MULTI-AGENT-BASED APPROACH FOR REAL-TIME COLLISION AVOIDANCE AND PATH RE-PLANNING ON CONSTRUCTION SITES

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ABSTRACT: Collisions on construction sites are one of the major causes of fatal accidents. The complexity of equipment operations require detailed planning and better real-time control of the work. Research involving artificial intelligence in construction industry has been done to enhance communication between team workers and resolve distributed problems, for example, agent systems have been used for construction claims and dynamic rescheduling negotiation. However, little research has focused on real-time control of construction equipment operations using agents to improve safety on site. The present paper proposes a multi-agent-based approach to provide real-time support to the construction staffs. Collision avoidance is achieved by informing workers and equipment operators about potential collisions, and by providing re-planning for equipment. A prototype system has been developed to and the functionalities of different agents are successfully tested.

Keywords: *Multi-agent, Real-time, Collision Avoidance, Path re-planning, Construction Site*

1. INTRODUCTION

A construction site is a dynamic and complex environment where different work teams are working together. A common case is that one general contractor works with several sub-contractors, 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 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. Macro and micro plans 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.

Even though detailed motion planning and efficient re-planning in near real-time are applied, the safety problems may not be completely solved without coordinating the tasks of different equipment working in the same area. In addition, a micro plan 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 equipment's movement based on negotiation among construction team members. The priorities of tasks also need to be considered when a conflict between two tasks is detected. Beavers et al. [1] have suggested that employers should have a system in place to assess the hazardousness of their construction worksites in relation to the potential of crane-related events. This need has inspired our research aiming to investigate the possibility of an intelligent system to support on-site workers by providing better communication and environment awareness. Therefore, multi-agent technology is proposed in this research to explore the feasibility of its application in construction to enhance safety.

The concept of agents in Artificial Intelligence (AI) refers to relatively independent and autonomous entities, which operate within communities in accordance with complex modes of cooperation, conflict and competition in order to survive and perpetuate themselves [2]. Agent systems have been used for construction claims negotiation [3] and dynamic rescheduling negotiation between subcontractors [4]. However, to the best knowledge of the authors, no research has focused on applying agent technology to real-time support for construction staffs.

In the present paper, a new approach based on multiple agents is proposed to provide real-time support to the construction staffs to improve safety on site. A multi-agent framework is developed to simulate the working environment of equipment and workers on site. Dynamic virtual fences are created near dangerous areas for workers and real-time warnings and guidance is provided to workers to mitigate safety risks. Location data are collected by using a Real-time Location System (RTLS) to calculate the positions of workers and the poses of equipment on site for collision avoidance purpose. A prototype system has been developed and a case study has been described in detail.

2. PROPOSED FRAMWORK

2. 1 Framework Structure

Fig. 1 shows the framework of an agent-based system for collaborative cranes. In a part of the construction site, several agents are involved in one or more tasks: *Equipment Agent-1*, *Equipment Agent-2*, *Worker Agent-1*, *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.

2. 1.1 Equipment Agents

An *Equipment Agent* has the knowledge base 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., the degrees of freedom (DoFs), can be defined according to the specifications. Engineering constraints are based mainly 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. 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 experiences. For example, in the case of two cranes lifting together the same object, the combinations of hoisting and swinging or hoisting and luffing at the same time should be avoided [5]. Taking scissor lifts as another example, one operation rule is that it is not allowed to move a lift to a new position when the worker is on it unless it is at the lowest position.

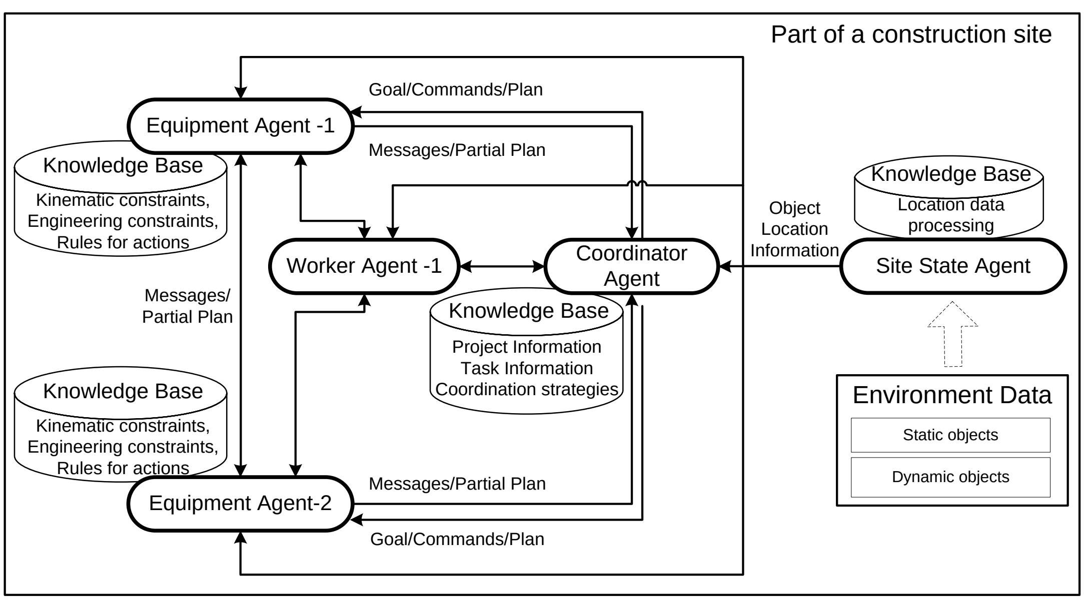

Fig. 1 Framework of multi-agent-based system.

Tags are attached to different components of the equipment (e.g., the boom, the hook, and the lift object of a crane) to monitor the poses (i.e., the position and orientation) of those components. These poses are used by the *Equipment Agent* to detect potential collisions with obstacles on the path to ensure safety. The motion planning and re-planning in near real time is discussed in detail in [6]. The *Equipment Agents* can communicate with each other and with the *Coordinator Agent* by exchanging messages or partial plans.

2.1.2 Worker Agents

A *Worker Agent* supports a worker on foot. Multiple tags are attached to a worker to monitor the position of the worker. Dynamic virtual fences are created automatically by the *Site State Agent* (see Subsection 2.1.3) based on the work space of construction equipment. The *Worker Agent* calculates the distances between the worker and the virtual fences. If the minimum distance is less than a predefined threshold value, a signal will be sent by the *Worker Agent* to the worker. In addition, if necessary, guidance to a safe area will be given to the worker by using a Graphical User Interface (GUI) on a small device, such as a smart phone, on which a graphical representation of the construction environment and the location of the worker can be shown. When the task of the equipment is finished, the related virtual fences are removed.

2.1.3 Site State Agent

The *Site State Agent* is responsible for collecting and processing data about static and dynamic objects on the construction site. Models of static and semi-static objects can be created during the planning stage using Geographic Information Systems (GIS) and Building Information Modeling (BIM). These models can be updated according to the project and task schedule. For example, newly built structures become obstacles for the next operation. Dynamic objects include moving objects on site, such as cranes, workers, and materials transported by the equipment. UWB technology is used in the present research 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 [7]. The quality of field data and the ability to capture in near real time decide the accuracy and feasibility of the system. The knowledge base of the *Site State Agent* includes location data processing algorithms to achieve the following tasks: (1) classifying information related to each object based on its tags' IDs; (2) processing raw location data from the sensors to describe the full geometry and poses of objects. For example, a simplified bounding box can be generated according to location data transmitted from multiple tags attached to the boom of a crane; (3) deciding, based on the position of each object, to which agent the information of that object should be sent so that each agent gets the information necessary to ensure safety while avoiding overwhelming the communication bandwidth.

2.1.4 Coordinator Agent

The knowledgebase of the *Coordinator Agent* includes information about the project and task schedules (macro and micro levels), the operating cost of equipment, and the safety regulations. The *Coordinator Agent* coordinates the work by deciding the priorities of the equipment. Once a potential conflict occurs, the involved agents communicate with the *Coordinator Agent* by exchanging messages and they make decisions based on negotiation in a hybrid approach. One efficient method to avoid collisions is to adjust the velocities of the equipment instead of re-planning the paths [8]. This decoupled method can be applied to re-planning when two *Equipment Agents* can negotiate with each other to adjust their velocities to avoid collision. If there is no way to avoid collision by adjusting the velocities, re-planning should be done by one of the *Equipment Agents*. In this case, the priority is decided by the *Coordinator Agent*, and the agent that has the lower priority has to re-plan the path for the corresponding equipment.

The priority of the *Equipment Agents* is decided according to the following scenarios in order to select which agent should re-plan its path: (1) Safety-based priority, (2) Task-based priority, (3) Time-based priority, (4) Cost-based priority, and (5) Alternating priority. These priority scenarios have been identified according to our discussion with construction engineers. In certain cases, more than one priority rule can be applied resulting in a conflict between these priorities. However, these cases are beyond of the scope of the present research.

2.2 Agent activation and object identification

Tags with IDs are attached to moving objects and are linked to the agents representing the specific objects they are attached to. Different parts of the construction site are monitored using different sensor cells. All the activities scheduled during a specific time period within a cell are retrieved from the project BIM database [9]. Accordingly, all the workers and equipment expected within the cells are identified and represented by agents in the system. Object identification is important since safety rules are generally applied differently to different object types. 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 can be retrieved through the agent, such as its ID, its task and the duration of the task, and possibly the path of the object. Based on this information, the *Coordinator Agent* can identify the priority of the tasks and communicate with each agent involved to coordinate the work and avoid conflicts.

2.3 Communication and negotiation between Agents

The communication is limited to agents within a part of the construction site where a task is carried out. 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 [10].

Negotiation between agents occurs in two scenarios: (1) if a potential collision is detected between the two pieces of equipment, the two *Equipment Agents* negotiate with each other and adjust the velocity to avoid collisions; (2) negotiation also happens when an *Equipment Agent* rejects the decision made by the *Coordinator Agent*. The *Equipment Agent* may suggest other options based on its own interest. The *Coordinator Agent* selects the best option and adjusts it using coordination strategies. It should be noted that there is no negotiation between the *Worker Agents* and the *Equipment Agents* because the workers on foot always have the highest priority.

3. PROTOTYPE SYSTEM DEVELOPMENT

A partially integrated prototype system is designed where it is assumed that two cranes with attached multiple tags are in operation near each other in a construction site. The prototype system integrates the basic functions of different agents with the motion planning and re-planning algorithms, and an Ultra Wideband (UWB) system. Autodesk Softimage [11] is used to take advantage of its 3D visualization and animation capabilities. Motion Strategy Library [12], which includes variations of planning algorithms, is used as a base library for developing an integrated motion planning solution in Softimage. Ubisense software [13] is used as the platform of the near real-time location system. A plug-in of Ubisense is developed to transfer data into Softimage.

Two radio-controlled (RC), scaled (1:18) hydraulic crane models were used in the integrated tests. 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). To control multiple cranes in the same area by a computer, one remote controller was interfaced with a microcontroller connected to the computer with a USB cable. An encoding scheme was implemented allowing for sending commands from the computer equivalent to pushing buttons on the remote control. Furthermore, the receiver circuits of the scaled cranes were modified to react only to commands sent to that specific crane. As a result, it became possible to send a series of commands from the computer that controlled each crane separately using software developed in C++ based on the API library of the microcontroller.

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 them into actions that can be sent to the crane operators. The two RC crane models with attached tags are controlled wirelessly to execute the generated motion plans. Once the two cranes start executing their tasks, 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 of object poses, the *Site State Agent* communicates the information with other agents.

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 of each crane. 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 Subsection 2.1.4 to continue its planned path, whereas the other crane has to re-plan its path to avoid collision.

4. INTEGRATED TESTS

The *Crane Agent* is tested for collision detection and re-planning based on environment information updated in near real time. Figure 2(a) shows a picture of the two scaled crane models, with UWB tags attached to the tip of the boom of Crane-2 and with a simple frame structure representing static obstacles. Figure 2(b) shows the virtual models representing the cranes and the frame structure.

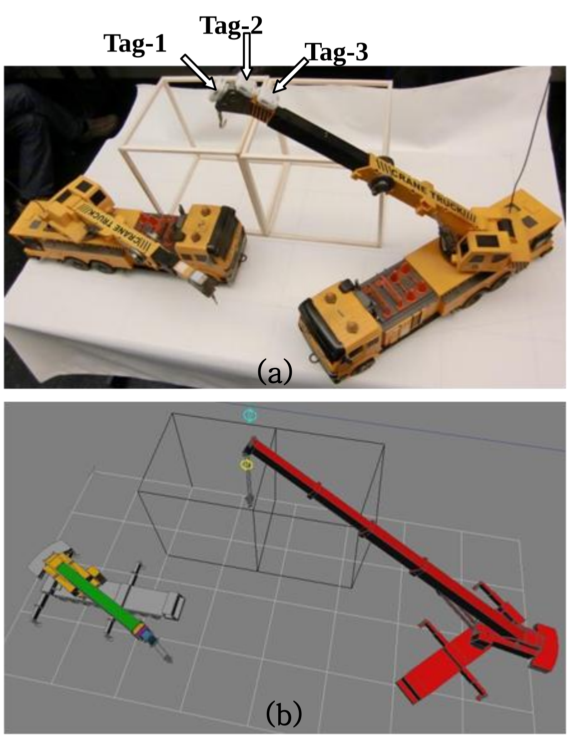

Fig. 2 Radio-controlled cranes and virtual cranes.

It is assumed that Crane-2 has a higher priority than Crane-1 based on the safety, task, cost, or time factors related to the tasks that are executed. The location data of the UWB tags attached to Crane-2 were used to update its pose in the virtual model. *Crane Agent-1* detects potential collisions for the next movement of Crane-1 based on this updated virtual model. The scaled model of Crane-2 was controlled by using the remote controller to swing the boom in a way that blocks the movement of Crane-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 re-planning was triggered to generate a new path by the *Crane Agent-1* and Crane-1 followed the new path to avoid potential collision with Crane-2. The test successfully demonstrated the applicability of the proposed methods for tracking and motion re-planning at the level of the integrated system.

The *Coordinator Agent* is tested in managing the priorities of the two cranes when a potential collision is detected. In this test, it was assumed that the two cranes were erecting different elements of a structure. Two scenarios were simulated. In the first scenario, it was assumed that the macro task 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 was not delayed. If a potential collision was detected, the high-priority crane (Crane-2) was considered as an obstacle for the low-priority crane (Crane-1) for re-planning its path. In the second scenario, it was assumed that both cranes had equal priority; consequently, the *Coordinator Agent* decided to alternate 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*.

5. CONCLUSIONS AND FUTURE WORK

The present paper has proposed a multi-agent-based system to improve the safety on construction site by providing collision avoidance and path re-planning in near real time. Motion planning and real-time re-planning for equipment are integrated in the agent system based on an updated environment using an RTLS system. A framework of the proposed agent system has been discussed in detail. This framework has several agents supporting construction crews. The functionalities of the *Equipment Agents*, *Worker Agents*, *Coordinator Agent*, and *Site State Agent* have been described including sensing, communication and decision-making.

Prototype system development and integrated tests have been described. The proposed approach is expected to have impact on the construction industry by improving safety and eliminating delays caused by unforeseen spatial problems on the construction site; therefore improving productivity. This prototype system can be further extended in the future by using a specialized agent environment to enhance the multi-agent communication and negotiation functions.

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