Multiagent Approach for Real-Time Collision Avoidance and Path Replanning for Cranes

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Abstract: Collisions on construction sites are one of the primary causes of fatal accidents. This paper proposes a multiagent-based approach to provide real-time support to the staff of construction projects. Collision avoidance is achieved by informing the crane operators about potential collisions and by providing motion replanning for crane operations. During the planning stage, a three-dimensional (3D) model of the static environment is created, and collision-free motion plans are generated by the agents for the cranes, considering engineering constraints and operation rules. During actual construction work, all mobile objects are tagged when entering the monitored area. A site state agent uses a real-time location system (RTLS), such as an ultra-wideband (UWB) system to collect location data, calculates the poses of the objects on site, and sends this information to other agents. By using this real-time updated information, agents can detect potential collisions and replan the path for the cranes for collision avoidance. A coordinator agent coordinates the movement of cranes by deciding their priorities. The site state agent, coordinator agent, and crane agents can communicate and negotiate with one another to make better decisions. The framework of the multiagent system is described in detail, and a prototype system is developed. Three case studies are used to verify and validate the proposed approach. The benefit of using the agent system is that real-time collision avoidance can be achieved by providing more awareness of the site situation and decision making through communication and negotiation between multiple agents, which results in safer and more productive work environment. **DOI:** **10.1061/(ASCE)CP.1943-5487.0000181.** *© 2012 American Society of Civil Engineers.*

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Introduction

A construction site is a dynamic and complex environment in which different teams work together. A common case is that one general contractor works with several subcontractors, which have their own tasks, schedules, and staffs. A group of specialists, such as engineers and equipment operators, are usually involved in planning and executing the job. The nature of the hierarchy of the project organization is usually based on a hybrid approach in which a project manager coordinates different plans, which are generated in a distributed manner. Macro- and microplans are generated at different levels and for different groups. More detailed plans are needed for supporting equipment operators, such as the lift plans for cranes. The team leader or the project manager has to coordinate these plans to avoid conflicts in terms of time, space, and resources, including workers, equipment, and materials.

However, even when detailed planning is applied, safety problems may not be completely solved because of dynamic changes on site. Communication and negotiation are essential to ensure that the construction tasks are safely performed. Previous research has indicated that machinery-related incidents were the fourth leading cause of traumatic occupational fatalities in the construction industry between 1980 and 1992, resulting in 1,901 deaths (2.13 deaths per 100,000 workers) [National Institute for Occupational Safety and Health (NIOSH 2010)]. The same research has indicated that the construction equipment most frequently associated with fatalities is cranes (17%). In 2006, there were 72 crane-related fatal occupational injuries in the United States [Bureau of Labor Statistics (BLS) 2006]. Lifting tasks are usually done through a trial-and-error process, based on the feedback provided by the crane operators' vision and assessment, on hand signals of a designated ground director at the work zone, or on radio communication. A lift plan is a microplan that should be integrated with other plans to ensure that the entire project is done properly. Extensive communication should be undertaken on site to coordinate the cranes' movement based on negotiation among construction team members. The priority of tasks also needs to be considered when a conflict between two tasks is detected. Beavers et al. (2006) have suggested that employers should have a system in place to assess the hazardousness of each of their construction worksites in relation to the potential for crane-related events. They have also suggested that a diligent and competent person should be assigned by the manager of construction operations to be in charge of overall crane operations. This person should have complete authority to stop any unsafe operations. These needs have inspired this research to investigate the possibility of an intelligent system to support crane operators by providing better communication and environment awareness. Therefore, agent technology is proposed in this research to explore the feasibility of its application in construction to enhance safety.

The concept of agents comes from developing a thinking machine with the capability of solving a problem on its own (Ferber 1999). As Russell and Norvig (2003) have described, agents are relatively independent and autonomous entities that operate within communities in accordance with complex modes of cooperation,

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conflict, and competition to survive and perpetuate themselves. An agent can be a piece of software that is capable of accomplishing tasks on behalf of its user. Agents are capable of perceiving their environment, but only to a limited extent. By exchanging information with other agents, they can acquire more information about the environment. Actions are taken by the agent to satisfy its objectives based on some satisfaction/survival functions that it tries to optimize using its skills. The actions performed by an agent change the agents' environment and thus its future decision making. Agents are endowed with autonomy, which means that they are not directed by commands coming from a user, but by a set of tendencies, which can take the form of individual goals to be achieved or of satisfaction or survival functions that the agent attempts to optimize (Russell and Norvig 2003).

In a multiagent system (MAS), agents carry out separate but interdependent tasks to meet their final objective. Every agent needs to send and receive messages and to make decisions (such as changing priorities for motion planning and replanning) based on near real-time site situations. Communication between agents expands the perceptive capacities of them by allowing them to benefit from the information and the know-how of other agents (Ferber 1999). Furthermore, the negotiation ability of agents fits the common way of problem solving between workers in construction projects.

This paper is a part of research at Concordia University for improving construction safety using advanced information technology. The multiagent system integrates real-time location systems (RTLSs), path planning and real-time replanning for construction equipment, and multiagent communication and negotiation (Zhang et al. 2009a). Crane motion-planning and replanning algorithms have been presented in Zhang et al. (2010) and Zhang and Hammad (2012). A motion-planning algorithm has been proposed to efficiently generate safe and smooth paths for crane motions, taking into account the engineering constraints and the path quality. Furthermore, a dynamic motion-planning algorithm has been proposed to ensure safety during the execution phase by quickly replanning and avoiding collisions. In addition, an anytime algorithm has been proposed to search for better solutions during a given time period by improving the path smoothness and by reducing the path execution time. To apply motion planning and replanning in real time, moving objects on site should be tracked and modeled. Zhang (2010) and Zhang et al. (2011) have discussed location data collection and processing in real time. They have proposed a near real-time monitoring system using an ultra-wideband (UWB) RTLS. Several tests of a UWB system have been applied in the laboratory and in indoor and outdoor environments. These tests show a good potential for using UWB tracking technology at construction sites by processing and organizing location data into useful information for near real-time environment updating.

The objectives of this paper are (1) to propose a framework of a multiagent system for supporting crane operators to improve safety on site; (2) to define the roles of different agents within the framework; and (3) to develop a prototype system to test the proposed approach using several case studies.

This paper is organized as follows. First, the literature review is presented in the "Related Research" section. Then, the "Proposed Approach" section describes the different aspects of the framework of the multiagent system. This is followed by the "Prototype System Development" and the "Case Studies" sections. The last section, "Conclusions, Discussion and Future Work", summarizes the conclusions of this research and discusses the current limitations and the future tasks to overcome these limitations.

Related Research

Path Planning in Multiagent Systems

One of the larger and more complex planning problems in MAS is the path-planning problem. There are several ways of planning for MAS either in a centralized or a distributed manner. The centralized method treats the entire team as a single complex agent and then generates plans for this agent, whereas the distributed method generates plans for individual agents and uses coordination techniques to combine these plans. Because of the the intelligence of agents, each agent can generate a partial plan independently, and the coordination of these partial plans can be centralized or distributed to form a single coherent overall plan (Ferber 1999).

Fig. 1(a) shows a distributed approach in which three agents communicate with one another and make decisions based on the result of their negotiation. Distributed problem solving involves multiple agents that combine their knowledge, information, and capabilities to develop solutions to problems that are difficult to solve by a single agent. An agent is unable to accomplish its own tasks alone, or it can accomplish its tasks better (more quickly, completely, precisely, or certainly) when working with others. Durfee (1999) has discussed the following motivations for using a distributed problem-solving approach: (1) Using parallelism, problem solving can be accelerated; (2) Expertise or other problem-solving capabilities can be inherently distributed; (3) Data are distributed; and (4) The results of problem solving or planning might need to be distributed to be acted upon by multiple agents. Fig. 1(b) shows a centralized approach in which A is acting as a team coordinator to communicate with the team members and is responsible for producing an overall plan. The team members transmit data to the coordinator to form a global view. However, this centralized approach may cause a tremendous amount of unnecessary communication compared to allowing the exchange of information directly among team members. Moreover, the complexity of the problem increases rapidly with the size of the team or the degrees of freedom (DoF) of the equipment; therefore, centralized approaches are typically used with small teams or simple problems. A variation of the centralized approach is that team members draw up their own partial plans independently and send them to the

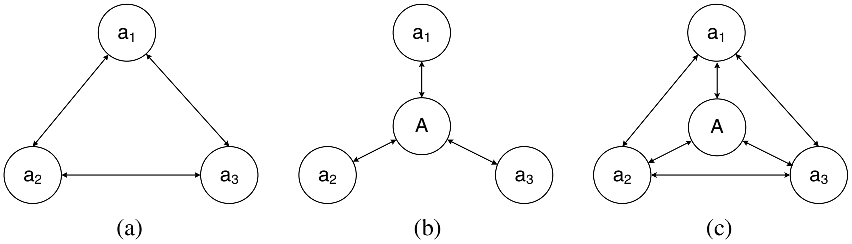

Fig. 1. Different approaches for planning: (a) distributed; (b) centralized; (c) hybrid

coordinator. Then the coordinator tries to synthesize all the partial plans into an overall plan by solving the contradictions among the partial plans. An example is that of using a distributed approach to generate paths for each individual agent. Then a centralized planner schedules the movement of all the agents along their respective paths to ensure that there are no collisions (O'Donnell and Lozano-Pérez 1989). Taking advantage of both centralized and distributed approaches contributes to the hybrid approach, as shown in Fig. 1(c). Kalra et al. (2005) have discussed that the team can work faster if the team members make decisions more locally and achieve coordination by a mechanism that is light on both communication and computation.

Ferguson (2006) has addressed the problem of path planning and replanning in realistic scenarios in the case of a single and multiple agents. Centralized algorithms are explored to deal with the planning problems for teams of agents. To efficiently cope with the high-dimension state spaces involving multiple agents, rapidly-exploring random trees (RRT) algorithms have been selected for path planning and replanning. Tavakoli et al. (2008) have proposed a cellular automata-based algorithm for path planning in MAS with a centralized approach. In this approach, several geographically distributed agents with the same priorities move toward a common goal location. The proposed algorithm distributes the agents to avoid long queues in which only a few possible paths are available toward the goal. These researchers have claimed that the new proposed algorithm is faster than the traditional A* when several agents have a common goal. Marsh et al. (2005) have introduced a simulation to test real-time path planning in a road network. A distributed architecture has been adopted to avoid a system failure caused by the central agent failure. Each agent broadcasts its sensed data to other agents to reduce completion time. Gireesh and Vijayan (2007) have proposed a fuzzy logic approach to secure a collision-free path avoiding multiple dynamic obstacles. A robot is equipped with several sensors, and decisions are taken at each step in the predefined path in the environment. Sud et al. (2007) have presented a novel approach by introducing a new data structure called multiagent navigation graph, which is constructed from Voronoi diagrams. Simulation scenarios consisting of hundreds of moving agents, each with a distinct goal, are used to test the proposed approach for real-time multiagent planning. In the previously mentioned literature, researchers have been actively exploring different methods and trying to effectively solve path-planning problems by considering specific applications. However, none of this research has considered the specific needs of the construction industry.

Motion Planning and Monitoring of Cranes

Although motion-planning algorithms have been studied in computer science and robotics for more than thirty years, little research has focused on motion planning for cranes. Cranes can be treated as robots, and the same motion-planning algorithms can be applied; however, appropriate domain heuristics should be added to find a good/optimal plan within a reasonable time (Reddy and Varghese 2002), and no industry-wide standard exists for heavy lift path-planning practices (Varghese et al. 1997).

In the research of Ali et al. (2005), a genetic algorithm (GA) is used and compared with the A* algorithm for the path planning of cooperative cranes. The former is considered a better solution for two cranes working together. However, the writers have assumed that the site contains only static obstacles, and the proposed solutions provide only offline planning rather than real-time control of the movement. Kang and Miranda (2006) have proposed an incremental decoupled method to plan motions for multiple cranes so that collisions among any of the cranes are avoided as are possible collisions between the cranes and their transported objects. Although this research considered dynamic changes on site to make the path more realistic, it was assumed that the environment information was known by exactly following the work schedule.

The real situation on site is that unknown objects should also be monitored and acounted for to ensure the collision-free movement of cranes. Information about unknown objects can be collected by sensors. In robotics research, sensor-based motion planning incorporates sensor information, reflecting the current state of the environment, into a robot's planning process, as opposed to *classical planning* in which full knowledge of the world's geometry is assumed known prior to the planning event (Choset et al. 2000). In sensor-based motion planning, prior knowledge of the world is not available, is inaccurate, or changes rapidly, and the robot is supposed to sense the data in real-time and make quick responses.

Several technologies can be used to monitor the location of equipment and workers on construction sites. The most popular tracking technologies used on construction sites is a global positioning system (GPS). However, GPS requires a direct line of sight from the satellites to the receiver, and accurate GPS receivers are expensive to install on every moving object on site. Other tracking technologies have been applied in several research projects, such as infrared, optical, ultrasound, and radio frequency identification (RFID) technologies. Chae and Yoshida (2008) have discussed collecting data on site using RFID active tags to prevent collision accidents. However, RFID can give only approximate locations. Recently, RTLSs have been applied in construction to track moving objects. Ward and Webster ["Location device and system using UWB and non-UWB signals," U.S. Patent No. 7,636,062 B2 (2009)] have compared different location technologies, such as passive RFID, electromagnetic, laser, ultrasound, infrared (IR) proximity, conventional radio frequency (RF) timing, UWB, wireless local area network (WLAN), received signal strength (RSS), and assisted GPS (A-GPS). Their comparison was based on the accuracy and the coverage offered by each technology and performed to identify the ideal technology. The result showed that UWB can provide a relatively high accuracy with coverage of approximately 100 m or more, depending on the signal strength of the tags. Giretti et al. (2009) have indicated that UWB behavior is rather constant during most parts of the construction process. They noted that in an open area, tests confirmed an accuracy of approximately 30 cm. Based on the review of different sensing technologies, UWB was selected for the present research to collect location data by the site state agent as explained in the "Proposed Approach" section.

Many of the algorithms for solving motion-planning problems are not amenable to sensor-based interpretation. It is not possible to simply add a step to acquire sensory information and then to construct a plan from the acquired model using a classical technique when the world model is unknown because the robot needs a path-planning strategy to acquire the world model. To address this problem, motion-planning and replanning algorithms were proposed in previous research, as mentioned in the "Introduction". These algorithms efficiently generate safe and smooth paths for crane motion while accounting for the engineering constraints and the path quality (Zhang 2010). This paper investigates how to integrate these algorithms in the crane agents.

Other Research about Safety Monitoring and Agent Systems in Construction

Real-time sensing has made construction site monitoring a reality. On-site information can be exchanged between construction equipment (e.g., excavators, dozers, and an office). SiteLINK 3D and

DigNAV are examples of systems used in practice for positioning and precisely controlling the operation of earthmoving equipment, leading to improved productivity and safety. However, these systems have limited intelligence and are based on a centralized architecture. Fullerton et al. (2009) have proposed using UWB for proactive safety, which works in real time to alert personnel of the dangers arising and for reactive safety, which collects data to be analyzed to determine the best practices and to make process improvements. Carbonari et al. (2011) have proposed safety management systems for tracking workers' trajectories to prevent accidents. Lee et al. (2009) have proposed a safety monitoring system to reduce the rate of fatal accidents on the construction site. However, none of these researches has introduced the concept of agents to organize the different functionalities of the system (i.e., sensing, collision detection, and path planning and replanning).

Some research involving agents has been done to enhance communication between team workers and to solve problems in the construction industry. For example, agent systems have been used for construction claims negotiation (Ren and Anumba 2002) and dynamic rescheduling negotiation between subcontractors (Kim and Paulson 2003). Bilek and Hartmann (2003) have presented an agent-based approach to support complex design processes in architecture, engineering, and construction (AEC). Wing (2006) has presented some research on the application of software agents together with RFID technology in construction. Lee and Bernold (2008) have presented an on-site agent-based communication system for collecting weather information and sending warning messages. To the best knowledge of the writers, no research has focused on applying agent technology to real-time support for crane operators.

Proposed Approach

Assumptions used in Proposed Approach

A construction site has three types of obstacles: static, semistatic, and dynamic. Static obstacles are those obstacles that do not move and about which the geometry information is known in advance. Examples of these obstacles include existing buildings and electrical poles. Several methods can be used to create the three-dimensional (3D) models of static objects. For example, photogrammetry is used for calculating the geometric properties of objects based on photographic images (Walford 2007). 3D modeling with geographic information systems (GIS) is also used to create an urban model based on extruding polygons representing the footprints of buildings on maps according to the heights of the buildings as in ArcGIS 3D Analyst. These data are becoming available in some cities.

Semistatic objects are defined in this research to represent the structures under construction, temporary structures (e.g., scaffolding), and material storage areas. Building information modeling (BIM) data is the primary source of describing the semistatic objects according to the project schedule. Other real-time environment perception technology can also be used to update the BIM based on real construction progress, such as 3D laser scanners (Gordon and Akinci 2005) and 3D range cameras (Teizer et al. 2006).

Dynamic obstacles are objects that move on site, such as workers and construction equipment. These dynamic obstacles should be detected and updated while the initial plan is being executed. Dynamic and semistatic obstacles may necessitate replanning because of potential collisions.

Fig. 2 shows the concept of the proposed methodology for the agent-based near real-time environment updating, motion planning, and replanning of cranes. During the planning stage, a 3D model of the static and semistatic objects is assumed available by using available technologies. Collision-free motion plans are generated for cranes to account for engineering constraints and operation rules based on this 3D model (Zhang et al. 2009a). During the actual construction work, a UWB RTLS is used to capture the location data of dynamic objects. The UWB system consists of several sensors and tags organized in several cells. Multiple UWB tags with identification numbers (IDs) are attached to the different components of cranes (e.g., the boom and the outriggers of a hydraulic crane) at predefined locations to monitor their poses. The number of tags used on site should be decided by considering the DoF for

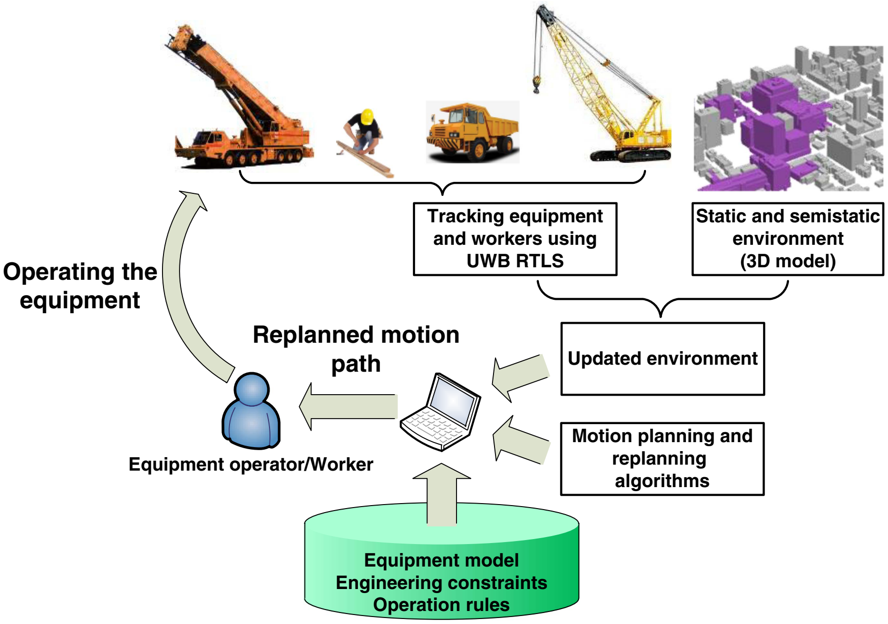

Fig. 2. Conceptual near real-time environment updating and intelligent assistance

J. Comput. Civ. Eng. 2012.26:782-794.

the object monitored (Zhang et al. 2009b). Consequently, moving objects can be modeled, identified, and tracked in such a way that the full geometry, speed, moving direction, and all the related information of the task are used to prevent collision accidents. Buffers are added to the moving objects on site, including the workers, to be used for detecting potential collisions. The size of the buffer can be adjusted according to the accuracy and the update frequency of the UWB system and the velocity of the object. Less accurate data, lower update frequency, and higher velocity require selecting a bigger buffer around obstacles.

The updated environment information is used for detecting any potential safety risks, such as collision between two cranes. In addition, compliance with safety regulations and engineering constraints can be checked to prevent accidents. For example, by providing the feasible configurations of cranes within the capacity limits, the risk of tip over can be reduced.

In the case of a potential collision between cranes, the cranes involved are stopped to ensure their safety. Then, based on the priority of tasks, a new motion plan is generated in near real time according to the updated environment (Zhang et al 2010). Near real-time replanning is defined as finding a new collision-free path for the crane based on the sensed data in a short period of time (a few seconds) after sensors have detected the obstacles. The short delay is caused by two factors: (1) the UWB system has a trade-off between the number of tags in a cell and the update rate; the more tags used, the longer the update rate, resulting in a short delay in synchronizing the tag data; and (2) the time required for calculating the pose of the cranes, detecting potential collision, and path replanning, depends on the hardware used for the calculation.

To provide effective near real-time intelligent support to the crane operators, agent-based technology is proposed to encapsulate knowledge, to organize the information, to make decisions, and to translate the motion plan into actions that can be applied by the operators. Crane operators and other construction staff are supported by agents in the multiagent system for near real-time decision making.

Framework of the Multiagent System

The framework of the proposed agent-based system is shown in Fig. 3. The system design has been revised several times based on the experience of the writers and the discussion with three engineers and experts from crane companies and the Commission of Work Health and Safety of Quebec [Commission de la santé et de la sécurité du travail du Québec (CSST) 2010]. The system design maps of the functionalities of the operators, coordinators, and data collectors in actual construction projects.

Because of the range limitation of the UWB system, the size of one cell is approximately 100 × 100 m. Multiple cells can be used to cover the entire construction area. In a part of the construction site (within one cell), several agents are involved in one or more tasks: crane Agent 1, crane Agent 2, coordinator agent, and site state agent. Each agent has a knowledge base, which consists of domain-specific knowledge that supports decision making. The design of this framework assumes that the agents can be activated or deactivated by the system based on the physical locations of the objects they represent (i.e., inside or outside the monitored area). There is one site state agent, several coordinator agents managing different areas, and multiple crane agents on site.

Crane Agents

A crane agent has the knowledgebase that includes the kinematic constraints, the engineering constraints, and the rules for actions of the equipment. Taking hydraulic cranes as an example, the kinematic constraints (i.e., DoF) can be defined according to the specifications. Engineering constraints are based primarily on the working range and load charts. The working range shows the minimum and maximum boom angle according to the length of the boom and the counterweight. Load charts give the lifting capacity based on the boom length, the boom angle to the ground, and the counterweight. For example, for a Grove crane TSM870 (Manitowoc Crane Group 2008), if the lift object is 6.8 t (15,000 lbs), and the counterweight is 8.2 t (18,000 lbs), the ranges of the three DoFs for this lifting task as extracted from

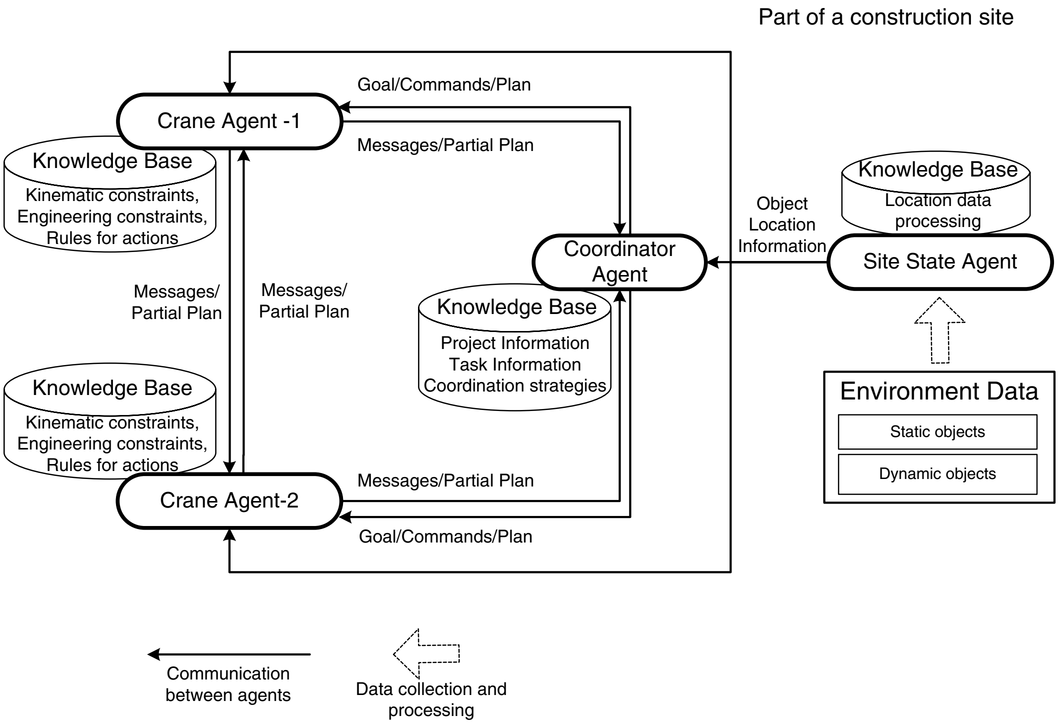

Fig. 3. Framework of agent-based system

the load chart of the crane are (1) boom length: 10.97–33.53 m (36–110 ft); (2) luffing angle: 23 to 80 degrees; and (3) swing angle: −180 to 180 degrees. Furthermore, the range of luffing angles varies according to the boom length; therefore, feasible configurations of the crane are constrained within these ranges. Task parameters are defined in advance, such as the counterweight and the lift weight. Based on this information, the working range of the crane is defined. The motion-planning algorithm uses these ranges to search for a feasible motion path for the crane. Crane manufacturers and large construction companies usually have databases of the different cranes used in their work. These databases include the specifications about the different models of certain types of cranes.

The rules of actions are based on expert opinions related to safety. For example, in the case of two cranes together lifting the same object, the combinations of hoisting and swinging or hoisting and luffing at the same time should be avoided (Shapiro et al. 2000).

Tags are attached to different components of the crane (e.g., the boom, the hook, and the lift object) to monitor the poses (i.e., the position and orientation) of those components. These poses are used by the crane agents to detect potential collisions with obstacles on the path to ensure safety. The motion planning and replanning in near real time is discussed in Zhang et al. (2010). The crane agents can communicate with one another and with the coordinator agent by exchanging messages or partial plans.

Using the location data of moving objects on site, the crane agent applies collision detection for the next movement. If it is not collision-free, replanning is triggered and a new motion path is generated (Zhang et al. 2009b).

Site State Agent

The site state agent is responsible for collecting and processing data about static, semistatic, and dynamic objects on the construction site. As mentioned in the assumptions of the proposed approach, information about static and semistatic objects can be created during the planning stage. The information can be updated according to task schedule of the project and progress monitoring. UWB technology is used to monitor dynamic objects. Location data are collected by the site state agent and processed into useful information to update the state of the environment model (Zhang et al. 2011). The quality of field data and the ability to capture these data in near real time decide the accuracy and feasibility of the system. The knowledge base of the site state a Agent includes location data processing algorithms to achieve the following tasks: (1) classify information related to each object based on its tag IDs; (2) process raw location data from the sensors to describe the full geometry and poses of objects; [e.g., the actual pose of a crane can be generated according to location data transmitted from multiple tags attached to the boom of a crane, raw data are filtered and the missing data are completed by using extrapolation according to previous location data, synchronization is applied to tags in the same group to calculate the pose of the object (Zhang et al. 2011)]; and (3) decide, based on the pose of each object, to which coordinator agent the information of that object should be sent so that each coordinator agent gets the necessary information to ensure safety while avoiding overwhelming the communication bandwidth.

Coordinator Agent

There are several coordinator agents managing different areas on site. The knowledgebase of a coordinator agent includes information about the project and task schedules (macro- and microlevels), the operating cost of equipment, and the safety regulations. The coordinator agent works differently in the following two cases: (1) two or more cranes working together to lift one object; and (2) two or more cranes working on different tasks in the same area for which coordination is needed to avoid conflicts. In the first case, collaboration requirements limit the possible movement of each crane. Accordingly, a centralized approach is preferred to reduce collaboration complexity in which the coordinator agent generates plans for the cranes based on the available data. Some important rules that should be considered in this case are that the distance between the two hooks should be equal to the length between the two attachment points, and crane load lines must be kept plumb at all times for multiple crane lifts (Shapiro et al. 2000). In the second case, the coordinator agent is not responsible for motion planning. It only coordinates the work by deciding the priorities of the cranes.

Once a potential conflict is detected, the involved crane agents communicate with the coordinator agent by exchanging messages, and they make decisions based on negotiation. If replanning is needed, the coordinator agent decides which crane has the higher priority. The agent of the higher-priority crane resumes its path and the other agent replans the path of the lower-priority crane. The priorities of the crane agents are decided according to the following scenarios to select which agent should replan the path:

(1) Safety-based priority The crane with critical safety issues has a higher priority. For example, the crane with the heavier load or the narrower workspace should be given the higher priority.
(2) Task-based priority The tasks on the critical path have priority over other tasks. Based on the project schedule, the tasks on the critical path cannot be delayed because the enntire project would be delayed. In this case, the coordinator agent should give the priority for the use of the limited workspace to the crane that executes the tasks on the critical path.
(3) Time-based priority The crane that has a shorter time in a given workspace for its task should be given a higher priority for movement. For example, the crane that has a one-time access to the area and will not appear again in the same area has the priority to finish its task.
(4) Cost-based priority The crane with a higher operating cost has a higher priority to optimize the budget of the project.
(5) Alternating priority If all the conditions are the same for both cranes, priority can be circulated between them so that each crane has the priority for a certain time period (e.g., one hour).

If more than one priority rule is applicable, a conflict may occur between priorities. For example, if the task of one crane has a shorter time but a lower operating cost than the other crane, the overall priority can be calculated based on functions that quantify the priorities with relative weights and sum them as a single priority value. However, formulating these functions is beyond the scope of the present paper.

In some cases, it is possible to avoid collision by adjusting the velocity of the two cranes instead of replanning the path of one of them. Kang (2005) proposed a decoupled method of planning for two cranes. Plans are generated for each crane separately by ignoring the other during a short period δ, and then by coordinating the two cranes by tuning their relative velocities to avoid collisions. If successful, the system plans the next time period δ until the work is finished. Otherwise, a new δ is considered, and steps are repeated for the entire project. This decoupled method can be applied to replanning. The two crane agents can negotiate with one another to adjust their velocity and avoid collision while considering the above-mentioned priorities. The crane with the higher priority would increase its velocity, and the crane with lower priority would decrease its velocity to allow the first crane to pass without collision.

Fig. 4 describes a scenario of replanning when two cranes have potential collision on their paths. The crane agents start executing their plans and continuously detect potential collisions for the

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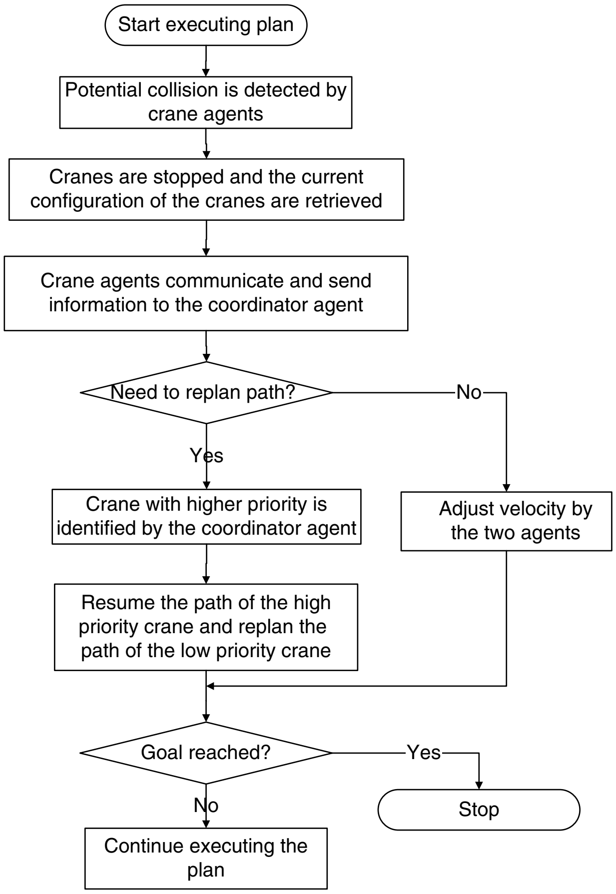


Fig. 4. Replanning scenario flowchart

next movements. Once a potential collision is detected, the crane agents send signals to stop the cranes and retrieve the current cranes' configurations. The crane agents communicate with the coordinator agent to get information about the obstacle and to send information about their paths and tasks to the coordinator agent. The coordinator agent decides whether replanning is needed or if adjusting velocity can resolve the conflict. If there is no need for replanning, the two crane agents negotiate with one another and with the coordinator agent to avoid collision by adjusting their velocities. In an extreme scenario, one crane fully stops and waits till the other crane leaves the conflict area.

Agent Activation and Object Identification

Tags with IDs are attached to moving objects and are linked to the agents representing the specific objects to which they are attached. The methodology of attaching tags onto the objects aims to provide enough tags to capture the pose of the objects and to provide some redundancy of data that can be used to improve the quality of the data and reduce the noise. Tags are attached at predefined positions of an object based on its geometry and kinematic properties so that the pose of the object can be calculated based on the collected data. For example, several tags can be attached to the boom of a hydraulic crane along the length of the boom to provide maximum visibility of tags. Tags can be attached to the base of the first part of the boom and its tip for easy installation and to avoid damaging the tags (Zhang 2010). Different parts of the construction site are monitored by using different sensor cells. All the activities scheduled during a specific time period within a cell are retrieved from the project BIM database (Howard and Bjork 2008). Accordingly, all the equipment expected within the cells are identified and represented by agents in the system. Object identification is important because safety rules are generally applied differently to different object types (Chi and Caldas 2009). The system monitors each object within the monitored area and initializes their agents when they are detected for the first time. Once the object leaves the monitored area, the corresponding agent is deactivated from the system, and the next time it enters the area, the agent is activated again. Information about the object, such as its ID, its task, the duration of the task, and possibly the path of the object, can be retrieved through the agent. Based on this information, the coordinator agent can identify the priority of the new task compared with the current tasks and communicate with each agent involved to coordinate the tasks by avoiding conflicts.

Communication and Negotiation Between Agents

Communication is limited to agents within a part of the construction site in which a task is performed. This partitioning of the site space is necessary to avoid communication bottlenecks. Furthermore, because the dynamic agent system activates and deactivates agents based on the boundary of the monitored area, ad-hoc wireless networking is a good solution for the proposed method (Yang and Hammad 2007). Based on the location of each object, the site state agent decides to which agent the information of that object should be sent. The coordinator agent communicates with all agents that are under its control and receives messages and partial plans from these agents. In addition, it decides the priorities for movement if any conflict occurs, and it sends commands to the agents to avoid collisions.

Negotiation between agents occurs in two scenarios: (1) if a potential collision is detected between the two cranes, in which case the two crane agents negotiate with one another and adjust the velocity to avoid collisions; and (2) if a crane agent rejects the decision made by the coordinator agent, in which case one crane agent may suggest other options based on its own interest. The coordinator agent selects the best option or adjusts it using coordination strategies.

Actions Based on Motion Plan

The motion plan of the crane is represented by a series of configurations that the crane needs to take in a sequence to achieve the goal. The initial configuration and the goal configuration of the crane should be defined according to the task (i.e., the initial and goal locations of the lift object for a lifting task). To support the crane operator, the configuration of each step on the motion path should be translated into a series of actions that can be understood by the operator, such as the instruction to swing the crane boom clockwise by 10 degrees. Taking a hydraulic crane as an example, the movement of the crane during lifting includes the following actions:

boom movement boom up, boom down, boom extend, boom retract, boom swing clockwise, boom swing counterclockwise, and boom stop; and

hook movement hook up, hook down, hook attach, hook release, and hook stop.

Prototype System Development

A prototype system is developed to test the proposed approach by integrating the motion-planning and replanning algorithms with the UWB system and some basic functions of the agent system. Autodesk Softimage is used to take advantage of its 3D visualization and animation capabilities. Motion Strategy Library (MSL), which includes variations of planning algorithms, is used as a base library for developing an integrated motion-planning solution in Softimage. Along with MSL, the Proximity Query Package (PQP) is used for performing collision detection queries on obstacles found in the environment. Ubisense is used as the platform of the near real-time location system. A plug-in of Ubisense is developed to transfer data into Softimage. This allows Softimage to read near real-time location data from the UWB system and to show the traces of the tags that are attached to the physical cranes for updating the location of the virtual crane in the virtual scene.

All software components are integrated into Softimage using its software development kit (SDK) and its C++ application programming interface (API) to ensure a seamless integration that takes full advantage of its 3D capabilities. The 3D environment is created in scenes, including static and dynamic objects.

Fig. 5 shows the partially integrated prototype system design in which it is assumed that two cranes with attached multiple tags are in operation near one another at a construction site. The location data of these two cranes are collected by the UWB sensors and sent to the Ubisense server, which is used by the site state agent. After processing these data into information about object poses, the site state agent uses a plug-in (developed by using the APIs of Softimage and Ubisense) to send the object pose information to other agents. A virtual environment scene is created in Softimage to simulate the actual site with all the obstacles and the two cranes. The two crane agents use the 3D model to generate collision-free motion plans and translate into actions that can be sent to the crane operators using an intuitive graphic user interface (GUI). However, the design of the GUI is beyond the scope of this research. The same actions can be sent directly to the cranes using an autonomous control that is similar to the auto pilot mode of an airplane in which the operators can intervene and take charge of operating the cranes if necessary.

Once the two cranes start executing their tasks, their actual poses are captured by using the UWB system and are sent to Softimage by the site state agent in near real time to update the virtual crane poses in the scene. Each movement of the two cranes in the actual environment is reflected in the virtual scene, and collision detection is applied by the crane agents for the next movement for each crane. In the current prototype system, it is assumed that the only change in the actual environment is the movement of the booms of the cranes. However, other changes can be captured in the future by using laser scanners or other technologies. Once a potential collision is detected by the two crane agents, the coordinator agent gives the priority to one of them based on the priority patterns discussed in "Coordinator Agent" subsection to continue its planned path, whereas the other crane has to replan its path to avoid collision. The priority switching is also embedded in the Softimage plug-in. The communication channels are open between the crane agents and the coordinator agent only, enabling the reporting of potential collisions by the crane agents and deciding the priorities by the coordinator agent. This prototype system can be further extended in the future in a distributed manner by using a specialized agent environment to enhance the multiagent communication and negotiation functions.

Two radio-controlled (RC), scaled (1:18), hydraulic crane models were used in the integrated tests (Hobby Engine, Hong Kong). Each crane has six motors that allow the movement of the body of the crane (drive forward/backward, turn right/left), of the boom (swing right/left, turn up/down, extend/retract), and of the hook (move up/down). A crane can be controlled manually or through the computer by using a remote control with different buttons and joysticks to allow the movement of one DoF at a time. The decision to perform the integrated tests in the laboratory was made because the lab testing environment can be fully controlled and can be repeated as many times as necessary.

Case Studies

The feasibility of using UWB for pose estimation and the path-planning/-replanning algorithms were tested in Zhang et al. (2011) and Zhang and Hammad (2012), respectively. To validate the proposed multiagent system at the integrated system level,

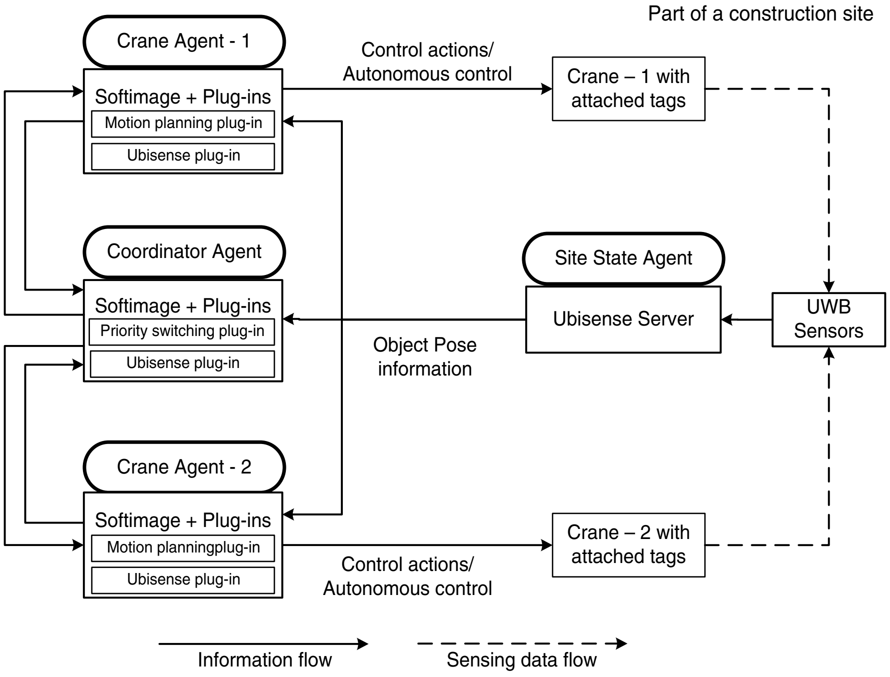


Fig. 5. Integrated prototype system design

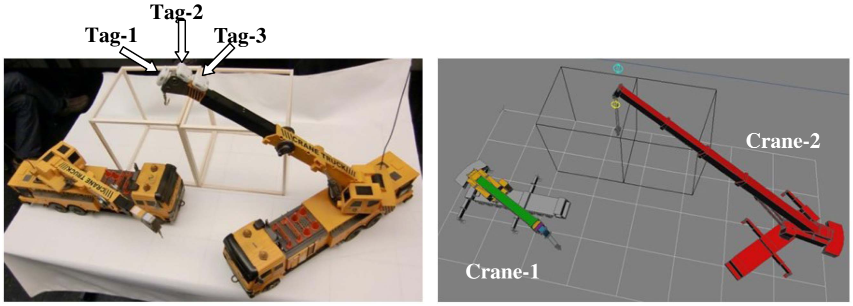
three laboratory tests were performed with the RC-scaled cranes. A simulation environment was built in Autodesk Softimage in which a scene was created with two identical hydraulic cranes (Grove Crane TMS870, Manitowoc Crane Group, Shady Grove, PA). The engineering constraints of these cranes was discussed in the "Cranes Agents" subsection. Computer-aided drafting (CAD) models of the cranes were imported into Softimage. A hierarchy of components and kinematics was created in a 3D environment. Four DoFs were considered in the current work (i.e., boom extension, swing and angle to the ground, and hook up—down movement). In addition, a model of a steel structure with 596 elements was created in the simulation environment. The steel structure represented static objects that were considered in the third case study when performing collision detection during the planning stage. The cranes were considered dynamic objects during the replanning stage.

The lab tests were simplified to focus only on the tags attached to the boom tip. The location of the base of the boom was fixed in the virtual scene; consequently, the movement of the boom of the virtual crane was defined by the tags attached to the boom tip. Three tags were attached to the boom tip to improve accuracy and visibility, and the average location of these tags was used to guide the movement of the boom in the virtual scene. Virtual tags were created in Softimage to show the locations of the tags attached to the crane. Furthermore, geometric constraints were used to control the movement of the virtual crane based on the location of the tags attached to the tip of the crane's boom. Three case studies have been applied for testing the functionalities of agents and the communication between them.

Case Study 1: Site State Agent

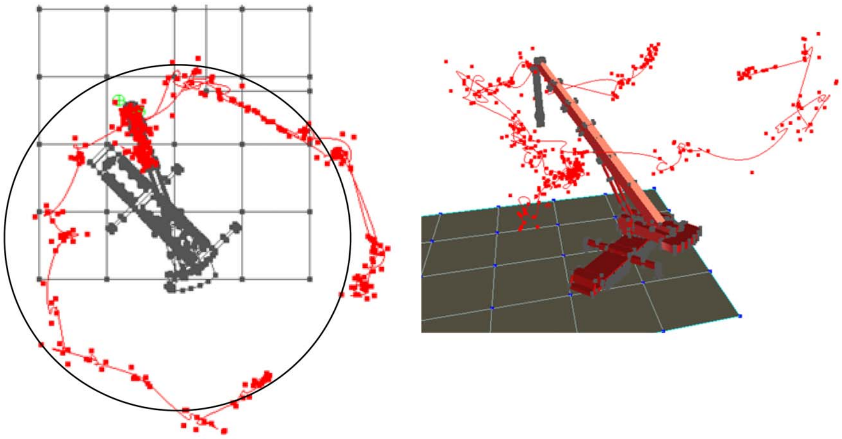
The purpose of this case study was to verify the performance of the site state agent in processing location data with the UWB system. The actual crane boom movement was visualized in the virtual environment and was used by the crane agent to detect potential collisions. In the test, the actual crane was moved by raising and extending the boom, then swinging the boom clockwise 170°, followed by swinging it counterclockwise by 340°; consequently, the boom moved on the surface of a cone and its tip moved on a horizontal circle. Three tags (Tag-1, Tag-2, and Tag-3) were used to improve visibility and accuracy, as shown in Fig. 6(a). About two hundred readings were collected for each tag for the swing motion. Location data calculated based on these three tags were used to update the position of the virtual boom because the base of the crane was fixed during the test. Fig. 7 shows the average trace of the boom tip in top and 3D views. The circle in Fig. 7(a) shows the real path of the boom tip.

The accuracy of the data was evaluated by measuring the difference between the radius of the real circle path r and the measured radius r' based on the collected data in 2D (i.e., x- and y-axes). Adjustments were made according to the tags' locations relative to the boom tip. The accuracy in the z-dimension was evaluated separately. Table 1 shows the accuracy analysis results. As shown



(a) (b)

Fig. 6. (a) Scaled cranes and (b) their virtual models



(a) (b)

Fig. 7. Boom tip trace: (a) top view; (b) three-dimensional view

Table 1. Accuracy Analysis

Tag	Mean radius difference (cm)	Standard deviation of radius difference (cm)	Mean difference in Z-direction (cm)	Standard deviation of difference in Z-direction (cm)
Tag-1	3.63	10.04	4.00	9.22
Tag-2	−6.36	10.83	5.18	10.87
Tag-3	−6.72	11.50	6.27	10.87
Average	−5.69	10.08	3.31	6.07

in the table, the averaged location data based on three tags can be used for updating the boom location with a good accuracy.

Case Study 2: Crane Agent

Crane Agent-1 was tested for collision detection and replanning based on environment information updated in near real time through the site state agent. Fig. 6(a) shows the two scaled crane models; UWB tags were attached to the tip of the boom of Crane-2, and a simple frame structure represented static obstacles. Fig. 6(b) shows the virtual models representing the cranes and the frame structure. It was assumed that the task of Crane-2 was on the critical path because the right part of the building had to be finished before the left part. Therefore, Crane-2 had a higher priority than Crane-1. The location data of the UWB tags attached to Crane-2 were used to update its pose in the virtual model, as described in Case Study 1.

The scaled model Crane-2 was controlled by using the remote controller to swing the boom in a way that blocked the movement of Crane-1. The pose of Crane-2 was calculated by the site state agent and sent to Crane Agent-1. In the virtual scene, the movements of the boom of Crane-2 followed the physical scaled crane. and a potential collision was detected by Crane Agent-1. Then, motion replanning was triggered to generate a new path by Crane Agent-1, and Crane-1 followed the new path to avoid a potential collision with Crane-2. The test successfully demonstrated the applicability of the proposed methods for tracking and motion replanning at the level of the integrated system as functions of the proposed multiagent system.

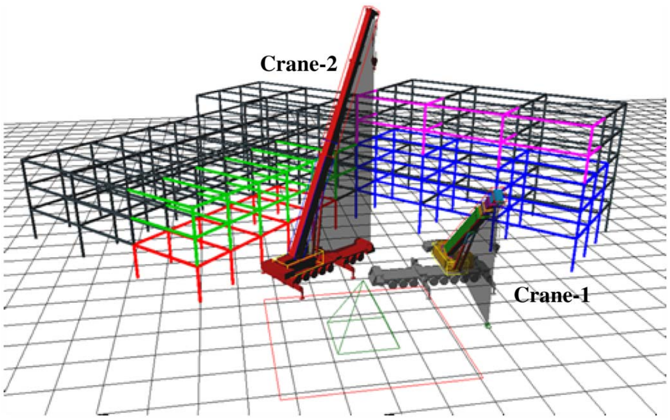


Fig. 8. Two cranes operating in the same area

Case Study 3: Coordinator Agent

The purpose of this case study was to demonstrate the role of the coordinator agent in managing the priorities of two cranes operating in the same area. In this case study, multiple lifting tasks were executed by each crane for erecting different elements of the steel structure, as shown in Fig. 8. These multiple tasks collectively represented a macrotask in the project schedule. The tasks executed by Crane-2 consisted of lifting the columns and beams of the left part of the structure. The tasks executed by Crane-1 consisted of lifting the columns and beams of the right part of the structure. The pyramid shape represents the picking area of the steel elements. Inverse kinematics were used to define the initial configurations and the goal configurations of the cranes based on the tasks. The motion-planning algorithm integrated in the crane agents was used to find collision-free and time-efficient paths. Fig. 9 shows two snapshots of the simulation before and after detecting a potential collision.

In this case study, two scenarios were simulated. In the first scenario, it was assumed that the macrotask of Crane-2 was on the critical path of the project; consequently, the coordinator agent gave the priority to Crane-2 to guarantee that the project would not be delayed. If a potential collision had been detected, the high-priority crane (Crane-2) would be considered an obstacle for the low-priority crane (Crane-1) when Crane-1 replanned its path. In the second scenario, it was assumed that both cranes had equal priority; consequently, the coordinator agent decided to alternate

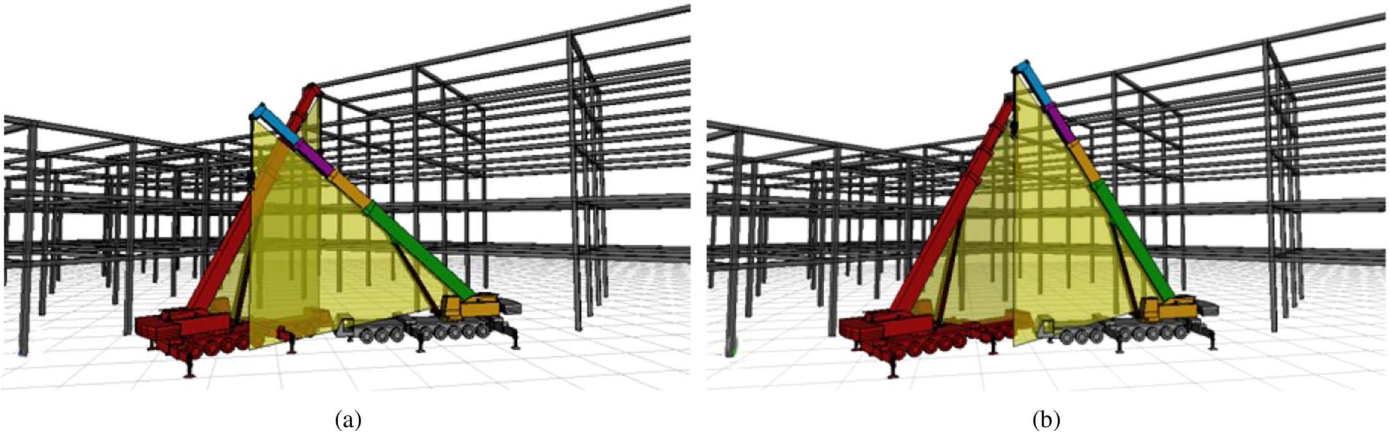

(a) (b)

Fig. 9. Simulation before and after detecting a potential collision: (a) potential collision detected; (b) collision avoided

J. Comput. Civ. Eng. 2012.26:782-794.

the priorities between the two cranes each time a collision was detected. Both scenarios were successfully tested, demonstrating the feasibility of changing priorities by the coordinator agent.

Conclusions, Discussion and Future Work

This paper has proposed a multiagent approach to improve crane operation safety by integrating motion planning and real-time environment updates. The merit of using agents is to encapsulate the UWB data processing and path-planning/-replanning algorithms and to hide the complexity of their details so that the overall behavior of the multiagent system can be explained by simple results. The following objectives were met: (1) a framework of the proposed agent system was discussed in detail. This framework had several agents supporting construction crews. The functionalities of the crane agents, coordinator agent, and site state agent were described, including sensing, communication, and decision making based on priorities; (2) a replanning mechanism was described by coordinating the tasks of the different agents to improve on-site safety by providing real-time data capturing and collision avoidance; (3) agent activation, object identification, communication, and negotiation between agents was investigated to specify the functionalities of the agents applied in coordinating construction equipment operations. In addition, a method for translating the motion plan into executable actions was proposed to guide the construction equipment operators; and (4) the proposed approach was tested by developing a prototype system and applying it in three case studies.

The proposed approach is expected to affect the construction industry by improving safety and eliminating delays caused by unforeseen spatial problems on the construction site therefore, improving productivity. Assisted by the intelligent agents, solving conflicts can be faster than the conventional manual methods. Real-time collision avoidance can be achieved by providing more awareness of the site situation and decision making through communication and negotiation between multiple agents. In addition, the framework of the multiagent system defines the basic functionalities of the system to support construction staff, and it can be extended to include other types of agents, such as agents supporting workers on foot. The prototype system was presented to engineers and experts from two crane companies and the Commission of Work Health and Safety of Quebec (CSST 2010). These engineers and experts provided the writers with a positive evaluation for applications of the present research in practice.

The intelligence of the multiagent systems can be extended from the replanning of equipment paths to a more advanced concept, which the writers call Smart Construction Site (SCS) (Zhang et al. 2009a). A vision of SCS can be established in which every worker, operator, and staff has intelligent support from agents encapsulating knowledge and decision-making strategies. Environment information is obtained and updated by using 3D scanners, range cameras, or sensors attached to moving objects on site. Path planning and replanning of equipment is done automatically to help the operators fulfill their tasks safely and efficiently. The benefits of a SCS are

Safety assurance Each moving object on site can be monitored and tracked with a precise location, and a warning system can be developed to warn the workers and operators when a potential accident is detected;

Productivity control The tracking records can be used to analyze worker and equipment performance and estimate their productivity;

Quality control More awareness of the site situation by tracking different equipment can help the staff make better decisions; and

Site Concept Construction staffs have a better understanding of the work process by visualizing the paths of equipment.

There are several limitations in this research:

1. The proposed framework has not been fully implemented. The roles and the relationships of agents were defined for this research; however, the framework needs to be refined by investigating the details of the negotiation between two crane agents when adjusting velocity. Furthermore, other development tools should be explored to develop more efficient agent system. The writers have explored some tools, such as Jadex (), which is a Java-based, foundation for intelligent physical agents (FIPA)-compliant agent environment for the development of goal-oriented agents.
2. There is no simple GUI that can support crane operators by showing the environment information in real time. A user-friendly GUI needs to be developed to support crane operators without otherwise disturbing their concentration.
3. Several practical problems exist. For example, the maximum number of tags that can be used to obtain certain an update rate is limited. This limitation should be explored by applying other commercial UWB systems to improve the scalability of the system. Furthermore, cables that connect the sensors may disturb construction activities; therefore, a wireless system should be investigated.

The writers' future work will try to overcome these problems. Furthermore, more testing should be undertaken on actual construction sites to test the functionalities of the proposed multiagent system in real situations. In addition, the proposed system could benefit from the integration with other systems, such as the progress monitoring of the project using BIM techniques, by exchanging information about the planned schedule, and the actual progress of the work on site.

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