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Status quo and open challenges in vision-based sensing and tracking of temporary resources on infrastructure construction sites

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ABSTRACT

Modern construction projects require sufficient planning and management of resources to become successful. Core issues are tasks that deal with maintaining the schedule, such as procuring materials, guaranteeing the supply chain, controlling the work status, and monitoring safety and quality. Timely feedback of project status aids project management by providing accurate percentages of task completions and appropriately allocating resources (workforce, equipment, material) to coordinate the next work packages. However, current methods for measuring project status or progress, especially on large infrastructure projects, are mostly based on manual assessments. Recent academic research and commercial development has focused on semi- or fully-automated approaches to collect and process images of evolving worksites. Preliminary results are promising and show capturing, analyzing, and documenting construction progress and linking to information models is possible. This article presents first an overview to vision-based sensing technology available for temporary resource tracking at infrastructure construction sites. Second, it provides the status quo of research applications by highlighting exemplary case. Third, a discussion follows on existing advantages and current limitations of vision based sensing and tracking. Open challenges that need to be addressed in future research efforts conclude this paper.

1. Introduction

In a broader sense, temporary construction resources (personnel, equipment, and materials) "aid the construction process by delivering man- or machine power, and the required material components to assemble or build a structure" [1]. Temporary structures (e.g., scaffolding, formwork, shoring systems) can also be defined as "any structure that assists the creation of a permanent part of a construction project" [2]. Their impact in construction is high as they are frequently used on most projects, impact safety, quality, speed, and profitability of construction, but are also a major cause of spatial conflicts and many disasters [1]. An industry-led study [3] on leading industry practices for estimating, controlling, and managing indirect construction costs identified project management, field supervision, material handling and scaffolding as the top most challenging and wasteful tasks in construction of large capital facilities and infrastructure. Subsequently, the topic deserves attention in research and development, i.e. using technological methods to advance the field of practice.

Construction sites associated to capital intensive infrastructure projects involve significant quantities of resources, including multiple levels of manpower, equipment, and materials. Proper coordination of these temporary entities positively impacts on-site productivity, which in turn influences construction safety, costs, and schedule [4–6]. However, leading industry practices in estimating, control, and management are based on frequent manual observations and often still rely on text-based, labor-intensive, time-consuming, inefficient documentation and reporting methods [2]. As such, the task of measuring the progress of construction site activities has often been a subjective and intensive manual process that is prone to error and, in real operations, frequently out-of-date [13].

Camera- or video-based monitoring technology in combination with processing algorithms typically provide a non-intrusive, easy, inexpensive, and rapid mechanism for generating a body of operational information and knowledge which, when made publicly available to project stakeholders, enable secure inquiry into construction operations that is currently not possible [12]. Longer term, vision-based research can serve as a valuable aid to project management by enabling tighter control and greater efficiency.

Demonstrating that an active vision system can effectively analyze and assess work-site progress will assist project managers by reducing the time spent monitoring and interpreting project status and performance, thus enabling increased attention to control of

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cost and schedule. By making project management and workforce more aware of the performance status of their project and their work environment, potential savings to the industry are envisioned by researchers and developers. Since benefits in construction often advance a broader theme of issues, they are likely to impact schedule, cost, safety, and quality at the same time.

Recent research efforts in this area seek to prove the hypothesis that it is possible to reliably track multiple resources with images (video, still and/or time-lapse) in order to reproduce the daily workflow of activities associated to a worksite. The main purpose behind the research is to understand the temporal and spatial nature of critical work packages on a worksite. The intent behind such monitoring and analysis is to automatically provide critical information on construction operations for improved decision making in construction engineering and management [6].

The information obtained from such desired semi- or fully-automated systems generates knowledge about worksite operations. In an information-based framework, much effort is spent acquiring and interpreting information. In a knowledge-based framework, efforts are allocated to making decisions based on the interpreted information. If successful, computer-vision based methods will transform the review of construction operations from being information-based to knowledge-based, thus saving human resources and improving decision effectiveness [7]. Given that current research seeks to demonstrate and validate reliable localization of construction resources (personnel, equipment, and materials), accompanying concepts reviewed within the scope of this article consist of two major components: (1) the derivation of algorithms suited to tracking temporary resources; and (2) the validation and analysis of the algorithm outputs with regards to pre-determined activities or work packages.

For the first research component (algorithms), research focuses on fusion of computer vision, machine learning, and methods derived for arriving at robust and adaptive tracking algorithms, which are directly suited for tracking the distinct classes of temporary worksite resources (personnel, heavy or mobile equipment, and temporary material aids, such as formwork, scaffolding) [8]. Heavy equipment and materials detection and tracking algorithms, for example, require investigation into classification and detector-based learning for classifying equipment and identifying bulk materials on the worksite.

For the second research component (validation and analysis), research proposes algorithms that are quantitatively compared against ground truth measurements obtained through alternative positioning technologies [9,10]. Existing and new photo or video data of actual construction site operations and work packages are annotated for validation of the algorithms and of the inferences produced from said algorithms. A review of existing academic research approaches verifies that the combination of vision-based tracking information with operational information modeling can provide knowledge about the state of operations of temporary resources on an infrastructure worksite [11].

2. Background

The first goal of this paper is to provide a state-of-the-art synthesis review that lays the foundation for a scalable deployment of a vision-based sensing and tracking concept for site operations analysis and validation of temporary entities through field experiments. Fig. 1 shows the core focus within the context of site operations analysis and feedback. In essence, the project level information available for supporting progress tracking and resource utilization tracking, in conjunction with the data produced by other sensing modules, form the basis for vision-based sensing and tracking for site operations analysis. Typically, project level information exists before the start of construction, but is hardly tracked frequently and without error during the project execution phase. (Semi-) or automating the observation processes assisted through sensing technology, however, requires effective and robust algorithms than can process the data. Once outcome and processes are assessed, existing knowledge management and decision making and feedback processes can advance resource and time allocation, subsequently adding new project level information to decision makers.

As several case studies related to resource sensing and tracking will be explained in much further detail, technology is then integrated in the daily work flow in construction if it comes at acceptable cost (hardware installation, data storage and processing, and operation and maintenance). Although vision based sensing of site operations is applied on several thousand jobsites every day and the technology generally comes at low cost and yields high benefits [12,14], the complexity of handling large data sets has prevented significant progress. Field applications so far have mostly focused on recording site status and data archiving [14]. Little to no research has focused on sensing or tracking temporary resources needed for construction [15].

2.1. Competing sensing techniques and tracking technologies

While a core sensing infrastructure may include a variety of existing sensors to track temporary resources in construction, fundamental work in vision-based research concentrates on the creation of algorithms for video and time-lapse image signals to perform site operation analysis. Following the concept architecture (see Fig. 1), updated project level information, i.e., schedule, computer-aided design (CAD) site layout plan, geographical information system (GIS), and building information models (BIM) form a base for progress evaluation. They can be geospatially linked to sensing data from resource tracking. This can be precisely interpreted by relating the spatial source of these data to an as-built model. These contain rich planning and execution information of the ongoing activities to be measured. Also, information on construction methods provides the ground for measuring detailed work hour utilization of a construction activity in addition to the total work hours consumed, resembling the connection between as-built model and progress tracking.

Progress and resource utilization tracking constitute two distinct components of productivity measurement. Specifically, progress tracking measures quantities installed while resource utilization tracking measures consumed work hours as well as the way by which such work hours were spent [4]. Current techniques for site operation analysis, as described by [5], focus on the monitoring of construction progress and the measurement of work task productivity, but are heavily based on manual efforts or are at best partially automated. Recent advances in the construction industry and applied research for sensing and tracking resources or the built environment have been focusing on the utilization of commercially existing technology, for example: Radio Frequency Identification (RFID) [15–17] and Ultra Wideband technology (UWB) [18–20], Global Positioning System (GPS) [21,22], laser scanning [23–26], range imaging [27,28], unmanned aerial vehicles [29,30]. Several case studies have demonstrated the successful application of these technologies in construction. To name a few that also contain some vision based sensing or tracking: defect detection [25,31–33], rapid 3D and 4D CAD modeling [34–36], progress monitoring [38–42], geo-referencing existing project level information [37,39,42], simulation [22,43], visualization [44,45], real-time resource tracking and data visualization [46–50], virtual design and augmented reality [45,51], and worker safety [52] and performance [53–55].