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A Mobile Sensor Platform for Construction Metrology and Automation: Design and Initial Results

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Abstract: At NIST, we are creating a test-bed to support experimental research in construction-site metrology and automation. We are extending our previous test-bed to include a vehicle to make measurements at construction sites. This mobile sensor platform will incorporate precision GPS for position and attitude sensing and scanning LADAR* for terrain mapping. The All-Terrain Vehicle's (ATV's) sensors are managed by an on-board computer, which communicates via wireless Ethernet. High-bandwidth wireless communications permits use of sensor data in ways that can significantly impact construction productivity. Sensor data from the ATV is already being used to update a remote 3-D world model in real time. A related aspect of this work is the investigation of open data formats and protocols for exchanging spatial data. We are investigating the use (and extension) of existing protocols (e.g., IEEE Std. 1278) to create a prototype for a standard for spatial metrology on construction sites. This paper outlines the design of the infrastructure system (concentrating on the mobile sensor platform) and shows initial experimental results from the sensors and from the "live" 3-D site model.

Keywords: 3-D Models, Automation, GPS, LADAR, Protocols, Spatial sensors, Wireless communications.

1. Introduction

The construction metrology & automation group at NIST is creating a test-bed system to support experimental research in construction-site metrology and automation (see Figure 1.) This infrastructure will be used on a NIST construction project starting in the near future -- a large emissions-control facility (piping, compressors, scrubber, stack, etc.) We are extending our previous construction-automation test-bed (from an indoor high-bay facility, see [1]) to include a vehicle that can make measurements at construction sites. We have designed and built a mobile sensor platform (based on an all-terrain vehicle) that incorporates precision (carrier-phase differential) GPS for position and attitude sensing and scanning LADAR for terrain mapping. Eventually, we intend to incorporate bar-code (or RFID) tag readers for part identification. The ATV's sensors are managed by an on-board, real-time computer, which can communicate over wireless Ethernet [2], both with stationary computers (e.g., file servers, database systems) or with other mobile computers on the site (e.g., laptop or wearable CPUs with compatible wireless links.)

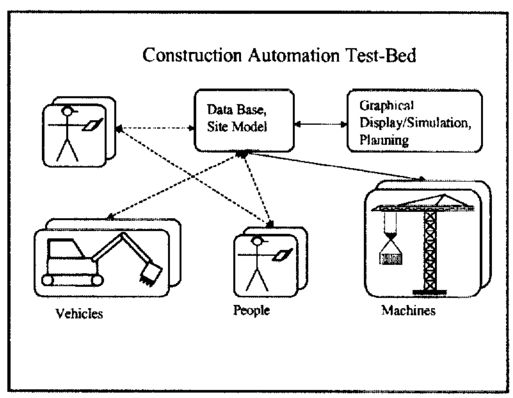

Figure 1. Schematic Diagram of the Construction Automation Test-bed, consisting of machines, vehicles, computers, and users linked together to share both design (e.g. CAD) and sensor data. Solid lines denote hard-wired (conventional) network connections; dashed lines denote wireless network connections. Wireless networking permits people or vehicles to work while moving around on the site.

* LADAR = LASER Detection And Ranging

The use of high-bandwidth wireless communications permits use of data in ways that can significantly impact construction productivity. Live sensor data from the ATV is already being used to update a remote 3-D world model in real time. In the near future, this data will be used to update a project database, so that both builders and owners can monitor location and status of discrete parts and terrain changes (earthmoving.) At project completion, the database will become a detailed "as-built" database, which can assist the owners with operations and maintenance tasks. This paper outlines the design of the infrastructure system (concentrating on the mobile sensor platform), and shows experimental results from the sensors and from the "live" 3-D site model.

An important aspect of this work is the investigation of open data formats and protocols for exchanging spatial data among construction-project sensors and computers. At present, there are many ad hoc methods (as discussed in [3]), but virtually all of them are specific to particular sensors and their vendors. This "metrology tower of Babel" greatly hinders integration of multiple sensors from multiple vendors. We are investigating the suitability of existing protocols [4], [5] as possible foundations for an open standard for spatial metrology on construction sites. We hope to encourage greater inter-operability and greater ease of integration of sensors used in construction.

A key goal of this research is to create an open system to put information, including site measurements, at workers' fingertips -- whether they are in the back office or out in the field. Once such an infrastructure is in place, it can be used as a foundation for increasing human productivity (e.g., "Show me where my materials are, and who last had charge of them."), for increased safety (e.g. tracking workers near machines, preventing excavation near utilities), and ultimately for automation of construction tasks (e.g. automated earthmoving or automated crane operations.)

2. Vehicle Hardware

The vehicle/sensor platform is based on a Honda All-Terrain Vehicle, which provides four-wheel drive for mobility over most terrain, DC power, and the ability to carry both a user and the sensor/computer system. An Aluminum frame has been added, which runs over the driver's head, like an exaggerated roll cage. The reason for the height (apart from consideration for tall operators) is to locate the antennas and some of the sensors (Compass, GPS antennas, and eventually the LADAR scanner) high up, where they can operate best. The structure has two levels for equipment. The upper is for systems that need the greatest height, e.g. GPS antenna(s) and (eventually) the scanning LADAR system. The lower deck houses the computer and those items that do not need a "sky view," such as the compass, the (first) GPS receiver, and the wireless Ethernet transceiver. See Figure 2.

Figure 2. Photograph of the instrumented All-Terrain Vehicle. The top layer of the frame supports the first GPS antenna (for position), the lower level houses the real-time computer, wireless Ethernet, compass and GPS receiver. The Scanning LADAR will be mounted forwardmost on the top deck.

When the engine is running, the vehicle can provide an average of 360 Watts of 12-volt (nominal) power; this is more than sufficient for the planned sensor and computer payload. However, a separate, rechargeable battery provides power to the sensors and CPU when the engine is not running.

The computer system is a stack of PC-104 cards, housed in a waterproof box. The stack presently consists of:

- a Pentium-based PC-104(plus) single-board computer (Ampro P5I),
- an analog-to-digital converter card (16 bit resolution, 16 channels),
- an incremental encoder interface,
- a switching power supply (with RFI filters for on-vehicle operation.)

There is mounting space and power for several more PC-104 cards, to accommodate future expansion. The CPU box also provides regulated power to the sensors (e.g. digital compass) that require it. However, most of the primary sensors are designed to work from the (12 volt nominal) vehicle power bus.

The current sensor/communications package includes:

- Electronic Compass (KVH C100),
- Odometer (incremental encoder coupled to rear axle),
- GPS receiver for real-time kinematic (RTK) position (Ashtech Z-surveyor),
- UHF modem, for RTK GPS corrections (Pacific Crest RFM96W),
- Wireless Ethernet (Proxim 7921XR, IEEE 802.11 compatible.)

We are in the process of integrating several more sensors to the system. These include:

- Scanning LADAR (Riegl LPM-98-100VHS),
- GPS-based attitude sensor (Trimble TANS-vector),
- inclinometers.

In the future, we may also incorporate a bar-code scanner, or an RFID tag reader, but at present, those work via a laptop CPU, and can communicate with the on-board CPU via wireless Ethernet. Thus, that functionality is available to the ATV system, without any direct-wired connection.

At present, the wireless Ethernet transceiver interferes with the UHF modem when their antennas are close to one another, despite their operating in significantly different bands. (A late-stage systems-integration problem -- both worked fine until they were operated within a few meters of one another.) Until we resolve this interference, we cannot get centimeter-level GPS measurements while using wireless Ethernet. If none of antenna placement, shielding, and/or UHF squelch adjustments solve the problem, we may run the RTK correction messages over the wireless Ethernet, eliminating the UHF modem from the vehicle. (This would limit RTK usage to areas with wireless Ethernet, rather than the larger UHF coverage radius.)

3. Scanning LADAR

Since the scanning LADAR data are difficult to use without good knowledge of the scanner's position and orientation, the mounting of the LADAR unit onto the ATV has been deferred. There is a parallel effort underway to acquire data from the LADAR system and merge multiple scans into a coherent spatial model, from stationary locations. Other researchers are carrying out this work, see [6]. A short summary of their work is included here, to indicate the type of sensing that will be available when the LADAR unit is integrated with the vehicle.

At present, the LADAR efforts are focusing on creating models of terrain, using elevation grids as the representation. (Admittedly, this initial approach will not handle discontinuities gracefully.) The initial test case for LADAR-based surface generation is a pile of sand on a flat surface. A series of known positions (and orientations) were set up, and used as a framework for a series of scans. (In vehicle-based scanning, the registration problem will be considerably more difficult, because the positions and orientations of the individual scans will be subject to greater error.)

Figure 3. One LADAR scan of a simple piece of terrain, a pile of sand. Several such views, from known locations can be merged to form a simple model of the surface.

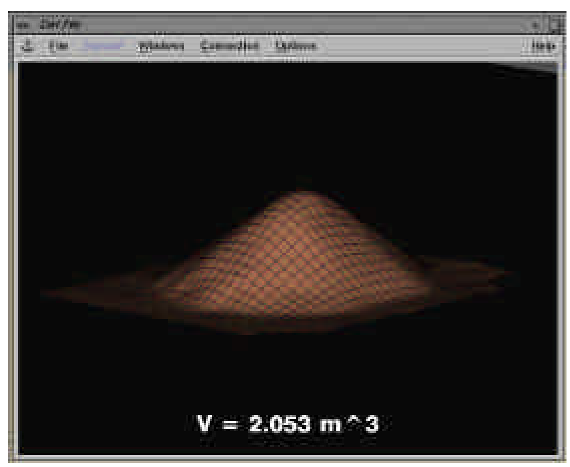

Figure 4. An elevation grid produced from four separate LADAR scans, after registering the scan data, clipping, and applying an N-nearest-neighbor-based interpolation.

Once the multiple scans are registered to a common coordinate framework, the data are clipped to a region of interest. Then the data are coerced onto a regular grid by applying an N-nearest-neighbor-based interpolation to compute the elevation at the grid points

4. Data Communications

An important aspect of the test-bed that this vehicle is a part of is the development of data formats and protocols to use for exchanging spatial data among construction-project sensors and computers. There are many ad hoc methods for doing so (as discussed in [3]), but virtually all of these are specific to particular sensors and their vendors.

As a result, most position or orientation sensors that might be used on a construction site are not "plug-and-play" interoperable. For example, GPS receivers or (surveying) total stations could both be used to make the same measurement (e.g. a distance between points), but the likelihood of the two systems reporting the measurement in the same format, the same units, at the same data rates are virtually nil. This "metrology tower of Babel" greatly hinders integration of multiple sensors from multiple vendors into test-beds (and into instrumented vehicles.) It also increases the difficulty and expense of updating a system to use new sensors.

To address this problem, we are investigating the use of existing protocols [4], [5], and extensions where needed, as a pathway towards a proposed standard for spatial metrology on construction sites. LiveView [7], is an initial design and implementation of some extensions to IEEE Std. 1278.1-1995 [4] that (among other things) defines a device-independent manner to communicate "point-cloud" data, such as that produced by scanning LADAR systems.

LiveView also provides a method to incorporate indirectly-observed, passive objects (e.g. steel girders) into world models (or databases, etc.) It does so via communications with external data-interpreter processes that observe certain sensory data (like point clouds), and infer from it the state of passive objects. These processes can then report the state of any passive objects they successfully observe, just as if the object had an instrumentation package attached. A simple test of this capability has been demonstrated: recognizing and updating the position of an I-beam section in a dynamic 3-D model. To encourage greater inter-operability and greater ease of integration of sensors used in construction, we plan to make the LiveView protocol implementation software freely available.

5. Vehicle software

The onboard CPU runs a POSIX-conformant real-time operating system, VxWorks 5.31 [8]. This operating system provides TCP/IP networking, including the ability to boot from, and mount remote file systems, a valuable capability for a computer with no onboard disk. (The onboard system has a small amount of flash-EEPROM that is used for the first stage of bootstrapping from a remote fileserver.) The operating system also supports remote login, which generally eliminates the need for a keyboard or display device on the vehicle, except during debugging.

Almost all of the application code running on the ATV is composed of reusable software components, produced with the aid of the ControlShell software framework [9]. At present, the vehicle's application software consists of three basic types: sensor-interface drivers, vehicle navigation components, and Data-communications components. The current navigation components implement dead reckoning, based on compass and encoder measurements. As soon as we can solve the wireless Ethernet/UHF model interference problem, the navigation software will use GPS when available, and fall back to dead-reckoning only when GPS measurements are unavailable (or are lower quality than dead-reckoning.) The data-communications components are in transition from an older (ad hoc) protocol to an implementation of LiveView (both protocols are described in [7].

6. Visualization Software

Data from the ATV are used to drive a 3-D, model-based visualization tool, called the virtual site simulator (VSS) [1]. The VSS runs on a remote computer on the same network as the ATV. Figure 5 is an image generated by the VSS.

The VSS is implemented using the WorldToolKit (WTK) [10] graphics/simulation library package, and currently runs on a UNIX-based (SGI) workstation. WTK provides data structures and routines to create a realistic virtual world, populate it with objects (using CAD data), and manipulate both objects and the user's point of view. Since WTK is a library, rather than an entire application, it is readily extensible. Extensibility is an important factor in the VSS, and greatly facilitated the incorporation of network-based updates of objects' positions and orientations into the VSS.

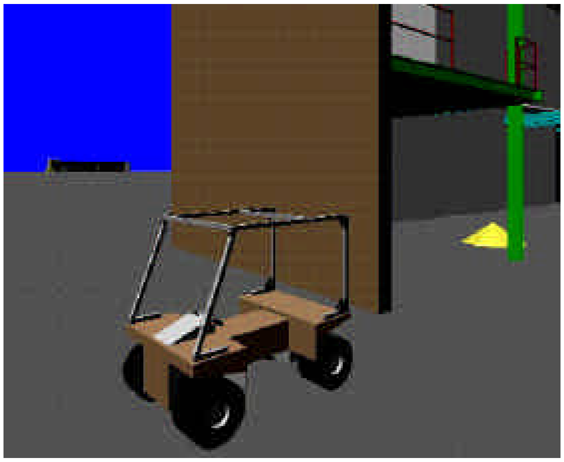

Figure 5. Close-up of a scene generated by the VSS program; The ATV is parked near the entrance to the high-bay area of NIST's Engineering Mechanics building. This "live" visualization of the ATV and its environment updates itself in real-time as the real world changes (e.g. as a user drives the vehicle.) Compare to the photograph, Figure 2. Note also the crude model of the sand-pile in the background. Eventually, terrain objects will update automatically when new terrain surfaces are generated.

7. Future Plans

The ATV is only at a very early stage in its development, and there are many more things to do to improve the ATV and the rest of our construction-automation test-bed. Among our planned tasks are:

- Integrate precision GPS positioning with the ATV (without sacrificing wireless Ethernet communications.)
- Integrate GPS-based orientation sensor into ATV navigation.
- Mount LADAR on ATV; provide means to steady ATV frame during scanning.
- Develop software tools to register LADAR scans in the presence of position and orientation errors.
- Develop software tools for LADAR data that will handle general surfaces, including discontinuities.
- Create better models of NIST environs, with particular emphasis on the site of the emissions control facility, which will begin construction in the near future.
- Use ATV to track discrete parts (e.g. structural steel, piping) during the construction of the emissions control facility.
- Develop and refine LiveView; make software available for public use and comment.

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References

[1] Stone, W., Reed, K., Chang, P., Pfeffer, L., Jacoff, A., "NIST Research toward Construction Site Integration and Automation," ASCE Journal of Aerospace Engineering, Vol. 12, No. 2, April 1999, pp. 50--57.

[2] IEEE, "IEEE Std P802.11, Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, draft", IEEE Customer Service, Piscataway, NJ 08855, (800) 678-IEEE, http://stdbbs.ieee.org/

[3] Pfeffer, Lawrence E., "Wireless Networking for Integration of Real-Time Construction Metrology Systems," in the proceedings of the 14th International Symposium on Automation and Robotics in Construction (ISARC 14), Pittsburgh, PA, June, 1997.

[4] IEEE, "IEEE Std. 1278.1-1995, Standard for Distributed Interactive Simulations -- Application Protocols," IEEE Customer Service, Piscataway, NJ 08855, (800) 678-IEEE, http://stdbbs.ieee.org/

[5] Lee, K., Schneeman, R., "A Standardized Approach for Transducer Interfacing: Implementing IEEE-P1451 Smart Transducer Interface Draft Standards", *Proceedings of SENSORS Conference '96*, Philadelphia, PA, Helmers Publishing, October 22-24, 1996, pp. 87-100.

[6] Cheok, Geraldine S., and Stone, William C. "Non-Intrusive Scanning Technology for Construction Assessment," to be published in the proceedings of the 15th International Symposium on Automation and Robotics in Construction (ISARC 15), Madrid, Spain, September 1999.

[7] Pfeffer, Lawrence, E., and Latimer, DeWitt T, IV, "Toward Open Network Data-Exchange Protocols for Construction Metrology and Automation," to be published in the proceedings of the 15th International Symposium on Automation and Robotics in Construction (ISARC 15), Madrid, Spain, September 1999.

[8] Vx*Works* 5.3.1 Programmer’s Guide, Wind River Systems, 1010 Atlantic Ave., Alameda, CA 94051, http://www.wrs.com

[9] Real-Time Innovations, Inc., ControlShell Programmer’s Reference Manual, version 5, 155A Moffett Park Dr., Ste. 111, Sunnyvale, CA 94089, http://www.rti.com

[10] SENSE8 Corp., WorldToolKit Reference Manual, Release 8, 100 Shoreline Highway, Suite 282, Mill Valley, CA 94941, http://www.sens8.com