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Interior construction state recognition with 4D BIM registered image sequences

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A B S T R A C T

Deviations from planned schedules in construction projects frequently lead to unexpected financial disadvantages. However, early assessment of delays or accelerations during the phase of construction enables the adjustment of subsequent and dependent tasks. Manually performed, this involves many human resources if as-built information is not immediately available. This is particularly valid for indoor environments, where a general overview of tasks is not given.

In this paper, we present a novel method that increases the degree of automation for indoor progress monitoring. The novel method recognizes the actual state of construction activities from as-built video data based on as-planned BIM data using computer vision algorithms. To achieve that, two main steps are incorporated. The first step registers the images with the underlying 4D BIM model. This means the discovery of the pose of each image of a sequence according to the coordinate system of the building model. Being aware of the image origin, it allows for the advanced interpretation of the content in consecutive processing. In the second step, the relevant tasks of the expected state of the 4D BIM model are projected onto the image space. The resulting image regions of interest are then taken as input for the determination of the activity state.

The method is extensively tested in the experiment section of this paper. Since each consecutive process is based on the output of preceding steps, each process of the introduced method is tested for its standalone characteristics. In addition, the general manner of applicability is evaluated by means of two exemplary tasks as a concluding proof of the success of the novel method. All experiments show promising results and direct towards automatic indoor progress monitoring.

1. Introduction

Building Information Modelling (BIM) is an essential step to the digital management of construction projects. One big advantage of BIM is the holistic collection, linking and provision of data for different planning, construction and operation tasks. In the context of construction management, the application of 4D building models by linking activities of a schedule with corresponding building elements is very common. Based on 4D building models the construction sequence can be analyzed and progress monitoring can be supported.

In current practice, progress monitoring is mainly performed manually. To this end, weekly or daily paper-based progress reports are collected by field personnel by hand [1]. This procedure leads to a high workload of the field personnel to fulfil the need for a reasonable frequency of inspections. Hence, manual progress monitoring involves either a massive amount of human intervention or inspection updates cannot be performed as frequently as required. In particular, interior finishing works represent a high-ranking section of every construction project that is sensitive to schedule disorders. The average share in a typical total budget lies between 25% and 40% [2]. As a result, a higher degree of automation in progress monitoring would result in reasonable cost savings. The derivation of the actual state requires the automatic comparison of the as-planned information that is present in BIM with the actual as-built state of the building.

Recently, the research community has been investigating methods that aim to achieve a higher degree of automation in progress monitoring. Several approaches and studies that address the comparison of as-built and BIM-based as-planned data for this purpose have been presented. For example, sensing technologies like Radio-Frequency Identification (RFID) [3,4], Ultra-Wideband (UWB) [5–8]), Wi-Fi [9], ZigBee [10], laser scanners [11,12], Global Positioning System [13], image [14–19], video [20–23], and depth image [24] capturing devices are used to obtain data of the as-built state.

Each of these technologies has its advantages and limitations in a

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specific environment. For instance, radio-based technologies are able to determine the presence of objects through walls and can, therefore, be deployed indoors, but are limited to presence detection or localization. Contrarily, stationary line-of-sight 3D laser sensing technologies obtain accurate measurements within general site scenes, but are too inflexible for indoor applications. Although depth images from portable devices are more flexible, they are currently limited in range. The main aspects of BIM-based automation of progress monitoring for a specific sensing technology and a target environment that need to be considered are:

1.1. Registration of as-built data to BIM model

Mapping of the sensed data to the BIM object instances and association to scheduled activities. The comparison of as-built and as-planned states is only possible if registration is performed. Objects from the BIM model need to be identified in the raw data. Detection solely of the type or class is not sufficient for precise progress statements. When a column is detected, the determined state needs to be associated with one specific instance of all available columns.

1.2. Activity coverage

The raw data delivered by the sensing technology must have the capability of supporting the state detection of all activities that are supposed to be performed in the actual environment. Sensing technologies like RFID or laser scans are not able to determine states defined by sole appearance changes, for example, wall painting.

1.3. Coverage of the location's spatial structure

The sensing technology must meet the requirements of the environment's structure. It needs to handle permanent and temporary construction obstacles and distances of the actual environment. For instance, utilization of common RFID technology for triangulation of objects on construction sites delivers positions with an error of about 2 m [25], resulting in not being able to determine whether materials are already mounted or still stored. However, low distance RFID might help detect the presence of materials or construction objects within a range of up to 1 m (ISO/IEC 18000–3), which is useful in interior finishing inspections.

1.4. Dependency on infrastructure

Sensing technologies may depend on infrastructure in order to collect data. For the usage of these technologies, it needs to be considered if the state of the building provides the required infrastructure. For instance, Wi-Fi-based localization of objects by triangulation assumes the presence of appropriate hardware and a dense distribution in every part of the building, which contrasts with the stage of interior finishing.

Currently, there exists no proper solution that covers the difficult situation imposed by view obscuring walls and registration issues along with the dense repetition of the similar (but distinct) building elements. This makes registration challenging for line-of-view sensing technologies and requires complex infrastructure for radio-based technologies. Moreover, there are challenges associated with the wide range of construction activities existing indoors.

Vision-based as-built data acquisition methods can meet all the four main aspects leveraging computer vision and image processing methods based on sequential imagery. Registration is possible on discovered correspondences between the image and the known geometry of the digital building model. A wide range of activities can be covered by appearance-based processing methods or scene and object structure recognition approaches. In addition, image sensing devices are highly portable and can easily elude barriers for a better view and do not depend on infrastructure. In Table 1, sensing technologies are rated for each of the four stated main aspects regarding BIM-based progress monitoring.

In this context, vision-based methods appear to represent the appropriate means to target indoor construction state recognition. However, current methods for indoor construction state recognition are independent of, and not associated with 4D BIM. This paper presents an approach to automate 4D BIM based progress monitoring.

2. Related work

Automation in progress monitoring has been the subject of research in recent years. Various sets of different approaches have been presented that are based on various acquisition and processing techniques. In this section, a summary of present approaches is given and the technologies are introduced that this work refers to.

2.1. Data acquisition

The acquisition of as-built data is a fundamental step to ensure accurate progress monitoring. Since the choice of the acquisition technique influences all subsequent steps, the applied technique needs to be well-chosen. Thus, the capabilities of the technique and the resulting raw as-built data need to be analyzed. There are several surveys that give an overview on available techniques and its applications incorporated for progress monitoring [26–28]. These overviews mainly list Radio-frequency Identification (RFID) technologies, laser scanning methods, as well as image and video capture systems as promising technologies for as-built assessment. With RFID, construction elements can be inexpensively and robustly tagged due to low sensor complexity, but requires mounting tags and does not enable determination of construction state [29]. Applications for radio frequency based technologies during the construction of buildings are the localization of materials [4,29–32], personnel [33] and inventory [34]. The disadvantages of RFID make these technologies unattractive for detailed progress measurement and RFID is seen to be a supporting approach for other techniques in recent approaches for construction progress measurement [35]. Further radio frequency based technologies are utilized to capture the as-built data, such as *global navigation satellite systems* (GNSS) and Wi-Fi. For indoor construction scenes, GNSS are not available because of the missing line of sight [36] and Wi-Fi is usually not present in buildings under construction. Laser scanning offers high accuracy point cloud measurements, but consumes a certain amount of time for each scan [37] and/or has problems at spatial discontinuities [38]. Besides high costs for laser equipment, heavy involvement of personnel induces additional expenses. However, several approaches apply laser scan technology for 3D object recognition using BIM and for comparison of information inferred from scanned data with designed 4D BIM [12,39–41] to track progress. Another promising form of as-built data is images and videos. Images and videos are acquired in several ways. The advantages of images and videos as the basis for progress measurement lie on low costs, short time, and the ease of collection. Continuous advents of high definition cameras and high performance processing units signify the potential of these types of data with an enhanced accuracy of information and fast processing. The technology's main advantages are low cost and portability. Additionally, no special knowledge is needed to operate and taking photos of construction sites for documentation reasons is a common practice. The camera system may either consist of a monocular [42] or a stereo sensor [17]. The perspective can be fixed and known [16,43–45], or uncertain [37,46–48]. Besides the approach of using single photos, videos have been recently used to capture as-built scenes [18,49]. Occlusions may occur due to the line-of-sight characteristic, but can be handled by traversing the indoor scene. Both automated registration and recognition can be achieved by computational processing of acquired data.

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