Automation in Construction 48 (2014) 18–30

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Natural markers for augmented reality-based indoor navigation and facility maintenance

Christian Koch [a,*], Matthias Neges [b,1], Markus König [a,2], Michael Abramovici [b,3]

[a] Computing in Engineering, Ruhr-Universität Bochum, Universitätstraße 150, 44801 Bochum, Germany
[b] IT in Mechanical Engineering, Ruhr-Universität Bochum, Universitätstraße 150, 44801 Bochum, Germany

ARTICLE INFO

Article history:
Received 11 February 2014
Received in revised form 4 July 2014
Accepted 20 August 2014
Available online 7 September 2014

Keywords:
Augmented reality
Facility maintenance
Natural markers
Performance study

ABSTRACT

The longest phase in a facility's lifecycle is its maintenance period, during which operators perform activities to provide a comfortable living and working environment as well as to upkeep equipment to prevent functional failures. In current practice operators need a considerable amount of time to manually process dispersed and unformatted facility information to perform an actual task. Existing research approaches rely on expensive hardware infrastructure or use artificial, thus unesthetic Augmented Reality (AR) markers. In this paper we present a natural marker based AR framework that can digitally support facility maintenance (FM) operators when navigating to the FM item of interest and when actually performing the maintenance and repair actions. Marker detection performance experiments and case studies on our university campus indicate the feasibility and potential of natural markers for AR-based maintenance support.

1. Introduction

The longest period in the lifecycle of a building is the operation and maintenance (O&M) or facility management (FM) phase. In this phase, facility managers and operators perform activities to provide a comfortable living and working environment (e.g. pleasant temperatures) as well as to upkeep equipment to prevent functional failures. Since over 85% of the entire lifecycle costs are spent on facility management [1], improvements to the maintenance procedure will significantly reduce the overall building lifecycle budget.

Today's maintenance practice is characterized by dispersed and unformatted facility information that operators often need to manually browse, sort and select. Although software systems have recently been introduced, 50% of the on-site maintenance time is still spent on localizing inspection targets and navigating to them inside a facility [2]. Moreover, linked maintenance instructions are often multi-page documents, which sometimes are difficult to comprehend, in particular in case of emergencies.

Although some recent research studies propose to use Building Information Modeling (BIM) by either integrating or linking work order information to them, not all necessary information is currently available in a digitally integrated and standardized model. Moreover, available Ultra-wide Band (UWB), Wireless Local Area Networks (WLAN), Radio Frequency Identification (RFID) and Global Positioning System (GPS) indoor navigation approaches have been validated, but they rely on a costly equipment infrastructure for tags and readers. Existing Augmented Reality (AR) based solutions use artificial markers for both navigation and maintenance instruction support. This kind of marker is tedious to install all over a facility and also has some esthetical issues.

In this paper we propose a natural marker based Augmented Reality framework that can digitally support facility maintenance operators in performing their daily on-site maintenance jobs. Since 50% of the on-site maintenance time is still spent on localizing and navigating, and existing maintenance instructions are often multi-page, incomprehensible documents [2], our framework supports operators when (1) navigating to the FM item of interest and when (2) actually performing the maintenance and repair action. The main contribution of this paper is to highlight the big potential of natural markers, such as exit signs, to enable AR-based facility maintenance support. The presented methodology is implemented as a prototype and has been successfully tested on the university's campus. The results indicate the feasibility and the potential of the proposed framework.

2. Background

2.1. Current practices

In today's maintenance and repair practice facility operators need to gather and access dispersed and unformatted facility information in

* Corresponding author. Tel.: +49 234 32 26174.
E-mail addresses: koch@inf.bi.rub.de (C. Koch), matthias.neges@rub.de (M. Neges), koenig@inf.bi.rub.de (M. König), michael.abramovici@rub.de (M. Abramovici).
[1] Tel.: +49 234 32 22109.
[2] Tel.: +49 234 32 23047.
[3] Tel.: +49 234 32 27009.

http://dx.doi.org/10.1016/j.autcon.2014.08.009
0926-5805/

order to handle work orders [3]. Typically, this information is handed over from the building design and the construction phase and is available in form of 2D drawings, spreadsheets, bar charts, field reports and paper-based guidelines. Collected in so-called Facility Document Repositories, the facility handover data is physically space consuming and might occupy an entire room [4]. Recently, Computer-Aided Facility Management (CAFM) Systems for space management and Computerized Maintenance Management Systems (CMMS) for work order management have been introduced to digitally support operators in integrating preventive maintenance schedules and intervals, shop and installation drawings, cost control and documentation, device specifications and manuals, warranty information, replacement parts providers, as-is performance data, etc. [3,4].

However, in order to prepare an actual on-site maintenance job, operators need to identify the location of the maintenance item inside the building, the route towards it as well as relevant maintenance instruction manuals. According to Lee and Akin [2], 50% of the on-site maintenance time is solely spent on localizing and navigating. Furthermore, linked maintenance instructions are often multi-page documents, which sometimes are difficult to comprehend, in particular in case of emergencies.

2.2. Current research efforts

In order to cope with current limitations and to improve building maintenance procedures, several research efforts have been undertaken.

2.2.1. Providing FM-relevant information

Building Information Modeling (BIM) is an up-to-date method involving the generation and management of a digital representation of the physical and functional characteristics of a facility during its entire lifecycle [4]. Although an increasing amount of maintenance-related information has been incorporated into BIM so far, not all data necessary to perform work orders is currently part of BIM solutions (e.g. manufacturer's maintenance instructions).

Even if supported by BIM standards, such as the Industry Foundation Classes (IFC), the actual FM data still needs to be manually rekeyed into the building model multiple times based on the handover documents [4]. To automate this process, East et al. [4] have proposed an open-standard IFC-based Facility Management handover model view definition that is based on the Construction-Operations Building information exchange (COBie) format [5]. The advantage is that when the FM handover occurs, the relevant information captured during the design and construction phase can be directly transferred into tools supporting the long-term management and maintenance of the facility. COBie data can be stored in the common ISO STEP format, in the ifcXML format or as a spreadsheet (SpreadsheetML). The use of COBie has been successfully documented in several case studies [4].

In order to store and manage as-is building performance data, Radio Frequency Identification (RFID) based solutions have been proposed [6–8]. All these solutions share the same idea of using tags permanently attached to components under maintenance. Besides the capability of uniquely identifying facility components, the memory of the tags is employed during the life-cycle by different stakeholders for performance data and maintenance history storage and on-demand access. While Ko [7] has presented a general web-based RFID building maintenance system, Motamedi et al. [8] have focused on the role-based access to lifecycle information. Ergen et al. [6] have aimed at determining the technological feasibility of RFID by conducting a longevity test for about several months. However, the installed RFID tags are only used for data storage and exchange, but not for component positioning and indoor navigation. Moreover, due to their low storage capacity they cannot provide detailed maintenance instruction information.

Akcamete et al. [3] have presented an approach to automatically link and visualize maintenance information in form of work orders with Building Information Models to enable spatio-temporal analysis for proactive maintenance decision making. Based on location and component identifiers (Global Unique Identifier — GUID) available in BIM, work orders are associated with building spaces and building elements. This allows querying type and location data of maintenance items and thus digitally supports activities such as FM data collection and item localization inside the facility under maintenance. Moreover, work order information can be visualized within a 3D environment using color maps and line charts. Asen et al. [9] have proposed a BIM-based visual analytics approach using an integration of BIM, COBie and CMMS to visualize FM data. However, indoor navigation and on-site maintenance instruction visualization are not considered.

2.2.2. Indoor positioning and navigation

The second important operator's activity concerns positioning and navigation. In addition to the location of the maintenance item (available in the BIM), it is necessary to know the operator's position inside the facility in order to support real-time indoor navigation. There is a vast amount of ongoing research in this area. For example, Khoury and Kamat [10] have evaluated three different wireless indoor position tracking technologies, in particular, Wireless Local Area Networks (WLAN), Ultra-Wide Band (UWB) and Indoor GPS positioning system. Indoor GPS has been identified as being superior in that study, since it could estimate a mobile user's location with relatively low uncertainty of 1 to 2 cm. Cheng et al. [11] have evaluated a commercially available Ultra Wideband (UWB) system for real-time mobile location tracking. Razavi and Moselhi [12] and Montaser and Moselhi [13] have presented a low cost location sensing solution for indoor facilities using passive Radio Frequency Identification (RFID) that have a mean error of 1–2 m for location identification. However, the main disadvantage of these technologies is the need for extra equipment installation and maintenance (both tags and readers), which involves a considerable cost factor. Moreover, only the location of the operator can be determined, his or her viewing direction is still not available.

Besides the position, the operator's view orientation needs to be determined to provide both location-aware and viewing direction-aware guidance. Here, sensors such as the Inertial Measurement Unit (IMU), a combination of accelerometers and gyroscopes, and magnetic orientation sensors (e.g. a magnetic compass) are utilized. Khoury and Kamat [14] have used a solid-state magnetic field sensor, installed on the user's head, to track the user's dynamic viewpoint. This information was then processed to identify potential building objects in the user's field to retrieve contextual information. Although, the user's position uncertainty is documented, the orientation accuracy has not been presented nor validated. Irizarry et al. [15] have presented a mobile AR tool that uses the iPad's in-built IMU sensors to estimate the orientation of the device. However, moving around an indoor environment and re-positioning were not part of the presented experiment.

Available AR-based indoor positioning methods usually need artificial markers to estimate the camera position and orientation. For example, Park et al. [16] have presented an AR-based field inspection scenario using artificial 2D markers within the frame of a BIM-based construction defect management system. Kuo et al. [17] have proposed an outside-in tracking approach that uses an infrared invisible marker mounted on the head of a potential operator. This infrared marker is detected and tracked from the outside to estimate the position and viewing direction of the operator. However, this approach assumes pre-installed infrared tracking devices all around the facility to be maintained.

Once the location of the maintenance component (target) and the operator's position (starting point) are determined, appropriate routes have to be calculated. For this purpose, topological routing graphs are generated based on either derived 2D floor plans (e.g. [18]) or 3D building geometry (e.g. [19]). Subsequently, routing algorithms (e.g. Dijkstra, A*) are applied to calculate paths with minimal path costs. Knowing the current position and orientation as well as the route, navigation