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COLLABORATIVE MULTI-AGENT SYSTEMS FOR CONSTRUCTION EQUIPMENT BASED ON REAL-TIME FIELD DATA CAPTURING

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SUMMARY: *This paper proposes collaborative multi-agent systems for real-time monitoring and planning on construction sites. A multi-agent system framework is discussed to support construction equipment operators by using agents, wireless communication, and field data capturing technologies. Data collected from sensors attached to the equipment, in addition to an up-to-date 3D model of the construction site, are processed by the multi-agent system to detect any possible collisions or other conflicts related to the operations of the equipments, and to generate a new plan in real time. The potential advantages of the proposed approach are: more awareness of dynamic construction site conditions, a safer and more efficient work site, and a more reliable decision support based on good communications.*

KEYWORDS: *Collaboration, Multi-agent technology, Construction equipment, Real-time, Field data capturing, Path planning*

REFERENCE: *Zhang C, Hammad A, Bahnassi H (2009) Collaborative multi-agent systems for construction equipment based on real-time field data capturing, Journal of Information Technology in Construction (ITcon), Vol. 14, Special Issue Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning, pg. 204-228, http://www.itcon.org/2009/16*

1. INTRODUCTION

Safety and productivity issues on construction sites are always among the major concerns of project managers. Many construction activities are carried out in a multi-equipment environment to achieve a specific goal, such as two cranes working together to lift heavy or big objects. The complexity of on-site conditions requires careful planning and coordination of different equipment to ensure safety and efficiency. Considering cranes as an example, in 2006, there were 72 crane-related fatal occupational injuries in the U.S. (Crane-Related Occupational Fatalities, 2008). In Canada, there were 56 accidents related to cranes in the province of British Columbia in 2006 (WorkSafeBC, 2008); and during the period of 1974 to 2002, there were 23 accidents with injuries, 26 accidents with death, and 13 accidents with material damage related to cranes in Quebec province (CSST, 2008). Furthermore, the numbers of reported accidents and the resulting deaths are increasing during the past 10 years (Crane Accident Statistics, 2008). It is estimated that one crane upset occurs during every 10,000 hours of crane use. Approximately 3% of upsets result in death, 8% in lost time, and 20% in damage to property other than the crane. Nearly 80% of these upsets can be attributed to predictable human error when the operator inadvertently exceeds the crane's lifting capacity (Davis and Sutton 2003). FIG. 1 (a) and (b) show two cranes working together to lift a deck panel in a bridge rehabilitation project (Zaki and Mailhot, 2003). The existing truss structure (FIG. 1 (b)) put spatial constraints on the job, and careful planning was done to ensure the safety on site.


(a) (b)

FIG. 1: Cranes working together to lift a deck panel (Zaki and Mailhot, 2003)

The objectives of the present research are: (1) to propose a new approach for guiding operations in collaborative work considering engineering and spatial constraints updated from real-time data collection and information exchange technologies; (2) to investigate different algorithms for path planning, path re-planning, and centralized and distributed decision-making; (3) to take advantage of multi-agent technology for supporting construction operators and engineers; and (4) to review emerging technologies for field data capturing, including the detection of both static and dynamic objects.

2. LITERATURE REVIEW

2.1 Simulation of Construction Processes

To achieve better understanding of construction processes, simulation tools have been developed to: (1) simulate and visualize these processes (FIG. 3) (Kamat and Martinez, 2001), (2) analyze and avoid collisions between equipment (Zhang et al., 2007), (3) test and visualize equipment location and then plan the path manually (Cranimation, 2006; LiftPlanner, 2006), and (4) train operators of heavy equipment using virtual reality (Simlog, 2006). Training simulation for equipment operation has been used as an effective and cost-efficient tool for the operators (Ritchie, 2004).

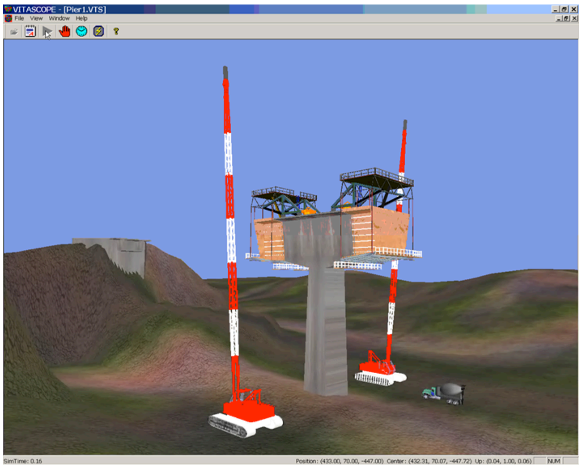


FIG. 3: VITASCOPE animation snapshot of a construction site (Kamat and Martinez, 2001)

The advantage of visualizing the work is that the user can simulate and check the functional constraints and interferences that may happen in reality between the 3D physical elements and virtual workspaces. However, the visualization part is based on the results of the simulation, which is not equipped with any collision detection mechanism, and it does not have any feedback about the unplanned environment changes. Therefore, if a spatial problem is detected in the visualization phase, the simulation has to be repeated after changing the input data.

In the simulation and visualization software, a 3D environment representing the site is necessary, which should include static objects, such as existing buildings, and dynamic objects, i.e., moving equipment and people. Several methods are used to create the 3D environment. Photogrammetry is used for calculating geometric properties of objects based on photographic images (Photogrammetry, 2008). Geographic Information Systems (GIS) based 3D modeling is also used to create an urban model based on extruding polygons representing building footprints in maps according to the heights of the buildings (GIS for Archaeology, 2008). These data are becoming more available in some cities. As shown in FIG. 5, the downtown campus of Concordia University is highlighted in a partial 3D model of Montreal City. FIG. 7 shows a crane located in a 3D environment for planning purpose (Cranimation, 2008). However, these models include mainly buildings and miss other small objects, such as the traffic signs, fire hydrants, and electric poles and lines. Plans generated based on these simplified models may not fit the real environment with more complex static and dynamic objects, and this may cause safety problems and require re-planning. Dynamic objects should be detected and tracked in real time and the resulting information can be used for path re-planning, as will be discussed in Subsection 3.2.1.

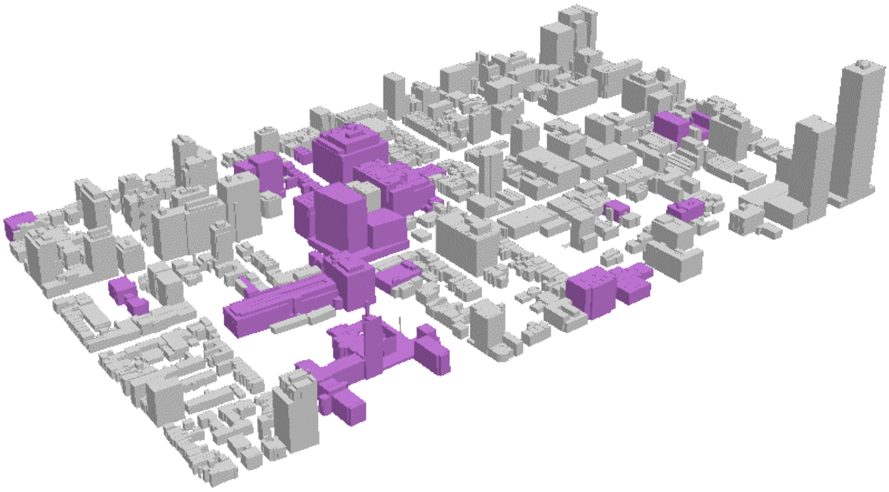


FIG. 5: GIS based 3D model of partial downtown area in Montreal

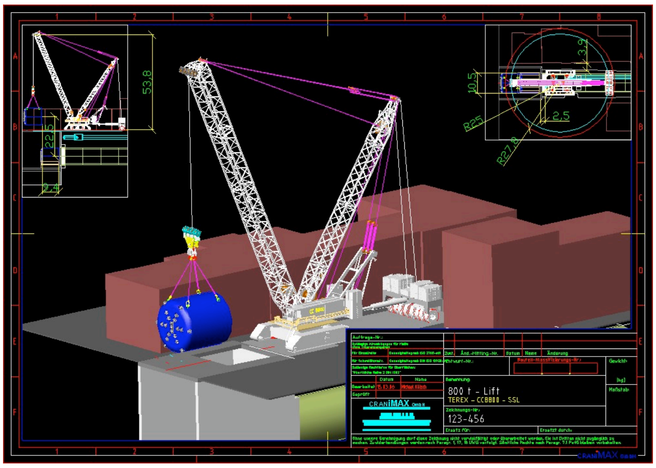


FIG. 7: Crane located in a 3D environment (Cranimation, 2008)

One method to represent the physical spaces occupied by objects on site is to create virtual workspaces to enhance safety, such as defining the workspaces of equipment as safety zones for carrying out specific tasks. In a study about the bridge rehabilitation project mentioned in Section 1, simplified shapes are used to represent the workspaces of equipment and to analyse possible collision between equipment, and between equipment and obstacles. FIG. 9 (Zaki and Mailhot, 2003) show a schematic representation of two cranes working together on the bridge. FIG. 11 (a) and (b) (Hammad et al., 2007) shows the side view and the top view of the workspaces representation on the bridge, respectively. However, the analysis only deals with the static environment without considering the dynamic features on site, thus reducing the practical value in supporting decision-making in real time.

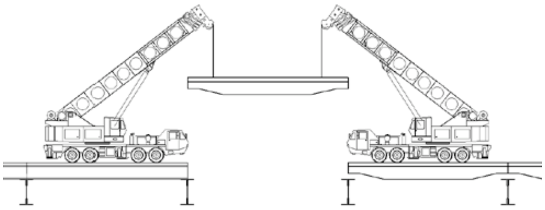
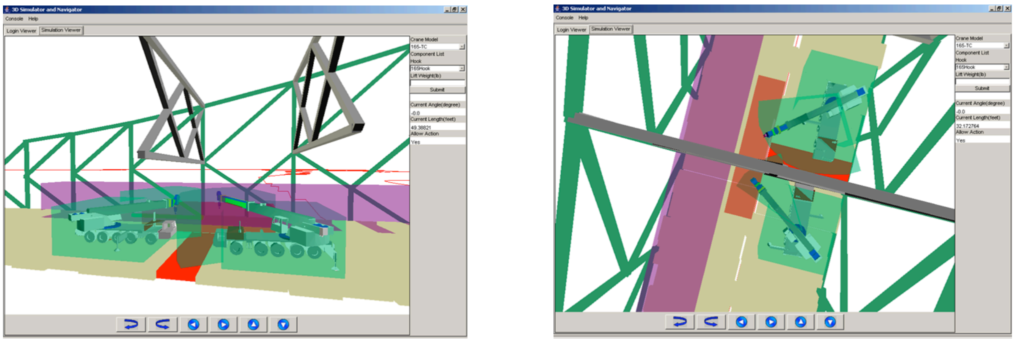


FIG. 9: Schematic representation of two cranes (Zaki and Mailhot, 2003)



Crane Model: 165-TC
Component List
Hook: 165Hook
Lift Weight(lb):
Current Angle(degree): -0.0
Current Length(feet): 49.38821
Allow Action: Yes

Crane Model: 165-TC
Component List
Hook: 165Hook
Lift Weight(lb):
Current Angle(degree): -0.0
Current Length(feet): 32.172764
Allow Action: Yes

(a) Side view (b) Top view

FIG. 11: Workspaces representation on the bridge (Hammad et al., 2007)

2.2 Path Planning for Coordinating Multiple Equipment

As discussed above, development in simulation software and visualization is making it possible to visualize simulation and train equipment operators using virtual reality. However, these simulation tools focus on equipment working individually rather than coordinating the work of several pieces of equipment working on different tasks at the same time. Furthermore, in many cases, multiple equipment should coordinate their work on the same task for achieving specific goals, such as two mobile cranes working together to lift a heavy object. As mentioned by Kang and Miranda (2006), "…very large cranes are often much more expensive and less available in certain areas. In many cases, modifying the design to allow the use of several smaller cranes may instead decrease cost and availability problems." Therefore, path planning for coordinating multiple equipment in either single or multiple tasks is necessary.

Varghese and his colleagues have been studying crane path planning and the cooperative work for a long time. They have tried different algorithms, such as A*, and Genetic Algorithms (GA), for optimizing the path for cooperative lift with two cranes (Sivakumar et al., 2003; Ali et al., 2005). FIG. 13 shows a path traced by hook ends of two cooperative manipulators using GA search. However, they assume that the site contains only static obstructions, and the proposed solutions only provide off-line planning, rather than real-time control of the movement.

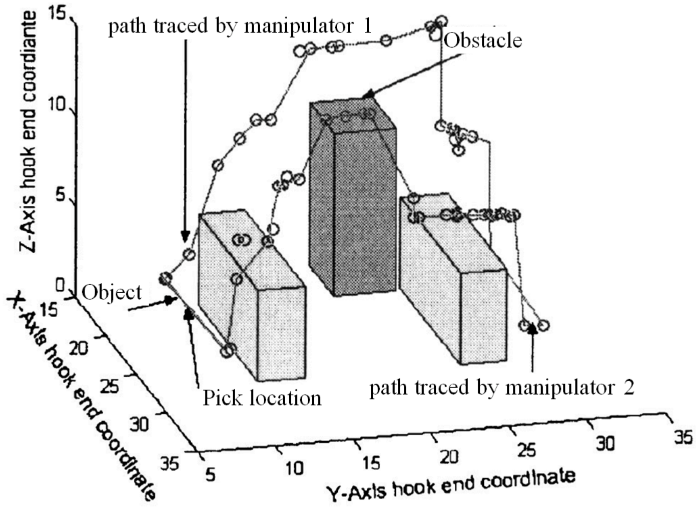


FIG. 13: Path of cooperative manipulators using GA search (Ali et al., 2005)

In robotics, decoupling planning has been introduced to solve multi-mover problems (Choset et al., 2005). It works in two stages: Initially, collision-free paths are computed for each robot individually, not taking into account the other robots but simply considering the obstacles of the workspace. In the second stage, coordination is achieved by computing the relative velocities of the robots along their individual paths that will avoid collision among them. Kang and Miranda (2006) have proposed an incremental decoupled method to plan motions for multiple cranes to avoid collision between them.

2.3 Automated Tracking and Control in Construction Projects

During the execution of the plan, dynamic obstacles may appear on site, such as moving trucks, workers, and so on. The position of equipment needs to be tracked and controlled to ensure safety and improve productivity. On-board instrumentation (OBI) has been used to collect data for positioning and orientation, or other data which need to be monitored. The Global Positioning System (GPS) is widely used in construction, mining, surveying, and infrastructure. For example, in earthmoving projects, GPS and construction total station technology are used to accurately position the blade or bucket in real time, significantly reducing material overages and dramatically improving the contractor's productivity and profitability (Trimble, 2008). Navon et al. (2004) have developed a tracking and control system using GPS and OBI to monitor, in real-time, the activity of major construction equipment, such as tower cranes, concrete pumps, etc. Alshibani and Moselhi (2007) have used GPS for tracking earthmoving equipment to forecast performance. Riaz et al. (2006) have tracked vehicles and workers using GPS and sensors to reduce accident rates. In recent research, wireless sensors are installed on the boom of a crane to make sure the boom withstand the varying stresses and strains as it turns, lifts, lowers, and reaches (Machinedesign, 2004). A locking mechanism based on the OBI is applied in some big cranes to limit the movement of the boom when it is approaching the target (Hirschmann, 2008). Also, sensors for detecting ground support settlements are applied during the lifting to ensure safety.

Unmanned construction is work performed by remotely operated construction machinery that corresponds to an operator controlled robot. Unmanned construction was used in civil engineering work for the first time in Japan in 1969 when an underwater bulldozer was used to excavate and move deposited soil during emergency restoration work at the Toyama Bridge that had been blocked by the Joganji River disaster. Since then, unmanned construction by excavators inside pneumatic caissons and by backhoes has been carried out, but the restoration work following the volcanic eruptions that began in 1994 at the Unzen-fugendake Volcano and restoration work executed following the eruption of the Usuzan Volcano in 2000 were the first executions of large-scale unmanned construction and have spurred rapid progress in unmanned construction technologies and encouraged their wide use (Ban, 2002).

Much research about construction automation is carried out in the National Institute of Standards and Technology (NIST, 2007) in the U.S. *Construction Metrology and Automation Group (CMAG)* is involved in the development of position/orientation tracking systems and sensor interface protocols. *Computer Integrated Construction (CIC)* is doing research on the visual representation and simulation of construction models (Furlani et al. 2002). *Intelligent Systems Division (ISD)* with *CMAG* are researching robotic structural steel placement project called *Automated Steel Construction Testbed (ASCT)* (Lytle et al. 2002; 2004).

NIST has been conducting research in crane automation since the mid 1980's. A robotic crane (RoboCrane) based on an inverted, cable actuated Stewart-Gough platform principle was invented at NIST at that time. Since then several versions of the RoboCrane concept have been developed for various applications. Currently, CMAG is developing a generic crane controller using NIST real-time control system (RCS) methodology in order to test and evaluate various automated crane control schemes. In addition, CMAG is working on methods and algorithms to identify construction components from high-resolution 3D laser scanning data and to determine their position and orientation. The use of low-resolution 3D range cameras for obstacle avoidance and crane load docking are also being investigated (Saidi and Lytle, 2008).

Computer Integrated Road Construction (CIRC) project has been aiming at introducing a new generation of control and monitoring tools for road pavements construction. Two prototypes are developed: *CIRCOM* for compactors (Bouvel et al., 2001), and *CIRPAV* for asphalt pavers (Peyret et al., 2000). FIG. 15 shows a compactor instrumented with a GPS antenna, a gyro, radar, and so on.

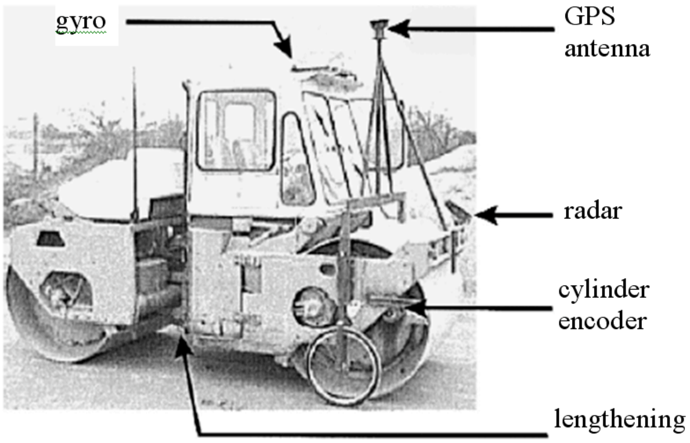


FIG. 15: Instrumented compactor (Bouvel et al., 2001)

Unmanned and semi-automated construction systems could be used not only at disaster restoration sites, but also to increase safety and efficiency at ordinary construction sites. However, it is mentioned that the efficiency of unmanned construction is roughly 60% to 70% of that of manned construction, but sharply decreases in cases where the machinery moves or high precision work is necessary (Ban, 2002). Therefore, full automation for heavy equipment is unnecessary in construction projects. Artificial intelligence and agent technology can be used as an auxiliary tool to support the equipment operators, as will be explained in Section 3.

3. PROPOSED APPROACH

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 task, schedule and staff. A group of human specialists, such as operators, engineers, technicians, are 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, such as workers, equipment, and materials. Plans are generated for macro and micro control at different levels and for different groups. More detailed plans are needed for supporting equipment operators. The nature of the hierarchy of the project organization is usually based on centralized planning for organizing lower level plans, which are generated in a distributed manner.

Furthermore, equipment is expected to fulfill the tasks efficiently and safely in a complex environment filled with known and unknown obstacles. During the planning stage, the *model-based approach* is used, where a 3D model of the site is available, which means full information about the geometry of the equipment and the obstacles is given beforehand, so path planning becomes a one-time off-line operation. During the execution stage, the dynamic environment needs another approach, called *sensor-based planning*, with an assumption that some obstacles are unknown, and this is compensated by local on-line (real-time) information coming from sensory feedback (Spong et al., 1992). Taking cranes as an example, lifting tasks are usually done through a trial-and-error process, based on feedback provided by the operator’s own vision and assessment, hand signals of a designated crane or ground director at the work zone, or radio communication (Arizono et al., 1993).

Based on the above mentioned characteristics of the construction site, multi-agent technology (Ferber, 1999) coupled with field data capturing technologies, is proposed to support construction equipment operators to fulfill their tasks collaboratively by planning before the operations and re-planning in real-time.

One advantage of multi-agent systems is that agents are capable of negotiation, which fits the common way of communication between managers, workers, and engineers during construction operations. It is useful to support these persons by agents, which encapsulate their knowledge and decision-making processes. Agents have separate, but interdependent, tasks to meet their final objective and to carry their work. Every agent has basic functionalities of sending and receiving messages, and decision making based on real-time situations on site. The communication between agents expands the perceptive capacities of agents by allowing them to benefit from the information and know-how that other agents possess (Ferber, 1999).

A framework of multi-agent systems is described in detail in Subsection 3.1; enabling technologies are reviewed in Subsection 3.2; and possible algorithms that could be used in realizing the proposed approach are described and compared in Subsection 3.3.

3.1 Framework

A framework of the agent-based systems is shown in FIG. 17. This figure demonstrates the concept of a centralized planning approach, where a coordinator is used to plan the path for two pieces of equipment. Distributed planning approaches are discussed in Subsection 3.2.3. In a part of the construction site, several agents are involved to carry out the task: Equipment Agent A, Equipment Agent B, Coordinator Agent, and Site State Agent.

The Equipment Agents and the Coordinator Agent share a Knowledge Base to support the decision-making. The Knowledge Base includes three parts: equipment model, engineering constraints, and rules for actions. The equipment model has the kinematic constraints, which can be saved in a database based on the specifications. Taking cranes as an example, the engineering constraints of cranes are mainly from the working range and the load charts (FIG. 19). 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, boom angel to the ground and the counterweight. Another example of constraints that should be taken into account during the lifting is having enough ground support. Rules of actions are based on expert rules, such as avoiding combinations of hoisting and swinging or hoisting and luffing at the same time; and avoiding boom's motion when a crane is traveling. For coordination purpose, other rules are considered. For example, in the case of two cranes working together, one important rule is that the distance between the two hooks should be equal to the length of the lifted object, and crane load lines must be kept plumb at all times for multiple crane lift (Shapiro et al. 2000).

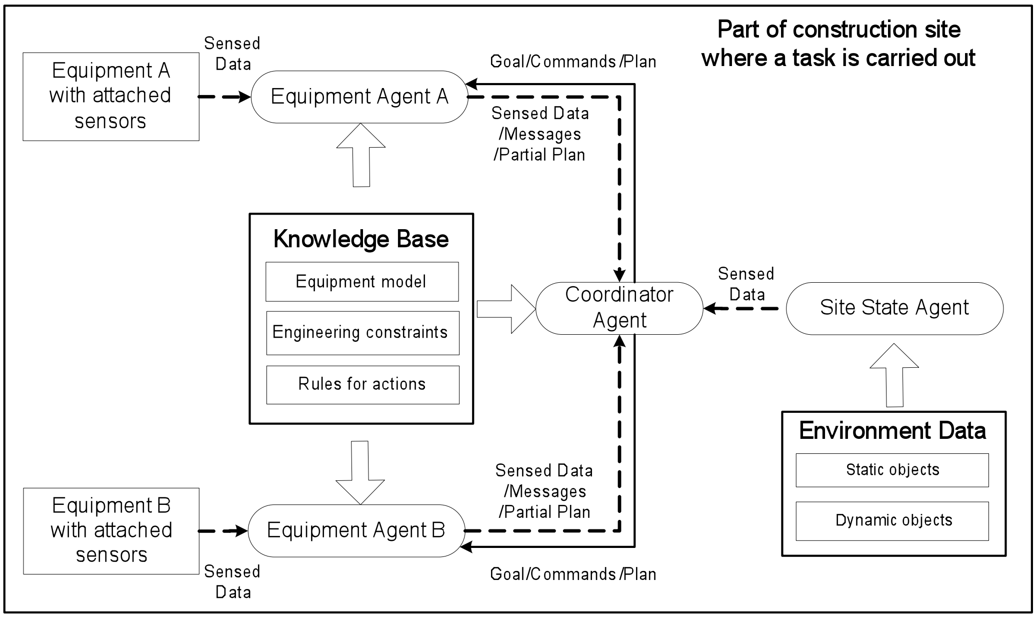
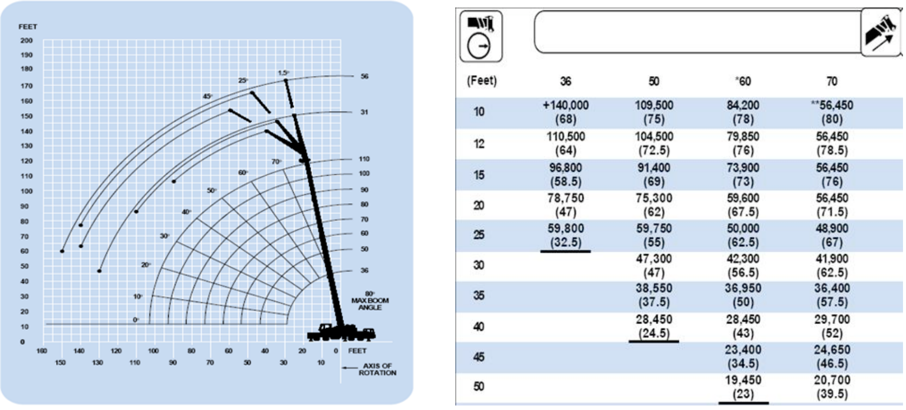


FIG. 17: Framework of agent-based system



(Feet)	36	50	*60	70
10	+140,000 (68)	109,500 (75)	84,200 (78)	**56,450 (80)
12	110,500 (64)	104,500 (72.5)	79,850 (76)	56,450 (78.5)
15	96,800 (58.5)	91,400 (69)	73,900 (73)	56,450 (76)
20	78,750 (47)	75,300 (62)	59,600 (67.5)	56,450 (71.5)
25	59,800 (32.5)	59,750 (55)	50,000 (62.5)	48,900 (67)
30		47,300 (47)	42,300 (56.5)	41,900 (62.5)
35		38,550 (37.5)	36,950 (50)	36,400 (57.5)
40		28,450 (24.5)	28,450 (43)	29,700 (52)
45			23,400 (34.5)	24,650 (46.5)
50			19,450 (23)	20,700 (39.5)

(a) (b)

FIG. 19: Working range (a) and load chart (b) of a crane (Groove Crane, 2006)

Sensors are attached to different components to monitor the position and orientation of each part of the equipment (e.g., the boom, the hook, and the lift of a crane) to ensure that the equipment does not collide with any obstacles during work. Equipment Agents are responsible for collecting these sensed data and checking the configurations to meet the engineering constraints according to the Knowledge Base.

The Site State Agent is responsible for collecting information about static and dynamic objects on the construction site. Information about static objects includes the 3D model of the site created during the planning stage and can be updated when necessary. For example, the newly built structures become obstacles for the next operation. Information about dynamic objects includes the moving objects on site, such as trucks, workers, and materials transported by the equipment. This information will be sensed by the Site State Agent and used to update the states of the environment model. Several field data capture technologies have been proposed in recent years to create the 3D model of a construction site in real time or near real time. Field data capture technologies include 3D imaging technologies (e.g., 3D scanners, 3D range cameras and photogrammetry) and radio-based identification and tracking technologies (e.g., Ultra Wideband technologies). Tracking sensors can be attached to equipment and workers. Details about these technologies are discussed in Subsection 3.2. The quality of field data and the ability to capture in real time will decide the accuracy and feasibility of the multi-agent system.

The Coordinator Agent is acting as a centralized coordinator on site. This centralized approach can be applied to two different cases: (1) two or more pieces of equipment working together for the same task, such as two cranes lifting one object; and (2) two or more pieces of equipment working for different tasks in the same area, where coordination is needed to avoid conflicts. In the first case, the Coordinator Agent generates plans for the Equipment Agents based on the data they sent. In the second case, the Equipment Agents generate their own partial plans individually and send these plans to the Coordinator Agent, which combines the partial plans into an overall plan without conflicts between the equipment.

This framework can be applied in both the planning and execution stages. During the planning stage, the 3D model of the construction site is created; then, a collision-free path plan for specific equipment is generated considering the engineering constraints, such as the working range and the load chart of a crane. During the execution stage, the 3D model of the construction site is updated by monitoring dynamic objects. All the information about the configuration of equipment and other moving objects are collected and sent to the agents. If obstacles are detected, the re-planning algorithm is triggered, and a revised path is generated, if necessary, to guide the movement of the equipment. Furthermore, agents representing other equipment can be added to, or removed from, the system according to the working area and the context of the task.

The communication between agents is wireless and the messages exchanged should follow specific formats, which will be explained in Subsections 3.2.2 and 3.2.3. The Coordinator Agent will inform the Equipment Agents about the goal and the plan for the task. In addition, it will send commands in case of emergency, such as a command to stop the movement when a collision is detected. The goal description of the crane operation can be simply represented by two points related to the lift object origin and destination. *Origin* (ob, P_o, Φ_o) represents the original position P_o and orientation Φ_o of the object *ob*. P_o (x_o, y_o, z_o) is given by the coordinates of the reference point of *ob*. *Destination* (ob, P_d, Φ_d) represents the destination position P_d and the orientation Φ_d of *ob*. *Duration* (t_1, t_2) represents the start time t_1 and the end time t_2 of the work. The plan can be represented by a series of configurations that the equipment needs to take in a sequence to achieve the goal, or further translated into actions that can be understood by the equipment operator. The Equipment Agents can accept or reject the commands and negotiate with the Coordinator Agent. 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 bottleneck. The Coordinator Agent will identify the agents with which to communicate.

3.2 Enabling Technologies

3.2.1 Field Data Capturing Technologies

As explained in Section 2, researchers are trying different technologies to create an accurate 3D model of the construction site, and to automatically track and control equipment. The data collected from these devices are normally in the format of point clouds, which can be transformed by software tools into volumetric objects representing a precise 3D model including all the buildings and other objects that are not available using the methods discussed in Subsection 2.1. Repeated work should be carried out to update the model in real-time. Gordon and Akinci (2005) collected data using a 3D laser scanner to support inspection and quality control on construction sites. FIG. 21 shows an example of data collected for a part of the bridge mentioned in FIG. 1 using a 3D laser scanner (Mailhot and Busuio, 2006). These point clouds are used to create the 3D model of the bridge to avoid collision between cranes and the bridge structures during the rehabilitation project.

Researchers at NIST have been studying the performance and applicability of 3D range cameras. The cameras measure the distance to an object by measuring the time needed for light to travel from the instrument to the object and back. They can capture the 3D scene in real-time at video frame rates (MESA Imaging, 2008). Lytle et al. (2005) have evaluated the performance of a 3D range camera for construction applications. Some important parameters are indicated to optimize the accuracy and minimize errors (Price et al., 2007). Teizer et al. (2006) have used a 3D range camera to model static and dynamic construction resources.

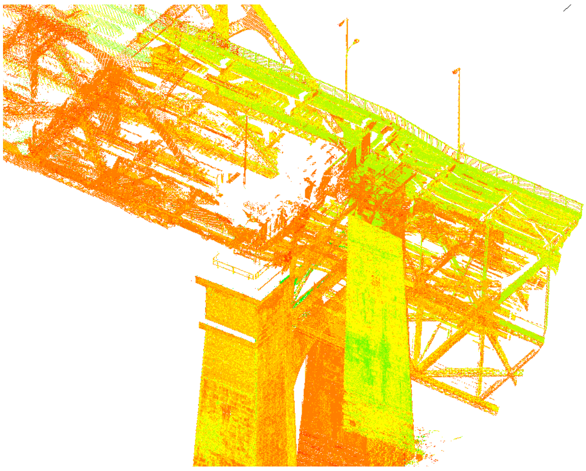


FIG. 21: Point cloud collected for a part of a bridge (Mailhot and Busuio, 2006)

In addition to 3D laser scanners and 3D range cameras, attachable sensors are used to track moving objects on site, such as trucks. Subsection 2.3 reviewed some of the sensing methods used or studied in the construction industry. More recently, RFID (Radio Frequency IDentification) based tracking technology has been investigated for the same purpose (Chae and Yoshida, 2008). BodyGuard - Vehicle Proximity Alert and Collision Avoidance System (Orbit Communications, 2008) offers continuous detection and notification of proximity between moving objects and other moving or fixed objects by setting up protection zones around a vehicle, equipment, and buildings to offer continuous protection for valuable resources.

Ultra wideband (UWB) is a wireless technology for transmitting large amounts of digital data over a wide spectrum of frequency bands over a distance up to 230 feet at very low power (less than 0.5 milliwatts). UWB has the ability to carry signals through doors and other obstacles that tend to reflect signals at more limited bandwidths and a higher power. These advantages make it possible to use on construction sites. The Real Time Location System (RTLS) of UWB is proposed for improving crane safety (Fontana, 2007). Several methods are used to measure the distance between the reader and the tags, such as Time Difference of Arrival (TDOA) and Angle-of-Arrival (AOA). With a known position of the reader, the objects on site with tags attached can be located. Commercial products, such as UbiSense (2008) and Multispectral Solutions (2008) are available for evaluating the usability of UWB technology. CMAG is involved in measuring the performance of UWB tracking technology in construction (Saidi and Lytle, 2008). Teizer et al. (2007) have investigated the usability of a UWB tag attached to a crane hook to track the position of the hook. The tag is attached to the top of the hook, as indicated by an arrow in FIG. 23.

FIG. 23: UWB tag on hook (Teizer et al., 2007)

3.2.2 Wireless Communication

Wireless communication technologies are needed for agents to communicate with each other on site. Many types of wireless networks are available, such as wireless personal area networks (WPANs), wireless metropolitan area networks, and wireless local area networks (WLANs). The Wi-Fi networks are able to solve many of the communication problems caused by the “islands of information” in construction (Lee and Bernold, 2008). As shown in FIG. 25, the dotted lines show wireless communication between different components of an agent-based crane alert model.

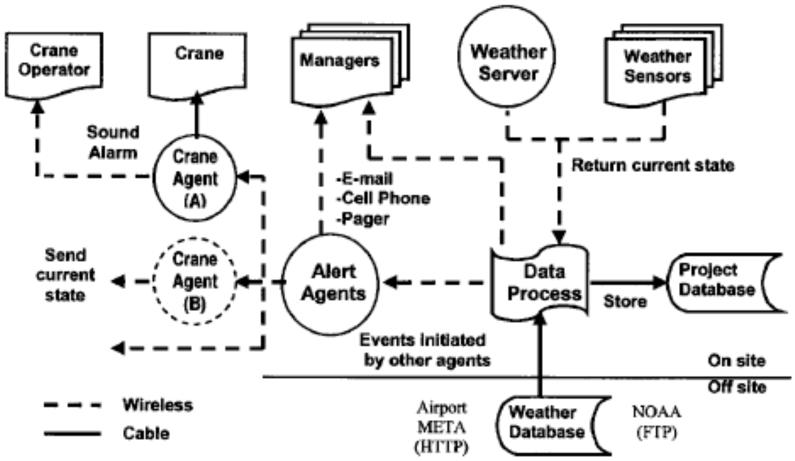


FIG. 25: Agent-based crane alert model (Lee and Bernold, 2008)

The latest Wi-Fi standard, known as 802.11n, will support actual data rates up to 100 Mbps. Another WLAN technique is ad-hoc wireless networking, in which some mobile devices are part of the network only for the duration of a communication session while in close proximity to the rest of the network. Yang and Hammad (2007) have investigated problems related to deploying ad-hoc wireless networks for supporting communication and onsite data collection. As discussed in Subsection 3.1, the dynamic agent system will add or remove agents based on specific focus and time. Therefore, ad-hoc wireless networking could be a good solution for the proposed method. Wang et al. (2007) have designed an outdoor distributed mixed reality system to support the interaction of multi-user and virtual objects manipulation in a construction simulation. FIG. 27 schematically shows two users operating two virtual cranes and communicating with each other using an ad-hoc network.

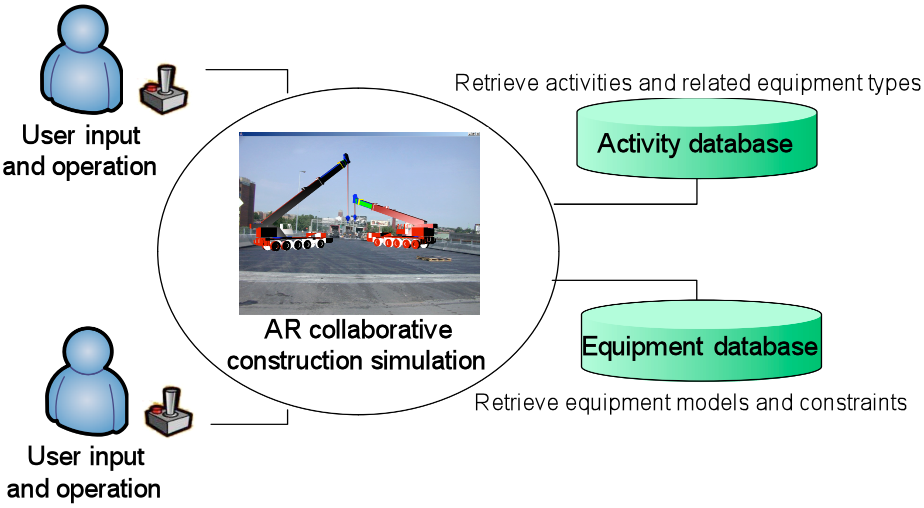


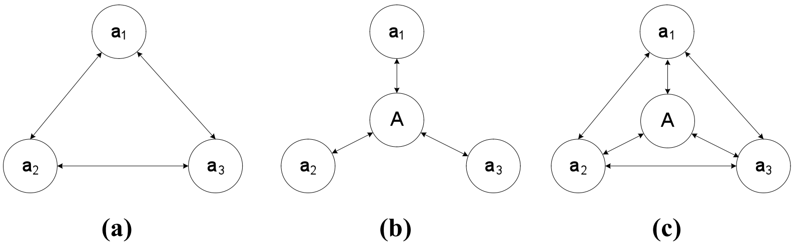
FIG. 27: Distributed mixed reality system for supporting multi-user interaction using ad-hoc wireless networking (Wang et al., 2007)

3.2.3 Agent Technology

Agents are 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 (Russell and Norvig 2003). An agent can be a piece of software that is capable of accomplishing tasks on behalf of its user. One of the most important features of agents is that they can negotiate with each other to collaborate for achieving complex goals. Collaborative agents emphasize autonomy and cooperation with other agents in order to perform tasks in open and time-constrained multi-agent environments (Nwana and Ndumu 1998). Using agents in real-time control of construction equipment operation can enhance communication to reduce conflicts, ensure safety and improve efficiency.

Some research involving agents has been done to enhance communication between team workers and resolve 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 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 agent based communication system on site for collecting weather information and sending warning messages (FIG. 25). However, little research has focused on real-time path planning of construction equipment operation using agents.

There are several ways of planning for a multi-agent system either in a centralised or a distributed manner. Due to the intelligence of agent, 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. 29 (a) shows a distributed approach where the three agents communicate with each other and make decision based on the result of their negotiation. FIG. 29 (b) shows a centralized approach where A is acting as a team coordinator to communicate with the team members and is responsible for producing an overall plan; or a team member draws up its own partial plan independently and sends it to the coordinator, then the coordinator tries to synthesise all the partial plans into an overall plan. The proposed framework in FIG. 17 follows this approach. However, in a construction site, the distributed and centralized approaches are both used in different cases. Team members can negotiate and make decisions without reporting every detail to the team coordinator. In other cases, the team coordinator has to solve the conflict between team members and make a final decision. Flexibility can be added to the agent system by giving the right of choosing the planning approach by the agent depending on different situations. FIG. 29 (c) shows a combination FIG. 29 (a) and (b). The same concept can be applied to all levels of groups, such as general contractor with sub-contractors, sub-contractors with different working teams, and a coordinator with different equipment operators working together.



(a) **(b)** **(c)**

FIG. 29: Different approaches for planning

Communication between agents is essential for coordinating the behaviours of the agents in time and space, which basically requires exchanging messages between agents. KQML (Knowledge Query and Manipulation Language) (Finin et al. 1994) provides a language for agents to exchange information and knowledge. It defines the operations that agents may attempt on each other's knowledge bases and provides a basic architecture for agents to share knowledge and information. For example, the messages transferred between equipment agents and the Site State Agent in FIG. 17 could follow the KQML format. Jadex is a Java based, FIPA (Foundation for Intelligent Physical Agents) compliant agent environment, and allows developing goal oriented agents following the BDI (Belief Desire Intention) model. Jadex provides a framework and a set of development tools to simplify the creation and testing of agents.

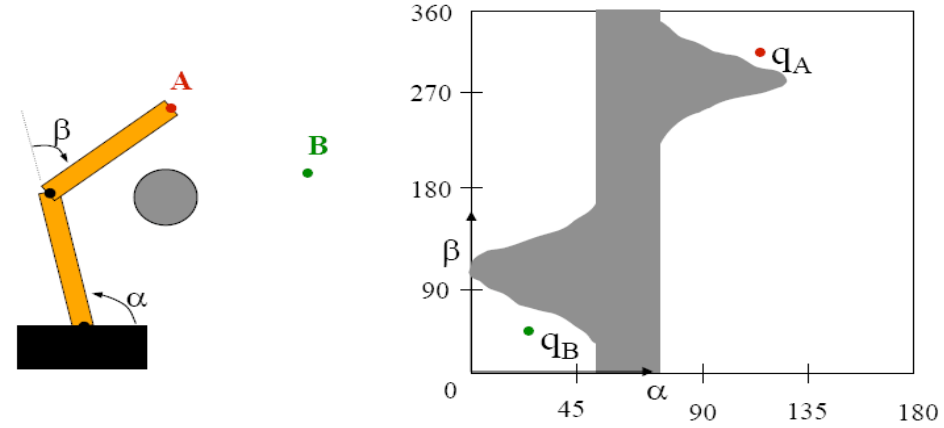
3.3 Algorithms for Path Planning and Re-planning

Search space generation, path planning, and re-planning need several algorithms to carry out the proposed approach.

3.3.1 Feasible Space Generation

To create path plans for equipment, we need a search space in either the geometric space or a space representing the configuration of the equipment, which is known as configuration space (C space) (Choset et al., 2005). We should be able to specify the location of every point on the equipment, since we need to ensure that no point on the equipment collides with an obstacle. A key limitation in using the geometric space approach is that an inverse kinematic problem has to be solved to find the different solutions corresponding to the Degrees of Freedom (DoFs) of the manipulator for a particular location of the end-effector. Approaches that transform the real space into a space represented based constraint have been developed in an attempt to simplify the representation and avoid the inverse kinematic problem. Therefore, the C space, which is one of the most important concepts in motion planning, is suitable to solve this problem.

The configuration of an equipment system is a complete specification of the position of every point of that system. The C space of the equipment system is the space of all possible configurations of the system; and a configuration is simply a point in this abstract configuration space. FIG. 31 (a) shows an obstacle in the workspace of a robot with 2 DoFs, α and β; FIG. 31 (b) shows the representation of the obstacle in the C space, which is a two dimensional representation of angles α and β. q_A and q_B correspond to the configurations of the endpoint positions A and B, respectively. Once the C space is generated, path planning requires only a search between the pick (origin) and place (destination) locations in the C space.



(a) An obstacle in the workspace of the robot **(b) The C space showing the obstacle and the two configurations of A and B**

FIG. 31: C space of a two-link arm robot (Choset et al., 2005)

The free configuration space is the set of configurations at which the equipment does not intersect any obstacle in the C Space. In FIG. 31 (b), the grey part shows the obstacle space, and the rest of the space is the free space for the robot. However, the engineering constraints of the construction equipment further narrows down the free configuration space into a feasible space, which fulfills the feasibility of the movement according to their load charts and the work ranges. Therefore, the free space can be reduced according to the equipment physical situation, e.g. the lift weight, the counterweight, and the outrigger radius of a crane.

Creating the feasible space can be done by testing all safe (within specified capacity) lifting configurations of the loaded crane for obstruction using collision detection algorithm (Ali et al., 2005; Chiddarwar and Babu, 2007). Current collision detection methods applied in robotics and computer graphics are generally more complex than necessary to be used for construction purposes and relatively difficult to implement efficiently (Kang and Miranda, 2006). Therefore, bounding box can be used for collision detection between lift object and obstacles in the environment). Pairs of convex polyhedra (Moore and Wilhelms, 1988) algorithm can be used to check the interference.

The number of DoFs of an equipment system defines the dimensions of the C space. Therefore, the more DoFs are considered, the more complex the C Space would be. For example, a loaded crane has a maximum of eight DoFs, and path planning for manipulators having more than four DoFs is considered to be complex (Hwang and Ahuja, 1992). The scope of the present work is limited to four DoFs, as shown in FIG. 33.

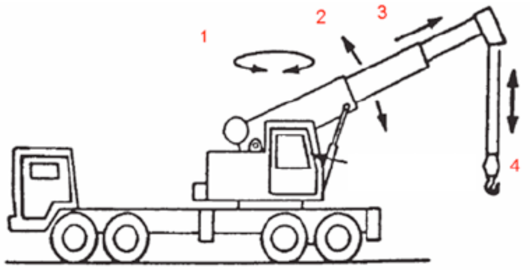


FIG. 33: DoFs of a crane

3.3.2 Path Planning

After generating the feasible C space, path planning becomes a problem of finding a path that connects the start configuration to a particular goal configuration, which is known as motion planning. A large number of algorithms are available for generating collision-free paths in the C space. Each algorithm has some advantages and disadvantages. An appropriate algorithm should be selected based on the following requirements of the multi-agent system, as discussed in Section 3.1: (1) the time spent for searching a path, considering off-line and on-line support; (2) the quality of the path. It could be the shortest path or the smoothest path; (3) reusability of the path in the re-planning stage; and (4) the possibility to implement the algorithm in a distributed fashion to match the multi-agent system design (centralized, distributed, and centralized coordination).

Based on the data structure representation of the C space, motion planning algorithms can be categorized under two major approaches:

(1) Motion Planning in Discrete Spaces: The C space is defined as a state-space model which has a countable finite set of states. The planning algorithm searches the state-space for the feasible path. Grid A* and Visibility Graphs are representative algorithms of discrete space planning.

(2) Motion Planning in Continuous Space: The algorithm is not limited to a pre-defined finite search space representation of the C space. Instead, a variety of strategies are utilized for generating samples (collision-free configurations) and for connecting the samples with paths to obtain solutions to path-planning problems in a continuous C space. RRT (Rapidly-Exploring Random Trees) and PRM (Probabilistic Roadmap Planner) as representative algorithms of continuous space planning.

A* is a classical search method that finds the least-cost path from a given initial node to one goal node (out of one or more possible goals). It searches a graph efficiently sing to a chosen heuristic. The input of A* is a graph itself. It is often applied on grids where each of the cells has its heuristic distance to the goal. Between free space cells, a vertical or horizontal step has relatively low cost while the cost for travelling from a free space cell to an obstacle cell is made arbitrarily high. This assumption connects all cells in the grid, not just the free space, and the prohibitively high cost of moving into an obstacle will prevent the equipment from collision (Chosen et al., 2005). FIG. 35 shows a grid example where dark cells occupied with obstacles are assigned high cost, while white cells have low cost.

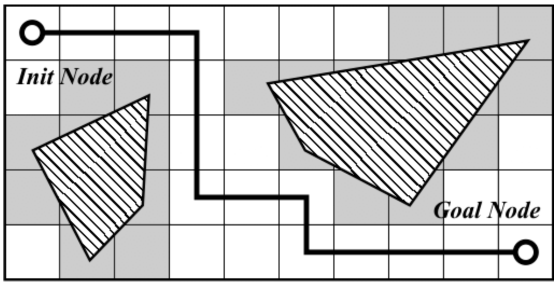


FIG. 35: Grid example

Visibility graphs tend to apply to configuration spaces with polygonal obstacles. Nodes of the graph are the vertices of the polygons. Two nodes of a visibility graph share an edge if their corresponding vertices are within line of sight of each other. The nodes v_i of the visibility graph include the start location, the goal location, and all the vertices of the configuration space obstacles. The graph edges e_{ij} are straight-line segments that connect two line-of-sight nodes v_i and v_j. Note that the nodes and edges are embedded in the free space and edges of the polygonal obstacles also serve as edges in the visibility graph. FIG. 37 shows an example for a visibility graph where the thin solid lines delineate the edges of the visibility graph for the three obstacles represented as filled polygons. The thick dotted line represents the shortest path between the start and goal. Using the standard Euclidean distance, the visibility graph can be searched for the shortest path (Choset et al., 2005).

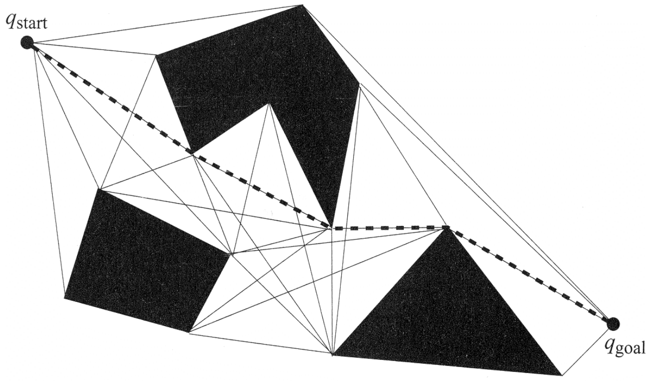
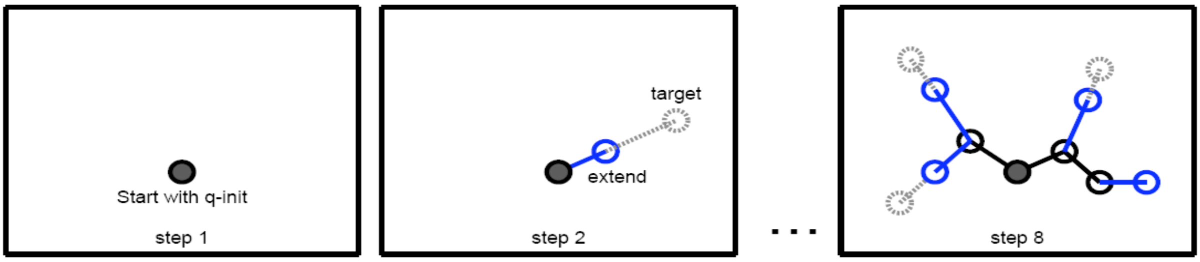


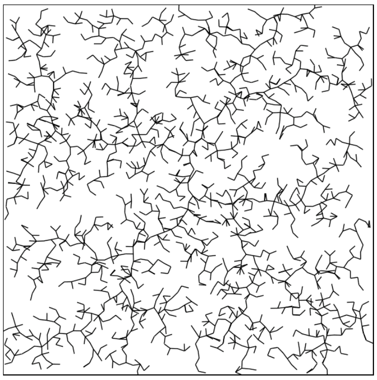
FIG. 37: Example of a visibility graph (Choset et al., 2005)

RRT algorithms incrementally construct a search tree that gradually improves the resolution but does not need to explicitly set any resolution parameters. In the limit, the tree densely covers the space. Thus, it has properties similar to space filling curves, but instead of one long path, there are shorter paths that are organized into a tree. A dense sequence of samples is used as a guide in the incremental construction of the tree, and this sequence is random. This method was originally developed for motion planning under differential constraints (LaValle, 1998). FIG. 39(a) shows the steps of the basic RRT algorithm: (1) Initially, start with the initial configuration as the root of a tree; (2) Pick a random state in the configuration space; (3) Find the closest node in the tree; (4) Extend that node toward the state if possible; and (5) Goto step (2). FIG. 39(b) shows the result of RRT with 2000 vertex.

A PRM divides the planning into two phases: the learning phase, during which a roadmap in free C space (Q_{free}) is built; and the query phase, during which user-defined query configurations are connected with the pre-computed roadmap. The nodes of the roadmap are configurations in Q_{free} and the edges of the roadmap correspond to the free paths computed by a local planner. The objective of the first phase is to capture the connectivity of Q_{free} so that path-planning queries can be answered efficiently (Choset et al, 2005). FIG. 41 shows the steps of the basic PRM algorithm: (a) Find random sample of free configurations (vertices); (b) Attempt to connect pairs of nearby vertices with a local planner. If a valid plan is found, add an edge to the graph; (c) Find local connections to the graph from initial and goal positions; and (d) Search over roadmap graph.



(a) Steps of the basics RRT algorithm (Bruce and Veloso, 2006)



(b) Result of RRT with 2000 vertex (LaValle and Kuffner, 1999)

FIG. 39: Example of an RRT

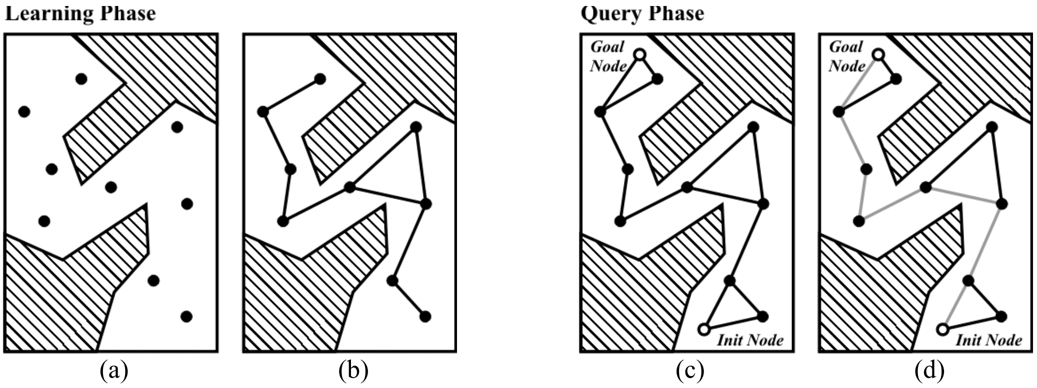


FIG. 41: Example of PRM algorithm steps

The comparison of these algorithms is shown in TABLE 1, which is based on the following criteria:

(1) Completeness: Complete planning approaches are guaranteed to find a solution when it exists, or correctly report failure if one does not exist (LaValle, 2006). For sampling based algorithms (e.g. RRT), completeness depends on that the probability of them producing a solution approaches 1 as more time is spent. Improvements to the standard RRT can be done to address this issue (Cheng and LaValle, 2002). For Grid A*, finding the solution depends on the resolution of the grid that is representing the C space, low resolution grids may result in failure in finding the solution even if it exists. PRM combines both cases of being probabilistic and resolution complete, this is due to its nature of finding the path in two phases.

(2) Optimal: In addition to completeness, algorithm optimality is considered as its ability to return optimal path with respect to some metric. Single-query sampling based algorithms (e.g. RRT) are not able to guarantee the generation of an optimal path based on pre-defined criteria; an optimization update is required to address this point. Fortunately, for many of these algorithms, the solutions produced are not too far from optimal in practice (LaValle, 2006).

(3) Efficient World Updates: Modifying the obstacles in the world is a very common case. Therefore, efficiency in re-planning the path after updating the world is important. Among the algorithms reviewed in this paper,

RRT is the best even though it is considered semi-efficient. RRT is a single query planner, which attempts to solve a query as fast as possible and do not focus on the exploration of the entire free space. A* efficiency in world updates can be improved with D*, by propagating cost changes, while maintaining the optimality of A* and making minimal changes to the universal plan.

(4) Efficient Query Updates: In addition to world updates, query update efficiency is important for cases like re-planning to new goals while fixing world constraints. The PRM algorithm is efficient in this type of queries, since it can reuse the roadmap that it constructed in the preprocessing phase.

(5) Good DoF Scalability: The DoFs directly affect the complexity of C spaces, thus configurations with high DoFs are not practical for solving by many algorithms. Grid A* and Visibility Graph are not suitable for solving configurations with high DoFs, which limits realistic kinematic modeling for construction equipment.

(6) Non-Holonomic: The capability of solving non-holonomic configurations is a key feature in path-planning algorithms, where the algorithm is not only limited of considering global constraints that are generated from explicit obstacles in the environment (Kuffner and LaValle, 2000), but it is also able to address local/differential constraints that may be found in some construction equipments. Among all reviewed algorithms, RRT stands with its high abilities in solving non-holonomic configurations.

TABLE 1 Summary of the comparison between different algorithms

Approach	Complete	Optimal	Efficient World Updates	Efficient Query Updates	Good DoF Scalability	Non-Holonomic
Grid A*	res	grid	no	no	no	no
Visibility Graph	yes	yes	no	no	no!	no
RRT	prob	no	semi	semi	yes	yes
PRM	prob, res	graph	no	yes	yes	semi

Res: Resolution Complete, Prob: Probabilistic Completeness

Brandt (2006) has made a comparison between A* and RRT for motion planning of robots, and found that RRT is much faster than A*, while the quality of the path found using RRT is less than that of the A*. Most implementations of planning algorithms are assisted by appropriate domain heuristics to find a good/optimal path within a reasonable time (Reddy and Varghese, 2002). The study of Varghese et al. (1997) has shown that no industry-wide standard for heavy lift planning practices exists at present. Experts rely primarily on experience to develop the plans or to perform optimization. Furthermore, collaborative requirements also limit the possible movement of each equipment, which reduces the actions that can be taken by agents. Therefore, coordination strategies are essential for generating an efficient and applicable plan in reasonable time. Leader-follower strategy (Zheng, 1989), time delay strategy (Chang, 1994), and speed alteration strategy (Hwang, 2003) have been used in the literature. Also, in the research of Ali et al. (2005), a GA algorithm is used and compared with the A*, and the former is considered as a better solution for two cranes working together (FIG. 13). Other examples of using GAs for path planning and motion planning can be found in literature (Abo-Hammour et al., 2002, Castillo et al., 2007, Tam et al., 2001, Ali et al., 2005).

The optimal path can be smoothed to improve the operational functionality. For example, Kang and Miranda (2006) have developed algorithms to make the path more realistic and easier to follow, either by robotic cranes or by crane operators, as shown in FIG. 43.

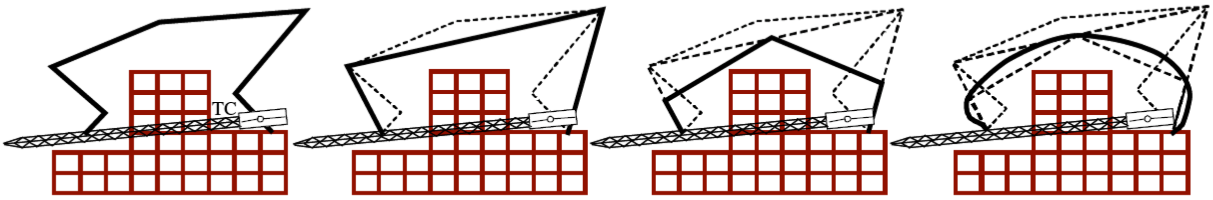


FIG. 43: An example of the path refining process (top view) (Kang and Mirande, 2006)

3.3.3 Path Re-planning

During the plan execution stage, obstacles not taken into account in the planning phase can be detected in real-time and agents are used to dynamically guide the actions of equipment and to find collision-free paths respecting the engineering constraints and action rules. The re-planning can be done based on the milestones defined in the original plan to save search time. A simplified example is shown in FIG. 45, where M_1-M_2-M_3-M_4 represents a planned path. An obstacle blocks the way from M_2 to M_3. One re-planning solution is by replacing the part M_2-M_3 by M_2-M_2'-M_3'-M_3; another solution is by adding a new milestone M_3'', which connects M_2 and M_4 to replace the part M_2-M_3-M_4. The better path will be selected based on the cost of the path considering its length or other factors.

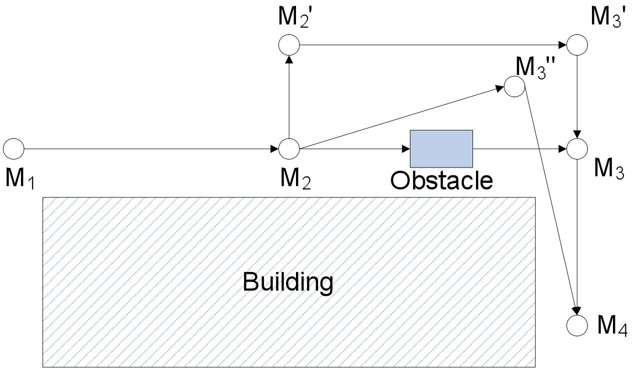


FIG. 45 Example of path re-planning based on milestones

When a collision is detected the actions of the agents can be described as follows (FIG. 47):

- Coordinator Agent sends signals to the agent(s) whose path is blocked to stop the movement and retrieve the current configuration of the equipment;
- Differentiate the type of the obstacle, e.g., equipment of worker, which decides the priority of agents; add a new agent to the system, if necessary, to support the obstacle object;
- Check whether the obstacle is for short or long duration (e.g. shorter or longer than 5 min.) based on the goal and the plan of the new agent;
- If it is a short duration obstacle, wait till the obstacle moves, then resume executing the plan;
- If it is a long duration obstacle, then select an agent or several agents to re-plan based on the coordination strategies, mentioned in Subsection 3.3.2;
- The selected agent(s) re-plan its path;
- Check whether a conflict exists between the new partial plan(s) and the existing plan ;
- Combine the new partial plan(s) to form the re-planned overall plan;
- Executing the new plan.

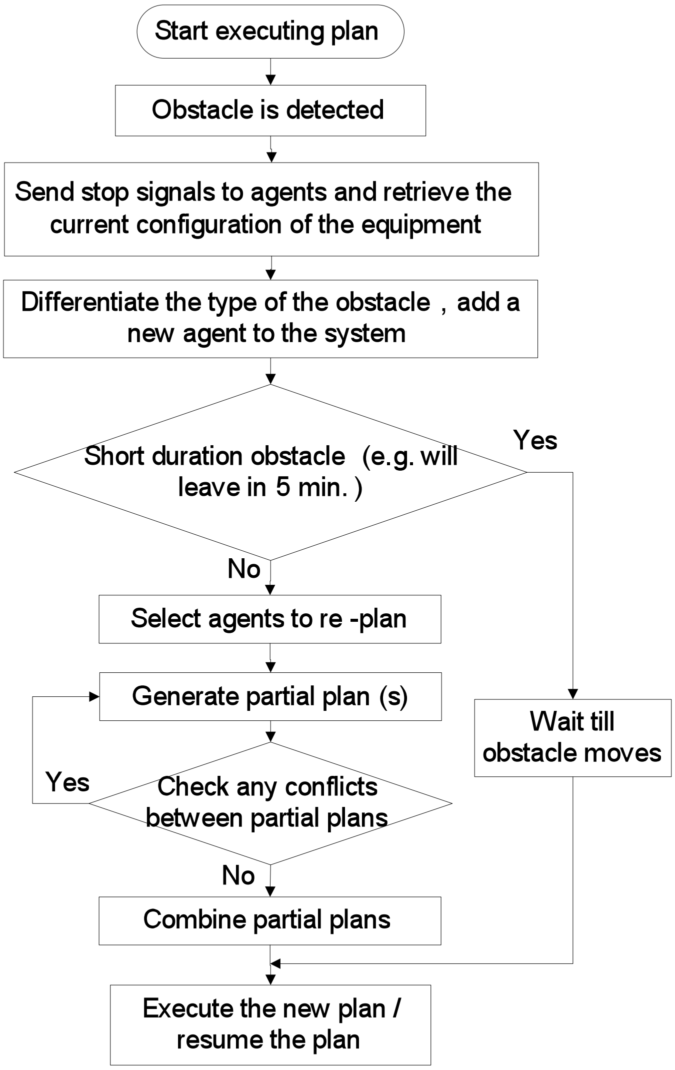


FIG. 47: Flowchart of re-planning example

3.3.4 Action Generation

In order to have a practical tool for path planning, the configuration of each step on the path should be translated into a series of actions that can be understood by the equipment operator, such as swing the boom 30 degrees. Taking a hydraulic crane as an example, the movement of the crane includes the following actions:
Base movement: BaseMove, BaseStop;
Boom movement: BoomRaise, BoomLower, BoomExtend, BoomRetract, BoomSwing, BoomStop;
Hook movement: HookHoist, HookLower, HookStop, HookGrip, HookRelease.

Based on the actions taken by the equipment, states can be calculated at each time step, for example, at State j:
ObjectLocation (ob_k, P_{kj}, Φ_{kj}): object ob_k is at position P_{kj} with orientation Φ_{kj};
CraneLocation ($crane_i$, P_{ij}, Φ_{ij}, θ_{ij}, α_{ij}, l_{ij}, P_{ij}^{h}): crane i is at location P_{ij}, with base orientation Φ_{ij}, boom swing angle θ_{ij}, boom angle to the ground α_{ij}, boom length l_{ij}, and hook position P_{ij}^{h};
HookGrip ($crane_i$, ob_k): the hook of $crane_i$ is gripping ob_k;
Distance ($hook_i$, $hook_{i+1}$, d_j): the distance between two hooks is d_j;

FIG. 49 shows a simple example for the movement of one crane. S_j represents different states after the actions taken. For each milestone, the calculated state will be compared with the information obtained from the sensors to make sure the work is going well, also could be used for calibrating purpose.

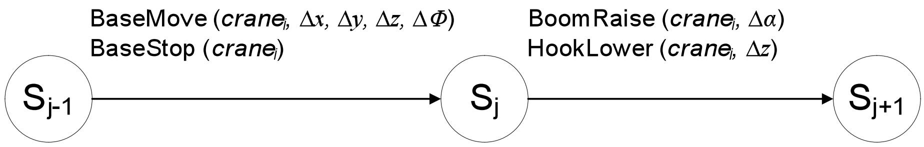


FIG. 49: Actions and states changes

4. CONCLUSIONS AND ROADMAP TO SMART CONSTRUCTION SITE

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. The enabling technologies introduced in Subsection 3.2 can be used to model and update the project environment. The intelligence of the multi-agent systems can be extended from the re-planning of equipment paths, which improves safety and efficiency, to a more advanced concept, which we call Smart Construction Site (SCS). FIG. 51 shows our proposed roadmap towards the SCS based on agent technology, field data capturing technologies, wireless communication, and path re-planning. This roadmap can be considered as an extension of the following concepts and emerging topics used in the Construction ICT Roadmap (2003), which was proposed by ROADCON project, focusing on new and emerging ICTs: (1) Adaptive and self-configuring systems (early warning/situation tracking), (2) Collaborative virtual teams (smart self-controlling teams, collaborative modeling and visualization), (3) Digital site (site team management tools), and (4) Smart Building (long term & real time data). The following paragraph explains the proposed roadmap starting from available technologies that are already in use and take-up technologies (the bottom part of the roadmap). This will be followed by describing the Research and Development (R&D) and emerging topics, which will lead to the realization of the SCS.

In the current state of construction projects, GPS is used to monitor the location of equipment and OBI systems are available for heavy construction equipment. Equipment path planning software is used in some big companies; however, during the execution phase, tasks are usually done through a trial-and-error process, based on feedback provided by the operator's own vision and assessment, hand signals of a director at the work zone, or radio communication. RFID has been proposed to track materials and tools. People communicate with each other using mobile phones or radio terminals. Furthermore, several technologies are ready for take up, such as vehicle proximity alert and collision avoidance systems, agent technologies, wireless networks, and path planning algorithms, as we described in Subsection 3.2. Based on these available technologies, R&D is under going to: (1) Capture field data in real-time and support early warning/situation tracking; (2) Develop collaborative multi-agent systems to provide intelligent assistants; (3) Create a seamless network interconnectivity for collaborative multi-equipment taking advantage of wireless communication; and (4) Develop automatic path re-planning algorithms as an efficient tool for site team management. By integrating all the emerging topics in the roadmap, a vision of SCS can be seen where every worker, operator, and staff has intelligent support from agents encapsulating knowledge and decision-making strategies. Environment information is fully obtained and updated by using 3D scanners, range cameras or sensors attached to moving objects on site. Path planning and re-planning will be done automatically to help the operators fulfill their task safely and efficiently.

One scenario of using the proposed approach can be described using the example introduced in this paper, which is about a bridge deck rehabilitation project (Figures 1, 5, 6, and 11). This project was done in 2001 to 2002, where groups of cranes and crews were involved in removing old deck sections and installing new panels. The complexity of the construction environment put a lot of constrains on the mobilization, transportation, collaboration of equipment, work interference (multi-groups), tight schedule (traffic should be open during day time), spatial constraints (existing structure of the bridge) and so on. The benefits of a SCS are: (1) 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; (2) Productivity control: the tracking records can be used to analyse the workers' and equipment performance and estimate their productivity; (3) Quality control: more awareness of the site situation by tracking moving objects and a knowledge base for different equipment can help the staff make better decisions; and (4) Easy understanding of the work process by visualizing the paths of equipment.

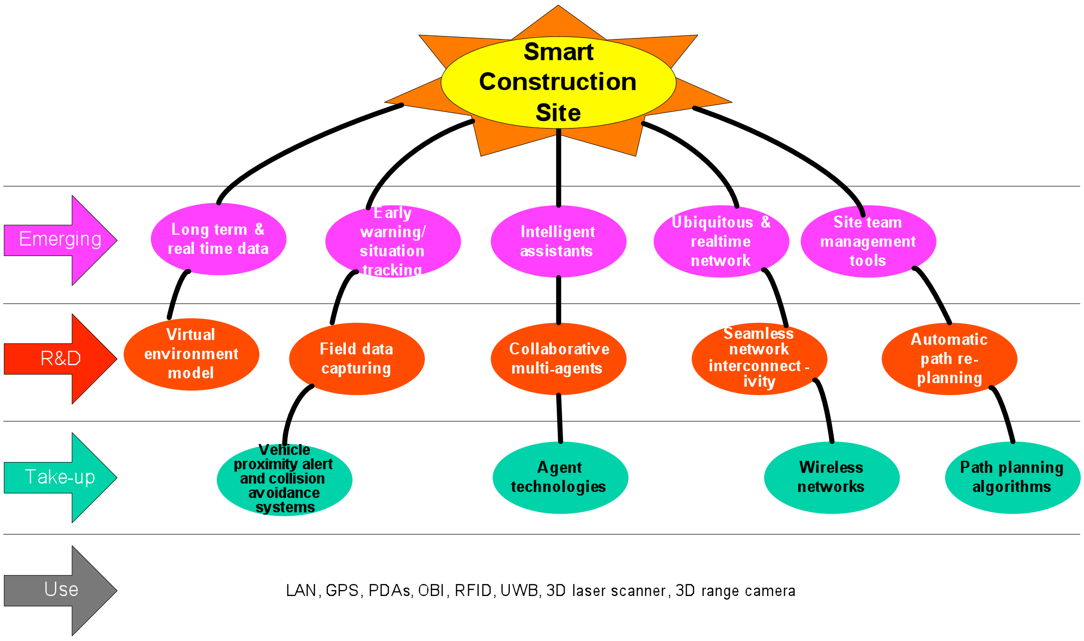


FIG. 51: Roadmap of Smart Construction Site

5. FUTURE WORK

Our future work will be: (1) Selecting the most suitable algorithms for real-time path re-planning based on the criteria of efficient world updates and query updates, scalability for large number of degrees of freedom, and suitability for distributed decision making using multi-agents; (2) Investigating the requirements of UWB tracking systems (i.e., number and location of tags, range, accuracy, etc.); (3) Refining the framework of the multi-agent system, by investigating the details of agent communication and negotiation, and real-time sensing issues; and (4) Validating the proposed approach using a proof-of-concept system in practical case studies.

REFERENCES

Abo-Hammour Z.S., Mirza N.M., Mirza S.M. and Arif M. (2002). Cartesian path generation of robot manipulators using continuous genetic algorithms, *Robotics and Autonomous Systems*, Vol. 41, 179-223.

Ali M.S.A.D., Babu N.R. and Varghese K. (2005). Collision free path planning of cooperative crane manipulators using genetic algorithm, *Journal of Computing in Civil Engineering*, ASCE, Vol. 19, No. 2, 182-193.

Alshibani M. and Moselhi O. (2007). Tracking and forecasting performance of earthmoving operation using GPS. *Proceedings of Construction Management and Economics 25th Anniversary Conference*, UK.

Arizono N., Shiota K., Uemura Y., Sasada T., Morikawa Y. and Onoda M. (1993). Crane operation support system, Res. Dev., Vol. 43, No. 1, 47-50.

Ban Y. (2002). Unmanned construction system: present status and challenges. *Proceedings of the 19th International Symposium on Automation and Robotics in Construction*, Washington, U.S., 241-246.

Bilek J. and Hartmann D. (2003). Development of an agent-based workbench supporting collaborative structural design. *Proceedings of the 20th CIB W78 Conference on IT in Construction*, New Zealand, April.

Bouvel D., Froumentin M. and Garcia G. (2001). A real-time localization system for compactors, *Automation in Construction*, Vol. 10, 417-428.

Brandt D. (2006). Comparison of A* and RRT-Connect motion planning techniques for self-reconfiguration planning, *Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, October, China.

Bruce J.R. and Veloso M.M. (2006). Safe multirobot navigation within dynamics constraints, *Proceedings of the IEEE*, Vol. 94, No. 7, 1398-1411.

Castillo O., Trujillo, L. and Melin P. (2007). Multiple objective genetic algorithms for path-planning optimization in zutonomous mobile robots, *Soft Comput*, Vol. 11, 269-279.

Chae, S. and Yoshida, T. (2008). A study of safety management using working area information on construction site, *Proceedings of the 25th International Symposium on Automation & Robotics in Construction*, ISARC 2008, Vilnius, Lithuania, 292-299.

Chang C., Chung M. and Lee B. (1994). Collision avoidance of two general robot manipulators by minimum delay time, *IEEE Trans. on Systems, Man & Cybernetics*, Vol. 24, No. 3, 517-522.

Cheng P. and LaValle M. (2002). Resolution complete rapidly-exploring random trees, *Proceedings of International Conference on Robotics & Automation*, Washington, D.C., U.S. Vol. 1, 267-272.

Chiddarwar S. and Babu N.R. (2007). Coordination strategy for path planning of multiple manipulators in workcell environment, *Proceedings of the 24th International Symposium on Automation & Robotics in Construction*, ISARC 2007, Mardras, 185-191.

Choset H., Lynch K.M., Hutchinson S., Kantor G., Burgard W., Kavraki L.E. and Thrun S. (2005). *Principles of Robot Motion – Theory, Algorithms, and Implementations*, The MIT Press, Cambridge.

Construction ICT Roadmap. (2003). http://cic.vtt.fi/projects/roadcon/docs/roadcon_d52.pdf

Crane Accident Statistics. (2008). http://www.craneaccidents.com/stats.htm

Crane-Related Occupational Fatalities. (2008). http://www.bls.gov

Cranimation (2006). http://www.cranimax.com

CSST (2008). Commission de la santé et de la sécurité du travail du Québec, http://www.csst.qc.ca/portail/fr/

Davis B.R. and Sutton S.C. (2003). A guide to crane safety. N.C. Department of Labor, Division of Occupational Safety and Health.

Ferber J. (1999). *Multi-Agent System, An Introduction to Distributed Artificial Intelligence*, Addison-Wesley, Pearson Education Limited.

Finin T., Fritzson R., McKay D. and McEntire R. (1994). KQML as an agent communication language. *Proceedings of the 3rd International Conference on Information and Knowledge Management*, Gaithersburg, Maryland, U.S. 456-463.

Fontana R.J. (2007). Ultra wideband technology – obstacles and opportunities, *Plenary Talk, European Microwave Conference*, Munich, Germany.

Furlani K.M., Latimer IV D.T., Gilsinn D.E. and Lytle A.M. (2002). Prototype implementation of an automated structural steel tracking system, *Proceedings of the 19th International Symposium on Automation and Robotics in Construction*, Maryland, September, 467-473.

GIS for Archaeology. (2008). http://www.esri.com/industries/archaeology/business/modeling.html

Gordon C. and Akinci B. (2005). Technology and process assessment of using LADAR and embedded sensing for construction quality control, *Proceedings of Construction Research Congress 2005: Broadening Perspectives*, San Diego, April.

Groove Crane. (2008). *TMS870/TTS870 Product Guide*, Manitowoc Crane Group.

Hammad A., Zhang C., Al-Hussein M. and Cardinal G. (2007). Equipment workspace analysis in infrastructure projects, *Canadian Journal of Civil Engineering*, Vol. 34, No. 10, 1247-1256.

Hirschmann (2008). http://hus.hirschmann.com.

Hwang Y.K. and Ahuja N. (1992). Gross motion planning: a survey, *ACM Computing Surveys*, Vol. 24, No. 3, 219-291.

Hwang K., Ju M. and Chen Y. (2003). Speed alternation strategy for multijoint robots in co-working environment, *IEEE Trans. on Industrial Electronics*, Vol. 50, No. 2, 385-393.

Kamat V.R. and Martinez J.C. (2001). Visual simulated construction operations in 3D. *Journal of Computing in Civil Engineering*, ASCE, Vol. 15, No. 4, 329-337.

Kang S. and Miranda E. (2006). Planning and visualization for automated robotic crane erection processes in construction, *Automation in Construction*, Vol. 15, 398-414.

Kim K. and Paulson Jr.B.C. (2003). Agent-based compensatory negotiation methodology to facilitate distributed coordination of project schedule changes, *Journal of Computing in Civil Engineering*, ASCE, Vol. 17, No. 1, 10-18.

Kuffner J.J. and LaValle S.M. (2000). RRT-connect: an efficient approach to single-query path planning. *Proceedings of IEEE International Conference on Robotics and Autonomous Systems*, 995-1001.

LaValle M. (2006). *Planning Algorithm*, Cambridge University Press.

LaValle M. and Kuffner J.J. (1999). Randomized kinodynamic planning. *Proceedings of Robotics and Automation*, Vol. 1, 473-479.

Lee J. and Bernold L.E. (2008). Ubiquitous agent-based communication in construction, *Journal of Computing in Civil Engineering*, ASCE, Vol. 22, No. 1, 31-39.

LiftPlanner (2007). http://www.liftplanner.net.

Lytle A.M., Saidi K.S. and Stone W.C. (2002). Development of a robotic structural steel placement system, *Proceedings of the 19th International Symposium on Automation and Robotics in Construction*, 263-268.

Lytle A.M., Saidi K.S., Bostelman R.V., Stone W.C. and Scott N.A. (2004). Adapting a teleoperated device for autonomous control using three-dimensional positioning sensors: experiences with the NIST RoboCrane, *Automation in Construction*, Vol. 13, 101-118.

Lytle A.M., Katz I. and Saidi K.S. (2005). Performance evaluation of a high-frame rate 3D range sensor for construction applications, *Proceedings of the 22nd International Symposium on Automation and Robotics in Construction*, Italy, September, 2005.

Machinedesign (2004). http://machinedesign.com/ContentItem/62380/Onboardvehicletestinggetsanupgrade.aspx

Mailhot G. and Busuio S. (2006). Application of long range 3D laser scanning for remote sensing and monitoring of complex bridge structure, *Proceedings of the 7th International Conference of Short & Medium Span Bridges*, August, Montreal, Canada.

MESA Imaging. (2008). http://www.mesa-imaging.ch/prodviews.php.

Moore M. and Wilhelms J. (1988). Collision detection and response for computer animation, *Computer Graphics*, Vol. 22, No. 4, 289-298.

Multispectral Solution. (2008). http://www.multispectral.com/products/sapphire.htm.

Navon R., Goldschmidt E. and Shpatnisky Y. (2004). A concept proving prototype of automated earthmoving control, *Automation in Construction*, Vol. 13, No. 2, 225-239.

NIST (2007). http://www.nist.gov.

Nwana H.S. and Ndumu, D.T. (1998). A brief introduction to software agent technology, *Agent Technology, Foundations, Applications, and Markets*, Springer.

Orbit Communications. (2008). http://www.ferret.com.au/c/Orbit-Communications/Vehicle-Proximity-Alert-and-Collision-Avoidance-System-from-Orbit-Communications-n778105.

Ren Z. and Anumba C. (2002). Learning in multi-agent systems: a case study of construction claims negotiation, *Advanced Engineering Information*, Vol. 16, No. 4, 265-275.

Peyret F., Jurasz J., Carrel A., Zekri E. and Gorham B. (2000). The computer integrated road construction project, *Automation in Construction*, Vol. 9, 447-461.

Photogrammetry (2008). http://www.photogrammetry.com/

Price M., Kenney J., Eastman R.D. and Hong T. (2007). Training and optimization of operating parameters for flash LADAR cameras, *Proceedings of the 2007 IEEE International Conference on Robotics and Automation*, Roma, Italy, April, 3408-3413.

Reddy H.R. and Varghese K. (2002). Automated path planning for mobile crane lifts, *Computer-aided Civil and Infrastructure Engineering*, Vol. 17, 439-448.

Ren Z. and Anumba C. (2002). Learning in multi-agent systems: a case study of construction claims negotiation, *Advanced Engineering Information*, Vol. 16, No. 4, 265-275.

Riaz Z., Edwards D.J. and Thorpe A. (2006). SightSafety: A hybrid information and communication technology system for reducing vehicle/pedestrian collisions, *Automation in Construction*, Vol. 15, 719-728.

Ritchie D. (2004). Crane simulators as training tools, *CraneWorks*, Vol. 16.

Russell S. and Norvig P. (2003). *Artificial Intelligence, A Modern Approach*, second edition, Prentice Hall.

Saidi K. and Lytle A. (2008). NIST Research in Crane Automation: 2007 Overview, *the 87th Annual Meeting*, Transportation Research Board.

Shapiro H.I., Shapiro J.P. and Shapiro L.K. (2000). *Cranes and Derricks*, 3rd Ed., McGraw-Hill, New York.

Simlog (2007). http://www.simlog.ca.

Sivakumar PL., Varghese K. and Babu N.R. (2003). Automated path planning of cooperative crane lifts using heuristic search, *Journal of Computing in Civil Engineering*, ASCE, Vol. 17, No. 3, 197-207.

Spong M.W., Lewis F.L. and Abdallah C.T. (1992). *Robot Control – Dynamics, Motion Planning, and Analysis*, IEEE Press, IEEE Control Systems Society.

Tam C.M., Tong T.K.L. and Chan W.K.W. (2001). Genetic algorithm for optimizing supply locations around tower crane, *Journal of Construction Engineering and Management*, Vol. 127, No. 4, 315-321.

Teizer J., Bosche F., Caldas C.H. and Hass C.T. (2006). Real-time spatial detection and tracking of resources in a construction environment, *Proceedings of the Joint International Conference on Computing and Decision Making in Civil and Building Engineering*, June, Montreal, Canada, 494-502.

Teizer J., Lao D. and Sofer M. (2007). Rapid automated monitoring of construction site activities using ultra-wideband, *Proceedings of the 24th International Symposium on Automation & Robotics in Construction*, ISARC, September, India, 23-28.

Trimble (2008). http://www.trimble.com/GCS900.shtml

UbiSense (2008). http://www.ubisense.net/index.php

Varghese K., Dharwadkar P., Wolfhope J. and O'Connor J.T. (1997). A heavy lift planning system for crane lifts, *Microcomputers in Civil Engineering*, Vol. 12, No. 1, 31-42.

Wang H., Hammad A. and Mudur S.P. (2007). Design of a distributed mixed reality system for construction simulation, *Proceedings of the ASCE International Workshop on Computing in Civil Engineering*, July, Pittsburgh, U.S., 846-853.

Wing R. (2006). RFID application in construction and facilities management, *Journal of Information Technology in Construction,* Vol. 11, 711-721.

WorkSafeBC (2008). http://worksafebc.com.

Yang L. and Hammad A. (2007). Ad-hoc wireless networking for supporting communication and onsite data collection, *Proceedings of the ASCE International Workshop on Computing in Civil Engineering*, July, Pittsburgh, U.S., 854-861.

Zaki A.R. and Mailhot G. (2003). Deck reconstruction of Jacques Cartier Bridge using precast prestressed high performance concrete panels, *PCI Journal*, Vol. 48, No. 5, 20-33.

Zhang C., Hammad A., Zayed T.M., Wainer G. and Pang H. (2007). Cell-based representation and analysis of spatial resources in construction simulation, *Journal of Automation in Construction*, Vol. 16, No. 4, 436-448.

Zheng Y. (1989). Kinematics and dynamics of two industrial robots in assembly, *Proceedings of the IEEE International Conference on Robotics and Automation*, May, Scottdale, USA, Vol. 3, 1360-1365.