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Optimization-based excavator pose estimation using real-time location systems

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ABSTRACT

Of various types of equipment engaged in earthwork projects, excavators account for the largest proportion of fatalities on site, with 36 reported incidents in the U.S. only in 2012. Furthermore, the operations of excavators play a defining role in the productivity of earthwork projects. Thus, it is of a crucial importance to constantly monitor the operations of excavators to ensure the smooth progress of the work, early detection of anomalies and prompt corrective measures. The first step in the monitoring of an excavator is estimating its pose. Real-time location systems (RTLSs) provide a robust and reliable technology to track and monitor excavators in near real-time. Location data captured by RTLSs can contribute to the identification of machine-induced safety hazards and the analysis of operation productivity. Nevertheless, while high-accuracy RTLSs require a considerable financial commitment, the more affordable variations of the technology, e.g. Ultra-Wideband (UWB), does not generate accurate enough data that can be readily used for the excavator pose estimation. As a result, the location data generated from such RTLSs require some processing before they can be effectively deployed for the pose estimation. The present research proposes a robust optimization-based method that uses geometric and operational characteristics of an excavator to improve the quality of the pose estimation through maximizing the compliance with the machine-imposed constraints and minimizing the amount of required corrections. The feasibility of the proposed method is validated through two laboratory case studies. The method generates very promising results in terms of maintaining the geometric integrity of the equipment data and estimating the pose of the equipment.
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1. Introduction

Earthmoving operations are a common part of projects such as building foundations work, dam construction, airport construction, road construction, and strip-mining. These operations are typically equipment-intensive and thus fraught with financial and safety risks [23,33]. The cost of earthmoving operations is considered an integral element of the total cost of civil engineering projects [12], so much so that more than 20% of the total cost of the road building projects is estimated to be dedicated to earthmoving operations [34]. On the other hand, based on the data published by The Bureau of Labor Statistics [4], only in 2012, 74 out of the total of 775 fatalities (nearly 10%), have been reported as primarily or secondarily caused by major earthmoving equipment, e.g., excavators, loaders, graders, scrapers, compactors, or dump trucks. According to Hinze and Teizer [11], one-fourth of construction fatalities are due to equipment-related incidents. Of various types of equipment engaged in earthwork projects, excavators account for the largest proportion of fatalities on site, with 36 reported incidents in the U.S. only in 2012 [4].

Regardless of the soundness of the initial plan in terms of the optimized time and cost, it is of crucial importance to constantly monitor and control the operation of excavators to ensure the smooth progress, early detection of anomalies and prompt corrective measures. Conventionally, the monitoring of earthmoving projects and the measurement of Project Performance Indicators (PPIs) are performed using manual methods of data collection, which are error-prone, time-consuming and costly [2,19]. The inadequacy of the traditional methods has led to the adoption of modern automated data capturing technologies (e.g., Radio Frequency Identification (RFID), GPS, Laser Detection and Ranging (LADAR), Ultra Wideband (UWB), inertial based systems and video/audio capturing) for the monitoring of construction sites [1,2,9, 17–19,21,24,26].

For instance, Rezazadeh Azar and McCabe [27], proposed a framework to use computer-vision techniques, both in the form of static image processing and video analysis, for the extraction of data about the pose of dump trucks. Such a framework is claimed to serve for the real-time estimation of productivity, calculation of service/idle time and detection of potential collisions. Also, at the detailed level of

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recognizing actions instead of objects, Golparvar-Fard et al. [9] proposed an algorithm which is capable of detecting single actions of construction equipment resulting from articulated motions based on the video captured form a fixed camera. However, the computer-vision based techniques are still immature in terms of (1) tracking and capturing the full-cycle of equipment traveling across a wide area, and (2) reliably and economically maintaining the functionality under climatic variations. Other scholars have suggested the application of sensors of the joints' velocity [30] and the pressure in hydraulic cylinders [28,29] to analyze the excavator state and provide command for automated excavation. However, the cost of instrumenting the excavator with these sensors is relatively high.

The pose of an excavator (i.e., its location and orientation) is the most basic and fundamental information required for the monitoring and analysis of the excavator operations. When the pose of an excavator is known, it can be effectively used to detect hazardous conditions and identify the state of the equipment, which in turn can be used to calculate the productivity-related indices [10,36]. Advanced technologies embedded in Automated Machine Control and Guidance (AMC/G) are capable of generating the tracking information with a high level of accuracy. However, as explained above, the high cost of procuring this technology, which costs approximately $80,000 for every new piece of equipment [22], limits the availability of AMC/G for small and medium size contractors. On the other hand, the more affordable variations of tracking technologies, e.g. Ultra-Wideband (UWB) and low-cost GPS receivers, do not generate accurate enough data that can be readily used for the construction equipment pose estimation [25,37]. As a result, in order to enable the efficient application of the more affordable RTLSs, it is of a paramount importance to process and refine the captured data. It is required to ensure that the refined data satisfy a set of geometric and operational constraints, which are induced by the equipment-specific and job-and-site-specific characteristics, respectively. Although several researchers have previously worked in this area [36,37], the area of RTLS data enhancement for construction equipment pose estimation is noticeably under-addressed.

Vahdatikhaki and Hammad [36] have proposed an iterative multi-step data processing method through which a set of geometric and operational constraints are used to improve the quality of the captured data. However, the proposed correction method has several shortcomings: (1) the increased number of required iterations when the number of constraints increases, (2) the inaccurate assumption that the error is equally distributed between two RTLS Data Collectors (DCs) along the axis formed between them, which may lead to a failed convergence when the number of constraints increases, and (3) the inefficiency in capturing non-distance geometric constrains, e.g., angular constrains. On this premise, it can be argued that the above-mentioned iterative correction method is not enough to maintain the full consistency of the data required for accurate pose estimation, especially when the number of DCs attached to one piece of equipment increases.

The present paper aims to propose a novel and robust optimization-based method that uses the geometric and operational characteristics of an excavator to improve the quality of the data captured by low-cost RTLSs so that the pose of the excavator can be estimated with a good accuracy. The method is purported to ensure that while the pose compliance with the machine-imposed constraints is maximized, it is estimated with a minimum amount of required corrections.

The structure of the paper is as follows. First, the proposed method is introduced and elaborated in detail. Then, the developed prototype and the implemented case studies are explained. Finally, the conclusions of the research and future work are presented.

2. Proposed excavator pose estimation method

The pose of a piece of equipment is a spatial feature that encompasses its location and orientation at any given point in time. The location can be measured in various formats, e.g., the triplet of longitude, latitude, elevation or the Cartesian coordinates in relation to a local reference frame. The orientation can be manifested in terms of the roll, pitch and yaw between the frame representing a rigid body and the reference frame [32]. The orientation reference frame can be established using either three RTLS DCs installed on the upper structure of the excavator or alternatively one RTLS DC and a digital gyroscope.

In this research, it is assumed that an excavator is equipped with a set of RTLS DCs, which continuously provide the location data of the objects to which they are attached with a certain update rate, and the pose is estimated during certain intervals (Δt), e.g., every 5 s. Also, in order to improve the accuracy of the location data, it is assumed that every rigid part of the equipment is represented by at least two DCs. This redundancy helps increase the data accuracy and the visibility, i.e., the chance of missing data is reduced. In order to compensate for the missing or erroneous data, the raw data gathered from the RTLS DCs require a multi-step processing before they can be used for the pose analysis. Fig. 1 shows the high-level flowchart of the proposed method, which consists of several steps to increase the accuracy of the pose estimation. The process begins with the averaging of data over a period of time and applying interpolation for filling the missing data. Next, the optimization-based correction is applied and the pose is calculated.

2.1. Averaging over a period of time and filling the missing data

The first step in the method is averaging over a period of time (dt), which is less than the analysis interval (Δt). For instance, Δt can be 5 s and dt can be 1 s. It should be noted that the length of Δt determines the extent to which the processing is real-time. The impact of averaging over a period of time on improved location data is elaborately discussed by Vahdatikhaki and Hammad [36]. However, in a nutshell, knowing that the RTLS records the location data with a certain frequency, which depends on the specifications and configurations of the used system, it is possible to increase the accuracy of data by averaging several consecutive data over dt. The rationale behind this step is that

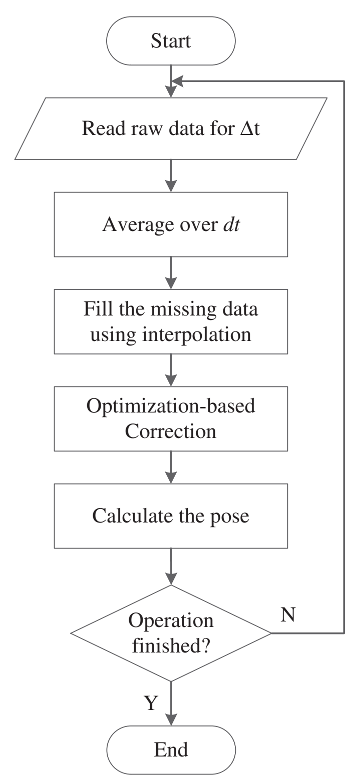

Fig. 1. Flowchart of the proposed pose-estimation method.

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