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A distributed data collection and management framework for tracking construction operations

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Construction work typically means producing on shifting locations. Moving materials, equipment and men efficiently from place to place, in and in between projects, depends on good coordination and requires specialized information systems. The key to such information systems are appropriate approaches to collect de-centralized sensor readings and to process, and distribute them to multiple end users at different locations both during the construction process and after the project is finished. This paper introduces a framework for the support of such distributed data collection and management to foster real-time data collection and processing along with the provision of opportunities to retain highly precise data for post-process analyses. In particular, the framework suggests a scheme to benefit from exploiting readings from the same sensors in varying levels of detail for informing different levels of decision making: operational, tactical, and strategic. The sensor readings collected in this way are not only potentially useful to track, assess, and analyse construction operations, but can also serve as reference during the maintenance stage. To this extent, the framework contributes to the existing body of knowledge of construction informatics. The operationality of the framework is demonstrated by developing and applying two on site information systems to track asphalt paving operations.

1. Introduction

Construction projects often involve a number of specialized equipment, located not only on site, but also at distance. As the work procedures and productivity of the equipment highly depend on the location and activities of others, informing construction personnel about the project progress is an important task. In this setting, equipment operators can make decisions on how to proceed with their tasks and project managers can decide if some changes need to be introduced into the process by, for example, increasing the amount of trucks that transport construction material or adjusting the hauling route. Later, the documented data can be used to identify inferences between project parameters and develop suggestions about how to plan future construction projects.

Consequently, in the scope of construction informatics the question how to best connect on-site sensors, process the obtained data, and provide information to spatially distributed equipment operators and site managers in real time along with informing strategic decision makers within construction companies is essential. Though several ways to meaningfully collect readings from sensors located at construction sites were introduced earlier (see, for instance, [1,2]), the previous approaches did not consider the purpose to collect and process sensor readings in different levels of detail to support operational, tactical, and strategic decision making.

To address this gap, this paper proposes a framework that allows for distributed data collection and management acknowledging these three levels of decision making. The framework suggests to store sensor readings at different locations in different levels of detail that correspond to the sensor readings update rate. The readings, obtained with high update rate are stored at the moment of data collection. Then, the update rate of these sensor readings is reduced to support close to real time visualizations to timely inform equipment operators and managers about the ongoing processes. Based on such visualizations, operators can decide how to perform their next activities to comply with the project pace, while the managers can decide if additional equipment should be introduced to the project. These well-founded decisions will ultimately lead to improved work productivity. Besides supplying the real-time information delivery needs, highly precise readings (with significantly higher update rate) can later be analysed to find inferences between project-related elements. Such analysis can provide suggestions how to plan future construction projects.

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To illustrate the application of the framework for developing systems to track asphalt paving this paper describes the operationalization of the framework. Two framework-based information systems were implemented according to the dataflow and were applied for real construction projects. These instantiations demonstrated the expected functionality and were positively accepted by equipment operators and managers on site.

This paper is structured as follows: the next section briefly reviews existing technologies and approaches to collect construction-related information using sensors. Afterwards, the third section reveals the proposed distributed data collection and management framework. The fourth section delineates the research methodology adopted to apply the framework to track construction activities. Then, two illustrative information systems oriented to follow asphalt paving operations are described. The sixth section provides discussions over the proposed framework. Finally, conclusions regarding the proposed framework are drawn.

2. Collecting construction process-related information with sensors – a brief overview

Recent years have seen an increase in research about how to best use automated data sensors to track on-going construction operations. At the same time, as using sensors meaningfully always requires the development of the corresponding information systems, research efforts also concentrated on development frameworks to support construction personnel in their work tasks.

This section gives a short overview about recently published work in the area of automated sensing to control and support construction activities. The overview includes some of the most commonly used technologies to track construction processes: RFID tags, computer vision based sensors, and GNSS (Global Navigation Satellite System that correspond to a number of navigation solutions, such as GPS, GLONASS, and Galileo). Afterward, the section summarizes recent efforts to incorporate several on-site sensors into a single system using frameworks that aim to support construction activities that the here presented work built upon.

2.1. A brief review of utilizing sensor readings in construction projects

One of the most widely explored applications is the use of RFID tags to track construction material on site (see for example [3–6] or [7]). An example of a recent published case study in this area shows how RFID tags can assist in tracking and managing materials on water supply projects [8]. For in-depth view on the latest developments, trends, and research solutions the interested reader can refer to special issues on advances in RFID technology, such as [9,7]. Essential features of the technology result in corresponding technology-specific advantages and limitations that characterize RFID-based solutions. Thus, the RFIDs can naturally overcome previous documenting techniques, such as barcodes, by providing opportunity to store additional data in some types of RFID tags and by rejecting the need for the line-of-sight between the tag and the tag reader. However, as the effective range of tag readers is constrained, the possibility to use RFIDs in harsh environments (or to follow equipment and materials on distance) is limited.

Next to the RFID technologies, computer vision sensors were effectively employed on construction sites, for example as described in [10–13]. Work in this area was, for example, concerned with developing algorithms that allow for the combination of different images and video frames [14,15] or with the evaluation of different needs for accuracy of these sensors [16]. This theoretical work has motivated more practical applications to, for example, track the workforce on a construction site [17] or support safety management by predicting equipment operator's blind spots [18]. Researchers in the field of computer vision have also recently developed artificial intelligence based methods to, for example, classify the different actions of construction workers on site [19], or for productivity analysis [20]. Another closely related strand of study related to computer vision include research on utilizing range cameras for the purposes of the construction domain, for example for representing 3D workspace [21] and analysing worker posture in terms of ergonomics [22]. Altogether, the ongoing research on utilizing computer vision sensors hold promises for wider exploitation in the future, such as non-intrusive data collection technologies to track construction activities. However, some factors currently hamper everyday use of computer vision sensors. Among others, these factors include difficulties to track objects in cluttered environments and the necessity to consider weather and lighting conditions.

Particularly related to this study is the research strand related to the utilization of GNSS measurements to track equipment and human movement on site. Among others, systems to track construction activities include documenting equipment movements on asphalt paving sites [23] or automating earthwork operations for highway projects [24]. In current practice, the GNSS technologies appear to be the most common solutions to track construction activities, though their applications are also limited by the demand to maintain an unobscured line-of-sight between the receiver and satellite constellations. However, while this condition is fulfilled and the atmospheric effects are taken into account, for instance by utilizing correction signals from a base station, this type of sensors can track equipment with an accuracy within the centimetre range.

How to best select specific sensors to follow a construction project typically depends on the characteristics of the project at hand, the purpose of the specific information system, and limitations of particular technologies. For instance, the choice between RFID, computer vision, and GNSS technologies can be justified by site specifics. GNSS can effectively track outdoor equipment at both on-site and at distance. At the same time, to track equipment movements at construction sites on which surrounding objects obstruct GNSS signals, one could utilize RFID tags or computer vision technologies for non-intrusive tracking. However, the latter technologies are operational within a relatively short range and could demand an obscured line of view between the object and tracking devices.

As a result, this need to choose specific sensors for particular operations requires the meaningfully fusion of various data streams originating from different sensors [25–27]. For instance, common fusion mechanisms include combining GPS with inertial navigation sensors measurements [28] or tracking materials during construction operations by fusing RFID and GPS sensor readings [29].

2.2. Frameworks to integrating sensor readings

To address how to meaningfully combine different sensors on a more generic level, researchers recently proposed several frameworks. Some of these frameworks aim to organize mobile computing for information management on construction sites [2,30] and how to facilitate decision making by project managers who take corrective actions during ongoing projects [31]. Other examples include frameworks to describe operational processes and their functional aspects [32] and to consider ontologies to support development of information systems oriented to assist different management levels in making decisions [33].

While some frameworks acknowledge the need to holistically manage information in relation to different layers within construction companies, including executive management, department management, project management, site management, and con-