DESIGN AND EVALUATION OF AUGMENTED REALITY INTERFACES FOR BRIDGE INSPECTION

A. J. Antony Chettupuzha[1], Baber Farooq[1], Chung Yan Shih[1], Jaime L Wright[1], Sanghoon Lee[2], Semiha Kiziltas[1], James H Garrett, Jr*[1], Hassan Karimi[3], and Asim Smailagic[4]

ABSTRACT

Augmented Reality (AR) technology, wherein computer-generated visuals are displayed to augment the real environment being viewed by a user, can be used to provide additional pertinent information while users perform tasks in the real world. AR environments offer significant potential benefits to bridge inspectors. While viewing a bridge, inspectors could be presented relevant information, such as information from previous inspection reports, overlaid over the real scene they are viewing. Furthermore, AR interfaces could be used to support actual bridge inspections without modification, if wearable computing technology is used to deliver AR functionality.

In this paper, some of the AR interfaces that were found useful for delivering the type of support described in the previous paragraph are presented along with an evaluation that was conducted. A case-study to identify current bridge inspection procedures and a set of requirements for inspecting a particular aspect of bridge inspections (i.e., delamination) were conducted and resulted in a set of use-cases, which are briefly described in this paper. AR interfaces that were created in a VR environment to mock up the functionality of the identified use-cases are then presented. Finally, a preliminary evaluation of the created AR interfaces was conducted and a discussion of the feedback received from these evaluators is presented.

The results of this evaluation indicate that using focal points to locate damage prone areas that were previously reported and integrating voice activated reports are features that are usable, intuitive and effective. This study illustrates that the features provided in the developed AR interfaces have promise for further development. The study also demonstrates the potential of the approach used to develop and test the AR interfaces in a VR environment. Creating an interface that is intuitive requires rapid prototyping and evaluation capability. Using a VR environment to mock up and evaluate an AR interface allows for such rapid prototyping and evaluation.

1 Dept. of Civil and Environmental Engineering, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, 15213, Phone +1 412/268 5674, FAX 412/268-7813, garrett@cmu.edu

2 School of Architecture, Carnegie Mellon University, 5000 Forbes Ave., Pittsburgh, 15213, Phone +1 412/268-2008, shl1@andrew.cmu.edu

3 Dept. of Information Science and Telecommunications, University of Pittsburgh, 135 North Bellefield Avenue, Pittsburgh, PA 15260, Phone +1 412/624 5230, FAX 412/624-5231, hkarimi@mail.sis.pitt.edu

4 Institute for Complex Engineered Systems, Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213, Phone +1 412/268 7863, FAX 412/268-5229, asim@cs.cmu.edu

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INTRODUCTION

Bridge inspection is essential to ensure that highway bridges are safe for public use. The procedure includes preparing for the inspection, performing the inspection and identifying items for repair and maintenance. While in the field, inspectors require frequent access to information (such as previous inspection reports, bridge plans, repair reports) and collect new information during the current inspection. Currently, these tasks are manually performed and document-based. Considering that there are numerous physical objects to be inspected and each object may be related to several documents, it is time consuming to access critical information created prior to the inspection and this results in delaying the collection of new data.

To make inspection more efficient, there is a need for computer-based bridge inspection systems that can help inspectors retrieve and record data on a timely basis while in the field. Augmented Reality (AR) technology, wherein computer-generated visuals are created and displayed to augment the real environment seen by a user, provides a means to support field personnel while collecting finely grained, spatially distributed inspection information at the bridge inspection site. Although many researchers have attempted to develop interfaces using AR in practical domains (Lehikoinen 2001; Suomela 2001), utilization of AR technology in the architectural, engineering and construction industry (AEC) domain has not been extensively investigated (Hammad, 2004). Current AR interfaces are designed either to use head-mounted displays in which a viewer observes a direct “see-through” view of the real world with virtual displays overlaid on the viewer’s scene, or to augment a video of the real environment by means of adding virtual objects into the video scene. A good example of the first category is the system designed by Reitmayr et al. (2003), which is an indoor location-based mobile AR system where head-mounted displays are used to provide location-based information. A good example of the second category is the ARToolkit which can be used to calculate camera position and orientation relative to physical markers in real time (Kato, 2000). Once the real camera position is known, computer graphics can be drawn that appear to exactly overlay the video image of the real marker (Kato, 2000).

As the hardware and software for AR-applications is still fairly expensive and challenged in harsh environments, it is currently difficult for researchers to explore the types of interfaces that will work for tasks performed in these environments. As such, we propose to explore the appropriateness of AR interfaces for applications, such as bridge inspection, using VR environments. Therefore, the objective of the research described in this paper is to use a VR-based approach to explore which AR interfaces may provide satisfactory support for bridge inspection.

In this paper, we discuss the approach that we used in designing and evaluating several possible forms of AR interface for given use-cases for this AR-based system, and the feedback received from an evaluation we conducted.

APPROACH

The approach taken in designing and evaluating a set of AR interfaces for use in bridge inspection consisted of three major steps: 1) develop a set of use-cases for bridge inspection and a set of AR-based interfaces that correspond to these use-cases; 2) develop a prototype that incorporates these different interface concepts and illustrates how they would work within a VR environment; 3) evaluate the developed interfaces in the prototype to determine that they are usable, intuitive and effective. The next three sections describe each of these steps in more detail.

USE-CASE DEVELOPMENT AND CORRESPONDING AR-INTERFACES

Initially we attempted to develop a set of use-cases for bridge inspection as a foundation for the development of AR-based interfaces. The use-cases were created based on the bridge inspector training materials used by inspector trainees at the Michael Baker Corporation. We focused on the inspector training material for gathering National Bridge Inventory Data using the Structural Inventory and Appraisal Sheet (Dunker, 1995). This portion of the training information was subsequently modeled as use cases for delamination of bridge decks. Focusing on delamination allowed the team to thoroughly examine all aspects for inspection of a particular deficiency. These use-cases served as the basis for developing the user interfaces that would then be implemented in a VR environment and evaluated.

A use-case is initiated by a user with a particular goal in mind, and completes successfully when that goal is satisfied. It describes the sequence of interactions between actors and the system that are necessary to deliver the service that satisfies this goal (Cockburn, 1997). In this study, the primary actors in all of the use cases studied will be the bridge inspector.

In the development of these use-cases, the system was treated as a "black box," making the processes involved in the delivery of the functionality of the system interfaces irrelevant to the user. The use-cases served two purposes: (a) to document what functionality the bridge inspectors require to address particular inspection needs; and (b) to formulate ideas for the interfaces that deliver this functionality. After concluding research on the techniques and methodologies used for bridge inspection, 12 use-cases related to delamination were developed (see Table 1).

PROTOTYPE DEVELOPMENT

The goal of the research project is to develop an augmented reality system (AR) that supports bridge inspectors on the bridge site. AR environments differ from VR environments in that they are based on an interaction between the real word and virtual world. Three-dimensional and two-dimensional virtual objects are projected onto the real world through an external device (e.g., a head-mounted display or a projected video image of the real world).

In order to explore which AR interfaces would be most appropriate for use by bridge inspectors, this research project focuses on the design and evaluation of prototype AR interfaces. This was done to initially gauge the effectiveness of using AR-based interfaces without dealing with the problems of implementing AR technology in outdoor settings experienced by Azuma (1999). It was therefore decided that the AR interfaces for bridge inspection could be explored for usefulness, intuitiveness and effectiveness in a virtual world.

Table 1: Use-Case Descriptions (Actor = Inspector)

Use-Case #	**Objective**	**Methods of Interaction**
1	Selecting a bridge component	User selects bridge component with pull down menu, voice command, or interactive map
2	Selecting a focal point	User selects a 3D object of a bridge to get information reported on previous inspections
3	Interacting with the *Tool-Belt* feature	User selects circulating kiosk that initiates different functions. (e.g., user selects “hammer” feature to engage test often used for detecting delamination)
4	Finding previous report	User accesses previous inspection reports on a focal point via alternatives listed below: Alternative A (4a): Relevant parts of report are made visible to user with “sticky notes” feature Alternative B (4b): Relevant report is provided via audio feature
5	Review reported damage in the last report	Alternative A(5a): *X-Ray Tool* allows user to see through interior of a selected component (e.g., rebar on bridge decks) Alternative B (5b): Sequential display of pictures from previous reports over time related to a selected component to see deterioration
6	Navigate to place of delamination	User navigates to commonly known for delamination
7	Display object linked view of delamination	Illustrates the action-response sequence for displaying the object linked view of a specific location
8	Monitor progress of delamination from previous year	Illustrates the action-response sequence for displaying the growth of delamination over time
9	Science behind delamination	User initiates the *Tool-Belt* feature to display science of what is delamination and how it occurs
10	Demo on how previous reported damage was determined	User initiates the demo that discusses how an inspector should report delamination
11	Explore extent of delamination	User displays screen similar to Minesweeper[+]. The system provides an exercise that teaches delamination detection and records progress.
12	Access bridge inspection trainee manual on inspection of concrete decks	User initiates reference manual feature found in *Tool- Belt* feature that provides documents classified according to the current inspection procedure or location on the bridge.

Thus, for this project, both the real and virtual worlds are modeled using a VR environment. We tested several environments, but in this paper we only present the interfaces implemented

[+] a game provided by Microsoft Windows.

in VR Modeling Language (VRML) (Ames, 1997). VRML provided the greatest flexibility in modeling interactions and interfaces in a 3D bridge environment. It supports the definition of scene graphs, and includes fields and routes to allow 3D objects to be connected together. We chose three use-cases on which to focus this initial evaluation: selecting a focal point (Use-Case No. 2), accessing previous reports (Use-Case No. 4), and review damage from last reports (Use-Case No.5). These three use-cases were selected because they appeared to offer significant opportunity for AR capabilities.

EVALUATION OF INTERFACES

Many techniques have been developed and are available for the evaluation of interfaces. McQuaid (2001) have further elaborated a heuristic classification technique developed by Nielson and Mollich (1990) that provides the most applicable evaluation method for our purposes.

Heuristic classification techniques focus on selecting a group of diverse people to provide feedback on the usability of particular interfaces. Through such feedback, one can learn all the potential problems that exist within a system. These problems are then taken and classified into general subcategories. The categories are then ranked in order of importance. The group of evaluators helps in the development this ranking scheme.

For this project, we developed three questions for each AR interface alternative associated with a use case, asking whether the interface was usable, intuitive, and effective. These questions were answered after each task was demonstrated to the evaluators. A space to provide written feedback was also provided.

RESULTING INTERFACES

Interfaces were created for each of the three selected use-cases to explore the options for using AR interfaces for bridge inspection. Each interface was built in a VRML programming environment, Internet Scene Assembler 2.0*, an environment which consisted of standard objects and functionalities (Ames 1997, Hartman 1996). A 3D bridge model, provided by 3DCafe and partitioned into various components, formed the context of every interface demonstrated. The partitions of the 3D model aided in defining structural elements normally found in the bridge inspection environment. In addition, the base interface consisted of a menu, which would be customized for every interface for a specific use-case. The remainder of this section presents the interfaces created for the three specific use-cases focused on in the research (i.e. Use-Case No.2, No.4 and No.5).

Use-Case No.2 focuses on selection of a focal point (Figure 1). A focal point is defined as a point of interest on the bridge. This is a broad definition, as there are several aspects that an inspector could be interested in for a single element, as well as instances where an inspector seeks to know about a single aspect that encompasses several components. In addition, a focal point may not merely refer to a particular geometric location, but could be an interesting statistic or piece of information related to a report. In designing this interface, priority was given to classification of various focal points, and appropriately giving an end

* commercial product by ParallelGraphics.

user the capability to decide on which set or subset of focal points he or she was interested in seeing displayed on the bridge. In this interface, a standard dropdown menu is provided, which is fixed to the display device and provides the user with a classification of the different kinds of focal points at different levels of abstraction. The user decides on what information he or she is interested in retrieving and specifies this via the menu. Focal points related to the user selected classes are then displayed on the overview map and on the bridge as small single colored spheres. Color codes are used to distinguish the functionality or information that a focal point is meant to represent. For example, the user may want to know about all focal points related to the deck, for which a member has a rating lower than 6. After making the appropriate selection on the menu, all focal points are displayed on the map.

Figure 1: Use-Case No.2- Selecting a Focal Point (the semi-spherical object on the deck is a “focal point” representing the location of previously reported delamination)

Use-Case No.4a in Table 1 (Figure 2) describes a methodology for providing an inspector access to previous inspection reports. A conventional approach would probably entail providing a link between the component in question and a method to access an online text-based version of previous inspection reports. However to emphasize how AR can improve on such techniques, we explored AR-inspired interfaces, where the user on examining a component is automatically fed with information about that component from the previous report, provided the appropriate state variable “report” is turned on. Relevant information is provided in the form of “sticky notes” related to pertinent inspection criteria. This is illustrated by showing all objects associated with a particular rating (e.g., structural deficiency with rating 6 and below for all members). Alternatively this could be a note for every deficiency noted about an object. A “sticky note” is a note which has details related to one aspect of the inspection criteria and is located with a component in 3D space. The level of detail as well as the number of aspects can be changed in the settings of the state variable report. If the user is now interested in seeing the same criteria for other components of the bridge, he or she may toggle the state variable “on” for that “sticky note”, and then all similar instances of that inspection criterion are switched on automatically, with information displayed in a similar fashion for each instance. Use-Case No.4b provides an audio feature in addition to “sticky notes” and enables trainees to retrieve data available from previous inspection reports through an alternative interface.

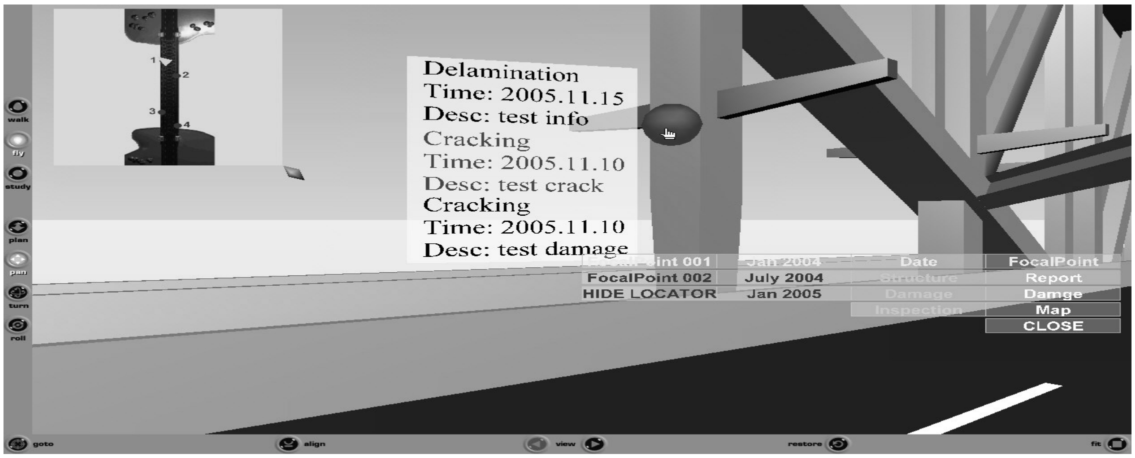

Figure 2: Use-Case No. 4a –Finding Previous Report (The displayed map provides the location of bridge inspector and focal points. Red symbols indicate focal points and the yellow triangle indicates the location of the inspector. The tabular menus can be used to indicate when to expose a focal point by: date, structure location, or by damage rating)

Once data has been retrieved through the interface presented in Use-Case No.4, Use-Case No.5 describes possible interactions to explore the retrieved data (such as damage) via two alternatives. Use-Case No.5a provides the inspector with a better understanding of the previous report by enabling the actor to examine the interior of any structural element with the *X-Ray Tool*; whereas, Use-Case No.5b, as demonstrated in Figure 3, enables the sequential display of pictures taken during each inspection report for a given structural element (e.g., the progress of damage over time). Since there could be several reports for the bridge, the user can literally “walk through time” noting how the structure has changed with successive inspections for a given criterion.

EVALUATION OF INTERFACES

Heuristic evaluation was used as the method of usability analysis, where a number of evaluators are presented with an interface design and asked to evaluate it (Nielsen and Molich, 1990). The reasons for choosing this method are that it is relatively inexpensive to perform, does not require a long-lead time to set-up, and can be used early in the development process (Nielsen and Molich 1990).

The evaluation was conducted at Carnegie Mellon University, with nine civil engineering graduate students as participating evaluators. The backgrounds of these evaluators spanned the sub-disciplinary areas in the department (i.e., advanced infrastructure systems, environmental engineering, science and management, and mechanics, materials and computing). After receiving the appropriate Institutional Review Board (IRB) approvals, the evaluation of the interfaces created for the three use-cases was conducted first by providing an overview of the current bridge inspection process and guidelines on how AR could be used to support that process. The overview highlighted the limitations of the current bridge inspection process (time-consuming, document-based and subjective) and anticipated the benefits of an AR-based bridge inspection support system. During the evaluation process, the evaluators were asked to view a demonstration of developed interfaces for each of the use-cases chosen for implementation. The evaluators did not explicitly interact with the interfaces; however, they were provided with the demonstration until they felt confident about making judgments about the evaluation parameters (i.e. usability, intuitiveness, and effectiveness) of the interfaces. These parameters were evaluated using a simple questionnaire after each presentation of interfaces for a use-case. The possible responses were “strongly disagree”, “moderately disagree”, “moderately agree”, and “strongly agree”.

Figure 3: Use-Case No. 5b- Reviewing Damage from Previous Report (the sequential display of pictures shows the increased exposure of steel in the deck. It illustrates the snapshots of delamination measurements found in successive inspection reports)

The results of the initial evaluation are provided in Figure 4. A majority of the responders agreed that the implemented interfaces would enable actors to achieve the specific goals defined in the demonstrated use-cases. In terms of usability, although the majority “strongly agreed” that all interfaces were usable, there was criticism for Use-Case No.5, which allows for the review of previous inspection reports through the aid of an *X-Ray-Tool* feature or the sequential display of pictures. The criticism stated that the interfaces were not supportive in their current form and suggested that the functionality need to be further improved to help novice bridge inspectors. Similarly, for the assessment of intuitiveness, the majority again “strongly agreed” that all interfaces were intuitive. However, criticism was raised stating that the intent of Use-Case No.4a, which enables accessing previous inspection reports, was not obvious in the associated interface. In terms of effectiveness, the majority agreed that all interfaces sufficiently allow for the objective to be achieved. The only criticism related to effectiveness that was raised for the implementation of Use-Case No.2, suggested that focal points need to be more clearly represented. Considering the overall evaluation results (Figure 4), the demonstrated interfaces were found to be useful, intuitive and effective for the three implemented use-cases. These results are also promising for the future development of an AR-based system for supporting bridge inspection processes.

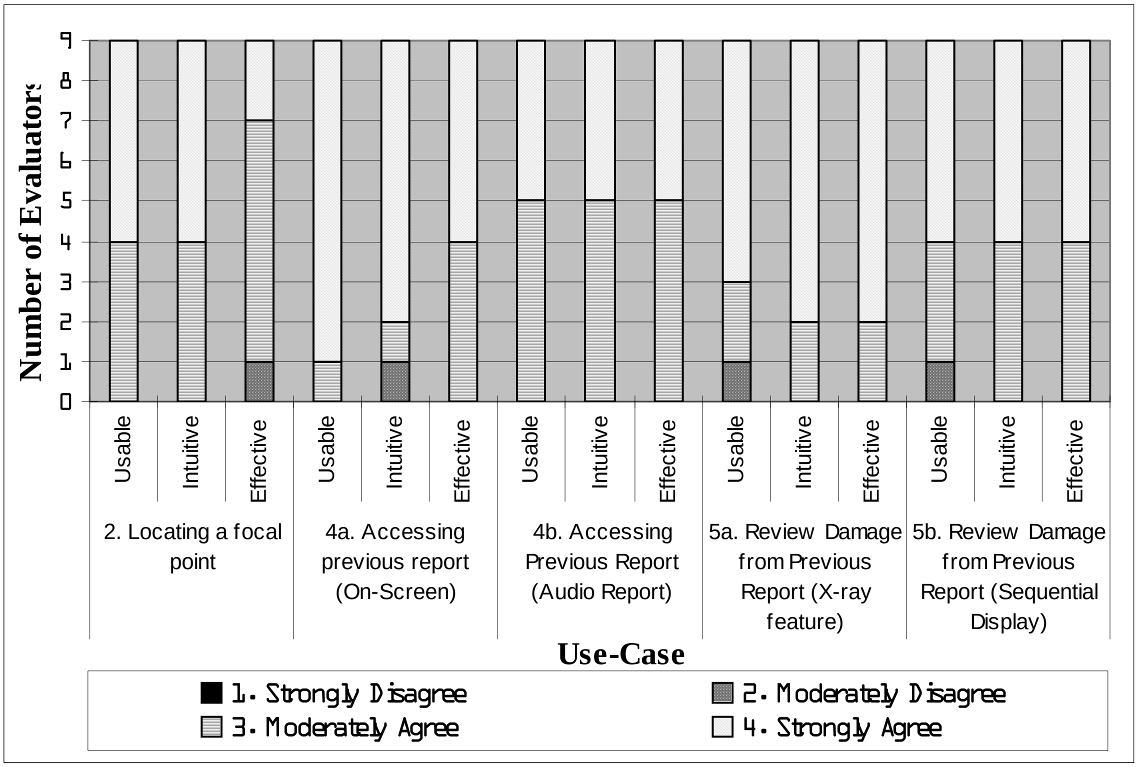

Figure 4: Results of the Initial Evaluation (indicates that the evaluators for the most part felt that the three use-case interfaces were useful, intuitive and effective by selecting "moderately agree" and "strongly agree" for each response)

CONCLUSION

While the results are clearly preliminary, the study presented in this paper illustrates that the features provided in the developed use-cases for AR in bridge inspection hold promise for effectively supporting bridge inspectors. This study also demonstrates that the described approach for prototyping and evaluating interfaces using a VR environment appears to be feasible. The 3-D virtual world provides an opportunity to simulate the bridge inspection environment and illustrate and evaluate interfaces that relate to each use-case. Moreover, using the heuristic evaluation method to evaluate various interfaces appears to be useful because it provides critical feedback on these interfaces early in the developmental phase.

Creating interfaces that are usable, intuitive and effective requires rapid prototyping and evaluation cycles. Using a VR environment to mock up and evaluate an AR interface, as was done in the research described in this paper, allows for such cycles of rapid prototyping and evaluation.

The evaluation reported in this paper provided additional insight and ideas that can be incorporated into the use-cases. For example, the evaluators suggested that the bridge inspector may want to identify the nearest focal points without being prompted, and that the number of menus being displayed should be reduced. For further investigation of the usefulness, intuitiveness and effectiveness of the interfaces for these use-cases, an evaluation using current bridge inspectors is planned as the next step. While doing this, a detailed evaluation process will be designed with increased number of questions targeting how the system can save time as compared to the current process of bridge inspection, reduce error and support the bridge inspectors while on site, and novices while on training.

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REFERENCES

Ames, A. L., Nadeau, D. R. and Moreland, J. L. (1997). *The VRML 2.0 Sourcebook* (2nd ed). John Wiley & Sons, Inc.

Azuma, Ronald T. (1999). “The Challenge of Making Augmented Reality Work Outdoors.” *Mixed Reality: Merging Real and Virtual Worlds*. Springer-Verlag, 379-390.

Cockburn, A. (1997). “Goals and Use Cases.” *J. of Object-Oriented Prog.*, Sept., 35-40.

Dunker, K. and Rabbit, B. (1995). “Assessing Infrastructure Deficiencies: The Case of Highway Bridges.” *Journal of Infrastructure Systems*, 1(2), 100-119.

Hammad A., Garrett, J., and Karimi, H. (2004). "Location-Based Computing for Infrastructure Field Tasks", *Telegeoinformatics: Location-Based Computing and Services,* 287-314.

Hartman, J. and Wernecke, J. (1996). *The VRML 2.0 Handbook*. Addison-Wesley.

Kato, H., Billinghurst, M., Poupyrev, I., Imamoto, K., and Tachibana, K. (2000). "Virtual Object Manipulation on a Table-Top AR Environment." *Proc. of ISAR*, Oct. 5-6, 2000.

Lehikoinen, J. (2001). "An Evaluation of Augmented Reality Navigational Maps in Head-Worn Displays." *Proc. of HCI Conference (INTERACT),* Tokyo, Japan, Jul 9-13, 2001.

McQuaid, H. L. (2001) “An Integrated Method for Evaluating Interfaces", Proc. of UPA, Las Vegas, LV.

Nielsen, J., and Molich, R. (1990). "Heuristic Evaluation of User Interfaces." *Proc. ACM CHI' 94 Conf.* . Boston, MA, April 24-28, 152-158.

Nielsen, J. (1993). *Usability Engineering*, Boston: Academic Press.

Suomela, R., Lehikoinen, J., and Salminen, I. (2001). "A System for Evaluating Augmented Reality User Interfaces in Wearable Computers." Proc. 5th International Symposium on Weearable Computers (ISWC), 77-84.

Reitmayr, G. and Schanlstieg. (2003)"Mobile Collaborative of Augmented Reality." Proc. STARS, 47-52, Tokyo, Japan.