Location aware tools for inspection of fixed structures

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Abstract

by

Ajit Pardasani, Vibhor Gupta, Brian Wong, Shafee Ahamed

Fixed structures, like buildings and bridges, are subject to inspections numerous times during their life - during their construction; after they are erected and before the steelwork is covered; on completion to determine their 'as built' condition; and periodically during their life to identify problems that need to be fixed. For example, large steel structures are subject to strict code requirements and must be properly inspected and certified after erection. The structure has to be inspected for proper installation of bolts and welds for both structural steel and reinforcing steel. Steel frame joint details are also inspected for compliance with approved construction documents.

At a construction site, carrying and selecting the relevant detail paper drawings for the inspection task at hand is both cumbersome and difficult. A location-aware portable tool that can provide detailed drawings of columns, beams, clips, etc. that are being inspected can not only free up the construction personnel from carrying paper drawings, but also can provide the latest, most accurate project information in the field.

This report describes the prior art of systems for visual inspection of structures; provides an overview of enabling technologies; presents three alternative conceptual designs of a location-aware portable inspection system; and discusses the limitations of location-finding technologies.

1 Background

The inspection of a fixed structure is an onsite review to evaluate its condition, and to monitor the progress and quality of work during its construction. The objective is to determine the extent to which the completed work is in conformance with the plans, specifications, and authorized changes. It provides a basis for acceptance of the completed work and is geared towards the reduction of defects which may increase construction cost by up to 10% [Josephson and Hammarlund, 1999].

Most construction projects require contractors to produce As-Built documentation (AB) to document the condition of the structure as it was actually constructed and accepted. AB serves as a final record of the project and shows all the results of unexpected site conditions, change orders, and material and equipment substitutions [Pettee, 2005]. Not only is AB a record of all authorized changes, it is also a certified record of what was built and can be used by the owners as a reference over the life of the asset. Moreover, at the end of the life cycle of the asset, AB becomes a demolition document. Inspection is a critical step in the creation of AB.

Large structures, like buildings and bridges are subjected to inspection several times in its life: during the construction; after the erection and before the work is covered for conformance to construction documents; final inspection for AB; and, periodic inspections for detection of problems. Large steel structures are subject to strict code requirements and must be certified by inspection agencies to ensure code conformance and proper connections in both structural steel and reinforcing steel. A building under construction is shown in Figure 1 and some examples of the types of connections are shown in Figure 2. The connections are inspected for compliance to approved construction documents.

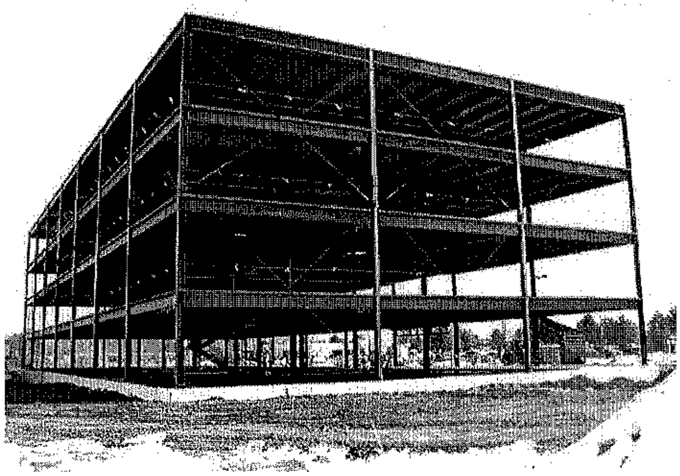

Figure 1: Partially completed steel building (Source: American Institute for Steel Construction, AISC)

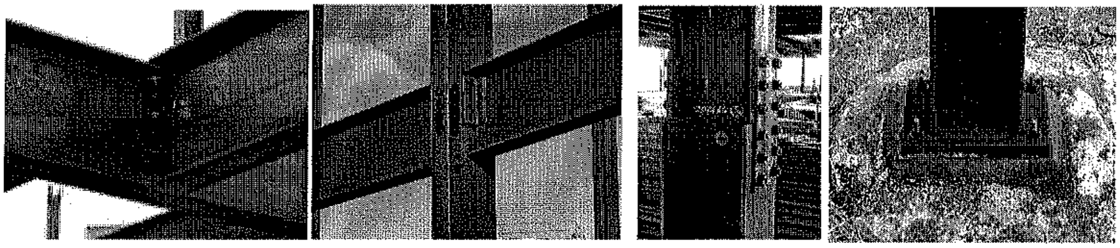

Figure 2: Different types of connections in a steel building: beam to beam, beam to column, column to column, and column base plate (Source: AISC)

Inspection consists of discovering deviations from the specified values of attributes. Figure 3 shows the various types of inspections during the life cycle of a building. The building design is inspected for conformance to land use plans and building codes before construction can begin. During and after construction, the building is inspected for quality control and for creating AB. The rest of this report focuses on this particular aspect of inspection (viz. quality control and AB), using 'location aware' technologies.

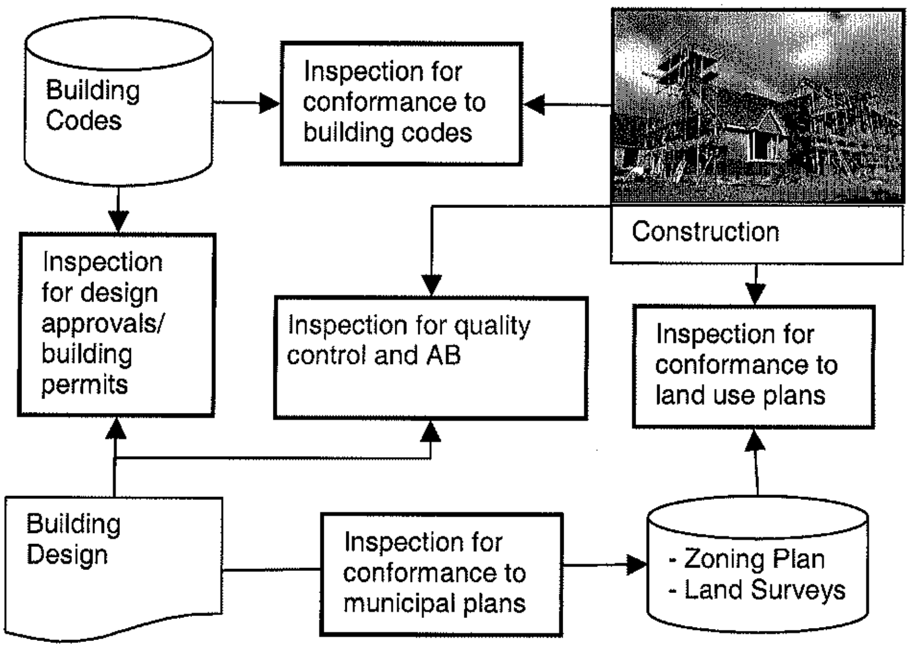

Figure 3: The process of inspection has a different objective at different stages in the life cycle of a building. The report focuses on the inspection for quality control and as-built.

The inspection for quality control and AB uses design specifications as a reference. There are many ways in which the design information from a CAD system can be used as a reference for inspection. A simple way is to output 2D plan, elevation, and sectional views from a CAD system and then use these as reference drawings. Figure 4 shows the framing plan for the first floor of the steel building shown in Figure 1. In addition, sectional views may also be generated from the CAD model. The inspector can make use of the relevant 2D drawings to reconstruct a mental 3D image of the area to be inspected, compare it to the actual, and record the differences. This process is done repeatedly, with multiple sets of drawings as the inspector moves from one part of the building to another. 3D models can also be visualized at the construction site on a laptop computer, using an appropriate CAD viewer. Figure 5 shows the 3D model of the steel building shown in Figure 1. CAD viewers may require a powerful computer, whereas a vendor-neutral lightweight 3D model (e.g. using Virtual Reality Modeling Language) can be easily viewed on portable computing devices (e.g. Pocket PCs).

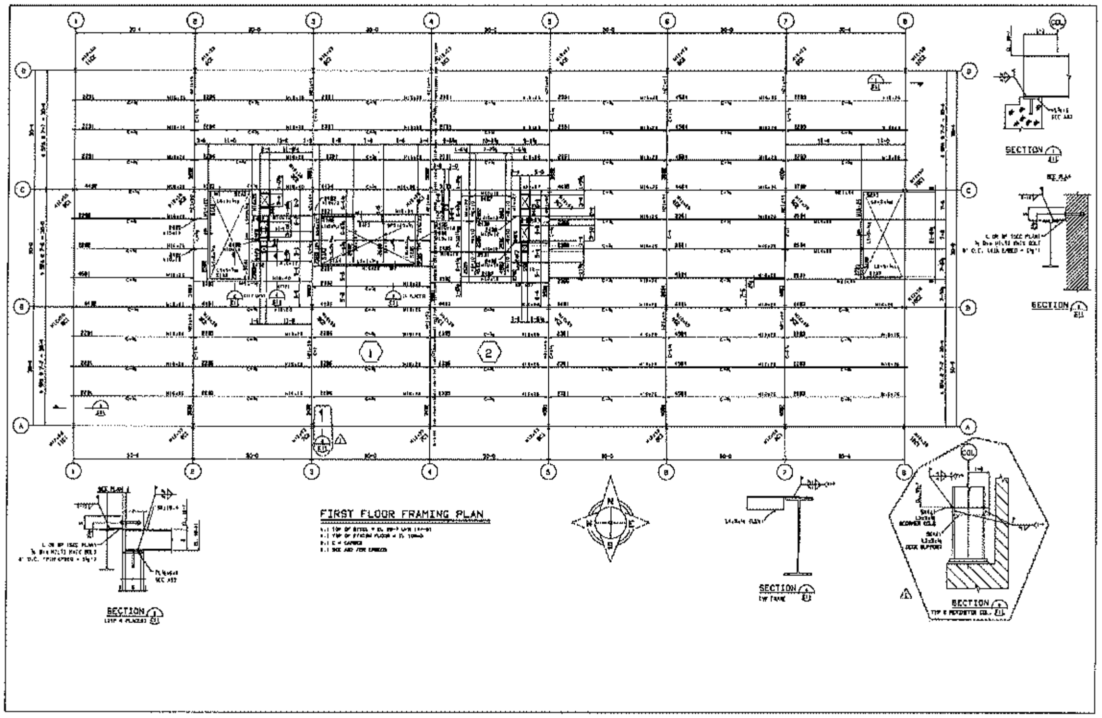

Figure 4: First floor framing plan of the steel building shown in Figure 1 (Source AISC)

For example, while inspecting steel buildings, inspectors need to refer to the relevant sets of drawings, as well as to the relevant specification documents. Searching through a pile of construction drawings and documents at a construction site is not an easy task. It is cumbersome and time consuming. It is also error-prone because different drawings (and different elements of the building) may look very similar [Brilakis, 2006]. A portable device that automatically displays the correct drawings of the columns, beams, joints, etc., depending on the location of the inspector, will be very useful.

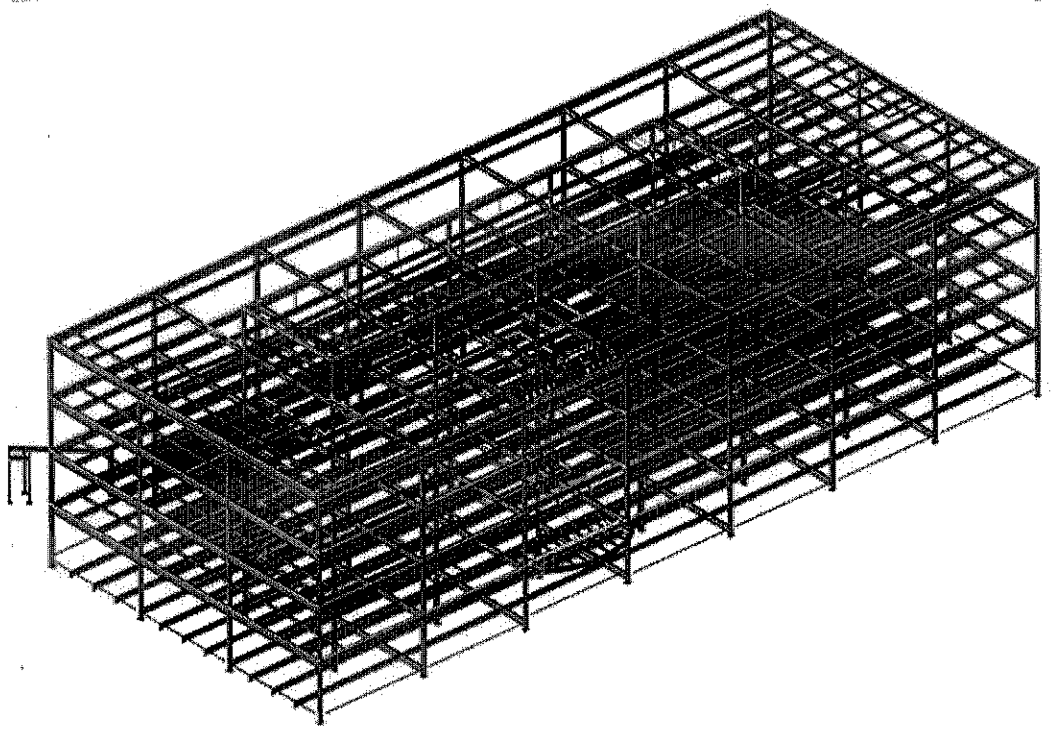

Figure 5: 3D Model of the steel building shown in Figure 1 (Source AISC)

2 A Review of Tools to Assist in Inspection

Many enabling hardware technologies are available to cater to the needs of inspection. Some specific technologies are portable high speed scanners, GPS enabled cameras, location and tracking devices, and online camera monitoring systems [Song et. al. 2005]. This section provides a summary of inspection technologies.

2.1 LADAR

LAser Detection And Range Data (LADAR) devices use a laser beam to scan and process the signal echoed from targets to create a virtual picture of the scanned areas/objects. The LADAR process looks at the target from different angles and computes the best angle to scan. LADAR systems detect features up to 15 centimetres from a distance of 1000 meters in just few minutes. Typically land-based LADAR systems can scan objects from 10 meters to 1 km in size with full details.

LADAR are line-in-sight instruments and as a result, no data is obtained for the back of the object. Generally, few scans have to be obtained from different viewpoints or by rotating the object to obtain better coverage. Also these scans have to be registered [Garboczi, 2006] so that they have a common reference frame. A minimum of 4 scans of each object are required to cover the entire details (and many more are often needed).

Based on the speed, high accuracy and large field of view, LADAR systems are being used for quality assessments by recording detailed 3D views of construction that can be compared with 3D CAD models or by providing 3D data of old facilities for which 3D models are required for the renovation process. [Bosche, 2006].

Researchers from Stanford University have used a long-range (50-100 meters) 3D laser scanner, Cyrax 2500, to record the progress of the construction of a building on campus [Shih, et. al., 2004]. They established a method for as built inspections by recording and comparing the progress of an on-going construction using 3D data retrieved by the laser scanner. Once the clouds are retrieved in a proper data format, the as-built data can be compared to the CAD model. Researchers found when 3D scans were made at various time intervals during the construction, the as-built data described the progress of the building construction process.

2.2 Using Video Images for Inspecting As-Planned vs. As-Built:

Traditionally, many video image-based technologies have been used to inspect and monitor the construction process for the purpose of facility management. Continuous real-time video monitoring is often used in new construction sites to monitor the process and perform a visual inspection of tasks. Typically, the inspection and monitoring system consists of three major components. The hardware unit includes the cameras and mounting devices. The software package includes software to capture, process, broadcast and display images in real-time. Both the hardware and software are bundled with services and support such as, custom configurations at the site, networking, multi-camera requirements, light effects and also serve to maintain the installed systems.

Many specialized services, tools and technologies exist to provide high resolution images that can be viewed using standard internet services on desktop systems. The orientation of the cameras is adjusted from a remote location as construction progresses. Also, these image data are mapped with the project management tools to review with the planned scheduling process.

The Photo-net® [Abeid and Arditi, 2003], [Abeid et. al., 2003] system is one of many other systems available commercially for inspection of the construction process. In this system, a digital movie of construction activities is created based on the sequence of images captured from the work site that can be played back using time-lapse techniques along with the animation of as-built vs. as-planned activities. The system hardware consists of two computer units, one is the field computer connected to the remote controllable CCD camera, and the second unit is at the office. The images captured by the field camera are sent to the office computer via the network for processing. The system analyzes data from both the project plan and field data from the camera to report on the progress of the work. Inferences are derived from the visual comparison of histogram data generated from as-planned and as-built data.

2.3 Portable Tools for Inspection

Ultra Portable Notebooks such as Asus's Eee PC, Tablet PCs and handheld computers such as PocketPC and Palm devices can help provide to the field personnel on the construction site timely information such as construction drawings .These devices paired with application software can be very helpful for gathering inspection data in the field. The most significant benefit of handheld computers is to provide construction personnel with real-time access to project information at the site [Saidi, 2002].

There are several commercial portable tools available to assist in civil projects in road construction and maintenance. Bentley OnSite is an electronic field book, which runs on Tablet PC and Pocket PC, for stakeout and inspection of civil projects, ranging from construction of highways and operation and maintenance of landfills and rail yards. OnSite works with standard GPS to create electronic as-builts during normal inspection tasks. It enables field personnel to carry all pertinent documents, spec books, plan sheets, construction details, and contracts electronically. It overlays the graphical status of the construction onto the design and graphically displays where construction differs from the design.

The Telegeoinformatics and Infrastructure Management Lab at Concordia University conducts research to develop new methodologies and to apply new technologies in telegeoinformatics for civil infrastructure management systems. The two main components of telegeoinformatics are mobile wireless computing, thus "tele," and geospatial data processing, thus "geoinformatics". Hammad [Hammad et. al., 2005] discusses the requirements for developing Mobile Model-based Bridge Lifecycle Management Systems that links all the information about the lifecycle stages of a bridge (e.g., design, construction, inspection and maintenance) to a 4D model of the bridge to record events throughout the lifecycle. Hu and Hammad [Hu and Hammad, 2005] propose an approach to support the activities required for the inspection of bridges by equipping the mobile application with a 3D model of the bridge and registering the inspection results on the model. The system is envisaged to provide navigation support to the inspector to get to the desired location, augment the 3D model with the results of previous inspections, and let the inspector annotate her/his observations about defects or conditions relevant to the elements of the model.

Researchers from Loughborough University present an architecture and a prototype implementation of a system for on-demand access to project information at the construction site through a context-based information delivery system [Aziz et al. 2005]. The implementation of the prototype system is based on a Pocket-PC platform and Ekahou [Ekahou, 2008] wireless position tracking system to capture context parameters such as the location of the user.

Researchers at the University of Michigan [Khoury, H and Kamat, V, 2007] have developed a methodology that enables the onsite retrieval of project information in the context of the user location. Under this methodology, they use GPS as a receiver for sensing the outdoor location, magnetic orientation devices for tracking the orientation and a georeferencing algorithm to compute the user viewpoint. The information from the viewpoint is used in building a viewing frustum for a given location using raycasting interference techniques. As the user moves around in the environment, the viewing frustum is aligned with the computer representation of the design model and displayed. This enables the user to inspect "as-built" vs "as-designed". GPS devices do not work indoors, hence the authors experimented with Wireless Local Area Network (WLAN) to track the user by intercepting signals from various known fixed locations inside the building.

3 Project Concept

Overlooked and inefficient inspections have a negative impact on the performance of construction projects and products [Gordon, C., 2007]. Tools that improve the efficiency and effectiveness of inspections will help in capturing defects early and reduce overall construction costs. A portable tool that is easy to use and can retrieve the required information with minimal effort can be very useful for engineers, construction managers, and inspectors.

The proposed system will consist of a portable hardware device such as a laptop, or a Tablet PC, or a Pocket PC with the capability to render 3D images and interface to a GPS system. All the information about the built structure will be stored, either on a server or locally on the device, in a neutral format that can be visualized using a viewer or an Internet Browser with appropriate plug-ins for rendering geometrical information. As the user navigates through the built structure with the portable device, the system will receive position coordinates from the GPS and display the 3D model data corresponding to the current location of the user. This will enable the user to inspect the details of a structure by comparing it against its design.

The system will enable the user to easily and quickly:

- View the 3D model of the steel structure indoors and outdoors (even in sunlight) on a lightweight portable display device (e.g. slate, convertible slate/tablet PC).
- Search for pertinent design information and specifications with minimal interaction, and to select a convenient viewpoint.
- Match the viewpoint to the actual view of the visible structure from his/her current location.
- Walk/fly through the 3D model.
- Pan, zoom, roll, and tilt the view.
- Change the viewing angle.
- Select and annotate elements of the 3D model.
- Link photographs to elements of the 3D model.

4 *Enabling Technologies and Methods*

This section provides an introduction to the major enabling technologies and methods that have the potential to become building blocks for developing a portable system for inspection. The lightweight 3D representation is a must for visualization on portable systems whereas knowledge of methods for geospatial coordinate systems, GPS systems, and NMEA protocol for communication between GPS devices and computer applications are necessary for the development of location-aware applications.

4.1 Lightweight 3D Representation

There are many ways in which 3D models can be represented to obtain a fast response for dynamic navigation. Virtual Reality Modeling Language and Stereolithography file formats are the two most common neutral 3D data representations that are discussed in this section. The information rich vector-based CAD models can be easily converted to these lightweight representations that are suitable for visualization:

4.1.1 StereoLithography (STL) Format

Generally, any 3D CAD models can be represented as a STL file format. This is mostly used for rapid prototyping to create scale models or functional prototype parts. STL files are relatively small in memory size compared to the native CAD formats, thus are suitable for dynamic visualizations of 3D geometry data.

4.1.2 Virtual Reality Modeling Language (VRML)

VRML is an open standard file format designed for representing three dimensional interactive vector graphics. VRML can be described as a "virtual scene description language", as the models are highly interactive and suitable for dynamic visualizations. VRML models can be viewed on standard Web-based browsers such as Internet Explorer and Netscape with VRML plug-in or on stand alone VRML viewers. Many viewers and browser plug-ins are available.

Generally, most 3D CAD models can be converted to a VRML file format and the file format is mostly used for the sharing of design models and to create virtual worlds.

4.2 Common Geospatial Coordinate Systems

In this section we only provide a summary of two commonly used coordinate systems for describing positions on Earth, namely as follows:

1. Latitude and Longitude (Lat/Long)
2. Universal Transverse Mercator (UTM)

4.2.1 Latitude and Longitude

Latitude is the distance measurement in degrees (°) to either the North (N) or the South (S) from the equator. It ranges from 0° at the equator to 90°N (+90°) at the North Pole and to 90°S (-90°) at the South Pole.

Longitude is the distance measurement in degrees (°) to either the East (E) or the West (W) of the meridian located at Greenwich, England. It ranges from 0° at the meridian to 180°E (+180°) and 180°W (-180°) covering the full circle (360°) of the earth.

It is often that latitude and longitude are expressed in degrees (°), minutes (') and seconds (").

The following shows different formats of the lat/long positions representing the same NW corner of the parking lot at the NRC London building shown in Figure 6.

Latitude	Longitude
+43.016111°	-81.279167°
43°00'58"N	081°16'45"W
+43°00'58"	-081°16'45"

We should keep in mind that the coverage distances from the latitudes and the longitudes are not the same due to the convergence of the longitude lines at either the North Pole or the South Pole on earth.

4.2.2 Universal Transverse Mercator

The Universal Transverse Mercator breaks the world into 60 zones in general (with a few exceptions). Each covers 6° starting from the longitude 180°W (Zone 1), and increasing eastward to the meridian, and ending at the longitude 180°E (Zone 60).

Similarly, there are 20 latitudinal zones (denoted by letters) each covers 8° in general (with exception) from 80°S to 84°N.

The UTM uses standard reference points to define 1000-meter grids maps for positioning.

The following shows the UTM position representing the NW corner of the parking lot at the NRC London.

17 477251E 4762642N

17 is the zone number. 477251E is called the Easting and 4762642N is called the Northing. This means the NW corner of the parking lot at the NRC London is 477,251 meters east of the Zone 17 longitudinal reference grid line and 4,762,642 meters north of the equator. On the margin of a typical topographic map, let's say NRC London is on this map, one should see the labels 476, 477, 478, 479 and so on for the vertical grid lines and the labels 4761, 4762, 4763, 4764 and so on for the horizontal grid lines; the grid lines represent distances 1000 meters apart. In addition, one should note which map datum was used for the making of a particular map.

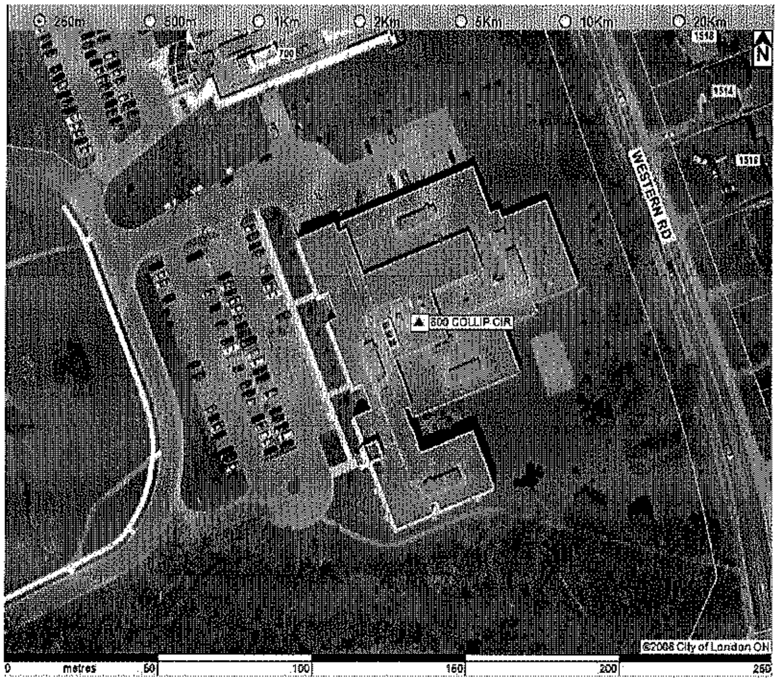

Figure 6: Aerial photo of the NRC-London facilities at 800 Collip Circle, London, Ontario. The picture is taken from London city maps hosted by the City of London, Ontario web site.

We should keep in mind that most of the grid lines are not exactly aligned with the true north except at the meridian; the grid declination information is usually printed on the map for the purpose of this correction.

4.3 GPS Technology

Recreation-grade GPS units have an accuracy of 5-15 meters and are good for navigation or finding the coarse location of objects of interest. Mapping-grade units are much more accurate (1 meter or better), and also allow the collection of point, line, or polygon data for GIS applications. An example of mapping-grade GPS is Trimble's Pathfinder® ProXH™ receiver that offers 30 cm accuracy. The system achieves this accuracy by post-processing the field data. Survey-grade GPS units use a differential correction for highest accuracy and are used for tasks that require sub-cm accuracy such as the marking of property lines, and bridge construction, etc. In survey-grade GPS units, the differential correction is received by the receiver via a radio signal and applied in real-time directly in the field.

Most GPS receivers function in open spaces. In an indoor environment, the satellite signals become too weak to be reliable because they are blocked by the roof, ceilings and walls. Consequently, the GPS receiver may take several minutes to download the satellite data, or may not be able to do so at all. To overcome this out-of-satellite-sight problem, some companies have developed technology solutions to provide location services in indoor environments.

4.3.1 Indoor GPS Technology

"Assisted GPS" technology provides location-based services for sites that have out-of-satellite-sight problem. In Assisted GPS, or A-GPS, assistance data is supplied to the GPS receiver to enable it to compute its position rapidly in a poor signal environment. This assistance data consists of the approximate location of the satellites (called 'almanac' data), the precise position of the satellites (called 'ephemeris' data), and time data. This leaves the GPS receiver with the task to collect only the range measurements to compute its position. The A-GPS system consists of a reference network of GPS submitters deployed worldwide to collect the assistance data from satellites; and servers that collect, process, and transmit the data. The GPS receiver can then request this data from the server, and is able to rapidly compute its position.

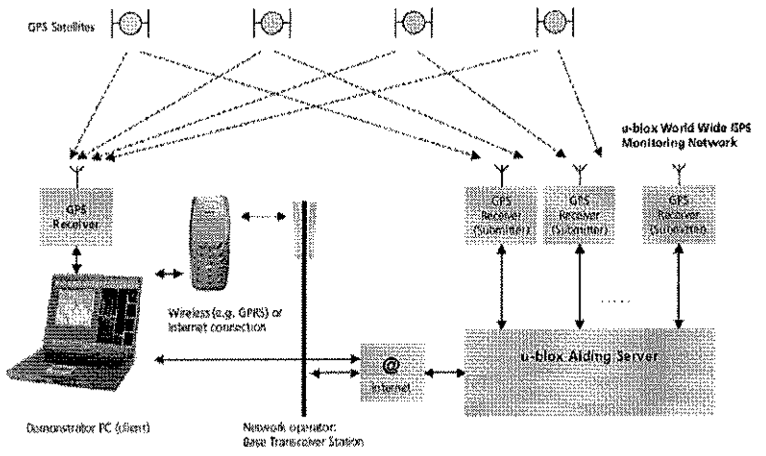

Figure 1: A-GPS - typical topology

Figure 7: Reproduced from u-blox document: AssistNow™ A-GPS Service for Demonstration Use (GPS.G4-SW-05022-A, November 16, 2006)

The *assistance data* can be downloaded on the GPS receiver offline through the Internet before putting the device to use. Ephemeris data is usually valid for 4-6 hours while almanac data is usually valid for 1-14 days (progressively losing accuracy as the time period increases). To obtain assistance data online, users download it directly from the server through a wireless connection (via the Internet or a cellular phone network). *Broadcom* and *u-blox* are two companies that maintain a world-wide GPS monitoring network, collect measurements from the base stations, and distribute information derived from these measurements to users through an Internet-connected server as shown in Figure 7.

The results of testing a u-blox GPS device at the NRC-London building are described in the Appendix.

4.3.2 TV-GPS Hybrid Positioning Module

The Hybrid Positioning Module (HPM) has been developed by Rosum Corporation and uses broadcast TV signals, as well as A-GPS signals, to determine the location in different types of environments. The HPM uses range measurements from TV transmission towers and all GPS satellites that are in the line-of-sight to compute its position as shown in Figure 8. TV signals work especially well indoors because of their high-power, wide-bandwidth, low frequency, and horizontal orientation. They can easily penetrate buildings and are strongest in urban areas where GPS signals are found to be unreliable.

The HPM automatically uses only TV signals (both analog and digital) when deep indoors, a mix of TV and A-GPS signals when in urban centres, and primarily GPS signals when in open, rural areas. By using the best available combination of TV transmission towers and GPS satellites as location beacons, the HPM can provide good location performance in different environments.

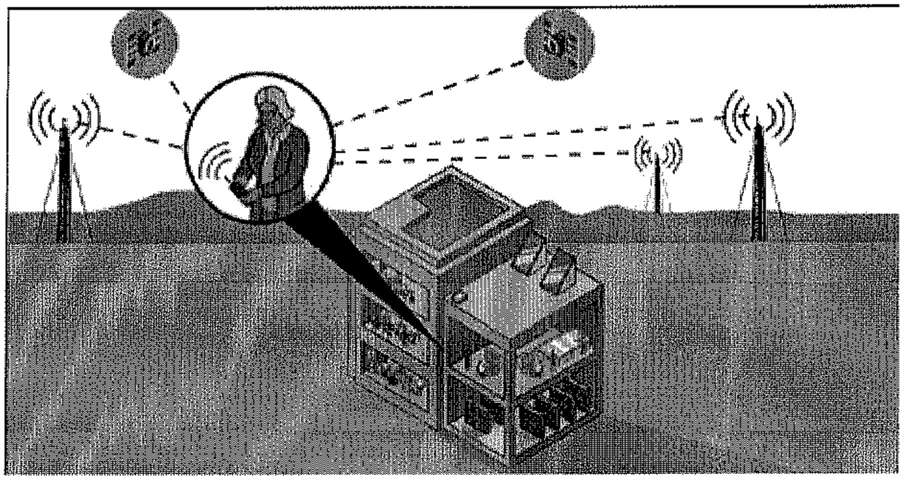

Figure 8: Reproduced from: The Rosum TV-GPS Hybrid Positioning Module

4.3.3 Wi-fi Positioning System

The Wi-Fi Positioning System (WPS) has been developed by Skyhook Wireless and uses ground-based Wi-Fi access points to determine location, instead of GPS satellites. It is a software-only location service for Wi-Fi enabled portable devices.

Currently, there are tens of millions of Wi-Fi access points providing high speed wireless coverage inside buildings all over the world. Every access point broadcasts a beacon signal (with its unique base station ID) that travels about 200 meters in all directions, every tenth of a second. Skyhook has created a massive reference database containing the specific geographic location of millions of these access points in thousands of cities by deploying hundreds of scanning vehicles that drive through each street in a city's grid. A WPS-enabled portable device can then identify the signals within range and calculate its position based on propriety algorithms developed by Skyhook. The device is also capable of updating the reference database in real-time to automatically 'heal' the Wi-Fi network, whenever individual access points change.

The WPS currently covers more than 8000 cities in N. America, Europe and Australia, with a database referencing over 23 million access points. Similar to the TV-GPS hybrid technology, portable devices that have a combination of GPS and Wi-Fi hardware can determine their location in different types of environments (since GPS works well in open spaces where Wi-Fi coverage may not exist, and WPS works best inside city buildings where GPS has difficulty due to line-of-sight and multi-path signal problems).

According to Skyhook, the accuracy of WPS to determine the location of a Wi-Fi device indoors is about 20 meters. Also, the accuracy range of Rosum's HPM in different kinds of indoor environments is said to vary between 15-30 meters [Rabinowitz and Spilker, 2005]. As a result, since a portable inspection tool requires the use of a much more accurate location technology, it was decided to test the indoor performance of a high-sensitivity A-GPS receiver for this project. This was done to enable the project team to gain familiarity with the working of an 'indoor' GPS receiver, at a reasonable cost. The u-blox Evaluation Kit was purchased for this purpose since this product was based on the latest technology (launched in Jan. 2008), was readily available in Canada, and was relatively inexpensive at about $200.

4.4 NMEA 0183 Standard

NMEA stands for the National Marine Electronics Association. The NMEA 0183 Standard defines the electrical specification and the data protocol for communications between navigation devices on a serial bus with a 4800 baud rate. In general, these devices could operate at a higher baud rate and they are classified as talkers or listeners (some devices being both). The Standard allows a single talker and many listeners on each data bus.

The data communications between the talker and the listener(s) are done by transmitting messages called sentences that contain printable ASCII characters, carriage return (<CR>) and line feed (<LF>) only. Each sentence begins with the "$" character, using the comma "," character(s) to delimit the data in-between, with no spaces and ends with the <CR><LF>.

Since the Standard is a copyrighted document and is only available from NMEA, it is highly recommended to obtain a copy from NMEA for accurate interpretations of the sentences formats.

In this report, there are three types of sentences, namely:

1. Talker Sentences
2. Proprietary Sentences
3. Query Sentences

Talker Sentences have the following format in general:

$ttsss,d1,d2,...,dn<CR><LF>

where

tt	= 2-Letter Talker Identifier
sss	= 3-Letter Sentence Identifier
d1	= Data Associated with the sss
d2	= Data Associated with the sss
dn	= Data Associated with the sss (Last Data in the Sentence)

Example:

$GPGLL,4300.9667,N,08116.7500,W,221529.487,A,A*4A<CR><LF>

where

GP	= Talker Identifier for Global Positioning System Receiver
GLL	= Sentence Identifier for Geographic Position - Latitude/Longitude
4300.9667	= Latitude in "ddmm.mmmm" format (d=degree, m=minute)
N	= North (N) or South (S) Indicator
08116.7500	= Longitude in "dddmm.mmmm" format (d=degree, m=minute)
W	= East (E) or West (W) Indicator
221529.487	= UTC Time in "hhmmss.sss" format (h=hr., m=min., s=sec.)

A	= Status (A=Valid, V=Invalid)
A	= Mode (A=Autonomous, D=DGPS, E=DR)
*	= Delimiter for Checksum
4A	= Checksum (Exclusive OR of all characters between "$" and "*")

Proprietary Sentences have the following format in general:

$Pxxxp0,p1,p2,...,pn<CR><LF>

where

P	= Proprietary Sentence
xxx	= 3-Letter Manufacturer's Mnemonic Code
p0	= Proprietary Data (Sometimes No Data Here)
p1	= Proprietary Data (Sometimes Associated with p0)
p2	= Proprietary Data Associated with p0 or p1
pn	= Proprietary Data Associated with p0 or p1 (Last Data in the Sentence)

Please refer to the documentation of a particular device's manufacturer for an example of this type of sentence.

Query Sentences have the following format in general:

$ttllQ,sss<CR><LF>

where

tt	= 2-Letter Talker Identifier (The Requester)
ll	= 2-Letter Talker Identifier (The Listener being requested)
Q	= Query Sentence
sss	= 3-Letter Sentence Identifier

Example:

$CCGPQ,GLL<CR><LF>

where

"CC" device is requesting from "GP" device the GLL sentence to be transmitted at a predefined rate until further query.

5 Conceptual Design

This section describes the three possible approaches to achieve the functional requirements and the corresponding conceptual architecture of a system for inspecting steel-framed buildings.

Most design tools for these buildings support export of design in CIMSteel Integration Standards, Version 2.0 (CIS/2) format. CIS/2 is intended to create a seamless and integrated flow of information amongst all parties of the steel supply chain involved in the construction of steel-framed buildings. CIS/2 data can be translated to VRML through CIS/2 to VRML translator developed by NIST. The VRML file then can be visualised in a VRML viewer or in a Web Browser with a VRML plug-in.

Researchers from NIST have experimented visualizing VRML models of steel structures on a Pocket PC [Lipman, 2004]. Due to limited capability of the processor and the size of the memory on a Pocket PC, only small sized models (e.g. three storey building) can be practically visualized. Not only is it possible to easily convert CIS/2 models to VRML models, but most CAD tools support export of models in VRML format. Therefore, if the needs of the inspector can be met with the 3D visualization of the design of the structure as shown in Figure 9 and Figure 10, VRML models will be sufficient for most projects.

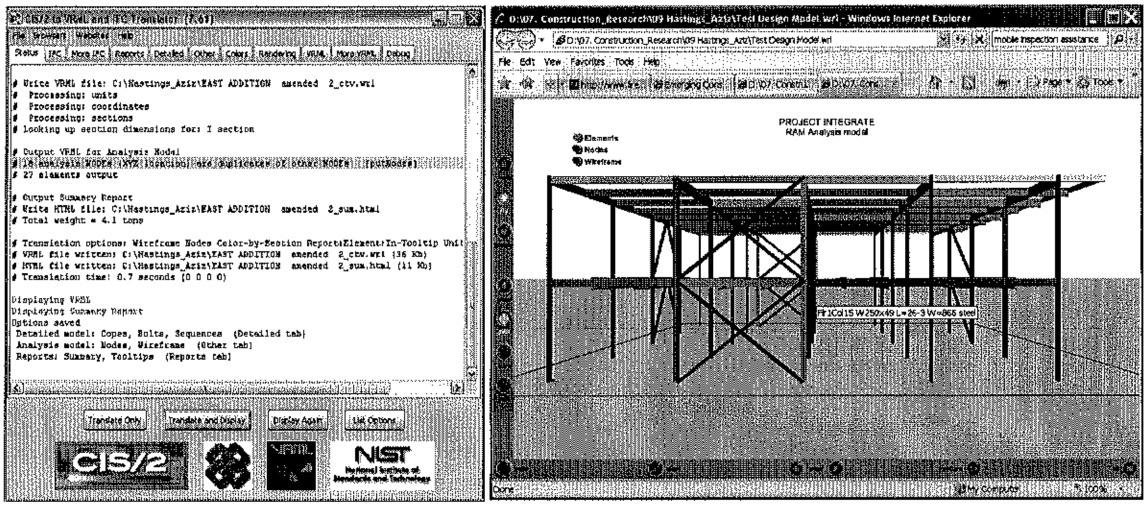

Figure 9: User Interface for CIS/2 to VRML Translator from NIST is shown on the left. The right side shows the VRML model of a steel structure design exported from Bentley RAM Structural in CIS/2 format and then converted to VRML through the NIST CIS/2 to VRML translator. (Courtesy: Hastings & Aziz Consulting Structural Engineers)

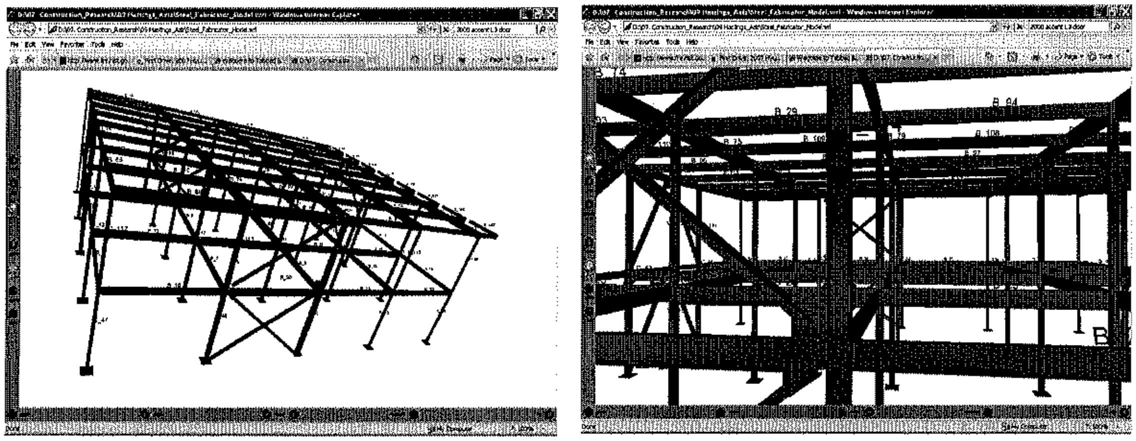

Figure 10: A partially detailed design is exported from Design Data SDS/2 to CIS/2 format and then converted to VRML through NIST CIS/2 to VRML Translator. The VRML model is shown on the left and a closer view is shown on the right. (Courtesy: Spencer Steel Ltd.)

5.1 Generate 2D Views Dynamically

The first approach is based on providing the inspector with all relevant design information to support the visual inspection of structural elements and assembly details in the form of 2D drawings on a portable computer. The underlying idea of this approach is to find the accurate location of the person at the construction site and then use location information to display the drawings. The system can be implemented as a stand-alone system or as a client-server system. The stand-alone system will store all 2D drawings locally, search for relevant drawings corresponding to the current location of the user, and will display them to the user. If there are multiple drawings corresponding to a location, the user will be presented with a list of drawings from which to to choose. In a client-server system the on-site client will retrieve the 2D drawings from the server. The drawings will either be stored on the server, or will be generated dynamically by the CAD application based on the user request, or will be generated automatically based on the location coordinates of the user.

5.2 Geo-reference the 3D Model

3D models created in CAD systems are based on the Cartesian coordinate system in Euclidean geometry. To geo-reference such 3D models, we need to assign corresponding geospatial coordinate values to all vertices. The first step involves establishing control points at the site or nearby. The control points are the points for which the geospatial co-ordinates are already known. The next step is to define the type of geospatial co-ordinate system (e.g. UTM, or Geodetic) followed by computation of the geospatial coordinates (e.g. longitude, latitude, and altitude) corresponding to the x, y, and z coordinates for each vertex in the 3D model.

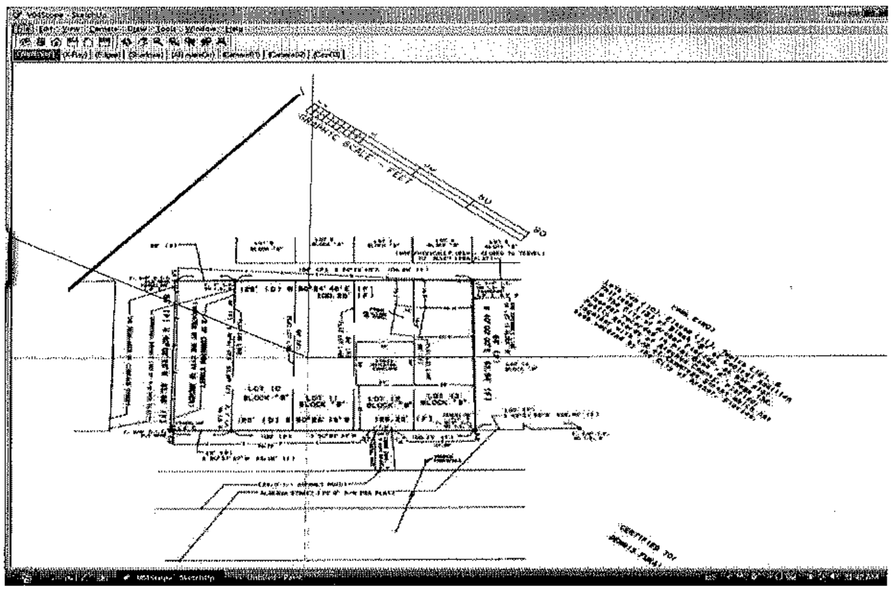

Figure 11: An example plat survey shown for illustration. The boundary of the plat is shown by bearings. Individual lots are marked by labels. Control points are shown on the extremities of the plat. (Reproduced with permission from Building SIMPLE: Building an Information Model, 2006)

It is easier to perform geo-referencing if either the property survey [Figure 11] for the parcel of land where the building will be located has been completed, or there are monuments/landmarks nearby for which exact geospatial coordinates are known. In most situations, the property survey for the land where the building will be constructed should exist.

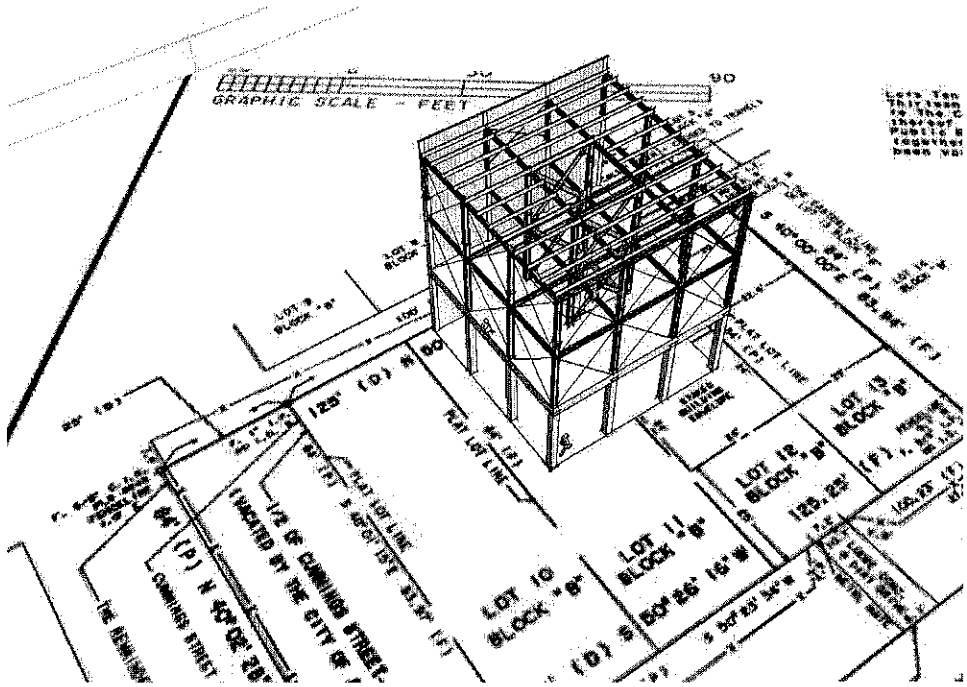

Figure 12: The placement of building on the survey. (Reproduced with permission from Building SIMPLE: Building an Information Model, 2006)

The process of geo-referencing can be achieved by the following a simple pseudo algorithm for the case where the land survey exists:

- Get the building foot print from the property survey.
- Choose the geospatial coordinate system e.g. UTM, Geodetic (i.e. Latitude-Longitude) Coordinate System. The accuracy of measurement depends on the coordinate system chosen. The maximum linear error of the UTM system is 1 in 2,500 (i.e. 4 cm in 100 meters). For the purpose of visual inspection, very high accuracy is not required and a Cartesian spatial coordinate system like UTM will produce acceptable results.
- Situate the 3D model of the building to the foot print of the building as shown through an illustrative example in Figure 12.

- If the axes of the Cartesian coordinate system matches exactly with that of the geospatial system, then compute the geospatial coordinates for the rest of the vertices of the 3D model using the following method:

    - If UTM coordinate system has been chosen, then locate the origin of the 3D model on the survey. Compute the UTM coordinates of the origin and then apply translations to find the coordinates of the rest of the vertices.

    - If a geodetic coordinate system is chosen then the coordinates of each vertex in the 3D model can be computed by applying Thaddeus Vincenty 'Direct' formulae[1]. It computes the destination point given a start point, an initial bearing, and a distance as shown in Figure 13a. Simply applying Vincenty 'Direct' formulae will require bearing of the line as an input which will require additional computational steps, so we propose an alternative method that still uses the Vincenty formulae but computes the latitude and longitude in two separate steps. The method is as follows:

      Start by locating the origin of the 3D model on the survey. We will call it the start point. Let the start point be (x_1, y_1, z_1) expressed in longitude, latitude, and altitude. Compute the longitude, latitude, and altitude of the destination point (x_2, y_2, z_2) in three steps, as shown on Figure 13, by first finding its latitude by projecting it on the meridian passing through the start point. In the second step, find the longitude by projecting it on the line of latitude passing through the start point. The method is implemented in the following steps:

        1. The first step involves computing the latitude of the destination point by finding the coordinates of its projection (point D1 as shown on Figure 13b) on the meridian passing through (x_1, y_1, z_1). Compute the coordinates of the projection point D1 by setting the true bearing to 0°0′ 0″, distance to (y_2 - y_1) from the initial point. The point D1 lies on the meridian line passing through (x_1, y_1, z_1).

        2. The second step involves computing the longitude of the destination point by computing the coordinates of its projection point (D2 as shown in Figure 13b) on the line of latitude passing through (x_1, y_1, z_1). Compute the coordinates of the point D2 by setting the bearing to 90°0′ 0″ and distance to (x_2 - x_1) from the initial point.

        3. Find the altitude of the point on the survey corresponding to the origin of the 3D model. Add this altitude to the z coordinate of all vertices in the model.

[1] JavaScript version of the Vincenty formulae is available at http://www.movable-type.co.uk/scripts/latlong-vincenty-direct.html

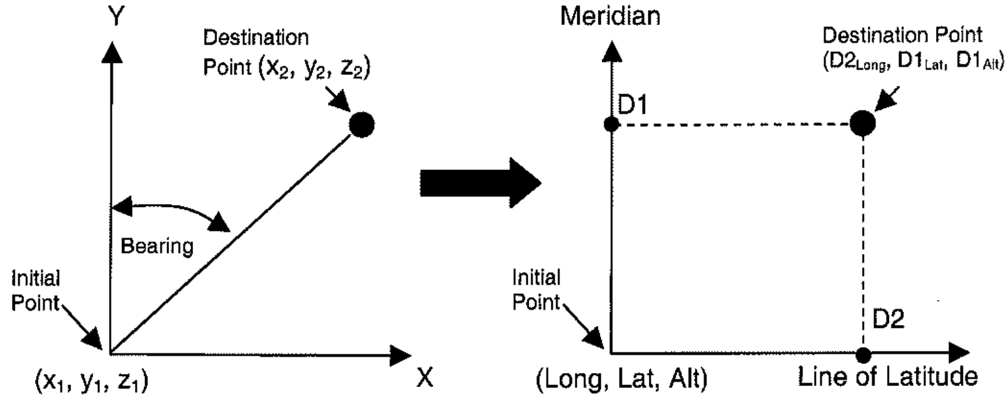

Figure 13 (a &b): Transforming the geospatial coordinates of a point in the Cartesian coordinate system to Geodetic

5.2.1 Visualization through GeoVRML

GeoVRML [Theresa-Marie, 1999] is an extension to the ISO standard Virtual Reality Modeling Language (VRML) to enable interactive, accurate, and dynamic 3D visualizations of geospatial data. The current version of GeoVRML is at 1.1 and was released in 2002. GeoVRML content can be browsed interactively in any standard VRML97 browser by installing the run time extension library available at www.geovrml.org. Cortona VRML viewer[2] from ParallelGraphics has native implementation of GeoVRML extensions. The implementation for these nodes is automatically downloaded and installed when The GeoVRML nodes are first used.

In VRML, similar to most 3D graphics systems, a world is modelled in a/the Cartesian coordinate system local (X,Y,Z) coordinate system with the origin being at (0,0,0) and the Y axis defined as "up", X axis to the "right" and z axis pointing out of the screen. GeoVRML provides support for georeferencing a VRML world by transforming it from a standard georeferencing system to the VRML local coordinate system.

VRML was primarily designed for the computer 3D graphics community and relies on single-precision (32 bit) IEEE floating point data values. This precision was sufficient for 3D graphics but is not capable of dealing with geographic data resolutions considering the large distances on Earth. Therefore absolute location data obtained from GPS cannot be accurately presented in VRML97 with sub-meter resolution. GeoVRML uses strings to define double-precision values[3] for accurate representation of geographic data, from whole-earth scales down to near-earth scales (i.e. city streets).

GeoVRML introduces a set of new nodes for VRML97 to perform geospatial tasks. The major nodes are: GeoCoordinate, GeoElevationGrid, GeoLocation, GeoLOD, GeoMatadata, GeoOrigin, GeoPositionInterpolator, GeoProximitySensor, GeoTouchSensor, GeoTransform, GeoViewpoint, and InlineLoadControl. The details of these nodes are in the GeoVRML documentation available at www.geovrml.org

[2] http://www.parallelgraphics.com/developer/products/cortona/geovrml
[3] Though only single-precision coordinates used for rendering

Out of all the nodes only the GeoLocation node is described in detail in this report. The GeoLocation node lets the user georeference an arbitrary VRML model by locating it at a specific point on the Earth. For example, with an available VRML model of a steel building, the GeoLocation node can specify the latitude/longitude location of that model. The model would then be correctly rendered at the specified geographical location. The GeoLocation node also orients the model correctly such that +Y is aligned with gravitational up, +Z points true North, and +X points East. Thus a model built using the standard VRML right-handed coordinate system will be placed on the Earth so that its base is aligned with the ground [Reddy, et. al. 2000]

5.3 Transform GPS Coordinates into Local Coordinates of the 3D model

The third approach is based on transforming the GPS coordinate system to the local coordinate system of the 3D model i.e. VRML, CAD, or CIS/2. Using this approach, each time the GPS sends new position information, it has to be transformed to the local coordinate system by the application.

Figure 14 and Figure 15 show two possible system architectures. Both the architectures assume implementation using a slate PC, a navigation system like GPS, and an instrument for finding the direction (e.g. Degrees North, South, East, etc). Figure 14 illustrates the simpler architecture for developing a system that is location-aware to enable the visualization of design details of the structure. The visualization is based on using VRML format files that can either be obtained by using the VRML export utility available in most CAD systems or through NIST CIS/2 to the VRML translator. This architecture works well for developing systems for visualization purposes, though it is easy to implement the redlining capability for putting down comments and notes.

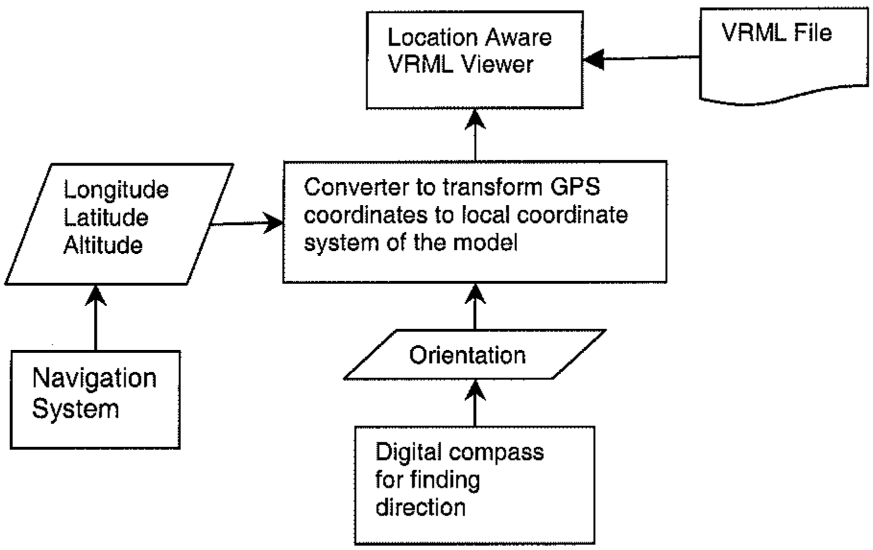

Figure 14: A location-aware Virtual Model Navigation system with only a visualization capability

The architecture depicted in Figure 15 overcomes the limitation of the previous one by providing a limited capability to create As-Built models by enabling the user to edit the model data onsite. The implementation of this architecture can be realised through tools such as the ST-Developer (http://www.steptools.com) which has utilities to visualize

CIS/2 and most CAD format files. The location-aware model navigator and editor module will position the viewpoint based on the location of the user, who then will be able to edit the model data based on his observations at the site.

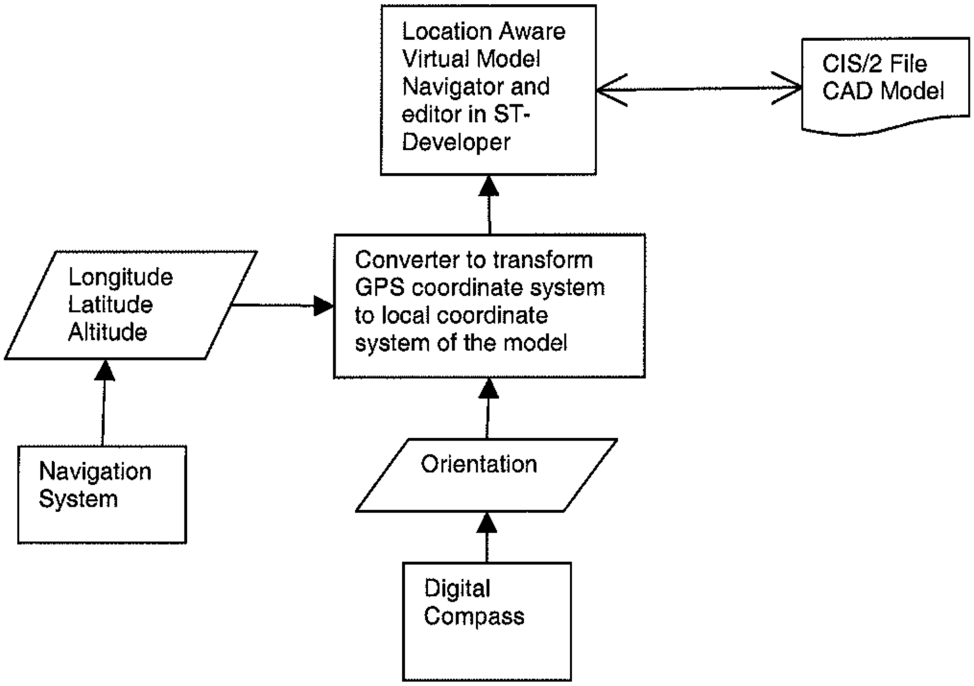

Figure 15: Location-aware Virtual Model Navigation System with model data visualization and editing capability.

6 Conclusions and Opportunities

It is important to determine the precise location of the user inside a building, and to ensure that the user's field of view is the same as that shown in the virtual model. The higher the precision in matching the user location to the viewpoint in the model, the lesser is the cognitive load when comparing the As-Built (actual view) to the As-Designed (model view). This precision depends on the accuracy of the GPS device and its ability to obtain a fix inside the building. GPS signals can travel through clouds, glass, and plastic but not through solid roofs and walls. The testing of the u-blox 5 GPS device inside the NRC London building shows that while the location fix was obtained in the second floor areas having plenty of windows, the signals were very weak on the ground floor and the location fix was not possible (see Appendix B for test results for u-blox 5). With the current state of GPS technology, therefore, a GPS-assisted portable inspection system is best suited for structures that have not been fully covered. If covered, the building structure must have plenty of windows/skylights to allow the signals to pass through.

The altitude data from the GPS device is not accurate enough to be of practical use. The elevation error is normally 1.5 to 2 times the horizontal position error. For example, if the horizontal position error is 5 meters, the elevation error will range from 7.5 to 10 meters. [http://www.dbartlett.com]. However, this problem can be overcome by providing a selectable elevation grid on the user interface of the portable inspection device. The user will thus be able to select the proper building level from the grid, and display the correct viewpoint.

As-Built construction documentation requires that the user be able to record the results of the inspection at the construction site. For this, a portable system must be able to retrieve and update the design parameters. Even though VRML and STL models are lightweight and can be used for visualization on portable, less powerful computers, they cannot be used directly to update the design model. The work-around solution may be to enable the user to annotate the lightweight model based on the observed discrepancies onsite, and update the design model off-site to create the As-Built model.

The design of the user interface is critical for the acceptance of portable tools by the on-site construction staff. It should require minimal interaction onsite, and at the same time enable visualization of the model and its elements (i.e. joints, beams, columns, etc) at the required level of detail. In this context, the automatic orientation of the virtual model, based on the orientation of the portable PC, will be useful. This 'automated model orientation' will require an electronic compass to be integrated into the system to provide the correct orientation for the viewpoint. Some high-end notebook computers come with systems to protect the hard disk drive by detecting sudden changes in motion and parking the read-write head. Examples of such systems are the Active Protection System for IBM ThinkPads and the Sudden Motion Sensor for Apple notebooks. Acer and HP have also implemented similar systems. A number of applications have also demonstrated the value of using a motion sensor in making the computer 'tilt-aware' for automatic scrolling. The usability of the system for field personnel can be increased through ubiquitous interfaces. This can lead to greater acceptance of computer tools at the construction site. The usability of the system can be further increased by using context as a filtering mechanism to deliver only context-relevant information to users [Aziz et.al. 2005].

In addition to inspecting fixed structures, many technologies that form the building blocks of GPS-assisted inspection systems, can also be used for developing a material-tracking application. Application of GPS devices has been demonstrated for tracking of fabricated pipes in construction yards [Caldas, et. al. 2004] by associating the GPS location with the unique identification marks on a pipe. To associate the pipe ID with its location, a person equipped with a Pocket PC and a GPS device walks around the storage yard and links the IDs of pipes with the GPS locations, using an application running on a Pocket PC. This method requires the user to manually link the location information to the ID. As an alternative, GPS-equipped digital cameras e.g. Ricoh Caplio 500SE, can be used to track materials in construction storage yards. In this approach, the camera is used to take a photo of the part such that the ID mark is clearly visible. The photos are then downloaded to a PC and an image processing application extracts the ID marks from the photos and associates it to the location coordinates.

7 Acknowledgements

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u-blox AssistNow Online and Offline – u-blox GPS Technology. <http://www.u-blox.com/products/Product_Summaries/AssistNow_Prod_Summary.pdf>

Vincenty formula for distance between two Latitude/Longitude points, http://www.movable-type.co.uk/scripts/latlong-vincenty.html

WPS Overview – Skyhook Wireless. http://www.skyhookwireless.com/howitworks

Appendix A – GPS and its Accuracy

(Extracted from Magellan Professional Website at http://pro.magellangps.com)

Global navigation satellites continuously transmit time and distance information as they orbit the earth in a precise formation. Navigation satellite receivers use this information to calculate an exact location through triangulation. Every point on Earth is identified by two sets of numbers called coordinates. These coordinates represent the exact point where a horizontal line, known as latitude, crosses a vertical line, known as longitude. The receiver locks on to at least three satellites and uses the information received to determine the coordinates of the device.

By comparing the time the signals were transmitted from the satellites and the time they were recorded, the receiver calculates how far away each satellite is. The distance of the receiver from three or more satellites reveals its position on the surface of the planet. With these distance measurements, the receiver might also calculate speed, bearing, trip time, distance to destination, altitude and more.

The satellite navigation device may display its position as longitude, latitude or simply as a point on an electronic map.

Line of Sight

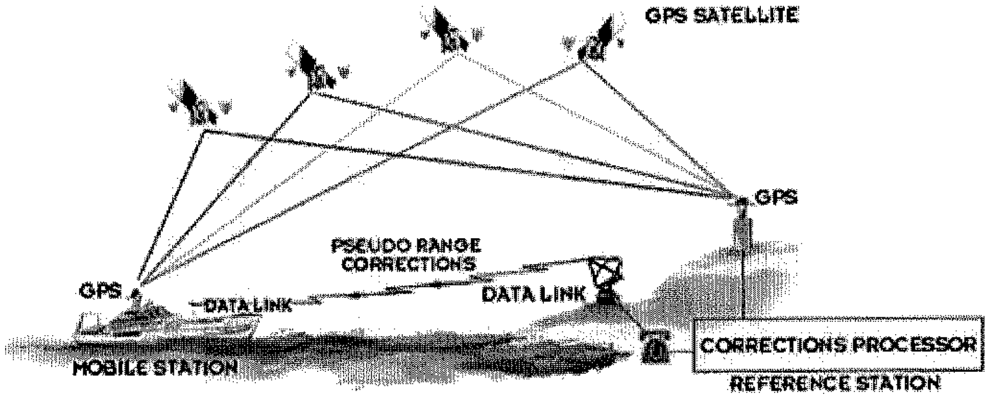
Satellite navigation receivers operate by line of sight with global positioning satellites. This means that at least three satellites must be in "view" of a receiver in order to calculate longitude and latitude. A fourth satellite must also be within line of sight to calculate altitude. On average, eight satellites are continuously within line of sight of every position on Earth; the more satellites in view, the more accurate the positioning.

Though the radio signals of navigation satellites will pass through clouds, glass, plastic and other lightweight materials, satellite navigation receivers will not work underground or in other enclosed spaces.

Accuracy

On average, a satellite navigation receiver is accurate to within 15 meters. However, this accuracy can be significantly improved by an augmentation system that reduces or eliminates errors in the satellite signals by providing improvements in accuracy, integrity, reliability, and availability. One type of augmentation, a technique known as Differential GPS (DGPS), is used to improve the accuracy of satellite navigation by measuring infinitesimal changes in variables to provide satellite positioning corrections.

Two or more receivers observe the same set of satellites, taking similar measurements that produce similar errors when positioned closely together. A reference receiver, placed at a known location, calculates its theoretical position and compares it to the measurements provided by the navigation satellite signals. The difference between the two values reveals the measurement error. The reference receiver then transmits a corrected signal to any number of receivers at unknown positions within the area covered by the DGPS. Accuracy of positioning is thereby increased from 15 meters to within a few meters. This technique compensates for errors in the satellite navigation system itself but may not always correct errors caused by the local environment when satellite navigation signals are reflected off of tall buildings or nearby mountains, creating multi-path signals.



Other sophisticated DGPS techniques can increase positioning accuracy even more. Raw measurements recorded by the reference receiver and one or more roving receivers can be processed using specially designed software that calculates the errors. By applying the corrections and recalculating the position, accuracy can be increased from several meters to within a few millimeters, depending on the specific methodology used and the quality of the data link.

Appendix B – Testing of u-blox 5

The indoor performances of the following GPS device, its accompanied software with the specified operating platform under certain conditions were tested.

Device:	u-blox 5 GPS and Galileo Receiver Evaluation and Development Kit EVK-5H	
Software:	u-center Application	
Platform:	DELL LATITUDE PROPERTY OF CNRC-IMTI NO. 000267 Windows 2000 Professional	
	Power Options:	Adjusted to not interrupt
	Screen Brightness:	Adjusted to save battery life

Using the USB for power and data communication (COM4), the u-center application was crashing or not stable. The Communications Port Settings for COM4 are as follows:

Bits per second (BAUD):	9600
Data bits:	8
Parity:	None
Stop bits:	1
Flow control:	None

Using the USB for power (COM4) and RS232 for Data Communication (COM1), the u-center application was able to run until battery life had gone. The Communications Port Settings for COM1 are as follows:

Bits per second (BAUD):	9600
Data bits:	8
Parity:	None
Stop bits:	1
Flow control:	None

The RS232 Serial Communication Cable Specification is a follows:

DB-9 Male		DB-9 Female
Pin 2	←--→	Pin 2
Pin 3	←--→	Pin 3
Pin 5	←--→	Pin 5

Note:

GPS Device Serial Port:	DB-9 Female
PC Serial Port:	DB-9 Male

The GPS device's indoor reception in general at the NRC London Facility was as follows:

Floor 100-Level: None Except for 2 or 3 Places

Floor 200-Level:	Varies or None
Stair No 3 Top:	Good

Three sets of indoor measurement were taken on a day with light snowing weather condition and they are shown as follows:

NRC London and Data	Latitude (°)	Longitude (°)	Altitude (m)
Corridor 159 North 001	+43.016349	-81.277832	190.40
Corridor 159 North 002	+43.016318	-81.277775	231.60
Corridor 159 North 003	+43.016182	-81.277652	216.50
Corridor 159 South 001	+43.015963	-81.277688	221.70
Corridor 159 South 002	+43.016071	-81.277506	228.50
Corridor 159 South 003	+43.016006	-81.277676	214.10
Stair No 3 Top 001	+43.015746	-81.278253	238.90
Stair No 3 Top 002	+43.015716	-81.278288	192.70
Stair No 3 Top 003	+43.015898	-81.278262	219.30

The published reference from CYXU (at London Int'l Airport) in London, ON, Canada is as follows:

London, ON, Airport	Latitude (°)	Longitude (°)	Altitude (m)
Place Near Runway	+43.0356	-81.1539	278