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MULTI-AGENT SYSTEM FOR IMPROVED SAFETY AND PRODUCTIVITY OF EARTHWORK EQUIPMENT USING REAL-TIME LOCATION SYSTEMS

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Abstract: The growing complexity and scope of construction projects is making productivity and safety of earthwork of a great concern for project and site managers. In earthwork operations, where heavy machines are being used, various safety and risk issues put the timely completion of a project at stake. Additionally, the construction working environment is heavily susceptible to unforeseen changes and circumstances that could impact the project, both cost and schedule wise. As a response to the looming safety threats or unforeseen changes of working conditions, re-planning is almost always required. In order for re-planning to yield the optimum results, real-time information gathering and processing is a must. GPS and other Real-time Location Systems (RTLSs) have been used for the purpose of real-time data gathering and decision-making in recent years. Similarly, Location-based Guidance Systems (LGSs), e.g., Automated Machine Control/Guidance (AMC/G), are introduced and have been employed mainly for the purpose of high-precision earthwork operations. However, the current application of LGS is limited to the machine-level productivity optimization, which is not sufficient to address the project-level monitoring and decision-making needs. In the context of complex earthwork operations where several teams are concurrently working towards different ends, the globally optimized operations should coordinate the actions of multiple teams of equipment to eliminate the productivity lost by organizational, logistics and operational management. Therefore, the objective of this paper is to develop a Multi-agent System (MAS) structure to orchestrate the machine-level information (i.e. states and poses) induced based on RTLSs to a coherent project-level system committed to support operations towards the enhanced productivity and safety of the overall project. 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 efforts. A case study is developed to demonstrate the applicability of the proposed MAS. Also, a two-layer safety mechanism is proposed based on which near real-time collision-free path planning and real-time collision avoidance can be performed. In the light of the results of the case study, it is found that the the proposed MAS structure is able to effectively address the team-level coordination of different pieces of equipment and improve the safety of construction site using the proposed two-layer safety mechanism.

1 INTRODUCTION

The construction industry is concerned with Improving the productivity and safety of construction projects (Beavers et al. 2006). In earthwork operations, where heavy machines are being used, various safety and risk issues put the timely completion of a project at stake. Additionally, the construction working environment is heavily susceptible to unforeseen changes and circumstances that could impact the project, both cost and schedule wise. As a response to the looming safety threats or unforeseen changes of working conditions, re-planning is almost always required. In order for re-planning to yield the optimum results, real-time information gathering and processing is a must. The Global Positioning System (GPS) and other Real-time Location Systems (RTLSs) have been used for the purpose of real-time data gathering and decision-making in recent years (Perkinson et al. 2010). Similarly, Location-based Guidance Systems (LGSs), e.g., Automated Machine Control/Guidance (AMC/G), are introduced and have been employed mainly for the purpose of high-precision earthwork operations. LGS integrates geo-positioning technologies with 3D design models and Digital Terrain Models (DTMs) to either (1) support the machine operator through the provision of continuous guidance on a digital screen mounted in the cabin of the machine, or (2) control the position and movements of the equipment (or part of it). While GPS and total stations are the main tracking technologies used in AMC/G, other types of emerging Real-time Location Systems (RTLS), e.g., Ultra-Wideband (UWB), can be integrated with similar monitoring mechanisms to provide monitoring and guidance capabilities for earthwork equipment.

The current application of LGS is limited to the machine-level productivity optimization in large projects, which is not sufficient to address the project-level monitoring and decision-making needs.There are several challenges that have to be overcome in order to maximize the benefits of using this technology in the 3D surveying-design-contract-construction-inspection workflow (Dunston and Monty 2009, Torres and Ruiz 2011, Vonderohe 2009). The problem of providing near real-time guidance or control support for the operators of earthwork equipment based on the consideration of the entire fleet can become complex, in line with the fleet size and equipment interactions. For such complex problems, the conventional approach of central problem solving becomes far-fetched, attributable to the fact it is difficult or impractical to globally grasp and analyze the multi-dimensionality and dynamisms of such problems. Distributed intelligent systems are designed to address such complex problems in terms of several collaborating intelligent agents, who try to solve the overall problem by synthesizing limited views of individual agents (Ferber 1999). Such systems are referred to as Multi-Agent Systems (MASs), which consist of several intelligent agents capable of interaction.

Furthermore, despite the growing availability of LGS, its application for safety is limited to real-time proximity-based object detection and warnings. In the existing systems, the increasingly affordable advanced sensing and location systems are used to mitigate the collision risks by warning the operators against the potential dangerous proximities in real time (Burns 2002, Carbonari et al. 2011, Zhang and Hammad 2012, Guenther and Salow 2012, Wu et al. 2013, Zolynski et al. 2014, Vahdatikhaki and Hammad 2015a). Cheng (2013) proposed to use the pose and speed data for the generation of the workspaces. This method does not consider the equipment state as a means to economize the use of space around the equipment and does not cover the equipment with rotary movements, e.g., excavators. Therefore, there is a need for a solution that is able to reliably predict the operation of the equipment for a long-enough time window to enable different pieces of equipment to adjust their planned paths to avoid collisions in near-real time.

Therefore, the objective of this paper is to develop a MAS structure to orchestrate the machine-level information (i.e. states and poses) induced based on RTLSs to a coherent project-level system committed to support operations towards the enhanced productivity and safety of the overall project. The paper also aims to develop a two-layer safety mechanism: the first layer of which enables the equipment to plan a collision-free path considering the predicted movement of all other equipment, and the second layer is acting as a last line of defense in view of possible discrepancies between the predicted paths and actual paths. The structure of the paper is as follows. First, the proposed method is introduced, followed by the explanation of the implementation and a case study. Finally, the conclusions and future work are presented.

2 PROPOSED METHOD

Figure 1 shows an overview of the scope for the proposed MAS framework. The main assumptions are that every piece of equipment on the construction site has a sufficient number of RTLS Data Collectors

(DCs) attached at specific locations to track its movement, and that every equipment operator is supported by an agent that can communicate with other agents in a MAS framework. The proposed MAS supports the project at three different levels: (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 perform equipment path planning (Zhang and Hammad 2012), which is operationalized in terms of strategic and tactical planning. At the execution and monitoring level, MAS is committed to (i) provide visual guidance to equipment operators, (ii) collect and process RTLS data, (iii) apply appropriate error correction techniques to identify the pose of the equipment (Vahdatikhaki et al. 2015), (iv) identify the state of the equipment (Vahdatikhaki and Hammad 2014), (v) apply the Near Real-time Simulation (NRTS) (Vahdatikhaki and Hammad 2014), (vi) generate equipment workspaces, i.e., Dynamic Equipment Workspaces (DEWs) (Vahdatikhaki and Hammad 2015a) and Look-Ahead Equipment Workspaces (LAEWs) (Vahdatikhaki and Hammad 2015b), and (vii) report the necessary information to pertinent agents. The aforementioned two types of workspaces differ in that while DEWs are generated based on the equipment pose and speed in real time to form a safety buffer around the equipment that can help prevent collisions, LAEWs are built based on the predicted future motion of equipment and operator visibility in near-real time to help find a collision-free path for the equipment, as explained in Section 2.2. Finally, at the re-planning level, the proposed MAS framework addresses the need for task-reassignment, path re-planning, and design change requests, which may become necessary in view of the potential unforeseen safety risks identified at the monitoring level. As can be seen in Figure 1, while the proposed MAS framework offers advantages at both the operational and managerial levels, only the operational aspects of framework are addressed in this paper.

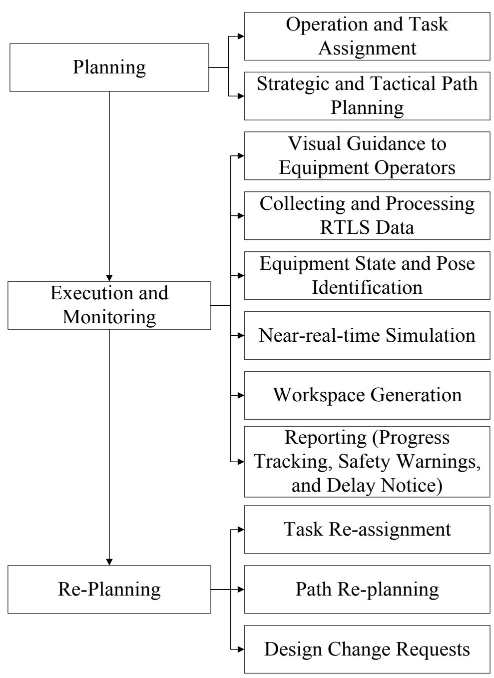


Figure 1: Overview of the Scope for the Proposed MAS Framework

The authors have previously presented the overview of the proposed MAS (Hammad et al., 2013). This paper extends this research by providing a more in-depth discussion of the agents' functionality in the MAS and how the LAEWs are being used by different agents to avoid collisions.

A multi-layer agent architecture is proposed in which agents supporting the operators of single machines constitute the lowermost layer of the agent hierarchy. These agents process and manage the huge amount of sensory data, provided by an UWB system or other types of location systems, into useful information that can be used in decision making at different operational and managerial levels. Figure 2 shows the proposed MAS architecture where several teams working in the proximity of each other are supported by different types of agents, with different tasks and project views. Three functional agent types can be distinguished according to the distribution of the responsibilities, namely, operator, coordinator and information agents. In a nutshell, Operator Agents (OAs) support the equipment operators and have the essential knowledge about their current task, state and pose. In a construction site, often a group of equipment 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' objectives. Depending on the level of coordination each TCA offers, several layers of TCAs and a General Coordinator Agent (GCA) can be defined. Further, these different types of agents are fed by information agents who provide the required site, design or project-related data to the agents, and frequently get updated based on the changes happening in the site as the construction progresses.

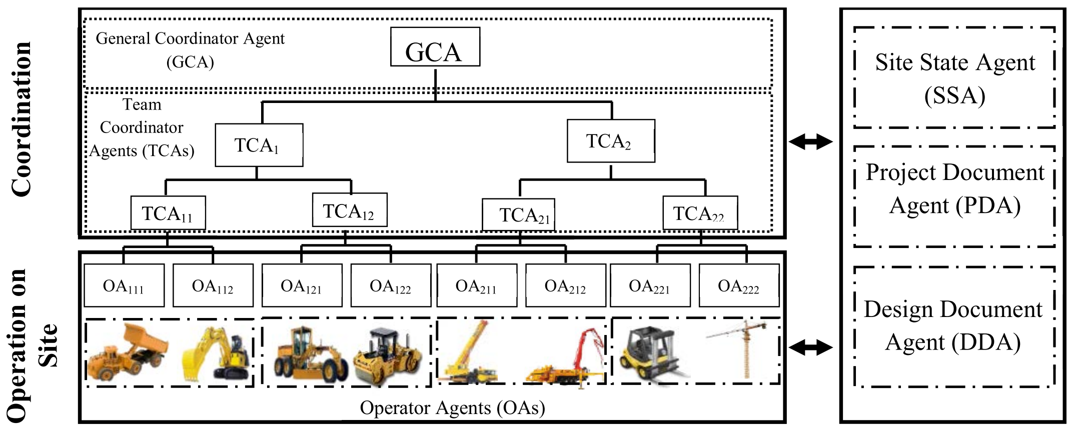


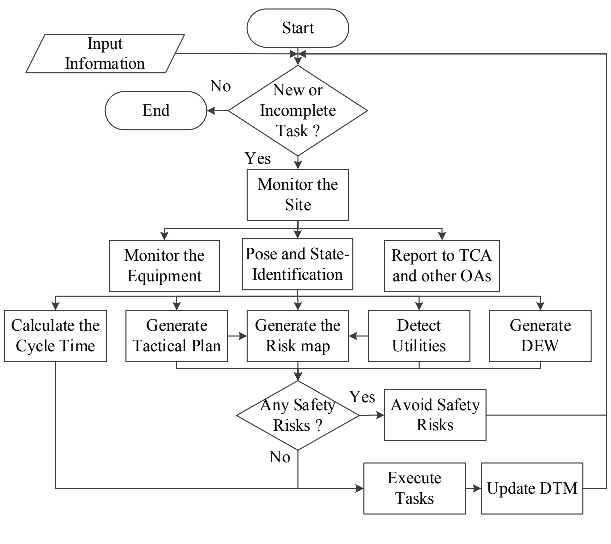
Figure 2: Multi-Agent System Architecture (Adapted from Hammad et al. 2013)

Information Agents are in charge of handling the information required for MAS and encompasses the Site State Agent (SSA), Project Document Agent, (PDA), and Design Document Agent (DDA). The SSA provides and updates the Digital Terrain Model (DTM), which is often obtained from Light Detection and Ranging (LIDAR) scans by surveyors. Additionally, the SSA uses a variety of local sensors coupled with the information from weather agencies to constitute a database of weather as expected at the planning time, at the current time and as forecasted. The main functionalities of the SSA are to provide information to TCAs and OAs, when needed, and to update their data whenever a change befalls. The DDA, on the other hand, encapsulates the designer-provided 3D models and updates them should any changes be made in the course of the project. The 3D design model is used by all the coordinator and operator agents as a reference for decision making and task execution. Finally, the PDA hosts all the basic project documents based on which an earthwork project is typically managed, including safety regulations, available resources, project schedule, construction methods, and available sub-contractors.

2.1 Agents Responsibilities and Functionalities

2.1.1 Operator Agents

The OA requires information about its surroundings, task and environment. These combined types of information are referred to as external information because they are provided by external sources. Surroundings information contains the poses, states and DEWs of other pieces of equipment. This information can be directly used by the OA to identify safety threats and take immediate actions, if required. Task information allows the OA to perform its (semi-)autonomous operations and contains safety warnings, LAEWs, a strategic plan, and NRTS-generated schedule provided by the TCA and 3D design model made available by the DDA. High-level flowchart of the functionalities of an OA is shown in Figure 3(a). Given the unequal priorities of various functionalities of the OA, and in order to embed these priorities in the MAS structure, a modified subsumption architecture is chosen for agents. Subsumption architecture is based on breaking the activities of an agent in vertical modules where every module has limited responsibilities and the results of the higher modules always supersede those of the lower modules, if there is a conflict between various modules (Ferber 1999). In a nutshell, OAs constantly monitor the operations and perform the routine calculations for the equipment condition monitoring, pose and state-identifications, cycle time, generation of tactical plans, generation of risk maps, detecting underground utilities, and generating DEWs.



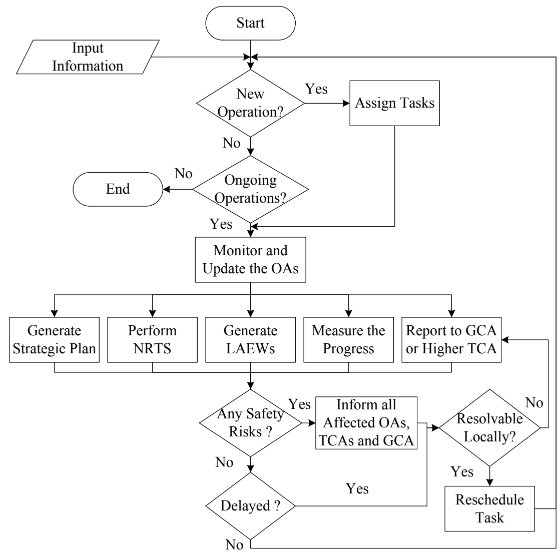


Figure 3: High-Level Flowchart of (a) the OA Functionalities, and (b) the TCA Functionalities

2.1.2 Coordination Agents

Coordination encompasses agents representing team coordinators who are responsible for making critical decisions, e.g., new work schedules or command for the suspension of the operation, using data from all other agents, and further communicating their decisions with the appropriate OAs for the execution. Essentially, this component consists of one GCA and several TCAs. However, depending on the characteristics of the project, the phase of the project and simultaneous operations, several layers of teams and sub-teams can be formed. Each team is coordinated and supported by a TCA.

The role of a TCA is to assign tasks to the subordinate OAs or sub-TCAs and to collect information from them. Figure 3(b) shows the high-level flowchart of the TCA functionalities. The main functionality of a TCA is to assign and monitor the tasks of the OAs. At the top of the flowchart, the TCA determines whether a new operation is assigned or an operation is ongoing. In the first case, the operation is broken into OA-executable tasks and assigned to the relevant available OAs. Next, in view of the reports from subordinate OAs, the progress monitoring, NRTS, and LAEWs (if any risk is identified), either the tasks are rescheduled if the problem can be resolved locally, or the GCA (or higher level TCA) is informed for directions. Local resolvability means that the problem can be solved by the information present to a single TCA, without the need to engage into negotiations with other TCAs. The negotiation between agents in a decentralized MAS structure is outside the scope of the present paper.

The GCA is responsible for monitoring and controlling the operations to ensure the smooth execution of the project. The GCA also generates the operations' schedule and the resource distribution based on the available resources, project schedule, the chosen construction methods and available sub-contractors. The functionalities of the GCA are realized through the accumulation of information about the project and the progress of different operations. The project information is the combination of all essential documents/information based on which an earthwork project is executed. At a high-level abstraction, safety regulations, available resources, project schedule, construction methods, and available sub-contractors, all of which are coming from the PDA, are the main ingredients of the project information. Safety regulations are used to derive basic safety rules that need to be observed throughout the project. Available resources and available sub-contractors are used for the resource configurations and distribution. The project schedule is used for the generation of operation schedules that can be assigned to different TCAs. The Construction methods provide the GCA with the initial information needed to retrieve the right operation procedures.

2.2 Safety Management in MAS

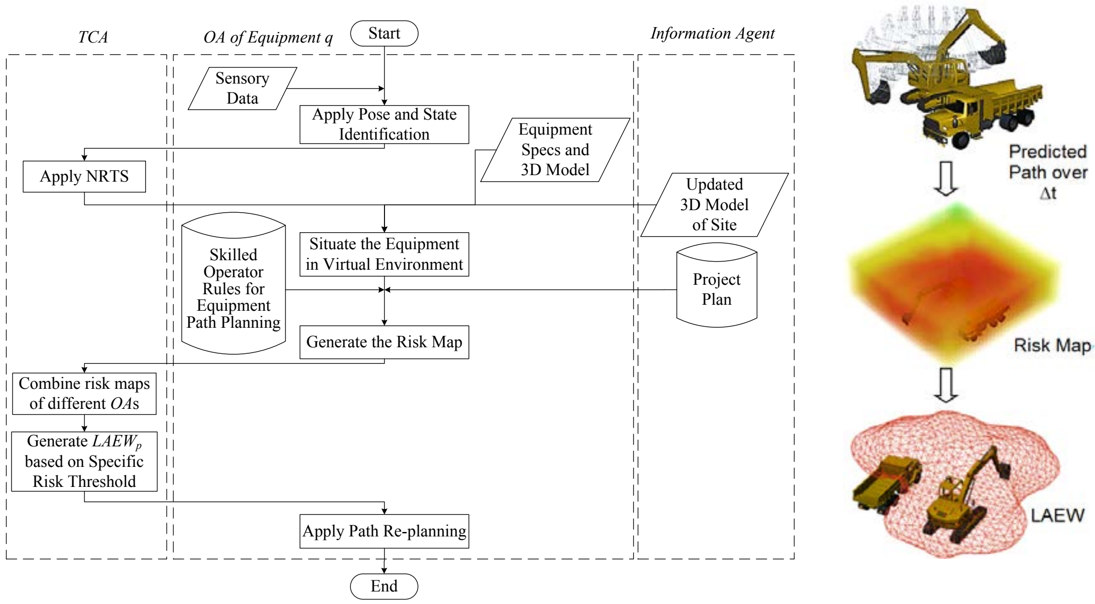
As stated in Section 2, the safety of earthwork operation in the proposed MAS structure is supported through a two-layer mechanism which includes near real time collision-free path (re-) planning using LAEWs and real-time collision avoidance using DEWs. These two layers are running independently in parallel with different update rates. Given the nature and functionality of DEWs, they are updated in real time with the same rate offered by the tracking technology (*dt*). LAEWs, on the other hand, require intensive computations and communications between various agents, and thus they are updated with a rate less than DEWs. The LAEWs are generated over every Δt and whenever a deviation from the predicted path of various equipment is observed. While the details of the two types of workspace are presented in the previous work of the author (Vahdatikhaki and Hammad 2015a, Vahdatikhaki and Hammad 2015b), a brief explanation of each workspace is presented in the following sections.

2.2.1 Look-Ahead Equipment Workspace (LAEW)

The flowchart of the proposed method for the generation of the LAEW of one piece of equipment (equipment *q*) is shown in Figure 4(a). As shown in this figure, the input of this method comprises the sensory data, the equipment specifications and its accurate 3D model, the current pose and state data generated by the OA of the equipment *q* (OA_q), and future state data coming from the NRTS that is performed by the TCA. A rule-based system is used to identify the states of different equipment with a high accuracy by leveraging a set of equipment proximity and motion rules that determine the states of the equipment (Vahdatikhaki and Hammad 2014). Also, a robust optimization-based method that uses geometric and operational characteristics of the equipment is used to improve the quality of the pose estimation (Vahdatikhaki et al. 2015). Additionally, the updated 3D model of the site, and the project's detailed plan (including the location of different scheduled tasks, their time frame, and the site layout) are available through the Information Agent. Finally, a set of heuristic rules that define the operation of a skilled operator is also required to be available to each OA. The generation of LAEW is based on the discretization of the entire site space into cells, and then calculating the risk associated with each cell given the future expected states of different pieces of equipment, which is performed by each OA. As shown in Figure 4(b), the pose data are used to identify the current state, which is then passed on to the TCA to perform the NRTS in order to generate the operational pattern of each OA. These data are then communicated with the OA_q who will first integrate the equipment pose with its 3D model and the updated 3D model of site to situate the equipment in the virtual environment. Then, the OA will use the project plan, and the rules that govern the operation of the machine by a skilled operator to generate the risk map of the equipment. Finally, the OAs transfer their individual risk maps to the TCAs who will first combine these risk maps and then use the tolerable risk level of each OA to generate the LAEW. It should be highlighted that $LAEW_p$ for equipment *p* is generated based on the combination of the risk maps from all pieces of equipment surrounding equipment *p*, excluding equipment *p* itself. $LAEW_p$ can be used by the OA_p to perform path re-planning, if required. Similarly, the path-replanning performed by the OA_q at the end of the flowchart shown in Figure 4(a) is realized using $LAEW_q$.

2.2.2 Dynamic Equipment Workspace (DEW)

DEWs aim to use the pose, state, and speed characteristics of the equipment to generate a space around the equipment that would allow the prevention of immediate collisions with other pieces of equipment or obstacles on site, considering the equipment stoppage time (t_s). t_s can be used to determine how much of the space in the moving direction of equipment is unsafe after the operator becomes aware of a potential collision considering the operator reaction time and braking time. In addition to the DEWs of the equipment, semi-dynamic obstacles (such as trenches, temporary or permanent structures, etc.), also need to be represented by their own corresponding safety zones to enable effective collision avoidance at the global level.



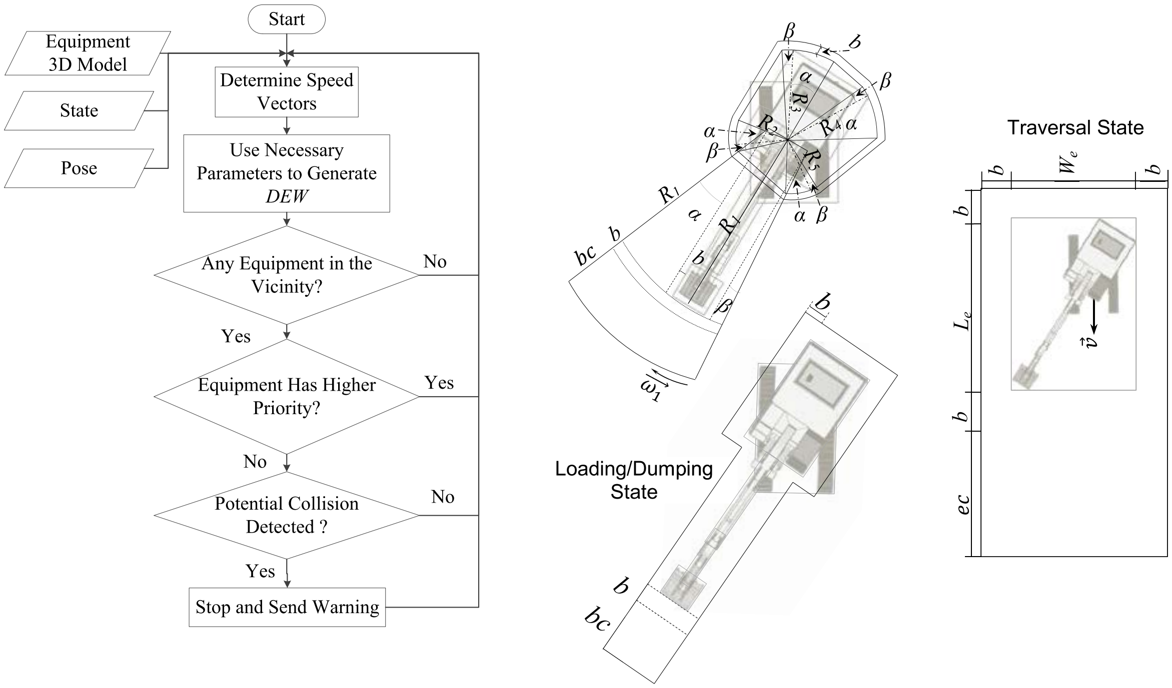
(a) (b)

Figure 4: (a) Flowchart for the Generation of LAEW, and (b) Schematic Representation of LAEW Generation Process

For the DEWs to be effectively used for the purpose of collision detection and avoidance, every OA needs to be able to generate its own DEW and have near-real-time information about the DEWs of other OAs. Figure 5(a) shows the flowchart for the generation of the proposed DEWs. With the 3D model of the equipment and its pose and state information available, the method proceeds to determine the linear and angular speeds of the equipment. For instance, an excavator can travel on its tracks with the linear speed of $\vec{v}$, move its bucket with the linear speed of $\overrightarrow{v_b}$, or swing with the angular speed of $\overrightarrow{\omega_1}$. Upon the determination of the speed vectors, the DEW can be generated based on the type of the equipment and the equipment state. For example, two distinct types of states can be identified for an excavator, namely stationary states (swinging, loading, dumping, and waiting) and traversal states (relocating, maneuvering). Figure 5(b) shows different DEWs of an excavator for different states. Next, to avoid redundant computation, an OA can perform pairwise comparisons of DEWs only with the OAs that are in its vicinity. To determine the equipment in vicinity, the multi-layer workspace concept (Chae 2008, Wang and Razavi 2015) can be applied. In this method, the pairwise distances between every two pieces of equipment are calculated and if the two pieces of equipment have a distance less than a threshold, then the collision detection between their DEWs is performed. In order to further reduce the computation efforts and avoid redundant calculations, the priorities of the different equipment can be used to delegate the calculation to the OA of the equipment with the lower priority. If a collision is detected between the two, the equipment with the lower priority will stop and send a warning to the OA of the other equipment. If both pieces of equipment have the same priority, then the OAs of both should perform the collision detection and if a collision is detected they should both stop.

3 IMPLEMENTATION AND CASE STUDY

In order to demonstrate the feasibility of the proposed MAS approach in improving safety using LAEWs and DEWs, a prototype system is implemented using Unity3D game engine (2015) and two simulated scenarios are examined. The scenarios used for the case study consider an excavation operation for a specific day of the project where two excavators are scheduled to dig a ditch and load two trucks, which will haul the soil to the dumping area, dump it, and return to the excavators for the next load.



(a) (b)

Figure 5: (a) Flowchart of the Generation of DEW, and (b) Examples of Excavator DEWs in Different States (Adapted from Vahdatikhaki and Hammad 2015a)

In the first scenario, the feasibility of applying LAEWs for collision-free path planning is investigated. The scenario covers a portion of the earthmoving cycle where Excavator A, which is assumed to have a higher priority than Excavator B, is expected to swing to Truck A, and Excavator B is expected to swing away from Truck B, as shown in Figure 6(b). The algorithm for the operation logic of excavators is shown in Figure 6(a) (Hammad et al 2014). The articulate digging and dumping movements of the excavator parts at a Digging Station (DS) are planned initially using parametric scripting. If the results of the LAEW-based safety check revealed a potential collision, the path re-planning is done using Rapidly-exploring Random Tree (RRT) (La Valle 2006). Figure 6(b) shows the initially planned paths for Excavators A and B. Since Excavator A has a higher priority, its initial planned path is approved. However, while the initial path of Excavator B would require it to swing counter-clockwise to the truck, given that this path had a collision with the LAEW, a new clockwise path is generated using RRT, as shown in Figure 6(c).

In the second scenario, the effectiveness of DEWs is investigated in another simulated scenario. In this scenario, as shown in Figure 7(a), while Truck A is hauling the material to the dumping point, Truck B is returning from the dumping point to the DS. It is assumed that although their planned paths have been collision-free, Truck A fell behind its planned path, which could lead to a potential collision. In this case, as explained in Section 2.2, DEWs can be used as the last line of defense to avoid the collision by requiring one of the equipment to stop. The algorithm shown in Figure 5(a) is implemented in Unity for the real-time generation and collision detection of DEWs. As shown in Figure 7(b), upon the detection of collision between the two DEWs, Truck B, which has a lower priority, is stopped, and Truck A is allowed to continue its path to the dumping point, as shown in Figure 7(c).

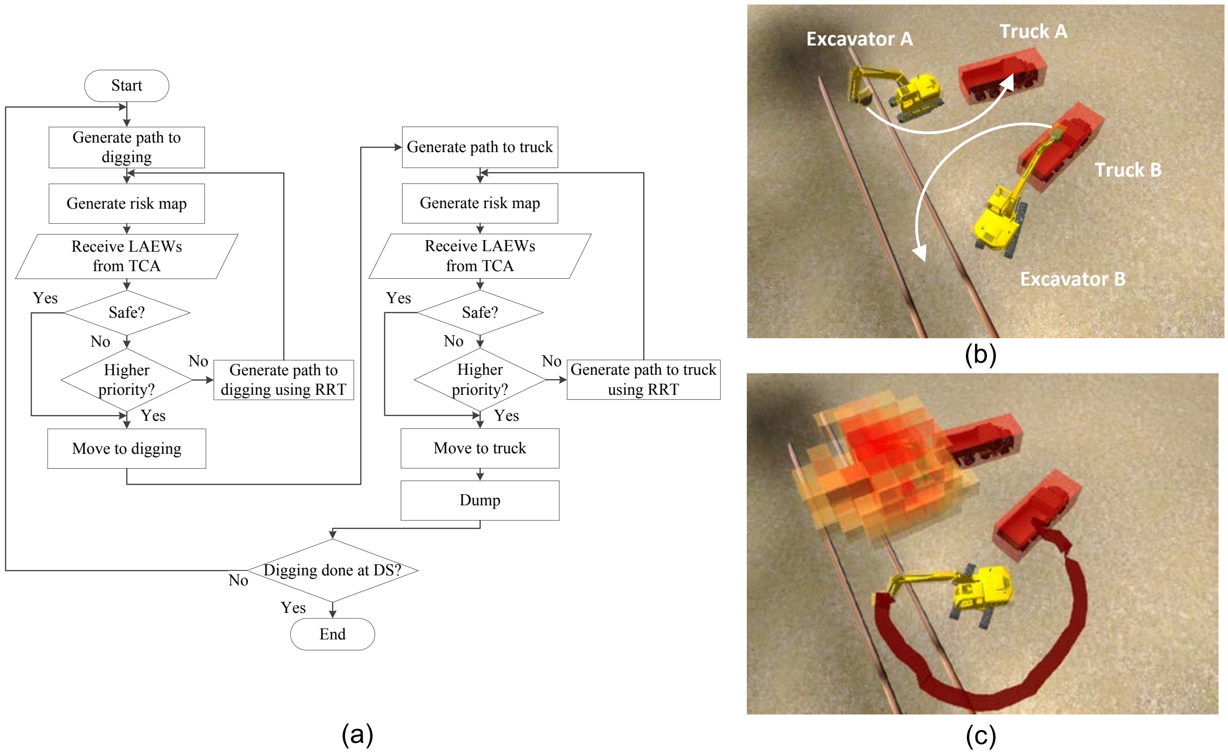


Figure 6: (a) Algorithm Representing the Operation Logic of Excavator, (b) Current Poses and Initial Paths of Excavator, (c) LAEW of Excavator B and Final Path of Equipment B

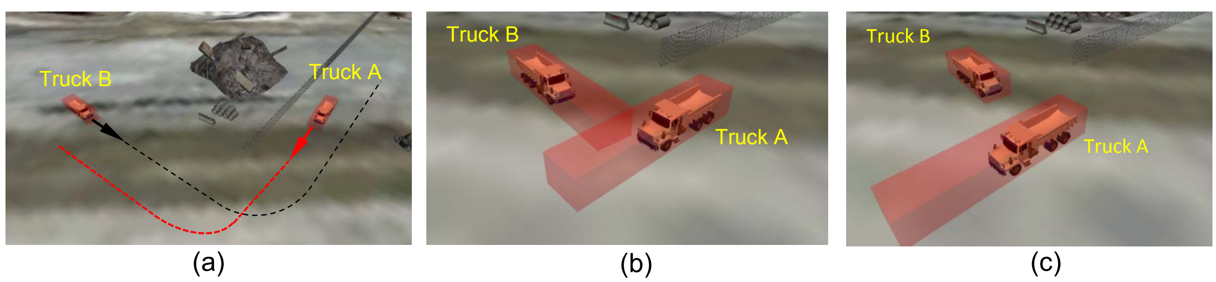


Figure 7: (a) The Layout of the Second Scenario, (b) Collision Detection between DEWs, and (c) Collision Avoidance Decision made by OAs

4 CONCLUSIONS AND FUTURE WORK

In this paper, a MAS structure is introduced for improving the safety and productivity of automated guidance and control of earthwork equipment. In the proposed MAS structure, every piece of equipment is supported by an operator agent to oversee the task and provide guidance whenever needed. A multi-layer agent hierarchy assigns monitors and coordinates the task executions, and a set of three types of agents feed the system with the relevant information. The functionalities, jurisdictions and the input-output scheme of every type of agents were discussed. A two-layer safety mechanism was introduced, where the first layer enables the equipment to plan a collision-free path considering the predicted movement of all other equipment and the second layer acts as a last-line-of-defense in view of possible discrepancies between the predicted paths and actual paths.

In view of the results of the case study, it is shown that the MAS is capable of effectively handling the harmonization of various pieces of equipment on the site beyond what is available by the conventional

LGSs. The combination of LAEWs and DEWs are found to be an efficient approach to deal with collision-free path planning and real-time collision avoidance. The authors are planning to investigate the negotiation between different levels of agents as part of their future work.

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