Path Re-planning of Cranes Using Real-Time Location System

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Abstract

The numbers of reported accidents related to cranes are increasing during the past 10 years. Although simulation and visualization software are available for path planning of cranes, the high dynamic characteristics of on-site conditions often require re-planning the crane's path to ensure safety and efficiency. Any unpredicted objects on site should be detected and tracked in real time and the resulting information should be used for path re-planning. This paper proposes an approach for monitoring and re-planning path of cranes on construction sites using a real-time location system. Data collected from ultra wide band (UWB) sensors attached to the equipment, in addition to an up-to-date 3D model of the construction site, are used to detect any possible collisions or other conflicts related to the operations of the cranes. Re-planning algorithms are discussed to generate a new plan in real time. The 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.

1. Introduction

Safety and productivity issues on construction sites are always among the major concerns of project managers. The complexity of on-site conditions requires careful planning and coordination of different equipment to ensure safety and efficiency. Cranes are one of the most frequently used equipment for lifting objects on site. From 1992 to 2006, there were 323 deaths related to cranes in the U.S. (NIOSH, 2008). These accidents were caused by contact with overhead power lines, struck by booms/jibs, struck by crane load, caught in between, etc. 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).

To fulfill tasks efficiently and safely in a complex environment with known and unknown obstacles, ideal conceptual methods are proposed for path planning. 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).

Most of the software for crane path planning support only off-line operations, and the main functionality is to locate the crane on site rather than path planning for specific tasks (Cranimation 2007, LiftPlanner 2007). The path planner usually visits the site in advance to check the environment and makes adjustment to the plan. After that, when the crane is carrying on the plan, 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). If any obstacle appears, the remainder of the path may need to be re-planned based on the experience of the operator. Few researchers are focusing on real-time crane path planning (Kang and Miranda, 2006). Providing an efficient algorithm for path re-planning can ensure safety and improve efficiency. Figure 1 shows groups of cranes working in parallel in replacing the deck of Jacques Cartier Bridge in Montreal. The crane operator has to cooperate with another crane operator to lift the deck panel together. Since trucks and workers on site may become obstacles on the path of cranes, precisely locating them will significantly reduce the chance of accidents.

Figure 1: Groups of cranes working on a bridge

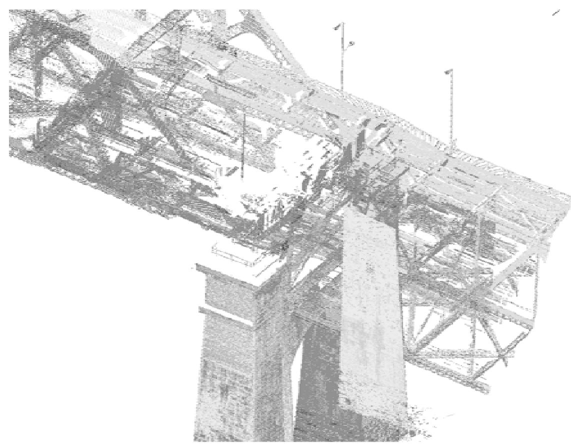


Figure 2: Point cloud collected for a bridge (Mailhot and Busuio, 2006)

This paper is part of a research project at Concordia University concerning real-time planning for construction equipment using multi-agent systems coupled with field data capturing technologies. Details of the overall framework and other enabling technologies can be found in Zhang and Hammad (2007) and Zhang et al. (2008). The present paper focuses on the algorithms for path re-planning and real-time location system (RTLS) using Ultra Wideband (UWB) technology. The objectives of the present paper are: (1) to investigate the usability of UWB tracking technology for cranes; and (2) to test an algorithm for real-time path re-planning based on the criteria of efficient world updates and query updates, and scalability for large number of degrees of freedom.

2. Environment Perception

2.1 Modeling static objects

Several methods are used to create the 3D model for static objects. 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. However, these models include mainly buildings and miss other small objects, such as traffic signs, fire hydrants, and electric poles and lines. Therefore, researchers are trying different technologies to create an accurate 3D model of the construction site. 3D laser scanners are used to collect point clouds, which can be transformed by software tools into volumetric objects, representing a precise 3D model including all the buildings and other objects. 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. Figure 2 shows a sample of point cloud collected for the bridge shown in Figure 1. Also, 3D range cameras have been evaluated for construction applications (Lytle et al. 2005) and 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.

2.2 Tracking moving objects

Moving objects should be detected and tracked in real time and the resulting information can be used for path re-planning. For instance, the positions of cranes need to be tracked and controlled to avoid collisions. On-board instrumentation (OBI) has been used to collect data about the equipment configuration, or other data which need to be monitored. Navon et al. (2004) have developed a tracking and control system using Global Positioning System (GPS) and OBI to monitor in real-time the activity of major construction equipment. However, GPS is unavailable without direct line of sight from the satellites, and accurate GPS receivers are expensive to install on every moving object on site. Therefore, other tracking technologies have been applied in several research projects, such as infrared, optical, ultrasound, RFID (Radio Frequency Identification), etc. Chae and Yoshida (2008) have discussed collecting data on site using RFID active tags for preventing collision accidents. However, RFID can only give proximity of locations. Recently, RTLS have been applied in various areas, such as logistics and manufacturing. RTLS can track and identify the location of objects in real time using nodes (badges/tags) attached to objects, and devices (readers) that receive the wireless signals from these tags to determine their locations. Figure 3 shows the trend of more precise RTLS using ultra wideband (UWB) technology, which delivers a robust localization with an accuracy of up to 15 cm.

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. Also, UWB works better with metals than other radio frequency (RF) devices. These advantages make it possible to attach UWB tags on construction equipment and other moving objects on site. In this research, Ubisense products are used to evaluate the usability of UWB technology. Both AOA (Angle Of Arrival) and TDOA (Time Difference Of Arrival) are used to locate tags based on triangulation. As shown in Table 1, the combination of TDOA and AOA provides the highest accuracy by using 2 or more sensors.

Researchers have started to investigate the usability of UWB on construction sites. For example, Teizer et al. (2007) have attached an UWB tag to a crane to track the position of the hook for safety issues. Giretti et al. (2008) have applied experiments on position tracking of workers on site for safety purposes. Construction Metrology and Automation Group (CMAG) is involved in measuring the performance of UWB tracking technology in construction (Saidi and Lytle, 2008).

Figure 3: Trend of a more precise RTLS using UWB (Ubisense, 2008)

Table 1: Combinations of the location method and the results (Ubisense, 2008)

Location method	Number of sensors detecting tag	Other information required	Result
Single-sensor AOA	1	Known height of tag	2D horizontal position (+ known height)
AOA	2 or more	None	3D position
TDOA+AOA	2 or more	None	3D position (highest accuracy)
TDOA only	4 or more	None	3D position

3. Path Re-planning Algorithms

There are a large number of algorithms available for generating collision-free paths. Varghese and his colleges have been studying crane path planning for a long time. They have tried different algorithms, such as A*, and Genetic Algorithms (GA), for optimizing the path of cooperative lift with two cranes (Sivakumar et al., 2003). In the research of Ali et al. (2005), a GA algorithm is used and compared with the A* algorithm and the former is considered as a better solution for two cranes working together. However, they assumed that the site contains only static obstructions, and the proposed solutions only provide off-line planning, rather than real-time control.

Finding the lowest-cost path through a graph is central to many problems, including planning for construction equipment (e.g. cranes). If arc costs change during the traverse, then the remainder of the path may need to be re-planned. This is the case for sensor-equipped crane with imperfect information about its environment. As the equipment acquires additional information via its sensors, it can revise its plan to reduce the total cost of the traverse.

During re-planning, the crane must either wait for the new path to be computed or move in an uncertain direction; therefore, rapid re-planning is essential. An efficient re-planning algorithm should be able to plan optimal traverses in real-time by incrementally repairing paths to the crane's state as new information is discovered. Re-planning algorithms focus on the repairs to significantly reduce the total time required for the initial path calculation and subsequent re-planning operations. Re-planning algorithms generalize path planning for dynamic environments, where arc costs can change during the traverse of the solution path. (Stentz, 1995).

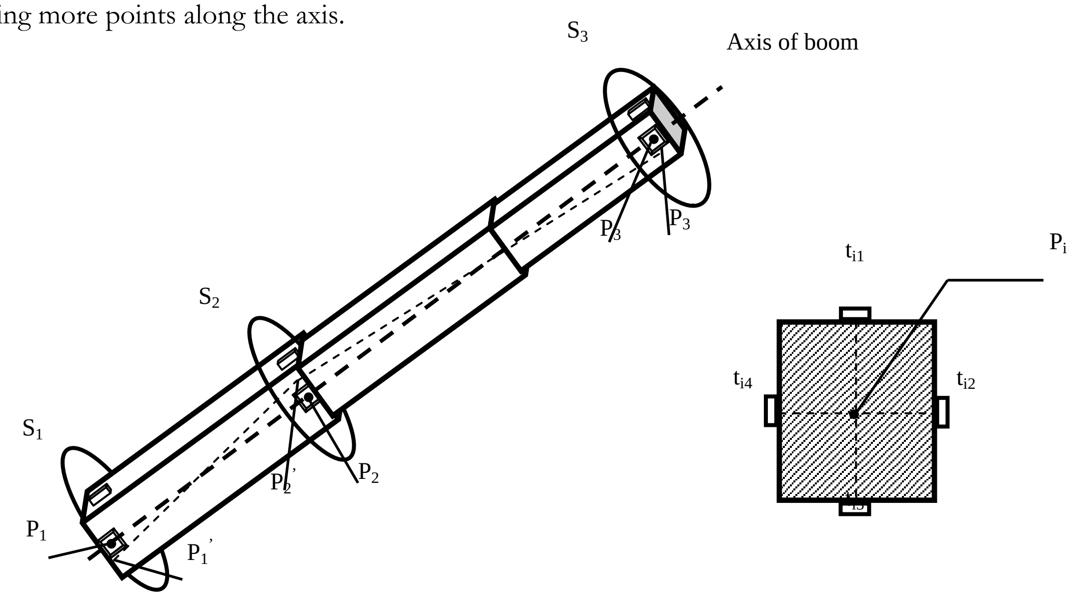
Deterministic re-planning algorithms, such as D*, efficiently repair previous planning solutions when changes occur in the environment. They do this by determining which parts of the solution are still valid and which parts need to be recomputed. However, as the dimension of the search space increases, for example, in the case of multiple cranes working together, deterministic algorithms such as D* simply cannot cope with the size of the corresponding state space. On the other hand, randomized approaches such as Rapidly-exploring Random Trees (RRTs) are a good choice for solving this problem since they are not crippled by its high dimensionality. RRTs have been shown to be effective for solving single-shot path planning problems in complex configuration spaces by combining random sampling of the configuration space with biased sampling around the goal configuration. RRTs efficiently provide solutions to problems involving vast, high-dimensional configuration spaces that would be intractable using deterministic approaches. Brandt (2006) has made a comparison between A* and an RRT algorithm for motion planning of robots, and found that RRT is much faster than A*.

However, in cases where the initial information available concerning the environment is incomplete or the environment itself is dynamic, typically the current RRT is abandoned and a new RRT is grown from scratch. This can be a very time-consuming operation, particularly if the planning problem is complex. For this case, researchers have started implementing the Dynamic RRT (DRRT) as a probabilistic analog to D* for navigation in unknown or dynamic environments (Ferguson et al., 2006). DRRT depends on repairing the current RRT when new information concerning the configuration space is received instead of abandoning the current RRT entirely. It efficiently removes just the invalid parts and grows the remaining tree until a new solution is found.

4. Proposed Approach

During the planning stage, 3D environment model is assumed to be available using methods explained in section 2.1. Based on the updated environment model, a collision-free path plan for a crane is generated using DRRT. During the actual construction work, multiple UWB tags are attached to different components of cranes and other moving objects and workers on site to monitor their position and orientation.

For tracking the location of a hydraulic crane, enough tags should be attached to its different components. Tags can be attached to the first section and the tip of the boom for easy installation and to avoid damaging the tags. Furthermore, tags should be located to fulfill the visibility, orientation, and accuracy requirements. Figure 4 shows a schematic boom with three sets of tags (S_1, S_2, S_3) attached to it. Each set includes four tags (t_{i1}, t_{i2}, t_{i3}, t_{i4}) fixed on each face of the boom, which ensures visibility by the UWB sensors when the boom rotates. The location of the center point of a cross section (P_i) can be calculated based on all or some of the four tags' locations of tags S_i. The orientation and the length of the boom can be obtained by connecting two axis points, P_1 and P_3. The purpose of adding the second sets of tags (S_2) is to get a third point (P_2) on the axis of the boom and to reduce the error of the axis location, and increase the accuracy by having more points along the axis.



(a) Schematic representation of tags on a boom (b) Cross section of the boom with set of tags (Si)

Figure 4: Locations of tags on the boom

The sensors should be set in a way to utilize their antenna pattern which is +/- 90 degrees in the azimuth and +/- 50 degrees in the elevation. The maximum range of sensors can be potentially up to 200 ft. Considering that the boom of the crane will be raised up during work, the sensors should be facing up to capture the movement of the boom. However, other movements, such as the movements of trucks and workers carrying tags attached to their hardhats, may be out of the vertical range of these sensors. Therefore, another set of sensors facing down is needed to capture different objects. Calibration of the sensors should be done to obtain an exact location of sensors with respect to a local coordinate system. Using a reference tag with a known location, the pitch and yaw angles of each sensor can be calculated. The roll angle is set to 0 because the sensors are levelled during installation.

After attaching tags to objects, information about the configuration of equipment and other moving objects are collected and used for collision prediction. 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 using the following steps: (1) Send signals to the crane for which the path is blocked to stop the movement; (2) Differentiate the type of the obstacle, e.g., equipment or worker, to decide the priority of movement; (3) 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 moving objects; (4) If it is a short duration obstacle, inform the crane to wait until the obstacle moves, then resume executing the plan; (5) If it is a long duration obstacle, then re-plan the path of the crane to avoid the obstacle; and (6) Execute the new plan.

5. Case Study

For the implementation part, we started developing a prototype of the system integrated with DRRT algorithm in "Autodesk Softimage" 3D software package with its 3D visualization and animation capabilities. Motion Strategy Library (2003), which includes variations of RRT algorithms, is used as a base library for developing an integrated motion planning solution in Softimage. The DRRT algorithm is implemented based on the RRT-Connect algorithm (Kuffner and LaValle, 2000).

A laboratory test was applied to a scaled model of a tower crane to simulate a lifting task with a tag attached to the hook. Raw data are collected using the UWB system software showing the tag's name, date, time, and the x, y, z coordinates. These data are transferred to the Softimage through the BVH motion file format, which indicates the hierarchy of the equipment and the motion at each time step. A continuous collision detection is applied to check whether a potential collision exists. Re-planning is triggered when an obstacle appears on the path and a new path is generated based on DRRT algorithm. Figure 5 shows a screen shot of the visualization environment, where the traces of the movement of the hook is shown. The path is not smooth because of the noise in the collected data, which could be cut using filtering.

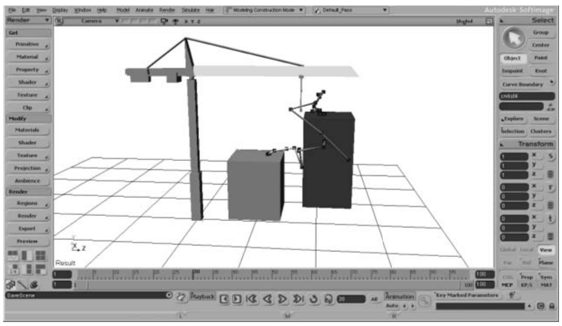


Figure 5: Visualization environment

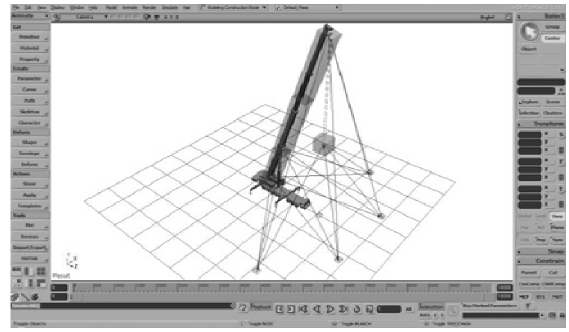


Figure 6: Design of the site setting

An outdoor test was applied to a hydraulic crane which only focuses on the movement of the boom of the crane. Softimage is used to design the setting of the site, as shown in Figure 6. Four sensors are located facing the boom of the crane, and several tags are attached on different parts of the boom. The out-door test was done on the yard of a crane company on December 12, 2008, under - 4°C temperature. Four sensors are installed around the crane to maximize the opportunity that more tags on the boom can get line of sight to at least 2 sensors (Figure 7). The power of the four sensors is supplied by a Power over Ethernet (PoE) switch. To synchronize the signals from different tags, timing cables are used to connect the four sensors. One sensor is acting as a master sensor to receive and synchronize the timing data from the other three. The sensors are calibrated using a tag as a reference point with known position. Tags used in the test are specially designed for use in harsh industrial environments and include several advanced features: an LED for easy identification, a motion detector to instantly activate a stationary tag and a push button to trigger events used by workers. As shown in Figure 8, tags are attached to the boom of the crane at different locations. Two tags are attached to the hook.

Figure 7: Locations of sensors

The result of the test is under analysis and will be reported at the conference. Another out-door test is planned in a warmer weather. Some problems were identified during the preliminary test: (1) Tags are difficult to fix using the adhesive pads on the boom due to the cold weather, and a magnetic mount could be a better solution; (2) Calibration of the sensors is difficult because they were facing up and the reference tag should be at a certain height difficult to reach.

6. Discussions and Future Work

This paper proposed an approach of path re-planning for cranes in real-time using an RTLS. Preliminary test was done on a crane with several tags attached to its boom and hook. DRRT algorithm is proposed for path re-planning and is under implementation. Future work includes: (1) Using multiple sets of sensors to monitor objects with various heights; (2) designing and testing different cases with various sensor locations and tag locations; (3) integrating the path re-planning algorithm and the RTLS.

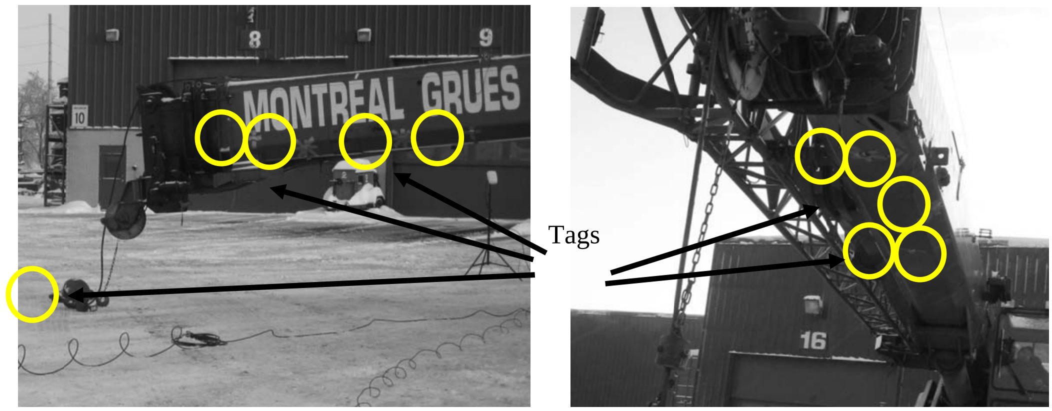


Figure 8: Tags attached to the boom and the hook

Acknowledgement

We would like to thank Mr. Christian Servais from the GUAY Crane Company in Montreal for providing us the opportunity to test the RTLS on a crane; and our colleges for helping in the test setting.

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