Structure of an Augmented Situational Visualization Framework for Rapid Building Damage Evaluation

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Abstract

This paper presents research being conducted at the University of Michigan to design and implement a new, rapid post-disaster building damage reconnaissance technology. The technology being designed will allow on-site damage inspectors to retrieve previously stored building information, superimpose that information onto a real structure in augmented reality, and evaluate building damage, structural integrity, and safety by simply measuring and interpreting key differences between the baseline image and the real view. In addition, by using feedback from the actual view of a building, it will be possible to update structural analysis models and conduct detailed what-if simulations to explore how a building might collapse if critical structural members fail, or how the building's stability could best be enhanced by strengthening key structural members. Building data, recorded earthquake strong motion data, and computing resources necessary for the carrying out the intensive simulation computations will be made available through a computational grid interconnected by a high-speed, high-bandwidth network. All analyses will be conducted on-site, in real-time, and at a very low cost using light-weight, field deployable computers connected to a grid gateway via wireless connections. This will enable a quantum leap over current damage evaluation practices that are significantly prolonged, expensive to conduct, and often inaccurate. The objectives of this paper are to introduce the overall structure of the framework and to present details on the method of computing global building damage measures using augmented reality.

Keywords

Augmented Reality, Buildings, Damage Evaluation, Earthquakes, Explosions, Reconnaissance.

1. INTRODUCTION

Augmented Reality (AR) is the superimposition of computer-generated images over a user's view of the real world. By presenting contextual information to the user, the real world is enhanced or augmented beyond the user's normal experience. The addition of information spatially located relative to the user can assist in the performance of several scientific and engineering tasks.

Researchers have explored AR for several applications in the AEC industry. [Webster96] presented a system that shows locations of columns behind finished walls, and re-bars inside columns. [Roberts02] used AR to overlay locations of subsurface electrical, telephone, gas, and water lines onto real-world views. Both applications demonstrated AR's potential in helping maintenance workers avoid buried infrastructure and structural elements when they make changes to buildings and outdoor environments. [Webster96] also presented an AR system that guides workers through the assembly of an architectural space frame. [Hammad04] augmented contextual information and maintainence data on real views of bridges to help bridge inspectors conduct inspections more effectively. [Thomas98] and [Klinker01] explored AR to visualize architectural designs outdoors. [Dunston02] have also demonstrated the usefulness of mixed reality AR-CAD in collaborative design.

This paper presents research being conducted at the University of Michigan to design and implement a new, rapid post-disaster building damage reconnaissance technology. The technology being designed will allow on-site damage inspectors to retrieve previously stored building information, superimpose that information onto a real structure in augmented reality, and evaluate building damage, structural integrity, and safety by measuring and interpreting key differences between the baseline image and the real view. The objectives of this paper are to introduce the overall structure of the framework and to present details on the method of computing global building damage measures using augmented reality.

2. IMPORTANCE OF THE RESEARCH

Accurate evaluation of damage sustained by buildings during catastrophic events (e.g. earthquakes or terrorist attacks) is critical to determine the buildings' safety and their suitability for future occupancy. Time is of the essence in conducting the evaluations since the damaged buildings cannot resume serving their regular purpose until they are deemed safe. The speed with which evaluations are conducted determines the duration for which the potentially damaged buildings remain unusable. The elapsed time directly translates into significant economic losses and to circumstances in which humans are exposed to precarious working and living conditions.

Notwithstanding the significant economic and safety considerations involved, current practices of evaluating damage to buildings after catastrophic events are labor intensive, time consuming and error prone. Whenever a catastrophic event occurs, evaluation reconnaissance teams comprised of two or more licensed inspectors per team are deployed within the affected areas. Such teams conduct visual inspections of buildings according to guidelines contained in ATC-20 [ATC89] and the ATC-20-2 [ATC95]. Both documents are written specifically for structural engineers and building inspectors, and describe detailed procedures for evaluating damaged buildings in the aftermath of disasters.

Depending on the findings of the evaluation reconnaissance teams, each inspected structure is posted with a notice (i.e. tagged) indicating its probable condition and permitted use. Tagging is intended to signal to the public any significant changes in the safety of inspected buildings as a result of the disaster.

Green tags are used to identify buildings that could be damaged but, based on minimal externally visible signs of distress (e.g. large cracks), are still deemed safe for occupancy. Red tags signify unsafe buildings that exhibit conspicuous signs of distress (e.g. large cracks or displacements), while yellow tags imply restricted use, i.e. based on visible exterior conditions, there is some risk from damage in all or part of the building that does not warrant red tagging.

The manpower required for such an exercise is substantial, especially in large cities where several hundred buildings could be potentially damaged at the same time after a catastrophic event such as an earthquake. This can delay critical inspections and can put unwarranted demands on relief agencies that help individuals who await inspection to enter their homes or businesses. What is more critical, however, is that results of the visually conducted inspections can be inaccurate, especially in buildings that, based on the lack of obvious visible distress signs, could be incorrectly green tagged at the time of the inspections.

A case in point is the earthquake that struck Northridge, CA in 1994. This earthquake caused substantial damage to structural element connections in more than 150 moment-resisting steel frame buildings in LA [FEMA97a]. A particularly disconcerting aspect of the damage was that it often occurred without accompanying distress to architectural finishes and cladding.

Thus, reconnaissance reports immediately following the earthquake often cited the apparent excellent behavior of steel frame buildings. However, severe damage found in buildings that were under construction at the time of the earthquake, and subsequent detailed investigations of steel buildings which suffered increasing amounts of damage during aftershocks, quickly identified the true performance [FEMA00a].

The converse of such a situation can also be true. Buildings that are yellow or red tagged may have sustained only superficial damage to their facades with little or no damage to the underlying structural system. Such buildings unnecessarily remain out of service when in reality they are safe and could be immediately reoccupied. While human safety is not compromised in such situations, significant economic losses are certainly incurred.

There is therefore a clear and critical need for a new methodology that can allow reconnaissance building damage inspectors to rapidly assess the true extent of damage sustained by buildings and make accurate, real-time decisions about their structural integrity, safety, suitability for future occupancy, and repair requirements.

3. OVERALL ARCHITECTURE OF THE NEW RECONNAISSANCE METHODOLOGY

The overall objective of this research is to integrate and advance knowledge adapted from several disciplines to develop a new, rapid post-disaster damage reconnaissance technology. The new technology will deliver unprecedented on-site capabilities to inspectors evaluating building damage in the aftermath of catastrophic events such as terrorist attacks, explosions, and earthquakes.

The research draws upon 1) computational structural simulation technology to provide basic and advanced analysis capabilities; 2) Augmented Reality (AR) technology to rapidly compose, visualize, and interpret simulation results; and 3) grid networking services to access required data and conduct intensive computations on-site and in real-time.

Figure 1 presents the overall architecture. When fully implemented, the system will allow on-site users to retrieve previously stored information about a building, superimpose this information onto the real structure in an augmented reality setting, and evaluate damage by simply comparing the two views.

Users will be able to use the developed tool to measure key differences between the baseline image and the real view and compute damage indices that will allow critical decisions to be made about a building's structural integrity and safety.

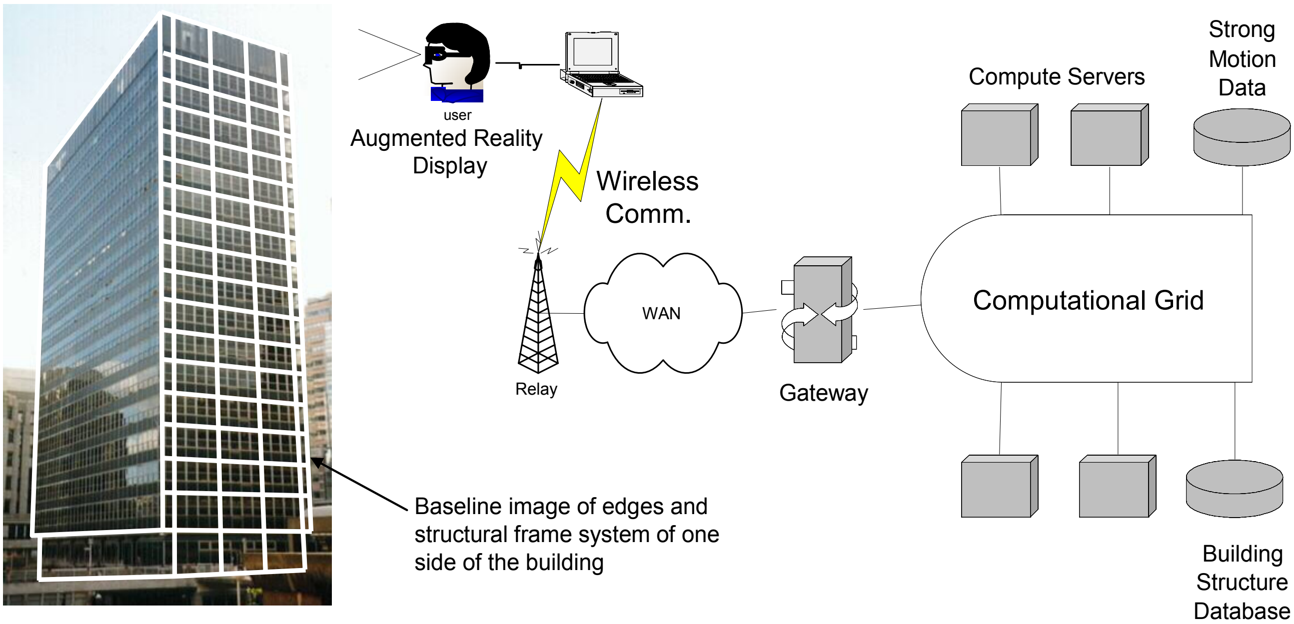


Figure 1: Overall Architecture of the New Damage Reconnaissance Methodology.

In addition, by using feedback information from the actual view of the building, users will be able to update structural analysis models and conduct on-site what-if simulations to explore how a building might collapse if critical structural members fail, or how the building's stability could best be enhanced by strengthening key structural members.

The new system will further make it possible to project additional information into the user's view field, such as structural details that can assist in planning for repair operations, as well as other building views, architectural data, or egress information needed for search and rescue operations.

In order to achieve these objectives, on-site users of the system will use equipment that will consist of an augmented reality see-through display attached to a lightweight computing platform such as a laptop (Figure 1). The user's platform will be sufficiently powerful to perform basic image processing and display. Building data, recorded earthquake strong motion data, and computing resources will be available through a computational grid interconnected by a high-speed, high-bandwidth network.

Grid resources, such as building databases, seismic record information warehouses, and compute servers, may be distributed geographically under different administrative domains. Communication between the on-site platforms and a gateway to the computational grid will be via wireless, possibly multi-hop, connection.

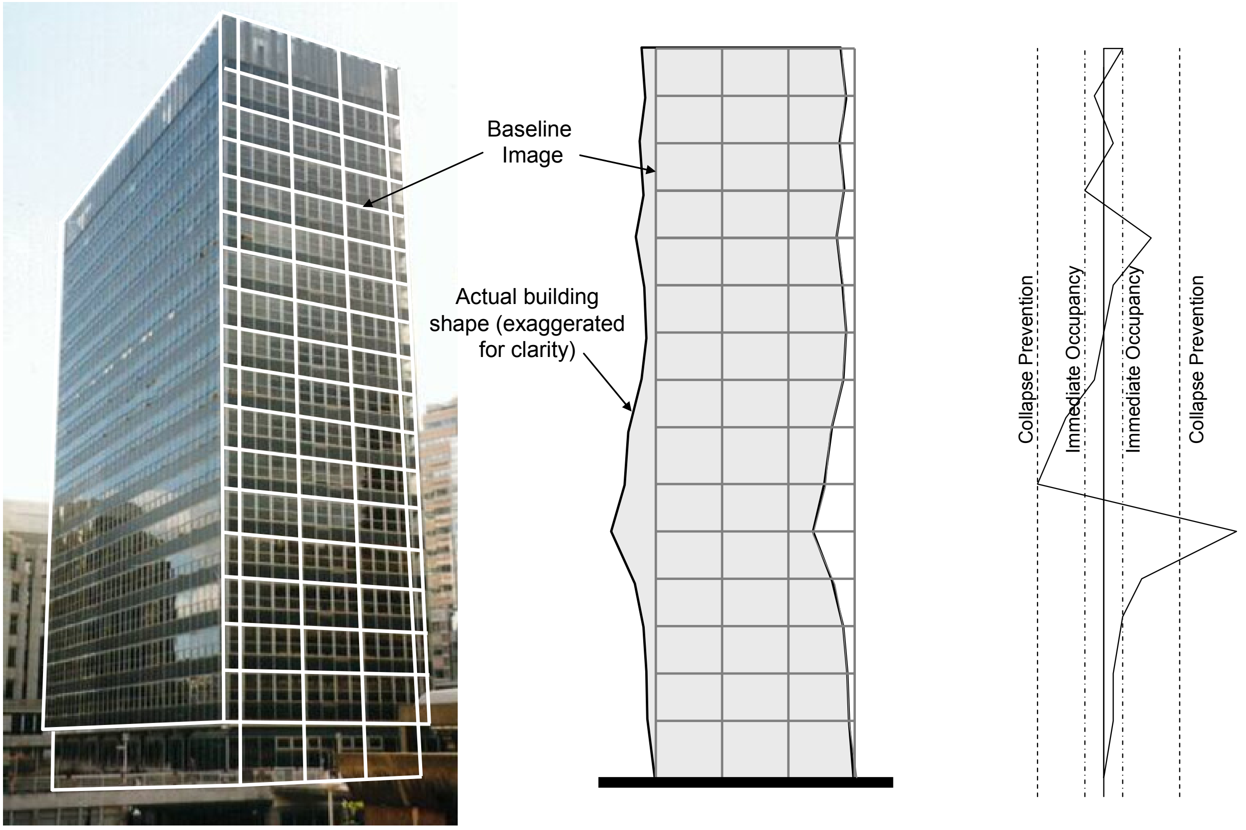
4. RAPID EVALUATION OF GLOBAL BUILDING DAMAGE MEASURES

Of the many damage indices proposed, the Interstory Drift Ratio (IDR) remains the most robust and indicative of damage at the story level [FEMA00b]. The residual IDR is a measure of how far each building floor has moved permanently relative to the one beneath, and is an indicator of both structural and non-structural damage.

Due to its comprehensive nature and the fact that it can be reliably correlated to other damage indices, the IDR forms the basis of the most recent seismic specifications for moment-resisting frame structures, e.g. [FEMA00a]. By comparing a baseline image to the actual shape of a structure after the seismic event, it can be possible to compute the residual IDR at each floor. This is shown schematically in Figure 2.

By comparing computed IDRs to predetermined thresholds, a very quick but thorough assessment of the level of structural and non-structural damage incurred can be made. Two particularly important thresholds are being investigated in this research: immediate occupancy and collapse prevention limits. Both are well documented for various types of construction in existing specifications such as [FEMA97b], [FEMA00c] and [FEMA00a].

We are also investigating the means for trying to relate the IDR values to ballpark cost estimates for repair that can be used to quickly and accurately assess the economic impact of a disaster.



(a) Baseline image superimposed on building view

(b) Deformed shape of building (exaggerated) compared to baseline shape

(c) Interstory drift index

Figure 2: Computation of Residual Interstory Drift Ratios (IDRs) After a Seismic Event.

The philosophy behind such an application follows the methodology used in loss estimation packages such as HAZUS (http://www.fema.gov/hazus) or can simply be based on square footage, type of construction, building height, and other pertinent parameters.

4.1 Data Models and Data Management

A significant amount of building data is required for this system to function as intended. At the very least, a model of the pre-disaster outer geometry of a building must be immediately available to serve as a baseline image in the IDR computation. We are currently investigating specifications for compact data structures that include all pertinent structural information to allow rapid on-site assembly of appropriate structural analysis models. The required metadata format must minimally include information about structural members, materials, connections, and boundary conditions in a building's frame. In order to achieve this, we are exploring the usability of standard, interoperable building product models such as the CIMSteel Integration Standards (CIS/2) and the Industry Foundation Classes (IFC).

CIS/2 (http://www.cis2.org/) is a logical product model for structural steel building information and has been adopted by the American Institute of Steel Construction (AISC) as their format for electronic data interchange [Lipman03]. CIS/2 has been implemented by many steel design, analysis, engineering, fabrication, and construction software packages to create a seamless and integrated flow and archival of information among all entities involved in the construction of steel framed structures. The CIS/2 standard provides data structures for multiple levels of detail ranging from frames and assemblies to nuts and bolts, and has been successfully deployed on mobile computing platforms [Lipman02]. CIS/2 structures can be represented as analysis, design, or manufacturing models. In addition, any software application can seamlessly have CIS/2 import and/or export capabilities. These features make the standard particularly attractive for exploration in this study.

The Industry Foundation Classes (IFCs) define a similar product model and is being used to explore data structures for compactly encapsulating concrete structural frames. IFCs [IAI04] are data elements that represent parts of a facility and contain relevant information about those parts.

IFCs are used by applications such as CAD tools to assemble a computer readable facility model that contains all information of the parts and their relationships. Like CIS/2, IFCs are designed to allow passing a complete, accurate product model from one application to another with no loss of information.

Pertinent information about buildings could be available from the databases that belong to the building owners or from government data repositories for important public buildings. Although a national database of building information does not exist at the moment, there is a growing momentum towards its creation. At the 2002 National Convention of the American Society of Civil Engineers (held in Washington DC), several papers and discussions in technical sessions were devoted to this issue. Furthermore, the creation of such a database is one of the goals of The Infrastructure Security Partnership (TISP), a recently formed organization.

TISP (http://www.tisp.org) is an association of public and private sector organizations collaborating on issues related to the security of the nation's built environment. We are surveying officials at TISP, owners of critical commercial and government buildings, and regulatory government agencies to enquire about the methodology for creating such a database, and the means for its management. The survey includes questions about the type of information to be stored, restrictions to its access, means for collecting the data, and means for disbursing the information.

5. USER-INTERACTION WITH THE MOBILE AUGMENTED REALITY SYSTEM (ARS)

Effective techniques and tools to facilitate interaction between a mobile ARS and on-site users conducting the building damage evaluation analyses are key to the success of the reconnaissance technology being designed.

5.1 Accuracy in Registration and Tracking

In ARS applications where a virtual image is superimposed onto a user's view of the real environment, it is extremely important that the computer generated imagery register (i.e. coincide) with the real-world within an acceptable level of accuracy [Holloway97]. Since the primary task of the mobile ARS user is to compare the augmented image of an undamaged building with the possibly damaged and dislocated real structure, it is imperative that the coordinate system of the virtual augmented world be accurately registered with the real world coordinate system.

Extremely high registration accuracy is necessary since the IDRs sought could be as small as a few centimeters. If a target of 5-cm of observed IDR is required, then the registration accuracy in the ARS that will allow us to visually capture the observations must be significantly higher than 5-cm.

In conventional AR systems, registration is achieved and maintained by monitoring (i.e. tracking) the movements (body motion and head rotation) of the ARS user and using that information to ensure that virtual images continually coincide with their real world counterparts [Barfield01]. This is achieved by monitoring trackers (or sensors) mounted on the user's body as she navigates and performs tasks in AR. Traditional tethered tracking systems employ magnetic [Raab79], ultrasonic [Intersense04], or optical [Welch01] technologies.

Although very accurate, these trackers rely on installations of large devices or dense arrays of beacons and sensors mounted in a finite enclosed area. This is not suitable for the ARS sought for this project since it must operate in outdoor, unprepared environments. Tracking systems can also be based on computer vision to track the motion of a camera mounted on an ARS user.

Examples include the placement and tracking of fiducial markers in the real environment [Kourogi01]. Since fiducial marker based vision tracking schemes require initial placement of several fiducial markers at strategic locations in the environment, it is again unsuitable for our unprepared environment application. Another class of tracking systems based on local sensors and dead reckoning techniques have been known to be inaccurate and error accumulating [Reitmayr03], and can thus be ruled out as well for this project's ARS.

We are currently investigating the means to rapidly achieve sufficient registration accuracy for our mobile ARS. We are exploring the use of GPS based rapid initial registration followed by fine manual augmentation adjustments (e.g. coinciding the lower left corner of an augmented image with the corresponding point on the real building) to allow our ARS to achieve the required registration accuracy.

Recent GPS advances such as Trimble's Moving Baseline Real-Time Kinematic (RTK) technique offer precise position (1-cm) and heading (0.03° RMS) accuracies without the need for external differential GPS corrections. In the prototype ARS setup being constructed in this project, we will use Trimble's state-of-the-art MS860 dual-antenna GPS receiver for precise positioning, tracking, and orientation of the ARS setup. Depending on the registration accuracy maintained during user movements, we will explore both head-mounted as well as fixed-base (e.g. tripod mounted) displays in our setup.

5.2 Intuitive User-Interaction Techniques

ARS users must be able to observe the real structure in the background and rapidly make changes to the registered augmented image to reflect the shape of the real, possibly distorted structure. In an ARS setting, this requires modification of geometry that is out of reach, is at a larger scale than the user, and co-located with the physical world [Piekarski03]. In augmented situational visualization, the user does not generally break the 1:1 relationship between the real world objects and the augmented virtual objects. This is distinctly different compared to Virtual Reality (VR) applications where most geometric modification (e.g. CAD modeling) is achieved by breaking the 1:1 scale between the user's real world and the geometric virtual objects [Barfield01].

For our AR application, however, it is effectively necessary to break the 1:1 relationship between the real building's view and the augmented image so that a user can visually make minute adjustments to the image to exactly superimpose it over the displaced real structure. We are attempting to achieve this by designing a zooming capability in our ARS application.

Each time the user centers the display over a particular displaced point on the building facade, she will be able to zoom in on that point until the display resolution is high enough to show modifiable separation between the real and the augmented images. This zoom based interaction will be complemented with a video or optical see-through display that supports on-demand real-world occlusion.

All necessary modifications to the augmented image will be performed using hands-free input devices. For this, we are investigating and building upon existing AR user interaction techniques for our specific task. In particular, we are exploring the suitability of pinch glove based input techniques to achieve all our user interaction objectives. Pinch glove based interaction operates based on the relative positions and contacts between a user's fingers and is particularly suited for outdoor ARSs because it frees a user's hands to perform other tasks in parallel [Piekarski03].

6. MOBILITY OF THE ARS

The developed ARS platform must be lightweight and portable. An inspector must be able to carry it to an evaluation site and quickly set it up and use it. The prototype that we are developing will consist of a stereoscopic color AR display and a pinch glove input device attached to an off-the-shelf portable laptop computer. By using off-the-shelf components we can reduce the cost and increase the flexibility and interoperability of the equipment. The laptop will have sufficient computation power for stereoscopic rendering and viewing, and it will also be used to perform some on-site analyses.

For example, a notebook computer with a 2+ GHz processor and an NVidia Quadro4 graphics accelerator will suffice to serve as the backbone of the ARS. Since the ARS will be used in the field, the connection to remote resources will be through a wireless network. The likely setup will involve using a wireless 802.11 connection between the ARS and a network relay installed in a curbside van. The relay could connect to the remote services via the Internet using satellite, cellular, or other wireless technology.

7. CONCLUSION

In this paper, we have introduced the overall structure of a framework that is being designed to facilitate the rapid evaluation of damage sustained by buildings in the aftermath of catastrophic events. The computation of global building damage measures such as the IDR is the logical first step in rapidly determining the extent of damage that a building has sustained in a seismic event. A methodology based on augmented situational visualization is presented that overlays facades of possibly damaged and displaced buildings with pre-existing images of the undamaged structures. The IDRs for the buildings' stories are then rapidly computed by comparing the displacements at key building locations with their original positions in the overlaid images. By comparing computed IDRs to predetermined thresholds, a very quick but thorough assessment of the level of structural and non-structural damage incurred during a disaster can be successfully made.

8. REFERENCES

[ATC89] ATC-20 (1989), Procedures for Postearthquake Safety Evaluations of Buildings, Report ATC-20, Applied Technology Council. Redwood City, CA.

[ATC95] ATC-20-2 (1995), Addendum to ATC-20, Procedures for Postearthquake Safety Evaluations of Buildings, Report ATC-20, Applied Technology Council. Redwood City, California.

[Barfield01] Barfield, W., and Caudell, T. [editors] (2001). Fundamentals of Wearable Computers and Augmented Reality. Lawrence Erlbaum Associates, Mahwah, NJ.

[Dunston02] Dunston, P., Wang, X., Billinghusrt, M., and Hampson, B. (2002). "Mixed Reality Benefits for Design Perception." 19th International Symposium on Automation and Robotics Construction (ISARC 2002), NIST, Gaithersburg, MD, 191-196.

[FEMA97a] FEMA-267A (1997), Interim Guideline: Advisory No. 1, Supplement to FEMA-267, Report Number SAC-96-03, SAC Joint Venture, Sacramento, CA.

[FEMA97b] FEMA-273 (1997), NEHRP Guidelines for the Seismic Rehabilitation of Buildings. FEMA 273/October 1997, Applied Technology Council (ATC-33 Project), Redwood City, California.

[FEMA00a] FEMA-350 (2000), Recommended Seismic Design Criteria for New Steel Moment-Frame Buildings, FEMA 350/July 2000, Building Seismic Safety Council, Washington, D.C.

[FEMA00b] FEMA 355D (2000), State of the Art Report on Connection Performance, prepared by the SAC Joint Venture for the Federal Emergency Management Agency, Washington, DC.

[FEMA00c] FEMA-356 (2000), Prestandard and Commentary for the Seismic Rehabilitation of Buildings, FEMA 356/November 2000, Building Seismic Safety Council, Washington, D.C.

[Hammad04] Hammad, A., Garrett, J.H. and Karimi, H. "Location-Based Computing for Infrastructure Field Tasks," (2004). In Karimi, H. and Hammad, A. (editors), "Telegeoinformatics: Location-Based Computing and Services," CRC Press, pp. 287-314.

[Holloway97] Holloway, R. L. (1997). Registration error analysis for augmented reality. Presence: Teleoperators and Virtual Environments, 6(4), MIT Press, Cambridge, MA, 413–432.

[IAI04] IAI - International Alliance for Interoperability (2004). Industry Foundation Classes. Available: www.iai-na.org [Accessed: Feb 10, 2004]

[Intersense04] Intersense (2004), 'Intersense IS-900', http://www.isense.com [Accessed: Feb 10, 2004].

[Klinker01] Klinker, G., Stricker, D., and Reiners, D. (2001). Augmented Reality for Exterior Construction Applications. In W. Barfield & T. Caudell (Eds.), Fundamentals of Wearable Computers and Augmented Reality. Mahwah, NJ: Lawrence Erlbaum.

[Kourogi01] Kourogi, M. and Sakaue, T. K. K. (2001), A panorama based method of personal positioning and orientation and its real-time applications for wearable computers, ISWC'01', Zurich, Switzerland, 107–114.

[Lipman03] Lipman, R., and Reed, K. A. (2003). Visualization of structural steel product models, ITcon Vol. 8, Special Issue on VR Technology in Architecture and Construction, 51-64, http:// www.itcon.org/ 2003/5 [Accessed: Feb 10, 2004]

[Lipman02] Lipman R (2002). Mobile 3D Visualization for Construction, Proceedings of the 19th International Symposium on Automation and Robotics in Construction, 23-25 Sep 2002, Gaithersburg, MD.

[Piekarski03] Piekarski, W., and Thomas, B.H. (2003). Augmented reality user interfaces and techniques for outdoor modelling, Proceedings of the 2003 symposium on Interactive 3D graphics, ACM, New York, NY, 225-226.

[Raab79] Raab, F., Blood, E., Steiner, T. and Jones, R. (1979). Magnetic position and orientation tracking system, IEEE Transactions on Aerospace and Electronic Systems AES-15(5), IEEE, Piscataway, NJ, 709–718.

[Reitmayr03] Reitmayr, G., and Schmalstieg, D. (2003). Location Based Applications for Mobile Augmented Reality, Proc. 4th Australasian User Interface Conference, Adelaide, Australia.

[Roberts02] Roberts, G.W., Evans, A., Dodson, A., Denby, B., Cooper, S., and Hollands, R. (2002). "Look Beneath the Surface with Augmented Reality", GPS World, February 03, 2002, Available: http://www.gpsworld. com/gpsworld/article/ articleDetail.jsp?id=9516 [Accessed: July 1, 2004].

[Thomas98] Thomas, B., Piekarski, W. and Gunther, B., (1998). "Using Augmented Reality to Visualize Architectural Designs in an Outdoor Environment", DCNet'98 Online Conference, Available: http://www. arch. usyd. edu.au/kcdc/journal/vol2/dcnet/sub8/ [Accessed: March 10, 2003].

[Webster96] Webster, A., Feiner, S., MacIntyre, B., Massie, W., and T. Krueger. (1996). "Augmented reality in architectural construction, inspection and renovation." Proc. 3rd Congress on Computing in Civil Engineering, ASCE, Reston, VA, 913-919.

[Welch01] Welch, G., Bishop, G., Vicci, L., Brumback, S., Keller, K. & Colucci, D. (2001), High performance wide-area optical tracking - the hi-ball tracking system, Presence: Teleoperators and Virtual Environments, 10:1, MIT Press, Cambridge, MA.