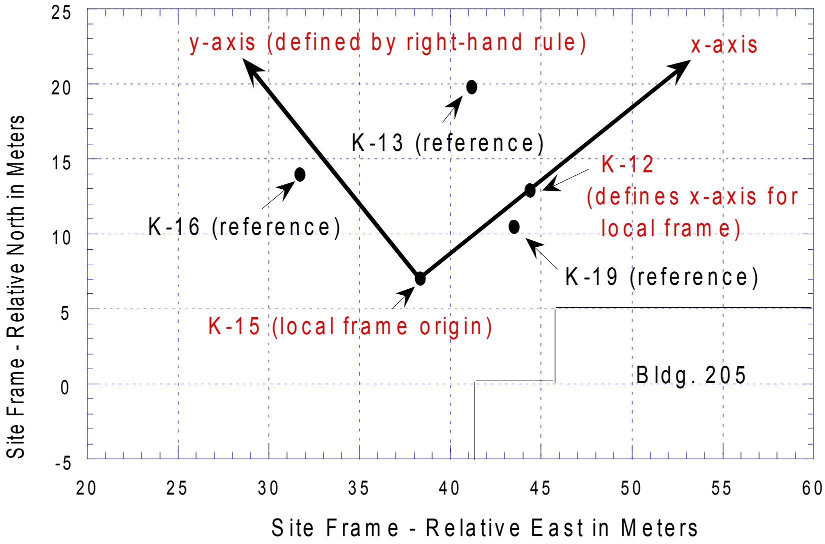

Figure 3. The local frame graphed within the site frame.

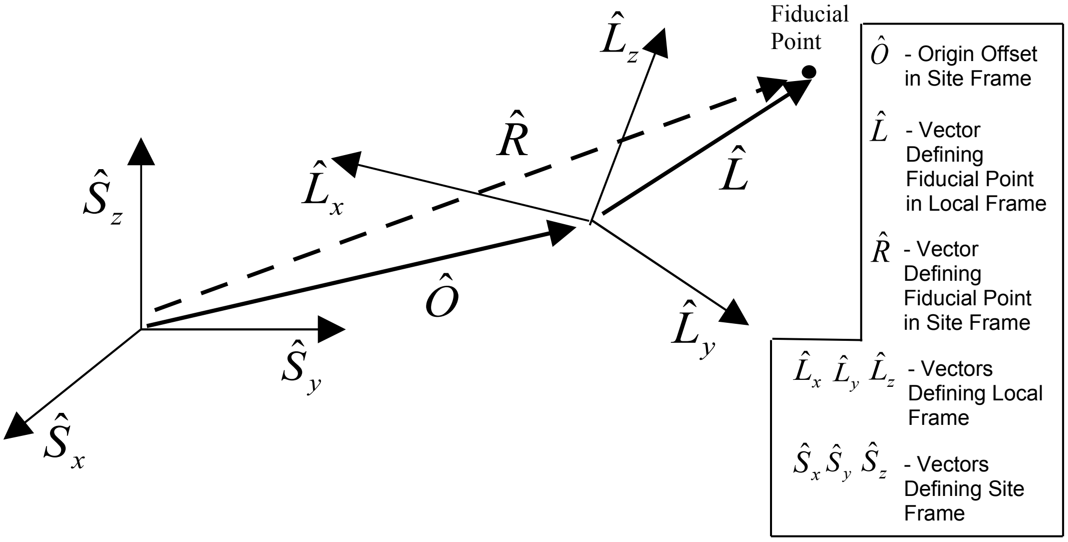

Figure 4. A vector transform from the local frame to the site frame.

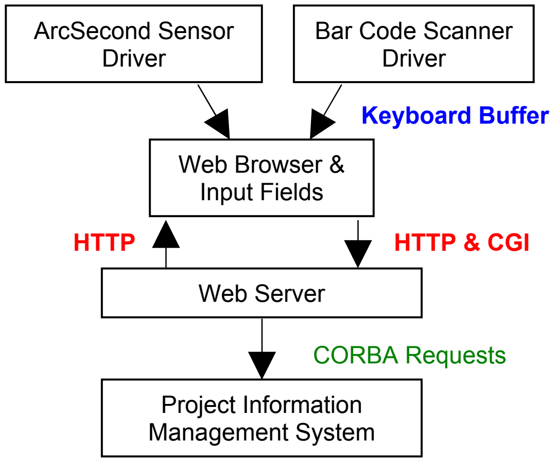

Figure 5. Communication methods used between system modules