Automation in Construction 58 (2015) 207–220

Contents lists available at ScienceDirect

Automation in Construction

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

Risk-based look-ahead workspace generation for earthwork equipment using near real-time simulation

Faridaddin Vahdatikhaki [a,1], Amin Hammad [b,*]

[a] Civil and Environmental Engineering Department, Concordia University, 1455 De Maisonneuve Blvd. West, Montreal, Quebec, Canada H3G 1M8
[b] Concordia Institute for Information Systems Engineering, 1455 De Maisonneuve Blvd. West, Montreal, Quebec, Canada H3G 1M8

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form 12 June 2015
Accepted 20 July 2015
Available online 15 August 2015

Keywords:
Look-ahead workspace
Safety
Earthwork equipment
Location systems
Real-time simulation
Risk map

ABSTRACT

The construction industry accounted for more than 17% of fatal work injuries, i.e., 806 counts of death, in the U.S. in 2012. Approximately 75% of struck-by fatalities in the construction industry are reported to have been caused by heavy equipment. Researchers have addressed the need for the enhanced safety of earthwork equipment in two different streams, namely using advanced planning methods to avoid overlaps between the workspaces of different activities of equipment or using real-time tracking technologies to avoid the collision between equipment in the immediate future. However, none of these solutions enables the equipment to reliably predict the operation of other pieces of equipment for a long-enough time window to find a collision-free path using path re-planning. Accordingly, the present paper proposes a novel method to generate risk maps based on the integration of the pose and state data of the equipment with near-real-time simulation and considering the proximity-based and visibility-based risks. These risk maps are used to define dynamic workspaces that can in turn be used to perform path re-planning in a timely manner. The proposed method is implemented and tested in a case study. In light of the results of the case study, it is found that the proposed method is providing a reliable basis for the safety analysis of earthwork sites by generating workspaces with different levels of risk that can be used to provide timely alerts to different equipment and crews.

1. Introduction

The construction industry accounted for more than 17% of fatal work injuries, i.e., 806 counts of death, in the U.S. in 2012 [5]. A large range of construction projects involve earthwork, such as building foundations work, dam construction, airport construction, road construction, etc. [23]. However, the safety risks involved in earthwork operations are high due to the equipment-intensive nature of the work [19]. Occupational Safety and Health Administration (OSHA) reports that heavy equipment accounts for approximately 75% of struck-by fatalities in the construction industry, which is in turn the second cause of fatalities on construction sites after falling [18]. Hinze et al. [12] identify the use of adequate protective support systems as the primary method of preventing struck-by incidents on construction sites.

Researchers have addressed the need for the enhanced safety of earthwork equipment in two different streams. The first stream is to reduce the possibility of collisions between different pieces of equipment through applying more optimized planning and scheduling methods that consider the space requirements of various activities to avoid the dangerous proximities between different teams of equipment [6,11,16,17,27]. Such spaces are referred to in this paper as *activity workspaces*.

The second stream approached the problem from the monitoring point of view and tried to benefit from the increasingly affordable advanced sensing and location systems to mitigate the collision risks by warning the operators against the potential dangerous proximities in real-time. Such methods exploit the real-time information regarding the pose, state and speed characteristics of the equipment to determine the spaces around the equipment that need to be safeguarded to ensure a safe operation within a short time window [3,4,8,28,33–35], such spaces are called *Dynamic Equipment Workspaces* (*DEW*) in this paper.

The integration of the two approaches can result in the overall mitigation of the equipment-related collision risks through considering the safety both at the planning and monitoring phases. However, there is still a middle level that is left uncovered. This is because, while the activity workspaces can be used to perform the initial path planning of different equipment, such planning tends to lose its efficiency in the face of the multitude of unforeseen circumstances that may occur during a project. On the other hand, the dynamic equipment workspaces are merely designed as "*the last line of defense*" [35] to warn the operators against imminent collisions and, thus, are not able to provide the information and time window required for the path re-planning of the equipment. Accordingly, there is a need for a

---

[*] Corresponding author. Tel.: +1 514 848 2424x5800; fax: +1 514 848 3171.
E-mail addresses: f_vahdat@encs.concordia.ca (F. Vahdatikhaki), hammad@ciise.concordia.ca (A. Hammad).
[1] Tel.: +1 514 848 2424x7074; fax: +1 514 848 3171.

http://dx.doi.org/10.1016/j.autcon.2015.07.019

middle-level solution at the monitoring phase that is able to reliably predict the operation of the equipment for a long-enough time window to enable different pieces of equipment adjust their planned paths to avoid collisions in near-real-time.

In one of the efforts to address this need, Hukkeri [13] proposed a safety mechanism based on the intention mapping technique in which every piece of equipment speculates the potential path of other mobile objects on the site and tries to avoid collisions. However, this method is based on a statistical modeling approach that ignores the underlying logic of a construction operation to predict the future movements of the equipment.

The emerging methods for near-real-time simulation of construction operations [1,15,25,30] are providing the adequate inputs for a middle-level solution. Such methods are trying to build on the underlying logic of the operation, which is embedded in a simulation model, and use the data collected from the operation to continuously update its initial simulation model. On this ground, the valuable information about the cyclic pattern of equipment activity, which is an inherent feature of different types of earthwork equipment, and their movement characteristics can be fully leveraged to correlate the shape of the workspaces with the future expected poses and states of the equipment.

Setayeshgar et al. [22] proposed a framework based on the integration of near-real-time simulation with the workspace analysis that uses Building Information Modeling (*BIM*), project schedule and predefined shapes of workspaces to identify the current states of different equipment and update the workspaces based on the results of the simulation. Nevertheless, in this research, the shape and size of the workspace are not dynamically modified to adapt to the moving characteristics of the equipment and the changing conditions of the site.

Stentz et al. [26] proposed another middle-level solution based on the prediction obtained from a parametric motion planning technique. Although the presented approach is efficient in finding a collision-free path for a single excavator, it is not able to consider a fleet of equipment and their interactions in determining the potential collisions between different pieces of equipment. Additionally, only predicted collisions are used as the basis for the warning. However, given the uncertainties involved in the predictive models, near-miss instances can present as much risk as collisions. Furthermore, in addition to distance-based risks, the blind spots of the equipment can place the safety of other equipment and crews at risk [24].

The authors have previously proposed a method for the generation of *DEW*s based on the continuous monitoring of a spectrum of equipment-related information, i.e., the current pose/state of the equipment, and the speed characteristics of each movement [28]. This method considers the required equipment stoppage time to determine how much space needs to be reserved in order to ensure that the equipment will not collide with other pieces of equipment in the immediate future. Although *DEWs* are an adequate means to preempt potential collisions in a proactive manner, their real-time nature renders them useful only to trigger warnings or immediately stop the equipment. On this premise, they do not provide the predictive characteristics to foresee the equipment motions for a long enough period to enable path re-planning of the equipment.

It is therefore imperative to develop a method to generate Look-Ahead Equipment Workspaces (*LAEWs*) that consider not only the proximity-based risks but also the visibility conditions of the site vis-à-vis the future states of the equipment. Such a method needs to consider the operation pattern of the equipment and the visibility conditions of the space around the equipment, in addition to the input information used for the generation of *DEW*s, to determine a relatively longer-term spatial risk assessment (e.g., for the next 10 s) of the space surrounding the equipment. The spatial risk analysis leads to the generation of equipment risk maps that represent the risk distribution in the space around the equipment. These risk maps can then be used to generate the *LAEWs* associated with a certain risk level.

Accordingly, the objectives of the present paper are: (1) Developing a novel method to generate equipment risk maps based on the integration of the proximity-based risks and visibility-based risks using the pose and state data of the equipment and the Near-Real-Time Simulation (*NRTS*); and (2) Generating *LAEW* based on the equipment risk maps so that the resulting workspaces can be used to perform path re-planning when a potential collision is identified. It is noteworthy that the present research is an extended version of a previous publication of the authors [29].

The structure of the paper is as follows. First, the proposed workspace generation method is elaborated, followed by the explanation of the implementation and a case study. Finally, the conclusions and future work are presented.

2. Proposed method

LAEWs are generated for the purpose of look-ahead re-planning of equipment motions and are updated in near-real-time with an interval of Δt. The update interval is a function of the available computational power and the extent to which the future states of the equipment can be reliably predicted. Generally, the larger the value of Δt, the greater the chance of the potential changes in the predicted conditions, and thus the less the reliability of the generated *LAEW*s. In order to put the sensible value of Δt into perspective, it is envisioned that it is most effective in a range between 10 s to 1 min. While a value less than 10 s has the risk of being impractical for being too short for the planning of future motions, a value greater than 1 min reduces the reliability of the generated risk maps.

The proposed method is part of a multi-agent system (*MAS*) that has been previously proposed by the authors to orchestrate the machine-level Location-based Guidance Systems (*LGS*s) technologies into a coherent project-level system committed to support earthwork operations toward the enhanced performance and safety of the overall project [10,32]. *LGSs* are defined as systems that combine location tracking systems and other sensory data with On-Board Instrumentation (OBI) to perform complex real-time monitoring of the current status of equipment. In the proposed *MAS*, several layers of agents are processing and managing the huge amount of collected sensory data into useful information that can be used in decision making at different operational levels. The proposed *MAS* has a semi-distributed structure to strike a balance between the optimality of the outputs and the required computational effort. Although the fully centralized *MASs* are more able to find the globally optimum solutions, they are not very efficient in solving complex problems because they require high computational effort. Fig. 1 shows a simplified version of the proposed *MAS* architecture. In a nutshell, Operator Agents (OAs) support the equipment operators and have the essential information about their current task, state and pose. Similarly, Worker Agents (WAs) represent the worker-on-foot on the site. In a construction site, often a group of equipment and workers is teamed up to serve one particular operation, for instance several trucks and an excavator work together to move the earth. The team coordinators are supported by Team Coordinator Agents (TCAs), whose main objective is to track the progress of operations based on the data gathered from their subordinate OAs and to ensure safe and smooth delivery of the operations. Several layers of TCAs and a General Coordinator Agent (GCA) can be defined. Furthermore, these different types of agents will be fed by information agents who will provide the required data to the agents and frequently get updated based on the changes happening in the site as the construction progresses.

The proposed MAS supports the project at three different levels, namely (1) planning, (2) execution and monitoring, and (3) re-planning. At the planning level, the MAS is able to streamline the operation and task assignments to different equipment as well as to support equipment path planning [34]. At the execution and monitoring level, the MAS is committed to: (*i*) provide visual guidance to equipment operator, (*ii*) collect and process Real-Time Location