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Requirements, Specifications and Deployment Models for Autonomous Jobsite Safety Proximity Monitoring

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Requirements, Specifications and Deployment Models for Autonomous Jobsite Safety Proximity Monitoring

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Dedication

I dedicate my dissertation work to my beloved parents, brothers and sisters for their endless support and encouragement and unconditional love and sacrifice

谨以此论文献给我最挚爱的父母，大哥，大姐，二哥，二姐

感谢他们对我永无止境的支持与鼓励，无私的爱与奉献

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Xiaowei Luo

May 2013

Requirements, Specifications and Deployment Models for Autonomous Jobsite Safety Proximity Monitoring

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Construction has a higher injury and fatality rate than most of the other industries. Given this situation, existing research has studied various issues and factors affecting construction safety management and has attempted to use all available methods to improve the construction safety performance. However, the construction accident rate remains among the highest in the United States and the world.

The primary objective of this research is to advance autonomous proximity monitoring and hence provide a safer environment for construction workers. In particular, I seek to advance current evaluations of proximity warning technologies to a more robust engineering approach to the design and deployment of autonomous safety monitoring systems. The contributions of the research are demonstrated through specifications, deployments, and testing of proximity monitoring systems for crane loads and falling from height.

My research advances current knowledge in three areas. First, I develop specifications for proximity safety monitoring in a sensed environment, built from existing guidelines and expert interviews. Second, I translate the specifications to computer interpretable rules and deploy them in a distributed computing environment. This demonstrates the feasibility of a systems approach and reusability of components to speed deployment. Third, I evaluate the accuracy of the specifications and systems under imperfect data. I further evaluate some approaches to dealing with imperfect data. Collectively, these advances move existing proximity warning research from evaluation of specific systems to an engineering approach to development and deployment of distributed systems with reusable components that explicitly treats imperfect data.

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Chapter 1 Introduction

Construction is a major industry in the United States. According to the National Research Council, the construction industry contributed about 4.4 % of GDP and employed nearly 8% of the total workforce in the United States in 2007 (National Research Council, 2009). However, based on statistics from the Center for Construction Research and Training (CPWR, 2008), the nonfatal injury and illness rates in the construction industry is higher than most other industries. Despite efforts to improve the industry's occupational safety and health standards, it is still one of the most dangerous industries.

Improving construction safety performance is very challenging because construction by nature is inherently dangerous. There are a number of factors (Besnard and Hollnagel, 2012, Neitzel et al., 2001) that contribute to high accident rates in the construction industry: 1) the dynamic working environment, involving numerous laborers, suppliers, contractors, equipment materials, etc.; 2) human error is inevitable, such as lack of safety awareness and unsafe behaviors; 3) the uniqueness of each project presents its own safety challenges; 4) the relatively high employee turnover rates lead to greater challenges with safety training. These conditions contribute to accidents. In particular, the Occupational Safety and Health Administration (OSHA) summarizes the four leading causes of worker fatality on construction sites: Falls, electrocution, struck by object and caught-in/between. According to OSHA (OSHA, 2011), these "Fatal Four"

accounted for 57% of construction worker deaths in 2011. As the Bureau of Labor Statistics (BLS) states, "eliminating the Fatal Four would save 410 workers' live in America every year" (OSHA, 2011). Proximity monitoring plays a role in many "Fatal Four" accidents. Advancement to autonomous proximity monitoring could augment other safety measures, and in particular may address lack of worker awareness to their surroundings. This research focuses on a subset of proximity monitoring to address two specific accident types with the Fatal Four: falling from height (proximity to edges) and crane load safety (proximity to workers and loads). Addressing these two types of accidents can significantly improve safety performance on jobsites by improving worker's awareness to these two major risks on jobsites.

1.1 Current Approaches to Safety Management in Construction

Traditional construction safety management focuses on hazard prevention and control and safety and health training. Although OSHA has published many regulations, best practices and standards to assist the construction industry in providing safer workplaces for construction workers, safety knowledge exists mainly in paper form, codes or databases. Moreover, construction workers are unlikely to memorize all safety knowledge through safety trainings and might not be aware of their safety situations under pressure.

Recent research focuses on hazard prevention and control through design. Behm's study (Behm, 2005) shows there were about 42% of 224 construction worker deaths linked to the lack of design for safety concept. Design for safety could be an effective

way to minimize any potential hazard related to construction activities as early as possible, but the challenging fact is that it is very hard for designers to fully consider safety issues in the design phases due to the lack of practical construction experience or safety knowledge.

Importantly, the construction industry has lagged behind other industries in implementing technological advances, limiting its ability to explore innovative approaches to address many problems that have plagued the industry, such as high accident rates. FIATECH and National Institute of Standards and Technology (NIST) proposed the concept of Intelligent and Automated Construction Job Site (IACJS) by integrating emerging information technologies into jobsite activities to advance construction processes by increasing construction productivity and improving construction safety performance (FIATECH, 2003). There have been several efforts (e.g., Ergen et al., 2007, Fullerton et al., 2009, Lee et al., 2009a, Lee et al., 2009b, Teizer et al., 2007) to evaluate advanced technologies for the jobsites. However, existing research puts a great emphasis on 'technology' itself. In other words, the current approaches do not adequately 'embed and embody' comprehensive safety knowledge in the automated site monitoring systems. Thus, my research aims at integrating safety knowledge with information and sensing technologies to improve the construction safety performance through increasing safety situation awareness.

1.2 Research Objectives and Research Questions

Motivated by the research gap between safety practices and the existing information technologies, this research has three research objectives: First, to establish a knowledge base for autonomous monitoring on jobsite based on safety standards, regulations and best practices. Second, to develop and demonstrate an autonomous safety monitoring system in a distributed computing environment that is mobile and resource constrained. Third, to establish a testbed to deploy the autonomous safety monitoring system and to explore data imperfections and their impacts on safety decision making. The three research objectives will advance existing computing knowledge and construction safety practices.

The following research questions have been developed in support of the research objectives.

Question 1. How to conceptualize safety knowledge in an autonomous monitoring environment?

Question 2. How to formalize the reasoning mechanisms in a distributed computing environment and how to implement autonomous safety monitoring?

Question 2.1 What deployment model can meet the distributed computing constraints to implement safety monitoring?

Question 2.2 What are effective reasoning mechanisms in autonomous safety monitoring?

Question 2.3 What are the constraints posed by a mobile computing environment with best available techniques?

Question 3. How do we address information imperfections to better support autonomous safety monitoring?

Question 3.1 What are the types and sources of information imperfections?

Question 3.2 What are the impacts of data imperfections on safety monitoring?

Question 3.3 Which approaches to deal with imperfections add value to the safety monitoring process?

Question 3.4 What is the improvement made by the various methods to deal with imperfect data?

1.3 RESEARCH SCOPE

After reviewing the safety injuries/fatalities reports and interviewing with safety experts in the construction industry, I found out that many injuries and fatalities are caused by workers/equipment entering unsafe areas without proper safety protection measures (e.g., a worker did not securely tie off, fell from the open edge and resulted in fatal injury). The proximity controls to dangerous areas are critical to onsite safety management and safety performance can be significantly improvement if worker proximity is appropriately monitored and controlled. Therefore, the research places emphasis on proximity to dangerous areas. Although equipment mechanical condition, ground conditions, safety training, and hazardous materials control are also important issues for safety management on construction jobsite, they are not covered in this research and they are potential topics for future research.

For safety monitoring on proximity controls, I chose proactive fall prevention and tower crane operations for detailed study in this research based on two reasons: 1) Both those two safety topics are closely related to the leading causes of accidents in construction, and addressing these two causes through autonomous safety monitoring can have a high impact in moving the construction industry towards zero accidents. Falling from height is the leading cause of accidents on construction jobsites and the one of the major reasons of accidents caused by falling from height is operation in dangerous areas without appropriate safety protection measures. Tower crane accidents are another leading cause of fatalities and injuries in construction. The tower crane component entering dangerous proximity to other entities (e.g., other tower crane, power line, occupied building) and a worker's exposure to the dangerous areas under a crane load are the high risk events in tower crane operations. 2) In addition, both fall prevention and crane operation safety have similar proximity monitoring needs and hence they can be used to test the generality of proximity monitoring approaches. Therefore, this dissertation focuses on proximity monitoring of tower crane operations and working at height.

This research focuses exclusively on proximity monitoring. It does not consider:

1) The environmental conditions including wind, snow, soil, floor. The research assumes that all the operations area under normal environmental conditions and they do not have impacts on the safety monitoring.
2) Monitoring of workers on scaffolding, ladders, towers and posts where the primary safety approach is to tie of or other use of personal protection

equipment. Instead, the research focuses on workers working near open edges on floors and top roofs.

1.4 READER'S GUIDE TO THE DISSERTATION

This PhD dissertation is divided into seven chapters. In the following chapters, I addressed each of the main research questions. As mentioned in section 1.1, falling from height and crane-related operations are two major causes of fatalities in the construction industry. Therefore, in chapter two, I selected the construction tower crane as a representative case to explore the first research question. The chapter includes background research of tower crane safety in the construction industry, the research methods used for developing safety knowledge and representation in an electronic environment, results from the research, and concludes with the validation of the safety knowledge generated. In order to further validate whether safety proximity specifications are generalizable, fall prevention was chosen as the case study in chapter three, beginning with a literature review of falling from height in the construction industry. Then, safety specifications and information requirements for fall prevention was developed. Next, validation and system information sampling frequency requirements were discussed at the end of the chapter three. Chapter four introduced current autonomous safety monitoring applications, identified research gaps in existing research, and showed my design of autonomous safety monitoring deployed in a distributed environment using the safety knowledge presented in chapter two and three. Two autonomous safety applications were developed and deployed in a mobile computing environment and

scaled testbed. The demonstration of these two safety applications showed that my design is extensible. Chapter five focused on data imperfections in the autonomous safety monitoring system with wireless sensor networks. Analysis of data collected from the testbeds, as well as simulation data, show the impact of imperfect information on safety monitoring. Chapter 6 provided an initial attempt to improve the system performance due to data imperfections with a small set of models to predict location. Chapter 7 briefly summarized research contributions and limitations as well as provided suggestions for future research directions.

Chapter 2 Safety Requirements and Specifications for Autonomous Tower Crane Safety Monitoring

This chapter will answer the research question 1, 'How to conceptualize safety knowledge in an autonomous monitoring environment', by applying a safety knowledge elicitation approach to tower crane safety monitoring.

2.1 INTRODUCTION

Tower crane accidents may occur for many reasons, but the unchanged fact is that they often lead to serious injuries and even death. Therefore, in this chapter, the construction tower crane is selected as a representative case to explore the first research question. A knowledge elicitation approach was proposed to conceptualize the safety knowledge for autonomous safety monitoring. Following this approach, I reviewed the current standards and practices to extract the safety knowledge for tower crane safety monitoring. Then the extracted safety knowledge was translated into computer interpretable specifications, decision making flowchart and information requirements. The results in this chapter demonstrated that the proposed knowledge elicitation approach can be used to conceptualize safety knowledge in an autonomous monitoring environment through the tower crane safety monitoring example.

2.2 LITERATURE REVIEW

The construction industry experiences the highest accident rate of all major industries in both industrialized and developing countries (Behm, 2005, López et al., 2008, Tam et al., 2004). One of the major causes of the high accident rate is due to the involvement of heavy equipment in construction jobsites (e.g., tower cranes, excavators, trucks). Most of the tower crane-related accidents cause serious injuries or fatalities (e.g., loads falling onto workers, electrocution, collisions) on jobsites. According to the following reports, there were 137 crane related fatalities from 1992 to 2001 in the United States (Kang and Miranda, 2004), 41 crane related fatalities in 2006 in Japan (Kawata, 2007), and 34 tower crane related accidents with 3 or more fatalities from 2004 to 2008 in Mainland China (Zhao et al., 2011) and 14 crane related fatalities from 1998 to 2005 in Hong Kong. Tower crane related accidents on construction jobsites do not only impact the construction safety performance, but also have serious and negative influences on project productivity, schedule, company reputation and even public safety.

In order to address tower crane related accidents, three common types of accidents have been identified: 1) loads falling onto workers; 2) tower crane boom in contact with a power line; and 3) a tower crane collides with other cranes or equipment. The causes of these accidents include: 1) the lack of timely recognition of dangerous situations (Fullerton et al., 2009); and 2) misjudgment of participants in tower crane operations. Autonomous computer-aided tower crane safety monitoring can provide real-time information to tower crane operators, minimize misjudgment and lag in danger recognition, resulting in lower tower crane-related accident rates. The recent

advancements of sensing, communication and computing technologies make the implementation of autonomous tower crane safety monitoring possible from a technology prospective. However, tower crane safety practice and knowledge still remain in manual and semi-automatic modes. To seamlessly implement autonomous tower crane safety monitoring on construction jobsites, safety knowledge and practices must be represented in a computing environment. More specifically, safety requirements and specifications for autonomous crane safety monitoring must be developed.

2.3 CURRENT APPROACHES TO TOWER CRANE RELATED ACCIDENTS

Shapira (Shapira and Lyachin, 2009) identified 21 factors affecting tower crane safety. Among these factors, project conditions (e.g., power line, obstacle and congested jobsite) pose greater risks for tower crane operations in terms of contacting power lines, crane component/load hitting other workers or properties. Actively monitoring crane operation areas, such as loading/unloading areas and proximity to power lines is important to ensure tower crane operation safety. Neitzel (Neitzel et al., 2001) reviewed crane related injuries, crane safety devices, and commonly used safety procedures. I recommended an enhanced safety system (Luo et al., 2011a), taking into account human factors interactions in addition to raw data, which can potentially result in significant decrease in crane related accidents.

Image based technologies have been widely used to monitor the crane operation in loading areas to minimize risks of blind lifting. For example, video-based systems (Lee et al., 2006, Shapira et al., 2008) in combination with radio-frequency identification

(RFID) and wireless communication technology was proposed and developed to provide images from cameras installed on trolleys to crane operators for an improved view of the lifting area and to minimize the risk of blind lifting. However, these systems provided images for crane operators but still relied on the crane operators to use their knowledge to judge dangerous situations. To further monitor crane operations automatically, Yang (Yang et al., 2011) used image processing techniques on video streams from surveillance cameras to track if the crane enters predetermined blind lifting areas. For tower cranes working closely to one another, Hwang examined the technical feasibility of using Ultra Wideband technology to avoid tower crane collision in a test bed environment. However, the research assumed a fixed safety distance which is not based on the safety knowledge (Hwang, 2012). Moreover, the study did not systematically develop a list of tower crane operations which can utilize potential computing technologies. To facilitate autonomous, not just semi-automatic, tower crane safety monitoring, safety requirements must be presented in a computing framework. Limited research has been conducted in representing tower crane safety monitoring knowledge in a computing framework. Once safety knowledge is represented, a technical feasibility study for tower crane safety can be extended to a practical safety monitoring prototype/system which complies with existing safety regulations and standards. Even when new technologies are developed with time, the identified safety knowledge and information requirements can still be useful as a foundation for the development of an autonomous safety monitoring system.

2.4 SAFETY REQUIREMENTS AND SPECIFICATIONS

To get a comprehensive understanding of safety management regarding tower crane operations on construction jobsites, I reviewed regulations, standards and best practices from industry alliances. The materials reviewed include OSHA 2007-0066 Cranes and Derricks in Construction (OSHA, 2010a), OSHA 1910 Subpart N Occupational Safety and Health Standards: Materials Handling and Storage (OSHA, 1987), ANSI (American National Standard Institute)/ASME (American Society of Mechanical Engineers) B30 series (ANSI/ASSE, 2007a, ANSI/ASSE, 2007b, ANSI/ASSE, 2009, ANSI/ASSE, 2012), and a series best practice guidelines published by Construction Plant-Hire Association. In this research, I focus on the dangerous area control related to tower crane operations as the worker and crane component entering dangerous area are exposed the tower crane, other facilities, crane operators and workers in dangerous situations. Based on the standards, regulations and best practices, I identified five dangerous areas (Table 1) for tower crane operations with the associated rules.

Table 1 Dangerous Areas for Tower Crane Operations

Category	Sub-category
Dangerous area for crane component	Proximity to occupied buildings
	Proximity to road, highway, railway and waterway
	Proximity to power line
	Dangerous area when two or more cranes are working closely
Dangerous area for worker	Area under the crane load

On top of the safety rules and objects, there is a need to develop specifications and decision rules for each dangerous area. Since the safety rules extracted from the regulations and standards rely on jobsite safety professionals to make some decisions (e.g., what is the specification of crane load's fall zone), there is a need to elicit their decision knowledge.

Consequently, I designed a semi-structured interview guideline, composed of five parts: 1) Interviewees' background; 2) safety concerns regarding crane operations; 3) current crane safety practices; 4) attitude towards information technology application in crane safety; and 5) safety knowledge regarding safety zones for crane operations.

Four safety experts, one from an owner company and three from contractor companies, all of which are active members of the Construction Industry Institute's (CII) Safety Community of Practice, were selected for the interviews based on the following criteria: 1) At least 10 years working experience in construction jobsite safety management; 2) At least 20 years industry experience in construction; 3) Familiarity with tower crane operation safety regulations in building construction.

The main part of the interview focused on identifying and specifying the dangerous zones in a set of specific crane operations related to the dangerous areas in Table 1. For each dangerous area in Table 1, a picture showing a crane and relative entities was shown to the interviewees and I explained the ongoing activity that the tower crane and other entities involved in, as well as the jobsite conditions. Each interviewee identified if there is a dangerous area related to crane operations in the specific scenario. If so, the interviewee was asked to describe the boundary of the dangerous area. The

description of dangerous area's boundary is translated into a rigid representation of a dangerous zone in terms of shape, location and size. After each interviewee identified the boundary of the dangerous areas, all interviewees are required to talk about their best practices in controlling those dangerous areas, including 1) who can have the access to those areas; 2) what actions they would take when unauthorized workers enter those areas; 3) what are the requirements to access those areas. The best practices were translated into safety rules of the controlling those dangerous areas.

A recall-based measure (Bitner et al., 1990) was used rather than recognition-based (Myers, 1914) during the interview process to determine if the extracted knowledge from the interview is comprehensive since the author wanted the experts to identify significant safety knowledge for tower crane safety monitoring regarding dangerous area controls. Figure 1 shows the cumulative count of information items identified by the OSHA regulations and three experts. The curve in the figure shows a diminishing return trend in terms on the numbers of interviewees, indicating that the extracted safety knowledge is comprehensive and no additional expert interview is necessary.

Here I use the dangerous area under the crane load to explain how I translated the input from the interviews to the rigid specifications of the dangerous areas. The interviews explained that the direct fall zone of the crane load is the projected area right under the crane load. The crane load might slip away from the projected area for up to 6 feet. Therefore, considering the crane load might rotate in the air, the direct falling area centered at the projected point of the crane's hook on the ground. The shape of the direct

falling area is a circle and the radius of the falling area is the largest horizontal distance from any point on the crane load to the crane's hook.

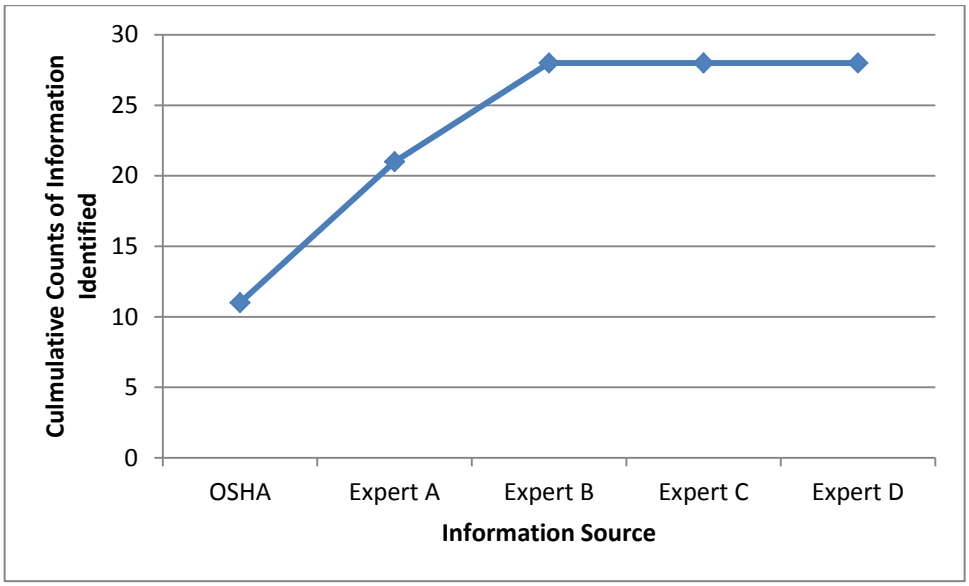


Figure 1 Cumulative Counts of Information Identified by Experts

At the end of the interview process, the specifications on dangerous areas and the information flowchart are summarized based on the safety rules. To help identify the information requirements on safety monitoring of these identified dangerous areas, I developed an information requirements table (Luo et al., 2011a) to store the information requirements for decision making support on construction jobsites based on literature review. By using the information requirements table (Table 2), I was able to systematically identify the information requirements and possible sources for safety monitoring of each identified dangerous area.

Table 2 Information Requirements Table for Dangerous Area Monitoring Related to Tower Crane Operator

Basic Production Factor	Production Elements	Component of Production Elements	Relevant Information	Possible Source	Example Data	Unit
People			Unique ID	RFID	WT0813221	N/A
			Location	RFID/GPS/ Crickets/UWB Sensor	(33.80, 15.82, 3.66)	Meter
Equipment	Tower Crane		Unique ID	RFID	TC0024151	N/A
			Base Location	Database/RFID	(15.24,15.24,0.37)	Meter
			Height	Database/RFID/GPS	5.49	Meter
		Main JIB	length	Database	24.38	Meter
			Angle	Angle Sensor/Calculation	50.72	Degree
		Counter Weight JIB	Length	Database	6.10	Meter
		Hook	Load	Load Sensor/RFID Reader	1,000	Ton
			Location	RFID/GPS	(22.86,22.86,4.57)	Meter
		Load	Largest Dimension	RFID	0.91	Meter
			Vertical Dimension	RFID	0.91	Meter
Environment	Wind		Wind speed	Windsock Sensor	3	m/s
	Humidity		Relative Humidity	humidity sensor	70	%
Jobsite	Buildings		Floor Shape	Database	Rectangle	N/A
			Floor Center	Database	(0.00,0.00,0.00)	kv
			Floor Parameters	Database	(6.10, 30.48)	Meter
			Height	Database	24.38	Meter
	Facilities	Road/Walkway/Highway/Waterway	Central line	Database	[(22.86,0.00,0.00), (22.86,15.24,0.00)]	Meter
			Width	Database	4.00	Meter
		Power Line	Location	Database	[(0,0,6.00), (0,15.00,6.00)]	Meter
			Voltage	Database	20	kv

To further validate the comprehensiveness and applicability of the safety knowledge extracted through the expert interviews, I contacted two construction companies with good reputation on safety performance and experience with high rise building construction in Mainland China. Two ongoing projects were visited and I discussed the identified safety knowledge with safety managers on these two projects. Further discussion on the validation process is described at the end of this chapter. The research method is summarized in Figure 2.

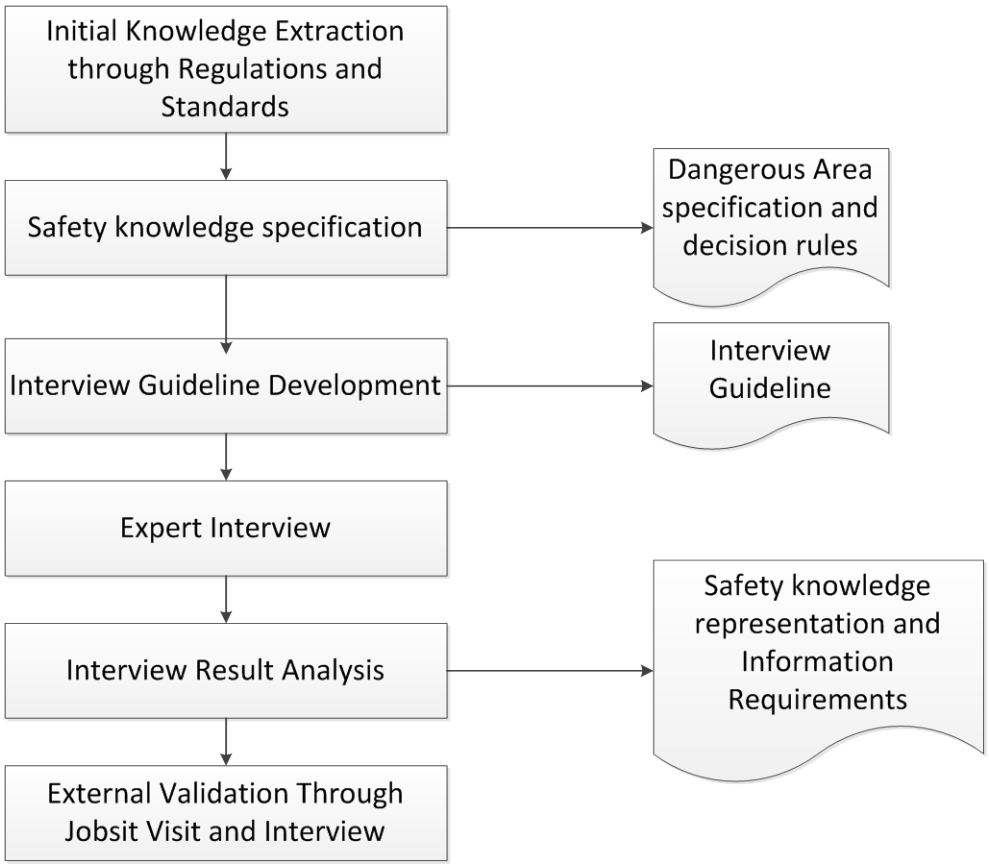


Figure 2 Tower Crane Safety Knowledge Elicitation Approach

2.5 RESEARCH RESULTS

2.5.1 Area 1 Proximity to Occupied Buildings

While extending the safety from construction workers to public safety, some local crane ordinances (California Division of Occupational Safety and Health, 2010, Lancaster, 2008) and cooperation standards (Kennecott Utah Copper Coorperation, 2011, Northern Industrial Insulation Contractors Inc., 2009) prohibit crane operators to swing loads over occupied buildings to prevent the risk of injuries caused by crane loads. When the crane component is getting too close to an occupied building, it might also cause property damage to both the tower crane and said building. After reviewing existing regulations/best practices and discussing with the safety experts, a red zone (Figure 3) for crane components is defined as the set of points within the clearance distance of 0.6 meters from the boundary of occupied building. The crane component should avoid entering this area. Otherwise, a collision between the crane component and the building façade might occur. Safety personnel can adjust the clearance distance, depending on the importance of occupied buildings and weather conditions. Existing regulations prohibit crane operators from swinging loads over occupied buildings. Therefore, a red zone is defined as the space above the occupied building and any part of the crane load may not enter the predefined red zone. If the crane load enters the red zone at any time, an alert should be sent to the crane operator demanding the operator to move the load away from the red zone. A buffer area of 0.6 meters is created as the yellow zone (Figure 4) based on the experts' inputs. If the crane load enters the yellow zone, a warning will be sent out to the crane operator to remind her that the crane load might enter the red zone soon.

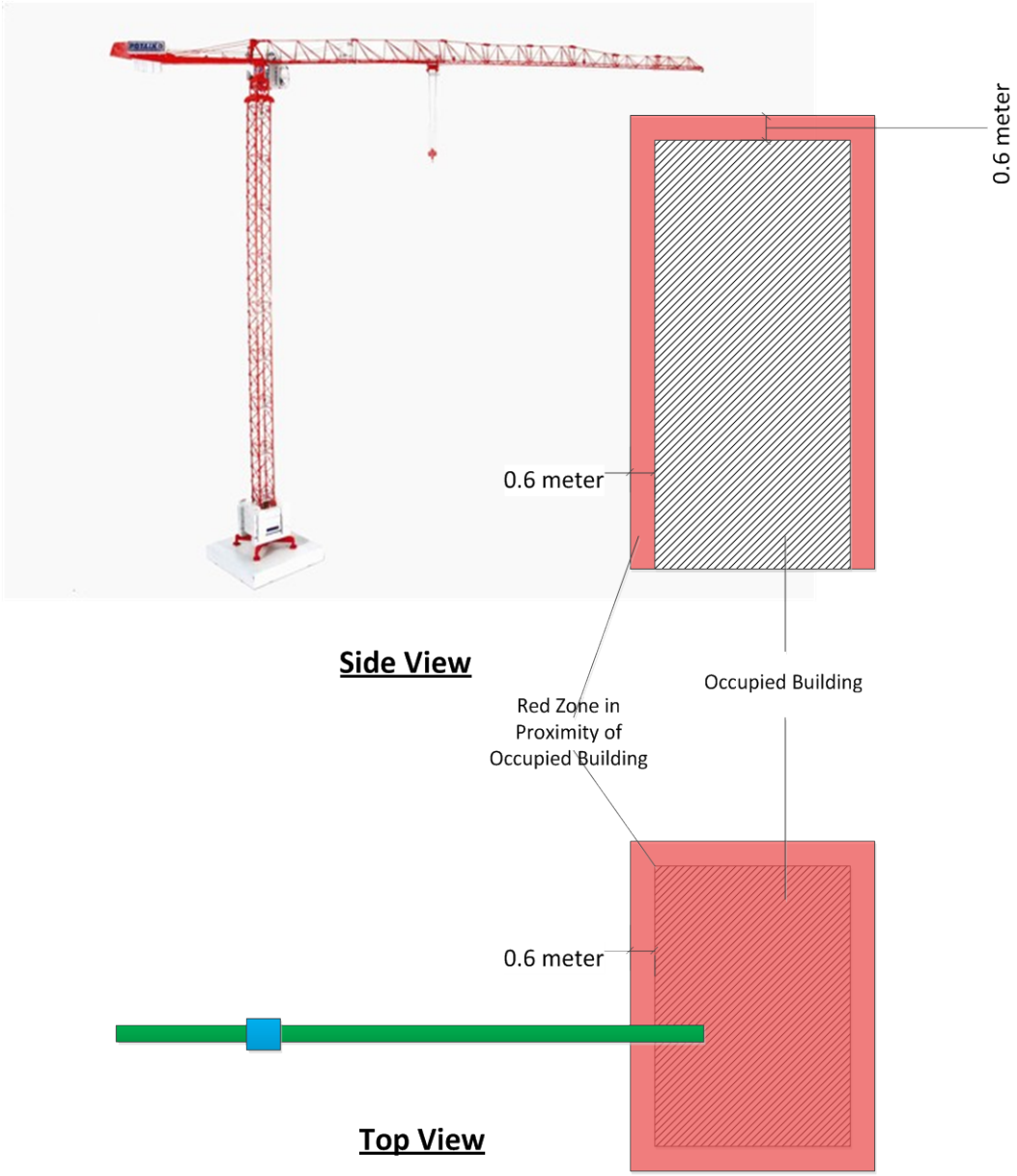


Figure 3 Specification of Dangerous Area in Proximity of Occupied Building for Crane Components

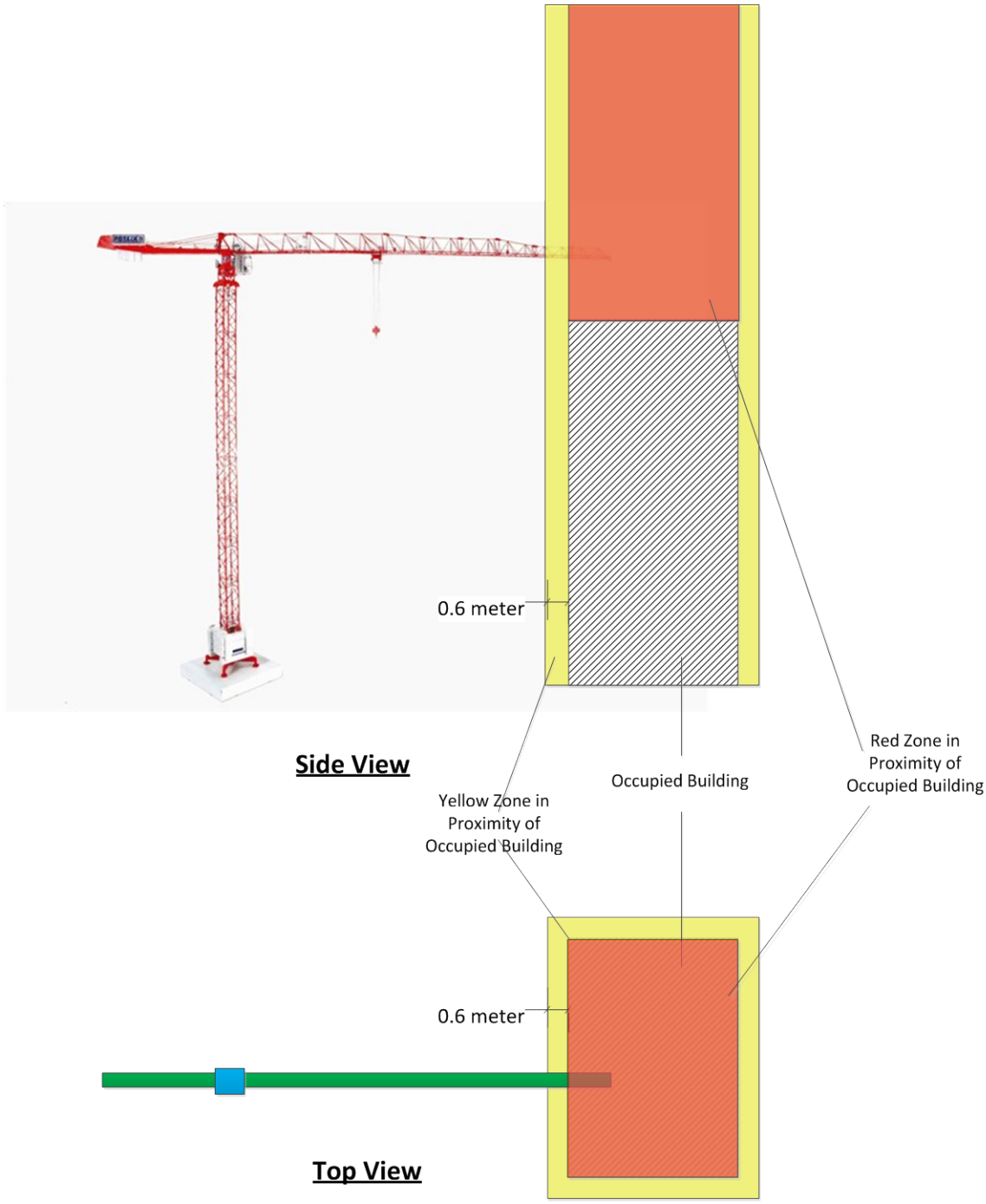


Figure 4 Specification of Dangerous Area in Proximity of Occupied Building for Crane

Based on the expert interviews, a decision flowchart (Figure 5) was developed to illustrate the decision making regarding the area control in proximity of occupied buildings. First, the safety professional observes the dimension and location of the occupied buildings to calculate and form the dangerous areas in proximity of occupied buildings in mind. Next, the safety professional keeps monitoring the crane load's location to create the crane boom's bounding box and the crane load's bounding box. Then the safety professional will compare the bounding boxes to the dangerous areas. If the bounding boxes intersect with the red zone the safety professional can send a critical alert to the crane operator to move the crane load away from the red zone immediately. If the bounding boxes do not intersect with the red zone, the safety professional compares the crane load's bounding box to the yellow zone. If the bounding box intersects with the yellow zone, the safety professional sends a warning to the crane operator to notify her that the crane load is approaching the red zone, so he/she should specifically pay attention to the movement of the crane load's direction and speed to make sure that the crane load is not going to be swung over the occupied buildings.

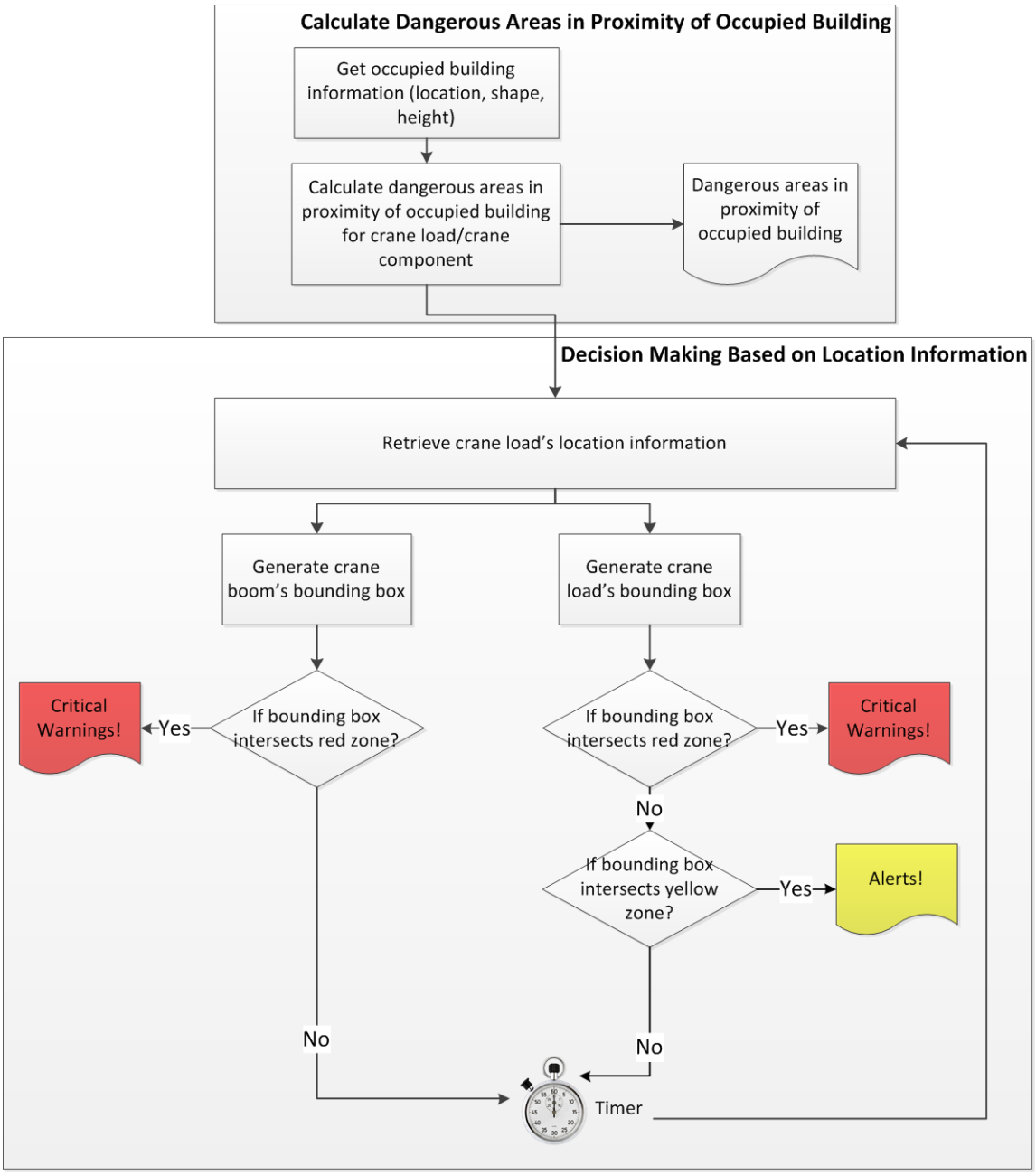


Figure 5 Decision Making Flowchart for Dangerous Area Control in Proximity of Occupied Buildings

To facilitate the implementation of autonomous crane safety monitoring, the information requirements for monitoring dangerous areas in proximity to occupied buildings are specified based on Table 2. There are three types of information requirements: 1) location information which can be acquired through localization devices; 2) classification information which can be stored at and retrieved from RFID tags or computers; and 3) geometric information which can be retrieved from computer database. The required information captured from various proposed sources can be fed into the decision making flowchart developed previously and implement the autonomous dangerous areas monitoring in proximity of occupied buildings.

2.5.2 Area 2 Proximity to Road, Highway, Railway and Waterway

According to existing regulations and best practices (OSHA, 2010a, Phillips, 2007), a crane operator cannot swing crane loads above transportation lines (including walkways, roads, highways, railways and water ways) unless access authorization to the transportation line is gained. Based on the regulations, the red zone (Figure 6) is defined as the area above the operating transportation lines which is covered by the crane operation radius. To eliminate the hazards of falling, the crane load cannot enter the red zone at any time. Otherwise, it may put public safety at risk. To create a buffer area, the yellow zone is created with a clearance distance of 0.9 meters to the red zone. If the crane load enters the yellow zone, the crane operator would be notified with a warning message.

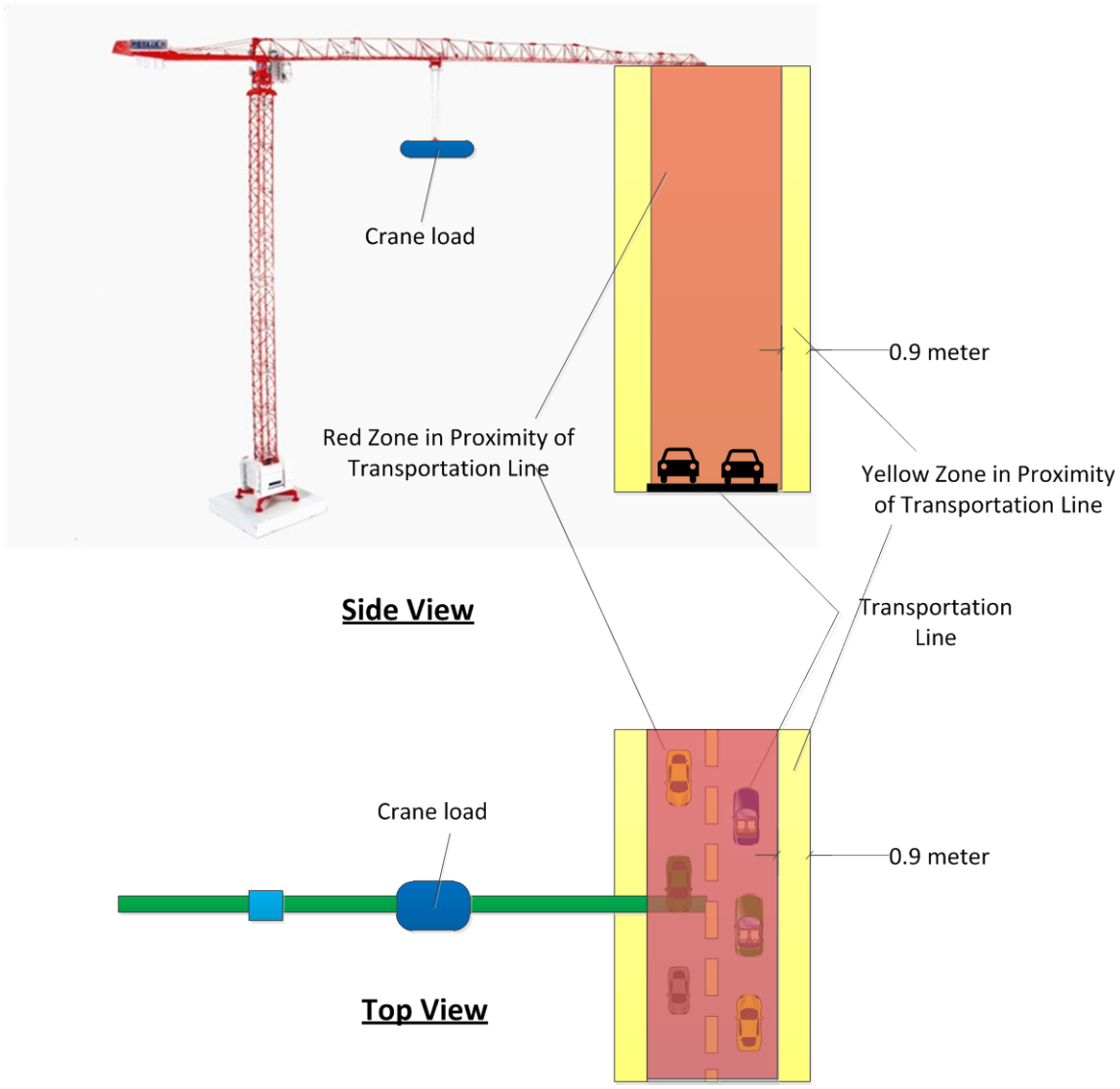


Figure 6 Dangerous Area in Proximity of Transportation Lines

Based on the expert interviews, the decision making flowchart (Figure 7) is developed to facilitate the autonomous safety monitoring of crane operations in proximity of transportation lines. The decision making process is similar to the one of crane load getting close to the dangerous area described in section 2.5.1 with the modification of dangerous areas shown in Figure 6.

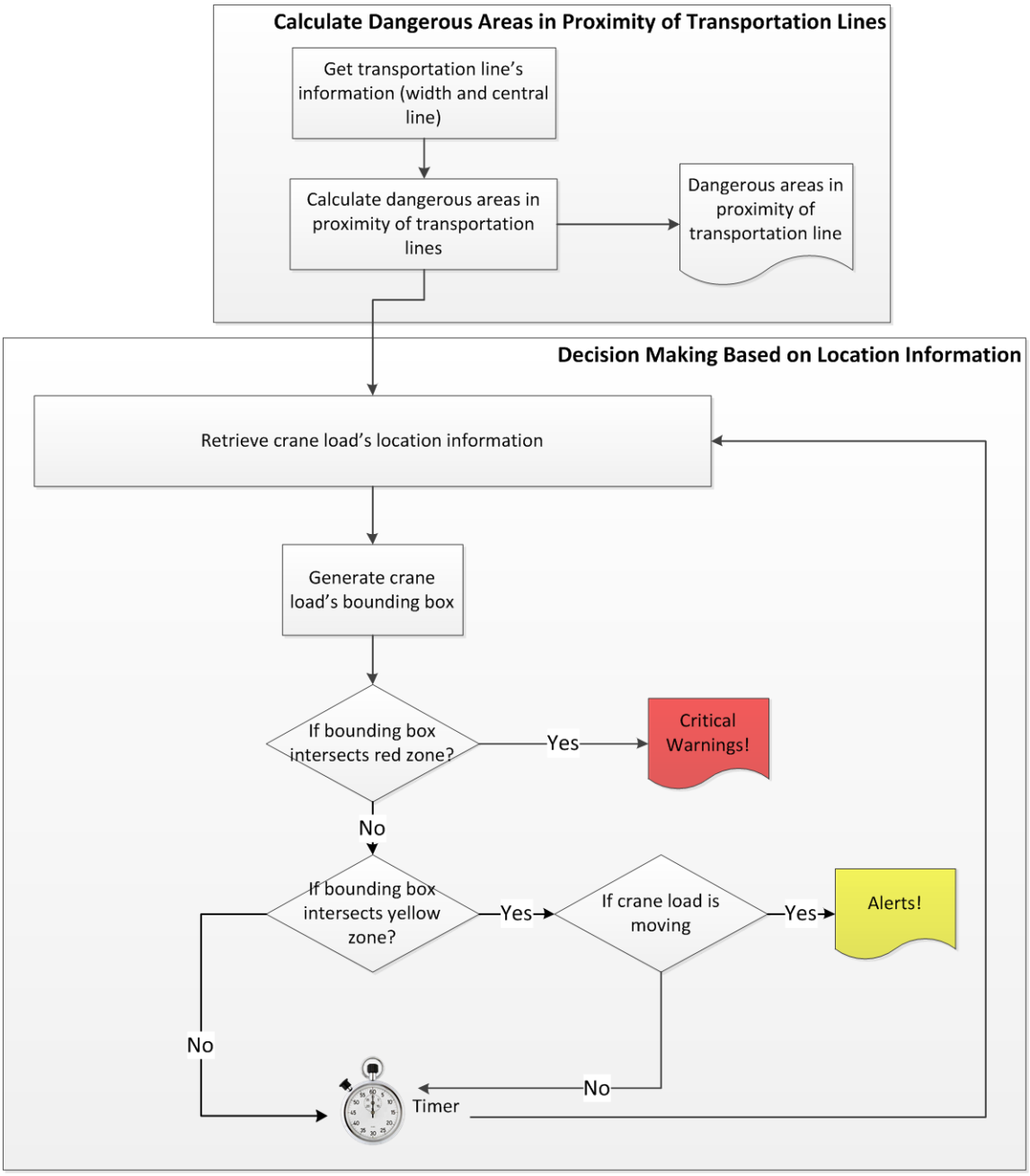


Figure 7 Decision Making Flowchart of Dangerous Area Control in Proximity of Transportation Lines

To facilitate the implementation of autonomous crane safety monitoring, the information requirements for dangerous area monitoring in proximity to transportation lines is specified based on Table 2. There are basically two types of information requirements: 1) location information which can be acquired through localization devices; and 2) geometric information which can be retrieved from computer database. The required information captured from various proposed sources can be fed into the decision making flowchart, developed and described previously, to implement the autonomous dangerous area monitoring in proximity of transportation lines.

2.5.3 Area 3 Proximity to Power Line

OSHA requires a clearance distance among the crane component, crane load, load line, and power lines when the tower crane is operating in proximity of power lines. The clearance distance depends on the voltage; a clearance distance of 3.05 meters is used for voltage of less 50 KV. If the voltage is greater than 50 KV, an additional 1.02 centimeters is added to the clearance distance for each 1 KV. Other factors to be considered when determining the clearance distance include but are not limited to: conditions affecting atmosphere conductivity, time necessary to bring the equipment, load and load line to a complete stop, wind condition, degree of sway in the power line, lighting condition, and other conditions affecting the ability to prevent electrical contact. Unless the power line is deenergized and visually grounded, the clearance distance should be maintained at any time. Using the clearance distance, the set of points within the clearance distance to the power line is defined as red zone (Figure 8). Since the crane load above the red zone can

fall from the hook and drop onto the power line, a crane load is not encouraged to be swung over the power line. Therefore, the area above red zone is defined as yellow zone for crane load.

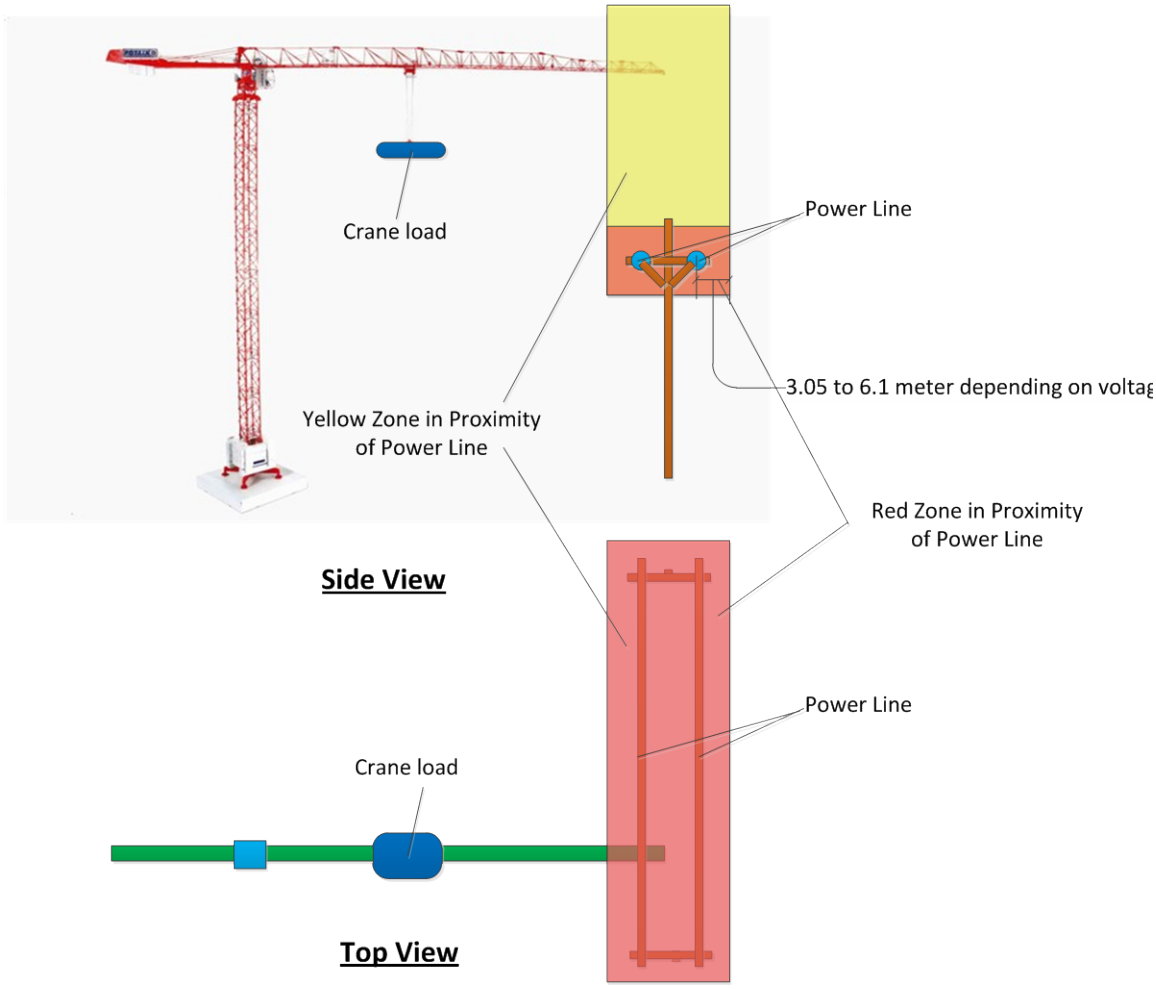


Figure 8 Specification of Dangerous Area in Proximity of Power Line

Based on the expert interviews, a decision making flowchart (Figure 9) was developed to facilitate the autonomous safety monitoring of crane operation in proximity of power lines. The safety professional first determined the dangerous areas in proximity

of power lines based on the power lines' locations and the aforementioned specifications of dangerous areas. If the power line's voltage is zero (which means the power line is deenergized) and visually grounded, no dangerous area exists for this section of power line. Otherwise, the clearance distance is determined based on a power line's voltage as described in OSHA's regulations. The bounding box of the red zone and the yellow zone are generated then. The safety professional continuously monitored the dimensions and the location of the crane load to determine the bounding box for crane load. Then a comparison is made between the load's bounding box and the red zone, if the bounding box intersects the red zone, a critical alert is sent to the crane operator and the crane operator should move the crane load away from the red zone immediately. If not, a comparison is made between the crane load's bounding box and the yellow zone. If the bounding box interests with the yellow zone, a warning message is sentto the crane operator and the crane operator is notified that the risk of crane load's free fall onto power lines exists.

To facilitate the implementation of autonomous crane safety monitoring, information requirement for dangerous area monitoring in proximity of a power line is specified based on Table 2. There are three types of information required: 1) location information which can be acquired through localization devices; 2) categorizing information which can be stored in and retrieved from RFID tags or computers; and 3) environmental information which can be captured from environmental sensors (e.g., windsock sensor). The required information captured from various proposed sources can

be fed into the decision making flowchart developed before and implement the autonomous dangerous area monitoring of crane load.

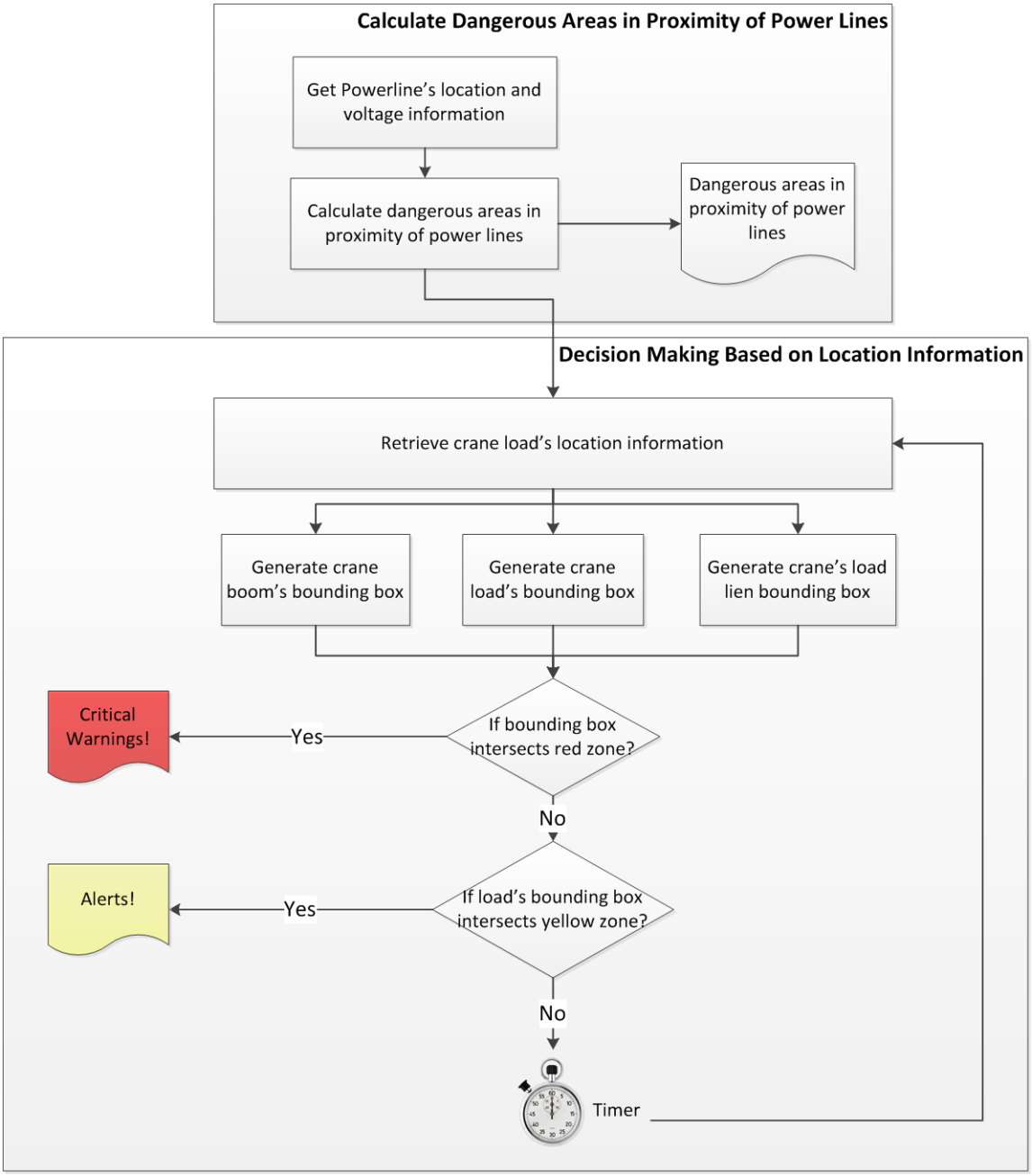
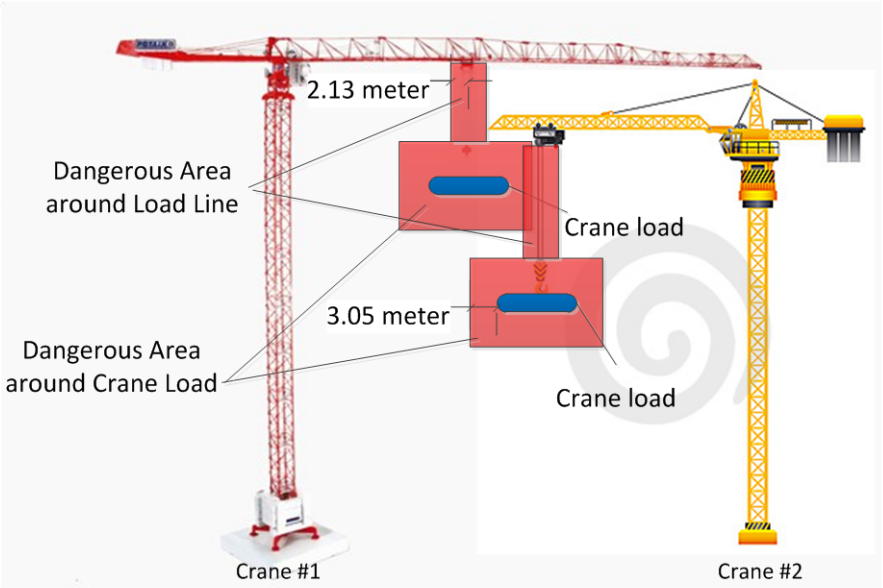


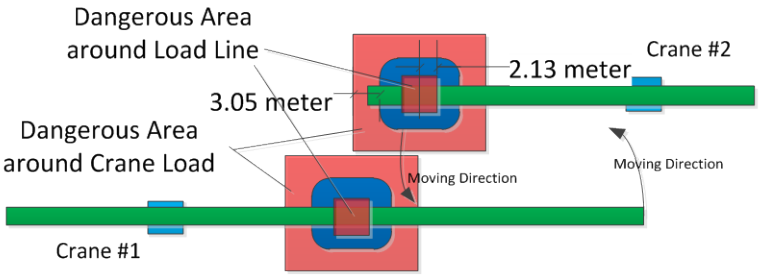
Figure 9 Decision Making Flowchart for Dangerous Area in Proximity of Power Line

2.5.4 Area 4 Dangerous Areas When Two or More Cranes are Working Closely

The new OSHA regulation (OSHA, 2010a) which includes several tower cranes operating in an area where their booms, loads or load lines could come in contact with each other, illustrates how critical it is to carefully monitor and coordinate the movements of these cranes. For a tower crane, the vertical minimum clearance distance between the boom of higher tower crane and the boom of a lower tower crane is usually 4.88 meters. Since the height of tower crane's boom does not change frequently on the jobsite, I consider there is no collision between tower cranes' booms once the tower crane is carefully deployed. Therefore, the dangerous areas where several cranes are working closely in a same area include the area around the load line and the crane load. Based on expert interviews, I use 2.13 meters as the clearance distance around a load line to form a bounding box around a load line and the crane operator should be cautious when another tower crane's boom, load or load line enters this dangerous area. According to the experts' knowledge, the clearance distance of 3.05 meters is used to define the bounding box as dangerous areas around the crane load. The crane operator should be cautious when other tower crane's boom, load or load line enters this dangerous area. These dangerous areas are illustrated in Figure 10. The clearance distances are subject to change based on the specific situations on jobsites.



Side View



Top View

Figure 10 Dangerous Areas around Crane Load and Load Line

The information flowchart in Figure 11 describes the basic decision making process of monitoring the dangerous areas in proximity of a crane load and a load line when several tower cranes are operating in the same area. The safety professional first gets the information of the crane load's location and combines it with the information of

the crane load's dimension to identify the bounding box of the crane load. Meanwhile, the tower crane's geometric information is collected and used to generate the load line's bounding box. Based on the clearance distance identified by aforementioned experts' interviews, the dangerous area around a load line and a crane load can be determined for each operating tower crane. Next, the crane boom's bounding box can be generated based on the crane load's location information and the crane's geometric information. A pairwise comparison is made among crane boom's bounding box and the dangerous area around the crane load, the crane boom's bounding box and the dangerous area around the load line, the crane load's bounding box and the dangerous area around the crane load of the other tower cranes, the crane load's bounding box and the dangerous area around the load line of the other tower cranes, the load line's bounding box and the dangerous area around the crane load of the other tower crane, the load line's bounding box and the dangerous area around the crane load of the other tower crane. If a collision is detected in any pair, a warning message will be sentto the operators who are operating cranes to ensure them to carefully coordinate their works. Otherwise; a collision might become a reality if no action is taken.

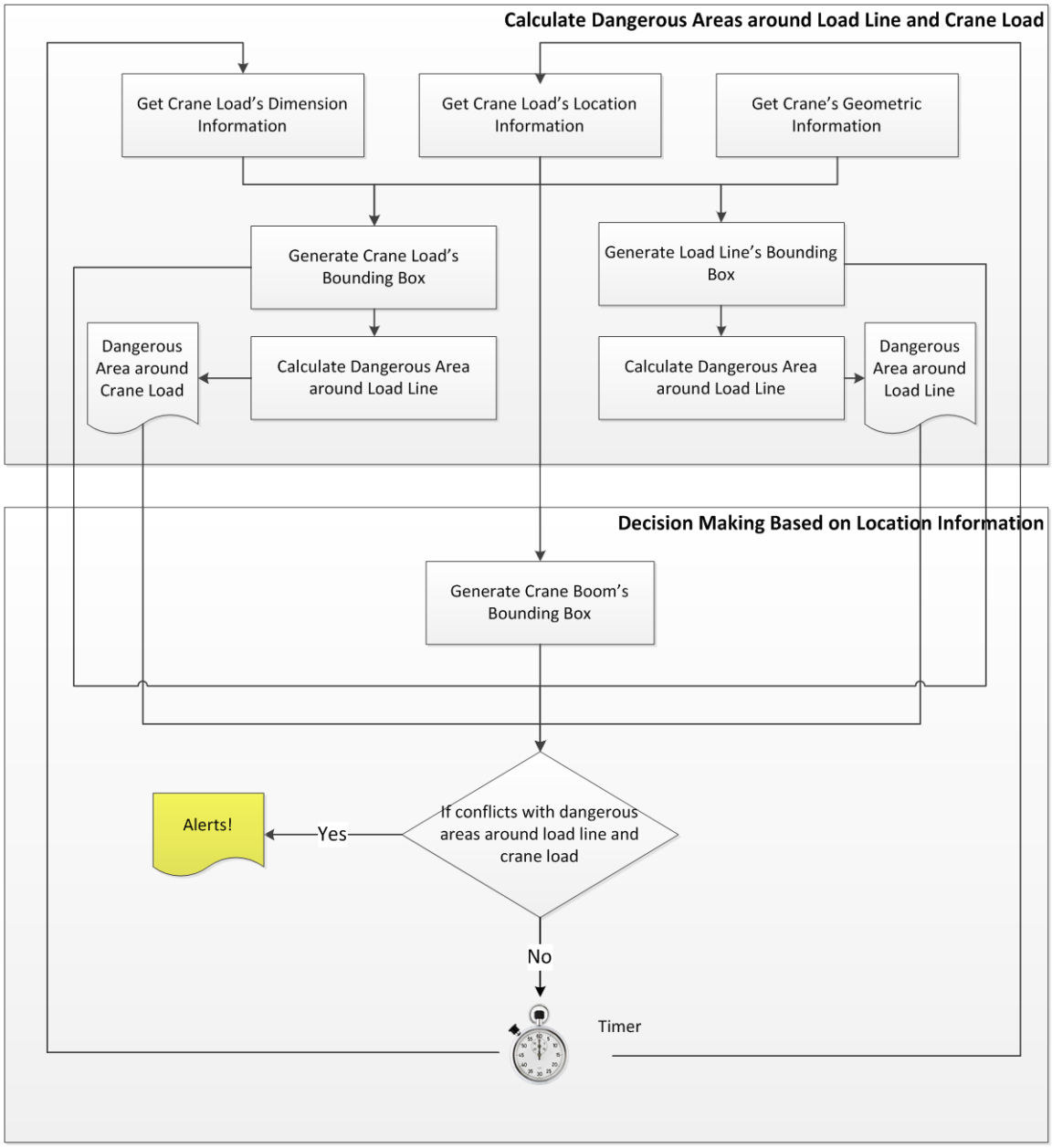


Figure 11 Decision Making Flowchart for Dangerous Area around Crane Load and Load Line

The required information for these dangerous areas monitoring can be identified based on Table 2. There are two types of information requirements: 1) geometric

information, for example the load's size, the boom's size. This information can be stored in computer's database or on RFIDs. 2) location information, which is dynamic and needs to be updated in real time.

2.5.5 Area 5 Fall Zone Under a Crane Load

OSHA requires all employees to be kept clear from a fall zone (OSHA 1424). A fall zone is defined as "the area (including but not limited to the area directly beneath the load) in which it is reasonably foreseeable that partially or completely suspended materials could fall in the event of an accident" (OSHA 1926.1401). Thus, the fall zone includes the area directly under the crane load and other areas where the suspended crane loads might reasonably fall into. OSHA also defined a few exceptions which allow authorized workers (e.g., worker engaged in hooking, unhooking or guiding a load, workers engaged in the initial attachment of the crane load and the worker operating a concrete hopper or bucket) to work in fall zones under specific circumstances.

Through the expert interviews, I identified the initial specifications of the fall zone. The fall zone defined in OSHA's regulation can be further divided into two areas at different dangerous levels: the red zone and the yellow zone: The red zone is defined as the dangerous area where the suspended load might fall into without any horizontal displacement; while the yellow zone is defined as the dangerous area where the suspended load would fall into due to the horizontal.

As shown in Figure 12, the red zone is a circle centered at the hook's location with a radius of the farthest horizontal distance between any point of the suspended load and

the hook's location. The yellow zone is the annular region between the red zone and the concentric circle with a radius of a value of the red zone's radius plus a clearance distance. Experts on each jobsite can decide the clearance distance based on their judgment according to the jobsite environment, risk tolerance and crane load's characteristics. Usually, 1.52 to 3.05 meters is used as the clearance. The clearance distance value might be subject to changes based on the conditions of wind, snow and ice. Based on the expert interviews, no employee should work in the red zone, and only authorized employees (as described in the aforementioned exception cases) can work in the yellow zone.

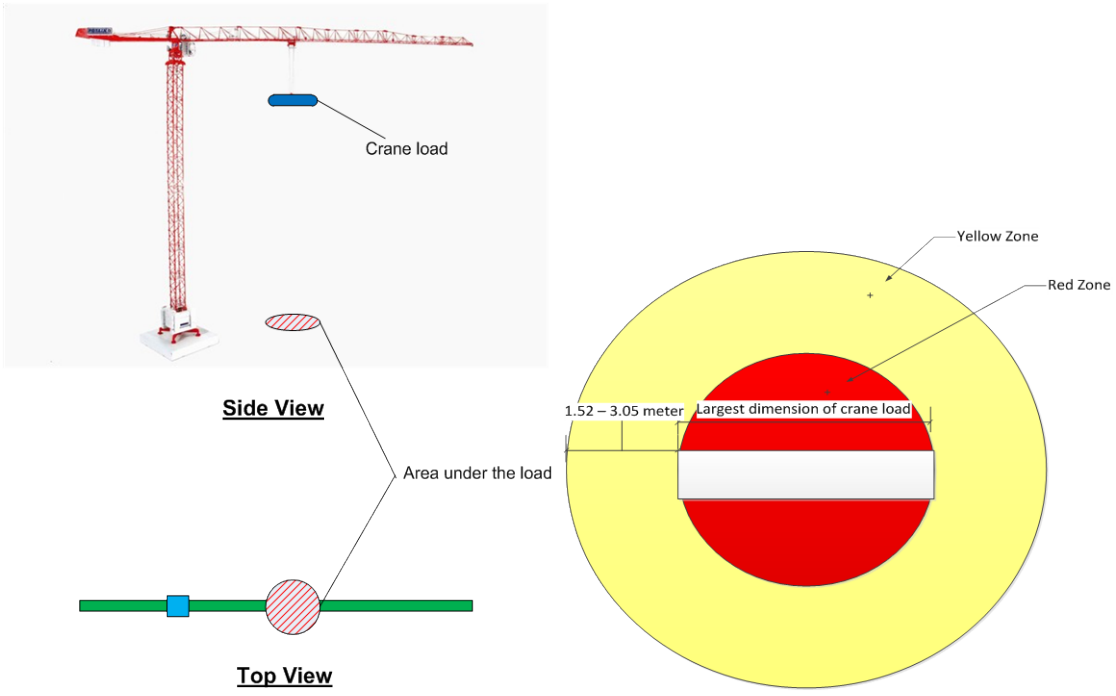


Figure 12 Specification of Dangerous Area Under the Crane Load

Based on the scenario walk through with the experts, a decision making flowchart is developed for dangerous areas under crane load monitoring (Figure 13). A worker would first get the working status of the nearby crane. If it does not carry a suspended load at this moment, there is no dangerous area for the worker. Thus the worker is considered to be in a safe condition. If a nearby crane is carrying a suspended load, the worker should acquire the information of the hook's location, the suspended crane load's dimension and the environmental data to estimate the red and yellow zones. Then, the worker would compare his/her own position to the estimated dangerous area under the crane load. If the worker is outside the yellow zone, she is considered in a safe condition; if the worker falls into the red zone, she is considered in a dangerous situation and should leave from the red zone. Otherwise, the worker should determine if she is authorized to work in the yellow zone according to authorized employee list (see more details below). If the worker is not authorized to work in the yellow zone, she should move to the safe zone. If she is authorized to work in this area, she should check if she carries all the required personal protection equipment (PPE).

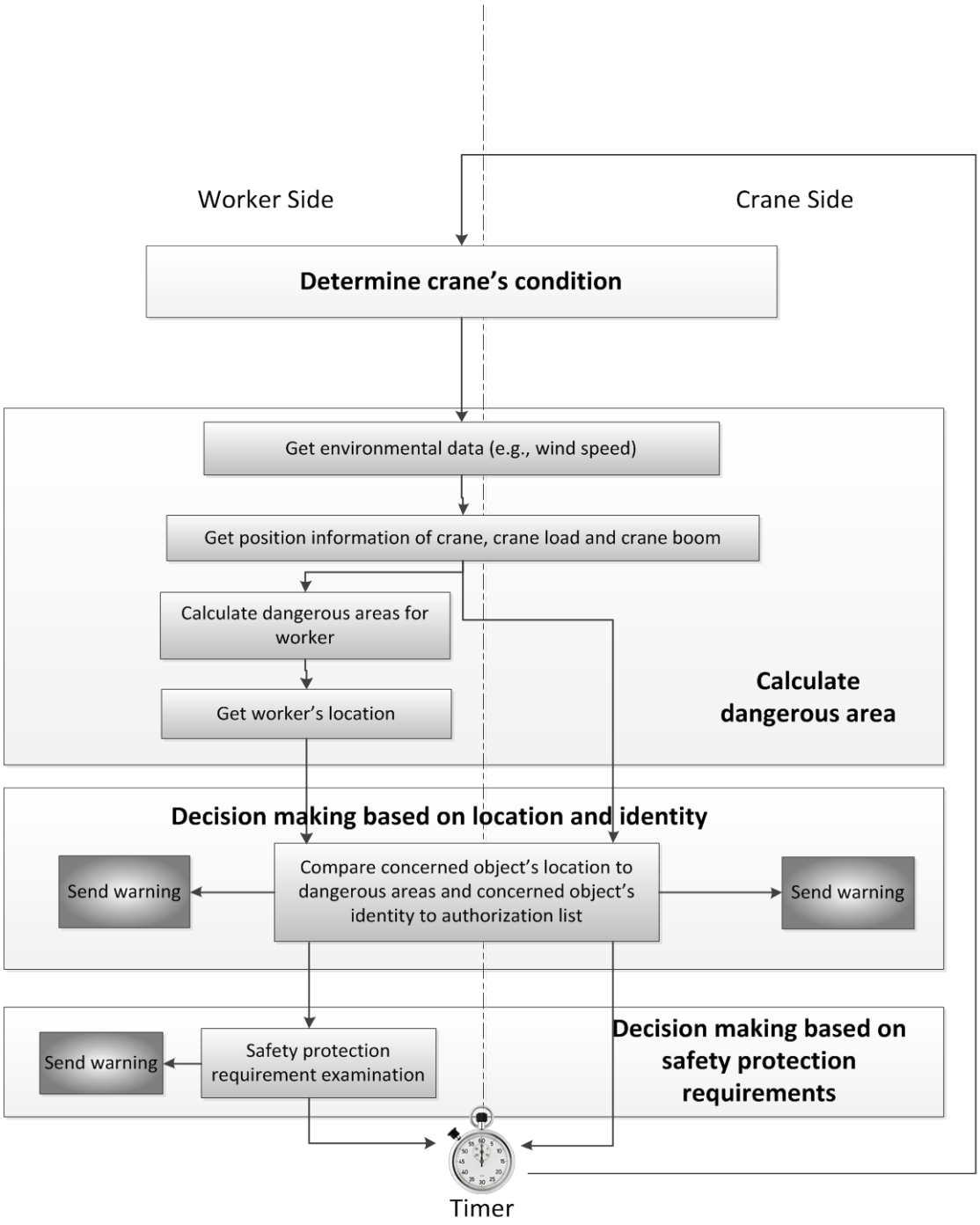


Figure 13 Decision Making Flowchart for Dangerous Area under Crane Load Monitoring

Specific employees are authorized to work in the yellow zone in a certain circumstance:

- Employees engaged in hooking, unhooking or guiding a load when such activities are ongoing at the designated area;
- Employees engaged in the initial attachment of the load to a component or structure when such activities are ongoing;
- Worker operating a concrete hopper or concrete bucket when releasing the mechanism is being performed.

To facilitate the implementation of autonomous crane safety monitoring, the information requirement for dangerous areas monitoring under crane loads can be specified based on Table 2. There are three types of information requirements: 1) location information which can be acquired through localization devices; 2) categorizing information which can be stored at and retrieved from RFID tags or existing project documentation/databases; and 3) environmental information which can be captured from environmental sensors (e.g., windsock sensor). The required information captured from various proposed sources can be fed into the decision making flowchart developed before and implement the autonomous dangerous areas monitoring of crane load.

2.6 KNOWLEDGE VALIDATION

The research validation started from safety knowledge validation through a representative test case, followed by interviewing the experts who did not participate in the safety knowledge elicitation process.

2.6.1 Case Study

To check if conflicts exist in the extracted safety knowledge, including the identified dangerous areas, associated specifications and decision rules, I observed the crane operations and activities on a congest education building construction jobsite to build a representative test case with associated scenarios. The construction project is located in the central campus of a state university in a downtown area in southwest of the United State. The complex in the project consists of two buildings connected by an atrium. The project is sized at 234,000 square feet. Figure 14 shows the building effect drawing and the project under construction.

(a) building effect drawing (b) construction jobsite

Figure 14 Construction Jobsite Used for Test Case Development

Based on the construction project, the entities related to tower crane safety proximity monitoring were chosen from the jobsite layout to develop the representative test case (Figure 15). According to my observation, there were two buildings under construction, two office trailers and two tower cranes on the jobsite. An inner campus

road with high traffic volume during the peak hours ran to the west of the jobsite and the trucks accessed the jobsite through the two entrances opening toward this road. There were three occupied buildings in the close proximity of the jobsite as shown in the Figure 15. To make the test case more comprehensive with dangerous areas in proximity of power lines, non-existing power lines sections are also modeled in the test case as shown in Figure 15. Based on the test case, eight different crane operation scenarios (see Appendix D for details) were proposed to cover the aforementioned dangerous areas and used to validate the associated safety knowledge. In each crane operation scenario, I changed the conditions of the operations to create some derivatives of them. The conditions I changed include: the crane load's location, moving path, size and type (e.g., precast panel, ladder, concrete bucket), as well as the worker's location, the worker's moving path, the activity that the worker is participating in and other equipment in proximity.

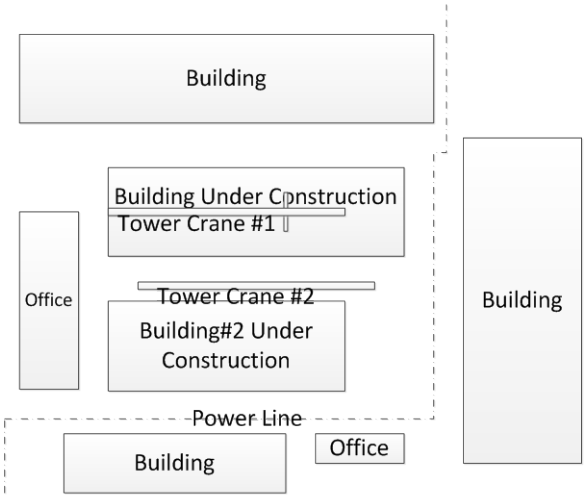


Figure 15 Represented Test Case for Tower Crane Safety Proximity Monitoring

For each scenario, I laid out the related elements on the paper and simulated the crane load's moving path, the worker's moving path, and the dangerous areas on the paper to review the scenario, in order to find out if there is any conflict or potential limitation in the extracted safety knowledge. For example, in test case #8, the tower crane is moving beam on the west side of the building under construction while a worker is walking through the passage between the office trailer and the building under construction. The dangerous area for the crane component and the crane load, as well as the dangerous area for the worker under the crane load can be determined and drawn on the paper based on the extracted safety knowledge described in section 2.5.1 and 2.5.5. I selected seven discrete points along the worker and the crane load's moving path to lay out the dangerous area on the paper. At each moment along the moving path, the safety situations of the worker and the tower crane are examined and compared with the actual safety situations.

In addition, I also developed another test case based on a high rise residential building construction project in downtown area in a city in southwest of the United States to validate the extracted safety knowledge. The residential building construction jobsite has one tower crane and several mobile cranes. Three scenarios were developed on the test case for knowledge validation purpose. Through the crane operation scenarios walk through, no conflict was detected in the extracted safety knowledge described in section 2.5. However, I did discover some limitations of the extracted safety knowledge, but which are also opportunities for future research. To simplify the research problem, the extracted safety knowledge including the dangerous areas and the decision making

process does not consider the crane load's moving speed and direction. However, considering the moving speed and direction in the extracted safety knowledge in a certain way would make the calculated safety situation closer to the actual one. Based on the observed activities on the jobsite, not all crane loads were forbidden to swing over the occupied buildings and the transportation line. For example, in the first test case, the tower crane sometimes swings the concrete bucket and ladders over the office trailers probably because the trailer is designed to withstand external forces at a certain level. In the second test case, when no train is approaching the jobsite or on the railway tracks right next to the jobsite, the tower crane would sometimes swing the concrete bucket over the railway. For future refinement of the extracted safety knowledge, an exception of crane loads which are allowed to be swung over the occupied building should be included.

2.6.2 Expert Interview

Recognition-based measure was used for the expert interview to validate the extracted safety knowledge. I selected two construction projects in China and interviewed the safety professionals on these two projects to walk through the extracted safety knowledge to examine if it is comprehensive and appropriate from their projects' perspectives. Those safety professionals participating in this round of interview did not overlap with the group of interviewees introduced in section 2.4. The first project is an observation towers construction project in north China. The project includes five connected towers over 200 meters tall above the ground and multiple floors under the

ground. Two tower cranes are placed very high in the air and multiple mobile cranes are used for other materials transportation around the jobsite. The safety manager and a crane operator with experience in operating various mobile cranes and tower cranes were interviewed on this project. The 2nd project is a high rise commercial buildings projectin the congested area in the downtown of a large city in southwest China. The project size is over 200,000 square meters. There are multiple high rise buildings and two roads with heavy traffics right next to the construction jobsite. Two tower cranes were used on the construction jobsite. The safety manager participated in the interview for the extracted safety knowledge validation. The two safety managers provided guided visits to their jobsites to give me an overview of the characteristics of the jobsites. Next, we sat down together to go through the extracted safety knowledge including the specifications and decision making processes described in section 2.5. The safety experts were asked to review the extracted safety knowledge in the context of their specific projects and examine whether: 1) the extracted safety knowledge is applicable on the two projects they were working on; and 2) any important information is missing. After going through the extracted safety knowledge, we discussed some limitations of the research and potential opportunities in the research.

The safety experts confirmed the extracted safety knowledge is appropriate for their projects and covered the dangerous areas on their jobsites. However, the clearance numbers in section 2.5 need to be customized according to the regulations and standards in China. To easily customize the extracted safety knowledge on the clearance numbers in the future autonomous safety monitoring system should be provided to facilitate the

applications for global construction projects, which are out of the United States. In addition, the safety experts pointed out some important issues during the interview:

1) The extracted safety knowledge did not consider wind conditions in the dangerous proximity control. It is acceptable to ignore wind conditions for non-high-rise building construction. However, wind conditions would become a critical factor for consideration when a tower crane is placed very high in the air (e.g., 200 or even 300 meters in both projects). Future studies on wind conditions' impact on proximity monitoring can expand the applicability of the proposed safety knowledge to high rise buildings in metropolitan areas.
2) I envisioned the autonomous safety monitoring system based on the extracted safety knowledge to the experts. They agreed that it would be a great idea if the system can work for improving the safety performance on construction sites. However, they were concerned about two issues before they accept such system on their projects: a) the cost of the system. They need to know if the cost of the system is acceptable since they have a limited budget on safety management from their companies; b) they wondered if the system is trustful and reliable. In another word, if the system can provide correct decision supports to them. There are two future research directions to address their concerns: a) a comprehensive cost effective analysis of the application of the system on construction jobsites; and b) a system performance study to see how the system performs using the existing information and sensing

technologies, and if the system is not trustful, is there anything that I can improve its performance in some cost-effective ways.

2.7 CONCLUSIONS

Tower crane safety has been an important issue in construction for decades. Although there are various standards and regulations for practitioners to follow in order to improve safety performance on construction jobsites, site and human errors contribute to our industry's high accident rate, as compared to other industries. This research envisions an autonomous crane safety monitoring system on jobsites to improve safety records in the construction industry. To achieve this goal, this chapter identified five typical dangerous areas related to tower crane operations and examined specifications, safety requirements and information requirements for these five dangerous areas through a comprehensive review of existing regulations and the expert interviews. Overseas validation indicated that the result can be expanded to other countries with minor changes, although the main data items are comprehensive. The result can be used to design and develop safety monitoring systems, which will be described in chapter 4.

Chapter 3 Safety Specifications and Information Requirements for Proactive Fall Prevention in Construction Jobsites

This chapter will answer the research question 1, 'How to conceptualize safety knowledge in an autonomous monitoring environment', by applying a safety knowledge elicitation approach to proactive fall prevention to demonstrate the applicability of the approach.

3.1 INTRODUCTION

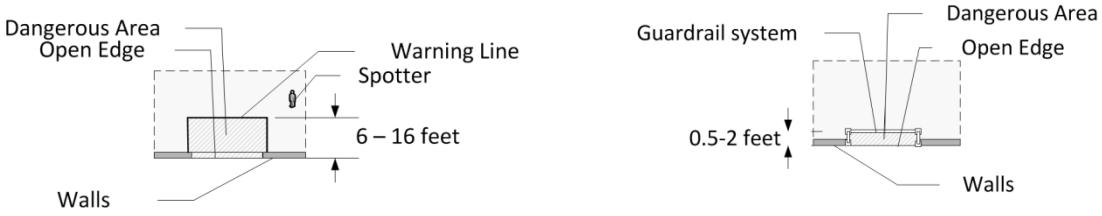
Preventing falls in jobsites is crucial since falling from height is the most frequent cause of worker fatalities at construction sites. Unlike tower crane accidents, the death rate of falling from height at construction sites has increased in recent years even though there have been many attempts and available methods for preventing fall (US Department of Bureau of Labor Statistics, 2012). Therefore, in this chapter, fall prevention is chosen as the case study for two reasons: 1) the increasing death rate related falling from height; and 2) applying the research methods that I used in chapter 2 to fall prevention to validate if the research problem solving process and methods is generic. Therefore, I will investigate fatal falls in construction and identity the causes of the accidents. Then, I will apply the same research process as I did in chapter 2 to develop safety specifications and information requirements for fall prevention. At the end of the chapter, validation and system information sampling frequency requirements will be discussed.

3.2 LITERATURE REVIEW

Falling from a height is consistently the leading cause of fatalities in the construction industry in the United States (CPWR, 2008). In 2007, the incident rate of falling from a height in construction was 30.4 for every 10,000 full time employees, which is among the highest of all occupations in the United State (US Department of Labor, 2008). Although the Occupational Safety and Health Administration (OSHA) and other agencies have published regulations and standards for fall prevention practices, there have been observed that a large portion of existing construction jobsite practices do not meet safety criteria on construction jobsites (Kaskutas et al., 2009). The causes of these risks include: lack of familiarity with construction methods, inadequate safety training and communication difficulties created by language barriers. In addition, workers were not consistently monitored, or alerted of their proximity to unprotected open edges (Kaskutas et al., 2009).

To address the causes of these risks, recent research focuses on off-site fall prevention and on-site fall prevention. Off-site fall prevention includes design for safety in the design phase (Gambatese et al., 2008, Hinze and Gambatese, 1996) and safety training. On-site fall prevention includes manual safety monitoring of laborers working at a height, active (e.g., warning lines and guardrail systems, shown in Figure 16) and passive measures (e.g., personal arrest system and safety net) of fall protection. An initial attempt of autonomous monitoring of fall hazards was conducted by Navon (Navon and Kolton, 2006) to monitor if guardrail systems were appropriately installed at open edges. However, not all open edges on construction jobsites are suitable for guardrail system

erection, for example, leading edges and open edges which act as material transportation entrances. A new and more effective solution for monitoring proximity to these edges is needed.



(a) with warning lines (b) with guardrail system

Figure 16 Fall Prevention with Various Passive Measures (Brasch, 2010)

The advancements in sensing, information and computing technologies provide opportunities to improve workers' safety awareness of construction jobsite conditions (Teizer et al., 2005, Weingarten et al., 2004). These technologies show promising advantages on decreasing risks when combined with existing management practices. Localization technologies, such as Radio Frequency (Castro et al., 2007, Teizer et al., 2010, Yanga et al., 2012), is one of the most widely studied technologies for proactive safety monitoring. The RF tags attached to existing passive personal protection equipment can actively provide information and feedback to a proactive safety monitoring system. Video cameras with machine interpretation of video stream are another recently introduced technology for autonomous safety monitoring on construction jobsites. An experimental study indicates that the combination of these technologies can provide an accuracy to meet the requirements of safety features for construction (Zhou et al., 2012). However, these studies focus on the general framework

and feasibility study of introducing new technologies for proactive safety monitoring. A few researchers (Lee et al., 2009b, Navon and Kolton, 2006) have attempted to implement these proactive safety systems following best practices and regulations. To embed safety knowledge into a proactive fall prevention system for practical use, safety knowledge must be specified and represented in a computing environment. These considerable engineering challenges and specifications must be done for the system's actual implementation in practice.

As soon as the specifications and requirements of proactive fall monitoring are identified, the aforementioned technologies can be connected to existing practices, forming a practical and effective proactive fall prevention system to decrease the risks of falling from height on construction jobsites. The research presented in this chapter aims to fill the gap between existing technologies and safety practices, by developing safety specifications and information requirements for proactive fall prevention.

3.3 RESEARCH APPROACH

To understand the existing safety practices of fall prevention near open edges, I reviewed regulations, standards and best practices from companies and safety standards in the United States and Europe. The materials that I reviewed include: OSHA 1926 Subpart M Fall Protection (OSHA, 2010b), ANSI/ASSE Z359 Fall Protection Code Package (ANSI/ASSE, 2007a, ANSI/ASSE, 2007b, ANSI/ASSE, 2009, ANSI/ASSE, 2012), Best Practice for Fall protection in the Telecommunications Industries (NTSP, 2006), and the Work at Height Regulations (HSE, 2005). The research focused on fall

prevention at open edges. Based on regulations and best practices, I identified two commonly seen scenarios on construction jobsites: working near open edges and working near an opening inside a building. For each scenario, the rules related to fall protection and prevention are translated into conceptual definitions and decision rules.

Subsequently, I designed a semi-structured interview guideline, composed of five parts: 1) interviewees' background; 2) safety concerns regarding working from a height; 3) current fall prevention practices within interviewees' companies; 4) attitude towards information technology applications in fall prevention; and 5) safety knowledge regarding safety zones for working at a height.

Six safety experts, one from an owner company and five from contractor companies, all active members of the Construction Industry Institute (CII) Safety Community of Practice, were selected for the interviews based on the following criteria: 1) at least 10 years working experience in construction jobsite safety management; 2) at least 20 years industrial experience in construction; 3) familiar with fall prevention regulations in building construction. Interviewees were asked to review the dangerous areas related to working at a height and comment on them, with respect to the dangerous areas, boundaries of these areas and decision rules of safety operations in proximity of these areas. After identifying the dangerous areas related to working at a height, I analyzed the decision rules of safety operations in proximity to these areas. After each interview, both new and revised information were summarized and reflected on the next interview guideline by updating knowledge in the interview guideline. To validate the

extracted knowledge for proactive fall prevention, I developed four test cases related to working at a height to test the applicability of the extracted knowledge.

3.4 RESEARCH RESULTS

After the interviews, the six experts agreed that unauthorized workers in close proximity to unprotected edges without being aware of dangerous situations or authorized workers working in close proximity to unprotected edges without appropriate protection are two of the major causes of falling from a height. Although the experts confirmed that they strictly followed specifications of dangerous area controls described in regulations and standards, they believe that by introducing dynamic and proactive specifications on top of existing standards and regulations would increase effectiveness of fall prevention systems. The control areas and the decision making process were identified and refined with the experts. In dynamic and effective fall prevention control systems, there are two basic safety zones as shown in Figure 17.

- Dangerous areas around an open edge (hashed area shown in Figure 17): the dangerous area is consistent with existing safety regulations and practices. The dangerous area is defined as a set of points within a predefined dangerous distance from any point of the open edge. Therefore, the dangerous area consists of: 1) a rectangle with the open edge as one border and a width of the dangerous distance; and 2) 2¼ circles centered at the starting point and ending point of the open edge, with a radius of the dangerous distance. 6 feet is used as the dangerous distance and can be increased to 10 feet if there is any moving equipment nearby.

The dangerous distance is increased because the equipment might hit workers towards the open edge. This dangerous area is static.

- Stopping area for a worker (circled area around the worker shown in Figure 17): the area covers all possible points that a worker might step into from the moment she starts to stop until her speed is zero. This area is dynamic depending on a worker's location, speed and nearby environment conditions (e.g., uneven, slippery, sloped). For simplification purposes, the stopping area is described as a circle centered at the worker's current location and the base radius of the stopping area is 6 feet. For each type of environment condition, the radius is increased by 1 foot.

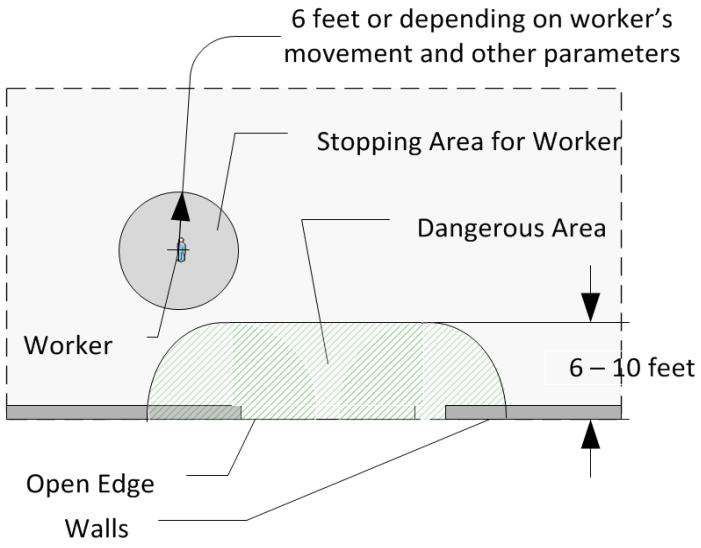


Figure 17 Specification of Dynamic Area Control near Edges

Based on the expert interviews, a decision making flowchart was developed to illustrate the decision making regarding proactive fall prevention near open edges (Figure

18). To determine the dangerous area near open edges, open edge information is collected. If the open edge is protected with proper means (such as a guardrail system), there is no dangerous area near the open edge and no further decision is needed. Otherwise, nearby equipment information and workers' location information are collected to determine the dangerous distance near an open edge. If a worker does not stand between the equipment and the open edge (Figure 19a), 6 feet is used as the dangerous distance. If the worker stands between the equipment and the open edge (Figure 19b), and the equipment is moving towards the worker's side, 10 feet is used as the dangerous distance; otherwise, 6 feet is used as the dangerous distance. Using the dangerous distance near an open edge, the start point and end point of an open edge, the dangerous area near an open edge can be determined. Meanwhile, the environmental conditions (e.g., if the floor is slippery, uneven or sloped) and worker's location information are collected and used to calculate and generate the stopping area for a worker. If the stopping area and the dangerous area do not overlap, the worker is assumed to be in a safe condition, regardless of her identity. Otherwise, work authorization near the open edge is recalled, and the worker's identity is used to compare the authorization list to see if the worker is authorized to work near the open edge. If the worker is authorized to work near the open edge, the worker's carried Personal Protection Equipment (PPE) information is collected to compare with the collected information of PPE requirement from the system near the open edge. If the worker carries all the required PPE, the worker is in a safe working condition. Otherwise, the worker is exposed to the risks of falling from height, and an alert is sent to the worker to remind him/her of the missing PPE. If

the worker is not authorized to work near the open edge and the worker has not stepped into the dangerous area near the open edge, she is assumed as in proximity of a dangerous area, and she might fall into the dangerous area even if she stops. Therefore, a warning would be sent to the worker to warn her that she is approaching a dangerous area. If the worker has stepped into a dangerous area near an open edge, an alert would be sent to the worker to ask her to leave the dangerous area.

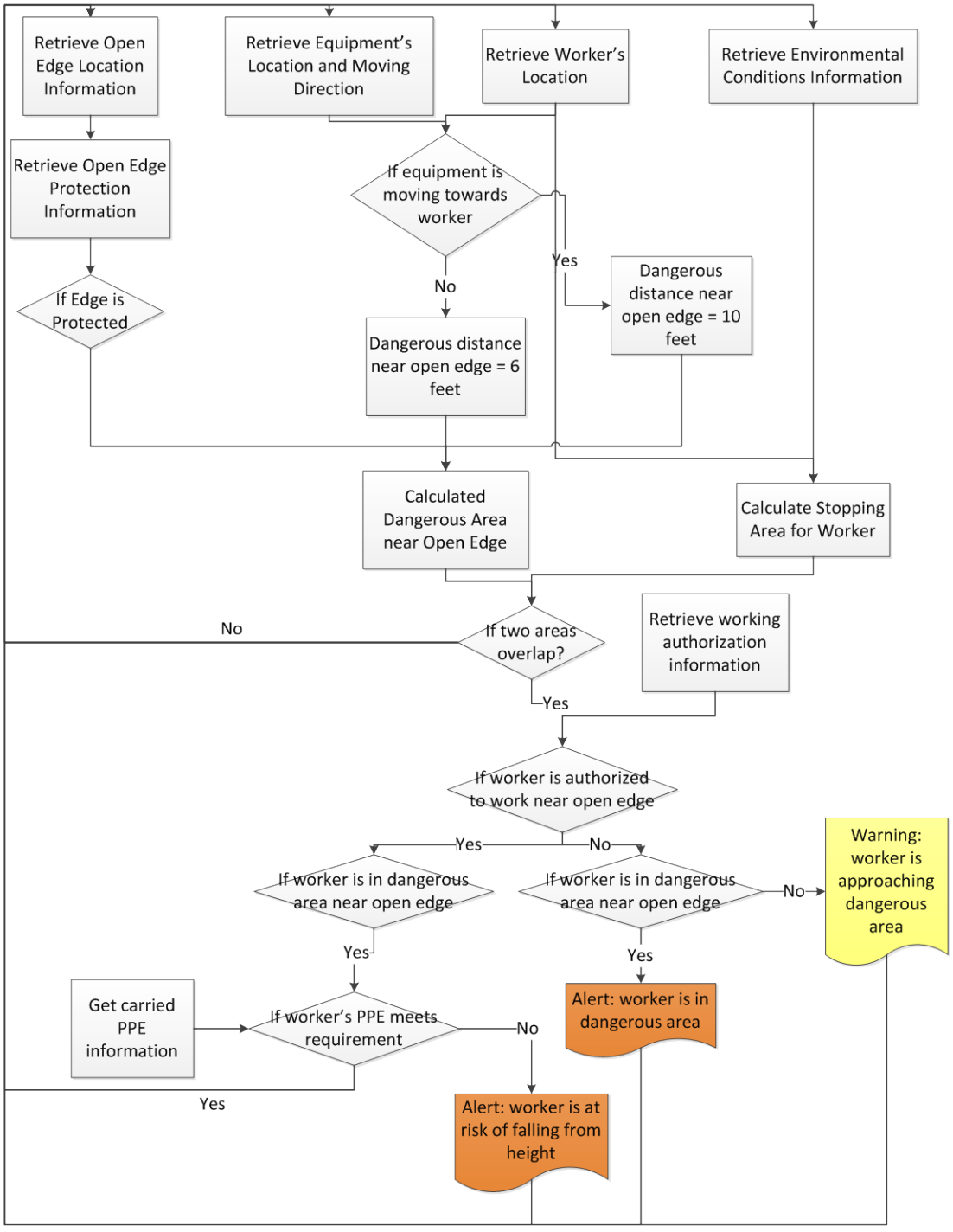
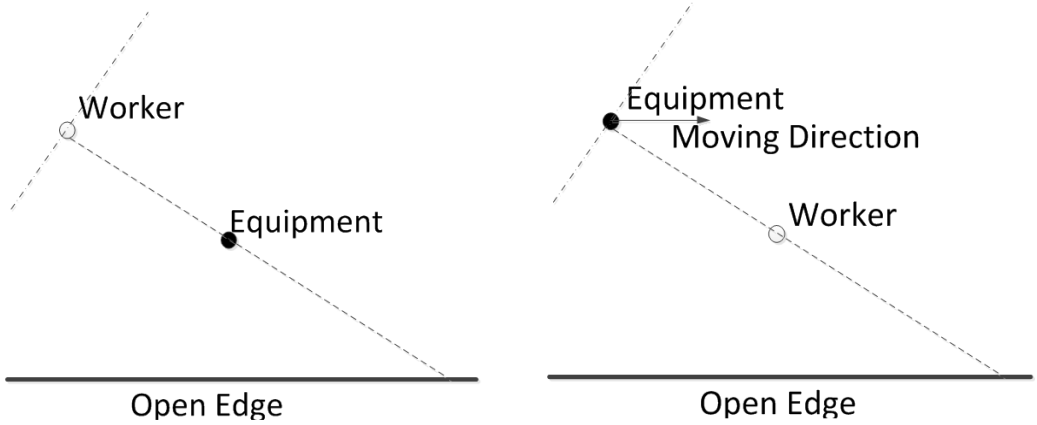


Figure 18 Decision Making Flowchart for Proactive Safety Monitoring near Edges



a) Worker does not sit between equipment and open edge

b) Worker sits between equipment and open edge

Figure 19 Relative Positions of Worker, Equipment and Open Edge

To facilitate the development and implementation of the proactive fall prevention system, information requirements are specified in Table 3, based on the decision making flowchart described in Figure 18. There are four factors related to decision making: people, equipment, environments, and jobsites. For each entity, the required relevant information, possible sources, example data and units are listed in the information requirements table. For example, the key required information for open edges included geometry information and working authorization information. Geometry information can be obtained from a database, such as building information models. By specifying the information requirements of proactive fall prevention, the system developer can determine what information needs to be collected and how to effectively distribute static and dynamic information across various sources and devices.

Table 3 Information Requirements for Proactive Safety Monitoring Near Edges

Basic Production Factor	Production Elements	Component of Production Elements	Relevant Information	Possible Source	Example Data	Unit
People			Unique ID	RFID	WT0813221	N/A
			Location	RFID/GPS/Crickets/UWB Sensor	(110.90, 51.91, 12.00)	meter
			Moving Direction	orientation sensor	(0.1, 0.1, 0.1)	radian
			Moving Speed	calculation through locations	(1, 2, 0)	meter/second
			Acceleration	Accelerometer	(0.2, 0, 0)	meter/second ^2
			Carried PPEs	RFID	(SB29845, HH10942)	N/A
Equipment	Forklift		Unique ID	RFID	FL00284	N/A
			Location	RFID/GPS/Crickets/UWB Sensor	(87.00, 64.73, 12.00)	meter
			Moving Speed	calculation through locations	(1, 2, 0)	meter/second
			Moving Direction	orientation sensor	(0.1, 0.1, 0.1)	radian
			Acceleration	Accelerometer	(0.2, 0, 0)	meter/second ^2
Environment	Wind		Wind speed	Windsock Sensor	5	Meter/second
	Humidity		Relative Humidity	humidity sensor	70	%
	Floor's condition		If slippery	database	TRUE	N/A
			If sloped	database	FALSE	N/A
			If uneven	database	TRUE	N/A
Jobsite	Open Edge	Geometry	Unique ID	database	OE00284	N/A
			Starting Point	database	(102, 50, 12)	meter
			Ending Point	database	(143,50,12)	meter
			If Protected	database	TRUE	N/A
		Working Authorization	Authorized worker's list	database	(WT0813221, WT0821542)	N/A
			Required PPEs	database	(hardhat, safety belt)	N/A

3.5 VALIDATION

The research validation began with the internal validation with the experts who participated in the knowledge elicitation phase, followed by decision rules validation through four representative test cases.

During the expert interviews, the experts were asked to identify the size, the location of the dangerous area, the authorized user categories and safety protection equipment used in each scenario. Recall-based measure (Bitner et al., 1990), in which subjects are asked to provide lists without further stimulus and therefore will identify more relevant items, was used in the knowledge elicitation phase given that the objective was for the experts to identify significant safety knowledge for fall prevention near open edges. Figure 20 shows the cumulative count of information identified by the OSHA regulations and the six experts. The curve in the figure shows a diminishing returns trend, indicating that even if more experts had been interviewed, additional information for dangerous area controls regarding fall prevention safety monitoring would not likely be obtained. Therefore, I concluded that the extracted safety knowledge is comprehensive, so no additional expert interview is necessary.

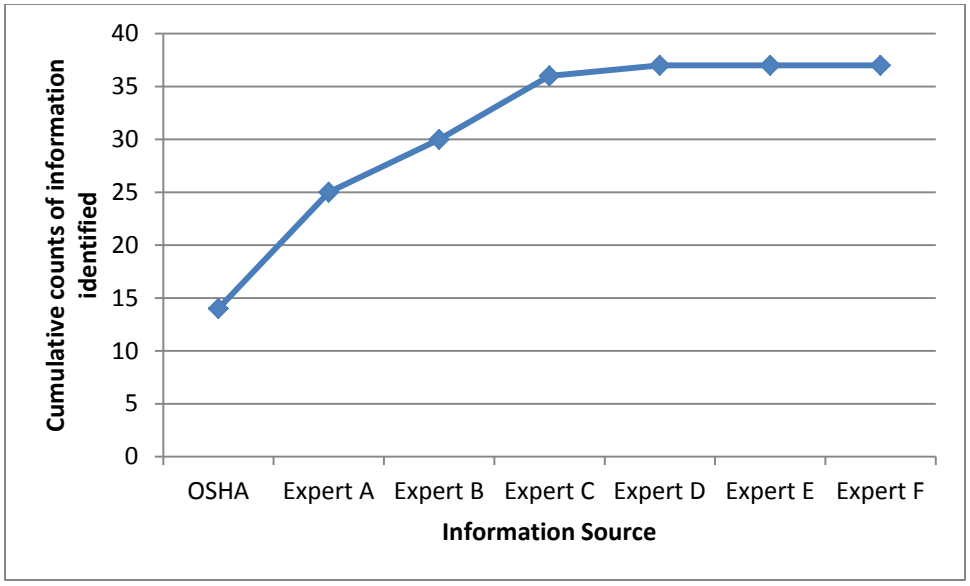


Figure 20 Information Retrieval Curve for Proactive Fall Prevention

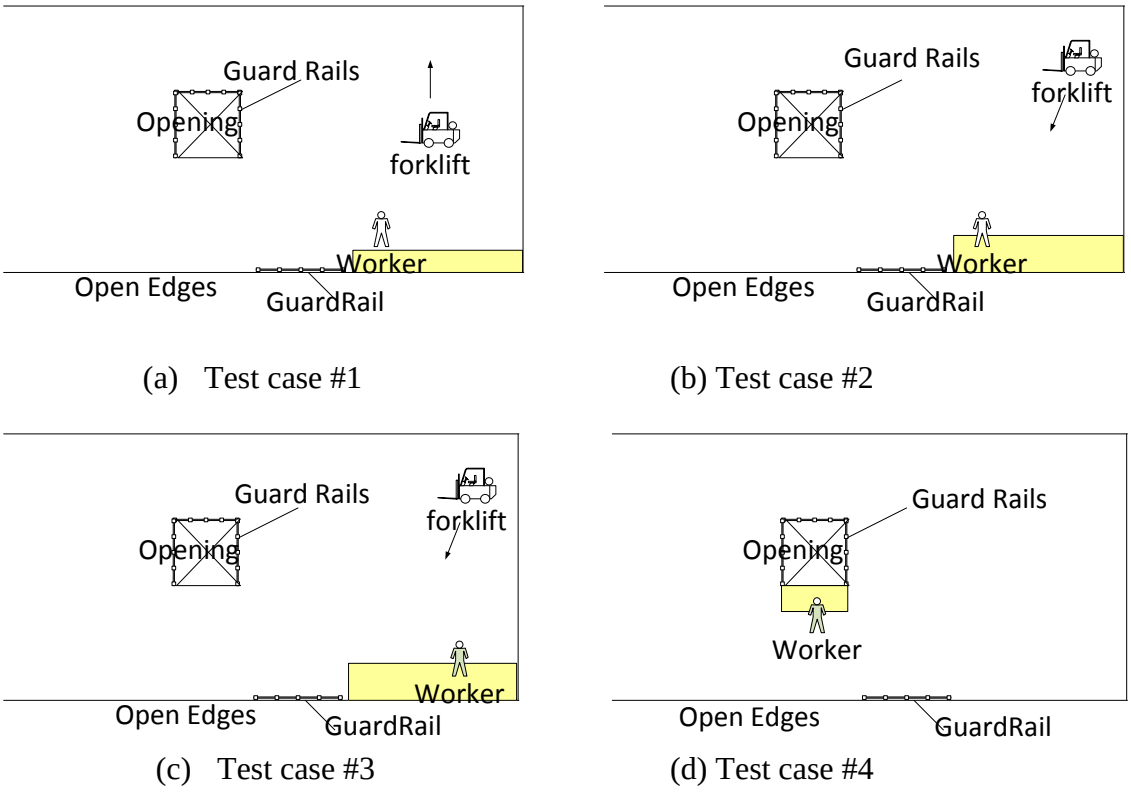
To confirm that the extracted safety knowledge can be appropriately applied to construction jobsite safety practices, I conceptualized a fall prevention test bed based on a real construction jobsite. The test bed design (Figure 21b) captured the major characteristics of the west portion of a 4rd floor (Figure 21a) of a building. There is a guardrail system installed at an edge where a ladder is erected for workers to climb up to the 5th floor. The opening in the center of the floor portion is used as the access to the 3rd floor through a temporary wood ladder. Guardrail systems were erected on the three edges of the opening, except the edge which is used as the access to workers.

(a) 4th floor of a Construction Jobsite (b) layout of the fall prevention test bed

Figure 21 Construction Jobsite (a) and Its Represented Test Bed (b)

Four test cases were developed to represent four possible scenarios by changing the moving equipment's location, its moving direction, the worker's identity, the worker's location, the worker's PPEs and the worker's moving direction. Detailed test cases are described below: 1) a worker, who is not designated to receive materials at the open edge, is in close proximity to the open edge section without guardrails while the forklift is moving away from the open edge section (Figure 22a); 2) the same worker is in close proximity to the open edge section without guardrail systems while the forklift is moving towards the open edge section to transport materials (Figure 22b); 3) a designated worker for material receiving, who is wearing a safety belt and is securely tied-off, is walking towards the open edge section while the forklift is also moving towards the open edge section to transport materials (Figure 22c); 4) A worker is backing off towards the open edge section of the opening without a guardrail (Figure 22d). Using the extracted safety knowledge, the system recognizes that the worker is approaching a dangerous area in test case #1 and #2 and a warning message should be sent out; the worker is in a dangerous

area and is exposed to the risks of falling from height in test case #2; the worker is in a safe situation in test case #3. The conclusions made upon the extracted safety knowledge and decision rules are consistent with the worker's actual safety statuses, indicating that the extracted safety knowledge is appropriate and consistent.



(a) Test case #1 (b) Test case #2

(c) Test case #3 (d) Test case #4

Figure 22 Four Test Cases for Decision Rules

3.6 DISCUSSION ON SAMPLING FREQUENCY

During the interviews, the experts agreed that proactive safety monitoring for fall prevention can provide a supplemental layer of safety management to current practices. However, there are still some issues requiring considerations for effective autonomous

proactive fall prevention: 1) human factors in system implementation. For example, the worker might leave her location tracking devices in the safe area while she is trying to intentionally access the dangerous area without authorization and appropriate PPEs. 2) Safety training is still a challenge in safety practice. Effectively educating workers with safety knowledge and making them truly realize the severity and loss of breaking safety rules remain to be an ongoing challenge in practice.

In this chapter, decision rules and information requirements were identified based on literature review and the expert interviews. A proactive autonomous safety monitoring system near open edges can collect and retrieve required information from deployed sensors (e.g., RFID, GPS, orientation sensor) and a database to determine workers' safety statuses based on the extracted decision flowchart described in this chapter. Most of the data collected and retrieved were digital data instead of analog data. More specifically, the data input for the sensors would be discrete at a certain frequency instead of continuous. The sampling frequency directly determines if the input data for the system was recent enough and if the decision made was real-time or near real-time. For example, if the location sensors collect the worker's location once every minute (an extreme case), the data and corresponding decision made are of little use because the worker might already have changed her safety status several times within this single minute. Therefore, a proper minimum sampling frequency needs to be determined to ensure the system can capture the latest information regarding workers' safety. The case used to determine the minimum sampling frequency (f)/maximum sampling interval (T) is described as: at time point t, the worker is at the transit status between safe and unsafe conditions; at time

point t + T, the system gets the next reading from sensors, discovers that the worker is in an unsafe condition and needs the worker to stop before falling from the edge. Therefore,

$$v_{worker} \times (T + t_{reaction}) + \frac{v_{worker}^2}{2}/a \leq 1.83 \times 2 \quad (3.1)$$

Where, v_{worker} is worker's walking speed, usually below 1.94 m/s;

T is the maximum sampling interval (s);

$t_{reaction}$ is worker's reaction time (s), average is 330ms (Posner, 2005);

a is worker's acceleration while stopping.

To simplify the problem, I assume that the stopping time for a worker can be ignored. Therefore,

$T \leq 1.56$ seconds

The minimum sampling frequency of the proactive fall prevention system should be 0.64 Hz.

3.7 CONCLUSIONS

Falls from a height are prominent and serious events leading to injuries and fatalities in the construction industry. Although there are various standards, regulations, best practices on fall prevention and protection, human unawareness and negligence of unsafe conditions are frequently observed on construction jobsites. This research envisions a proactive fall prevention system to improve laborers' safety awareness while working at a height. This chapter described the extracted safety knowledge of a proactive fall prevention system based on a comprehensive literature review and the expert interviews. Validation through the expert interviews and test cases indicated that the

extracted safety requirements and specifications are comprehensive and appropriate. The safety knowledge and information requirements summarized in this chapter can be used as a knowledge base for proactive fall prevention system's design and implementation, which will be presented in the next chapter.

Chapter 4 Autonomous Jobiste Safety Monitoring System Using a Three Layered Distributed Computing Architecture

The previous two chapters answered research question 1 and conceptualized the extracted safety knowledge for tower crane safety monitoring and proactive fall prevention. To integrate the extracted safety knowledge with the sensing and computing technologies towards an autonomous safety monitoring system, I need to answer the research question 2 'How to formalize the reasoning mechanisms in a distributed computing environment and how to implement autonomous safety monitoring'. By answering this research question, I can demonstrate the autonomous jobsite safety monitoring for both tower crane operation and proactive fall prevention.

4.1 INTRODUCTION

Recent advancements and developments in wireless sensing technologies and distributed mobile computing provide opportunities to implement safety monitoring in the construction industry in a more intelligent way. Autonomous safety monitoring applications can be coupled with automated data collection processes and have an embedded reasoning mechanism using mobile computing and sensing technologies. Autonomous safety monitoring can cover both the construction and operation phases of a project or facility. In construction phase, autonomous safety monitoring mainly focuses on workers' safety and safe operations of equipment (Hwang, 2012, Lee and Mak, 2010, Lee et al., 2009b, Teizer et al., 2010), whereas safety monitoring during operation

typically targets safety from a structural health perspective (Harms et al., 2010, Jang et al., 2010, Pakzad et al., 2008). The applications of autonomous safety monitoring in the construction and operation phases demonstrate the potential broader uses of wireless sensing and mobile computing technologies. An architecture for decision support in ad-hoc sensor network was proposed by O'Brien (O'Brien et al., 2008) to facilitate the decision making application design and development process as a solution to reduce complexity and cost. The architecture leverages the commonalities across multiple applications and separates the physical layer from the application level. However, research on autonomous safety monitoring primarily focuses on specific applications that tightly couple the hardware with the software logic. This chapter demonstrates a component reuse oriented multi-tier distributed computing architecture. Two specific applications are presented in the context of a jobsite safety monitoring system. This chapter details the translation of the extracted safety knowledge necessary for an autonomous monitoring system into the application design in a distributed computing environment.

The remainder of this chapter is organized as follows. In the next section, the author presents a review of safety monitoring applications in construction and related works on architectures for safety management systems. The approach adopted by this research for deploying the safety monitoring system in a distributed computing environment follows. Two envisioned autonomous job site safety monitoring applications focusing on crane safety monitoring and proactive fall prevention are presented. These are built from the specifications developed in the previous chapters. A Unified Modeling

Language (UML) design of the system is presented based on safety knowledge extracted from the previous research. Translation of the extracted safety knowledge of the two applications into the application development and deployment using the distributed architecture follows. The next section focuses on the discussion of results of the deployment on these applications in a test bed scenario.

4.2 LITERATURE REVIEW

Many researchers in this field have developed a range of new safety monitoring tools to improve workers' situation awareness on safety at an operational level during the construction phase of a project. Sensing and mobile computing technologies, such as Ultra Wideband, infrared wave, computer vision and wireless environmental sensors are used to model and track location based the hazards related to locations and to monitor the environmental conditions to maintain a safe work environment. Radio frequency and Ultra Wideband (UWB) technologies are commonly used to monitor and track moving equipment and workers to maintain safety clearances (Bai et al., 2012, Hwang, 2012, Teizer et al., 2007, Woo et al., 2011). Technologies used for tracking can be classified under two categories. In range-based systems, ultrasonic, infrared wave, radar, and radio frequency are used to detect whether a target falls within the proximity (dangerous area) of an open edge or moving equipment (Lee et al., 2009b, Reyes, 2010, Ruff, 2010, Teizer et al., 2010). Vision based systems rely on video and image streams to track locations of targets and their safety at any instance of time (Chi and Caldas, 2012, Yang et al., 2011). Range and vision based technologies have been used for various safety related

applications including fall prevention, crane safety monitoring, and safety of earthmoving equipment operation. This aforementioned research primarily focused on implementing a specific technology or a solution for a specific safety monitoring application. As such, these solutions may not scale well or may not be readily deployable for other scenarios since the application architectures typically do not consider the ease of coding, development or deployment.

Different multi-layer architectures for supporting safety systems and applications have been presented in computer science and construction domains. The architectures proposed in computer science heavily emphasize on improving the hardware and network performance (de Haan et al., 2011, George et al., 2010). Aziz (Aziz et al., 2009) proposed a five-tier architecture to support the development of an IT-supported platform to improve collaboration in urban emergency response and recovery. The five tiers include: resource tier, resource interface tier, data access tier, business logic tier and presentation tier. The proposed system architecture separates the physical hardware layers from the software functions. However, since the system architecture was designed to implement the specific emergency response system, it did not consider component reuse and deployment of system functions in a different hardware configuration that may have its own specific constraints. Xia (Xia et al., 2011) proposed a three-tier architecture for a construction site safety monitoring system. The proposed architecture divided the system into a data fusion layer (focusing on data collection, storage and processing), a data processing layer (data filtering and fusion) and a decision making layer (predicting safety performance trends). The proposed architecture does not provide a clean separation

between the fusion and processing layers of the system. Furthermore, the operational complexities that would arise during the system deployment have not been adequately explored or presented.

Although the three-layer architecture proposed by O'Brien and Julien (O'Brien et al., 2008) addresses the separation of physical layers from the software components and promotes reuse of components across applications to facilitate the coding and development process, a detailed validation and demonstration of the architecture's workability in a physical distributed computing environment is lacking. This chapter aims to demonstrate the proposed architecture in action through the development and deployment of two distinct autonomous safety monitoring applications in a distributing computing environment that leverage the extensibility and reusability of the system.

4.3 Research Approach for Distributed Deployment

Module reuse and separation of decision making and data processing functions from the physical data collection devices are desirable functionalities for any distributed computing application. The architecture proposed by O'Brien and Julien (O'Brien et al., 2008) divided the functions of a system into three layers, as shown in Figure 23. The top layer, the Decision Support Layer (DSL), provided decision support functionality for application users. Data processing in the form of aggregation and fusion, and other processing is enabled by the Data Processing Layer (DPL). The Sensor Communication Layer (SCL) enables generic communication among sensing and mobile computing devices. A system developer can divide system functions into these three layers and

functions on each layer can be further divided into reusable subcomponents. Developed and deployed in this way, a system can achieve better performance by considering the system's hardware constraints when designing as well as when deploying the system. The flexible to support component reuse and extensibility is an added plus. The following sections of this chapter demonstrate the use of this multi-tier architecture as well as its extensibility and reusability.

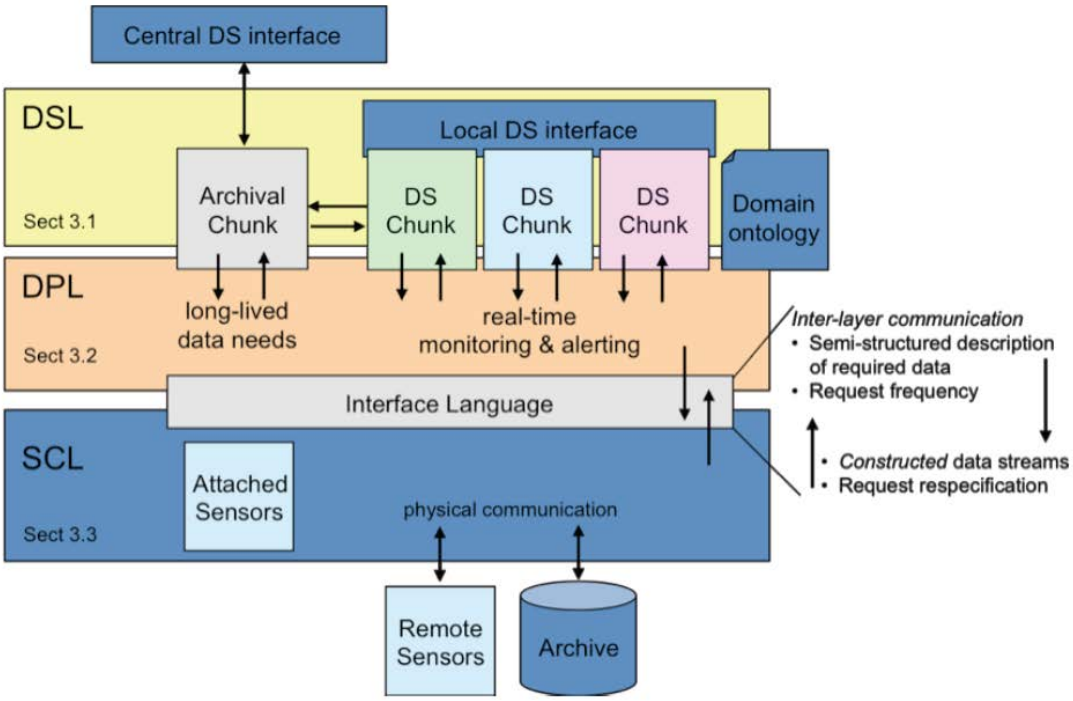


Figure 23 Three-layer Architecture for Decision Support in Mobile Ad Hoc Sensor Networks (O'Brien et al., 2008)

4.4 VISION OF AUTONOMOUS SAFETY MONITORING SYSTEM

Crane operations and falling from a height are among the leading causes of fatalities and accidents on construction job sites (US Department of Labor, 2008). There is an impending need to better utilize computing hardware and information technologies to develop autonomous safety monitoring systems for targeting these specific areas. In the envisioned autonomous safety monitoring system, data is collected through wireless sensors attached to equipment and people on a jobsite. In addition, mobile computing devices (e.g., smart phones, tablets) are carried by workers or mounted in the cabins of equipment. The applications running on these mobile computing platforms can collect information (e.g., location, unique identification, geometry information) from the deployed sensors and other data repositories. The information collected can be processed and used to support the decision making process and to monitor a worker or equipment when being exposed in a dangerous situation. Warnings or alerts can be sent to the corresponding worker/equipment's operator to notify them to take remedial actions. The envisioned safety monitoring system will support the existing safety management practices on construction jobsites and can act as an extra layer of safety monitoring by improving context awareness.

The development of the crane safety monitoring and proactive fall prevention applications are presented in this chapter. For the proactive fall prevention system, a worker carrying a portable computing device (e.g., PDA or smart phone) along with a localization device could be performing a task on a particular floor; the handheld device continuously tracks the location of the worker and retrieves edge information from a

database. Dangerous areas around the worker are dynamically tracked as the location of the worker and the surroundings conditions change. If the worker is entering a potentially dangerous area, the worker will be warned and any specific safety protection equipment to be carried for specific locations will also be checked. A corresponding warning message can be sent to safety managers or superintendents so they can take proper actions. Since construction is usually in a nosy environment and it is not possible for the workers to notice all the sounds from the computing devices, the multimodal warning messages can be used in the form of vibration, beeping sounds and/or visual warnings (e.g., flashing on the hardhat brim).

4.5 GENERAL DESIGN OF SAFETY MONITORING SYSTEM

4.5.1 Component Design

To support the development of the autonomous safety monitoring system, the author studied the existing regulations, standards and best practices, as well as interviewed the construction safety experts with rich experience in crane operation safety, to extract safety knowledge and summarize information requirements for the autonomous crane safety monitoring system in the previous chapters (Luo et al., 2011b). Decision making processes for crane safety monitoring and proactive fall prevention were developed based on the extracted safety knowledge. Figure 24 shows an example of the decision making flowchart of a scenario when a worker is working in proximity of the crane load's fall zone. In this scenario, the system first determines if the tower crane has a load on its hook. If the tower crane is not loaded, the dangerous area related to the crane

load does not exist and both the worker and crane are considered to be in a safe situation. However, if the tower crane is carrying a load, the system first gets environmental information from the weather station or database, location information of the tower crane, crane load and the crane boom from localization devices, and the crane load's dimension information from the database or Radio Frequency (RF) tags. Based on the crane load's dimension and environmental data, the size and shape of the fall zone can be calculated. Combined the crane load's location, the center of the fall zone can be determined. Next, the system gets the worker's location data and compares the worker's location with the dangerous area to determine the relationship to the dangerous area. If the worker falls into the calculated dangerous area, the system retrieves the authorization working list and compares the worker's identification with the authorization list. If the worker is not authorized to work in the area, warnings will be sent both to the worker and the crane operator. If the worker is listed in the authorization list, the system retrieves the information about the personal protection equipment (PPE) carried by the worker and compares with the PPE requirements in the area to determine if the worker meets the PPE requirements. A warning will be sent to the worker to remind the worker of any missing PPEs.

A review of the decision making flowcharts highlights some common components that exist in the decision making process of the crane safety monitoring system. The common components can be summarized into five common components and these components are supported by the subcomponents as listed in Table 4, which means the common components can be created by assembling some of these sub components.

Referring back to the three tier architecture, these components would form the core of the Decision Support Layer. The subcomponents process the data from Data Processing Layer to support the common components in Decision Support Layer. New components can be added to this component registry as needed. A specific safety monitoring application can therefore be developed by assembling these existing components and adding new decision steps in the system. The common components in the registry are introduced below:

- **Localization.** This component is a data processing component used to track an object's location. The component is assembled by two sub components: one is used to get the distance between the object and a beacon (a device with known location to help the target to track its location), and another one uses the retrieved distance to determine the object's location using triangulation algorithms. New localization calculation subcomponents can be developed and added to the registry for different localization algorithms (e.g., Min-Max, K-Nearest Neighbors, Maximum likelihood).

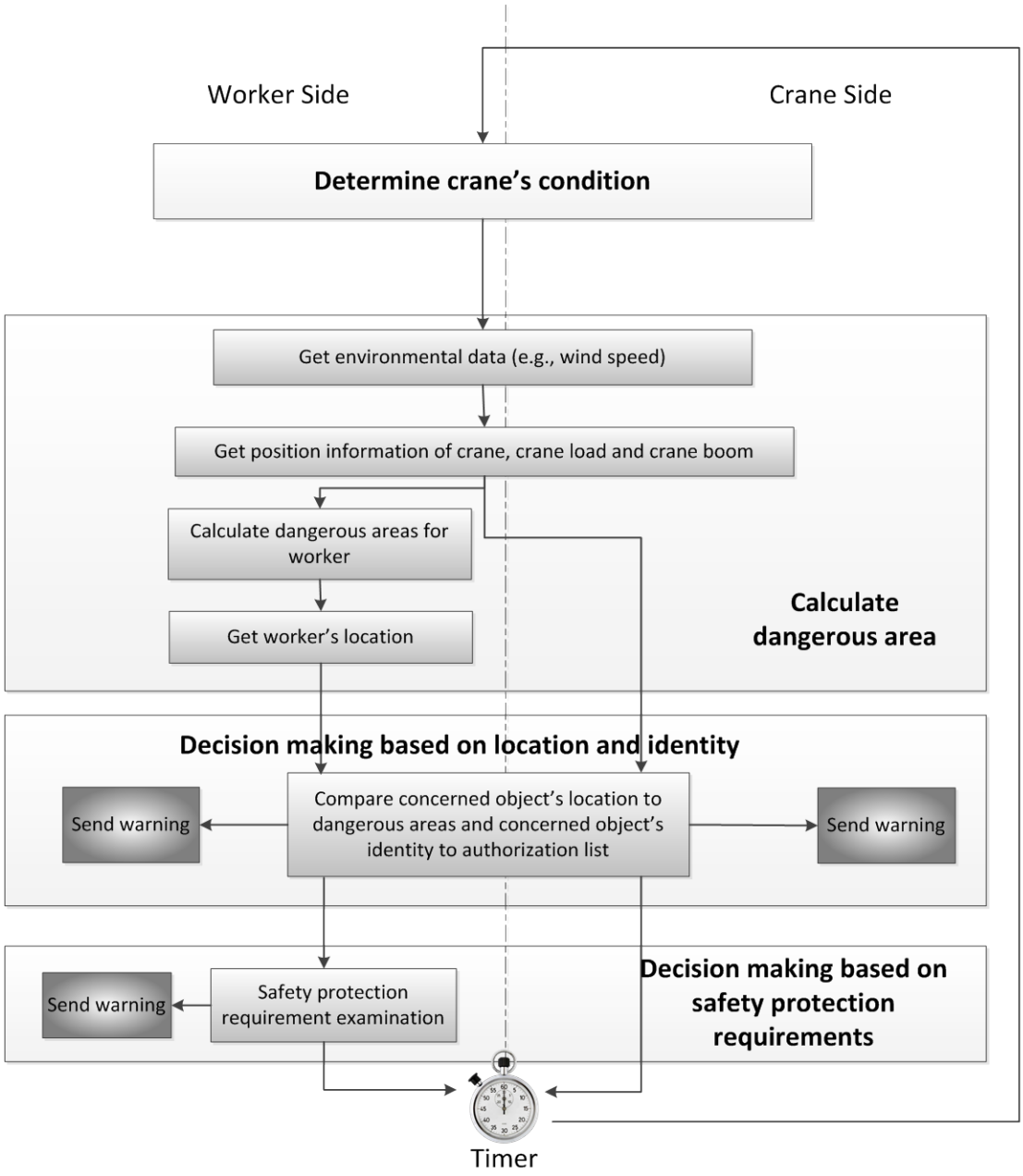


Figure 24 Decision Making Flowchart for Safety Monitoring Under Crane Load

- **Dangerous Area Calculation**. This component is a decision making component used to calculate the dangerous area of a target (e.g., tower crane, crane boom, power line, truck). The location retrieval subcomponent is used to get the location of a target; a

crane load's dimension retrieval is used to get the crane load's 3D dimension from wireless sensors (e.g., RIFD) and available databases; facility parameter acquisition is used to get the facility parameter depending on the facility's type (for example, voltage, starting point and ending points of power line; width, central line and traffic control information for transportation lines); target type identification is used to retrieve the target's type (e.g., crane load, worker, building and others)as the target's type would determine which subcomponents should be selected for the dangerous area generation subcomponents; edge information retrieval is used to get the edge information of a floor (including the geometry and protection information); and the dangerous area generation essentially calculates the dangerous area (including the red zone and the yellow zone) for a target utilizing the aforementioned subcomponents.

- **Object's Relationship to Dangerous Areas:** This component is used to compare the object (point or 3D object) and the dangerous areas. The basic sub components listed within this component includes point to point, point to 2D, point to 3D, 2D to 2D, 2D to 3D and 3D to 3D comparisons. If a new type of dangerous areas is proposed for a new autonomous safety monitoring application, a new subcomponent can be developed by extending the existing sub components or developing a new one using the existing sub components.
- **Authorization Checking**. This component is used to check if a worker/equipment is authorized to work at a specific location. The 1st sub component uses the target's location to determine the control area where the target is located. The 2nd sub component is used to retrieve the authorization list of the identified control area while

the 3rd component is used to compare the target's identification with the authorization list to determine whether the target is authorized to work at the location.

- **PPE Checking**. This component is used to check if the worker meets the PPE requirements of working in a specific area. The 1st sub component is used to retrieve the list of required PPEs; the 2nd sub component is used to get the identification of PPEs carried by the worker from RFID or other sensing devices attached to the PPEs; the 3rd sub component compares the carried PPE to the calculated PPE requirements by the 1st sub component and remind the worker of any missing PPEs.

Table 4 Common Component Registry in the Autonomous Safety Monitoring System

Component	Sub-component
Localization	Distance Calculation
	Localization based on Triangulation
Dangerous Area Calculation	Location information retrieval
	Crane load dimension retrieval
	Facility parameter acquisition
	Target type identification
	Edge information retrieval
	Dangerous area generation
Object's Relationship to Dangerous Area Checking	Point to Point Checking
	Point to Area Checking
	Point to Box Checking
	Area to Area Checking
	Area to Box Checking
	Box To Box Checking
Authorization Checking	Belonging control area calculation
	Authorization list generation
	Comparison to the authorization list
PPE Checking	Required PPE list generation
	Carried PPE information retrieval
	Comparison of required and carried PPEs

4.5.2 Class Diagram

To assist the design and development of the autonomous safety monitoring system, common classes are developed and presented in the class diagram (Figure 25). Three important classes in the class diagram are described here:

- Equipment (Figure 26): The equipment class is a generic class of all equipment on construction jobsites, including cranes, trucks and other operating equipment. Equipment class extends the higher level Object class, which has a location attribute to record its base location. Two important attributes of the equipment class are the YellowZone and the RedZone. Both attributes can be instances ofshape, which can be circle, box, cylinder and others. The calculateDangerousArea method is used to calculate the RedZone and/or YellowZone of a specific piece of equipment. The calculateDangerousArea function can be implemented for each subclass of the equipment, since different equipment might have different dangerous areas.

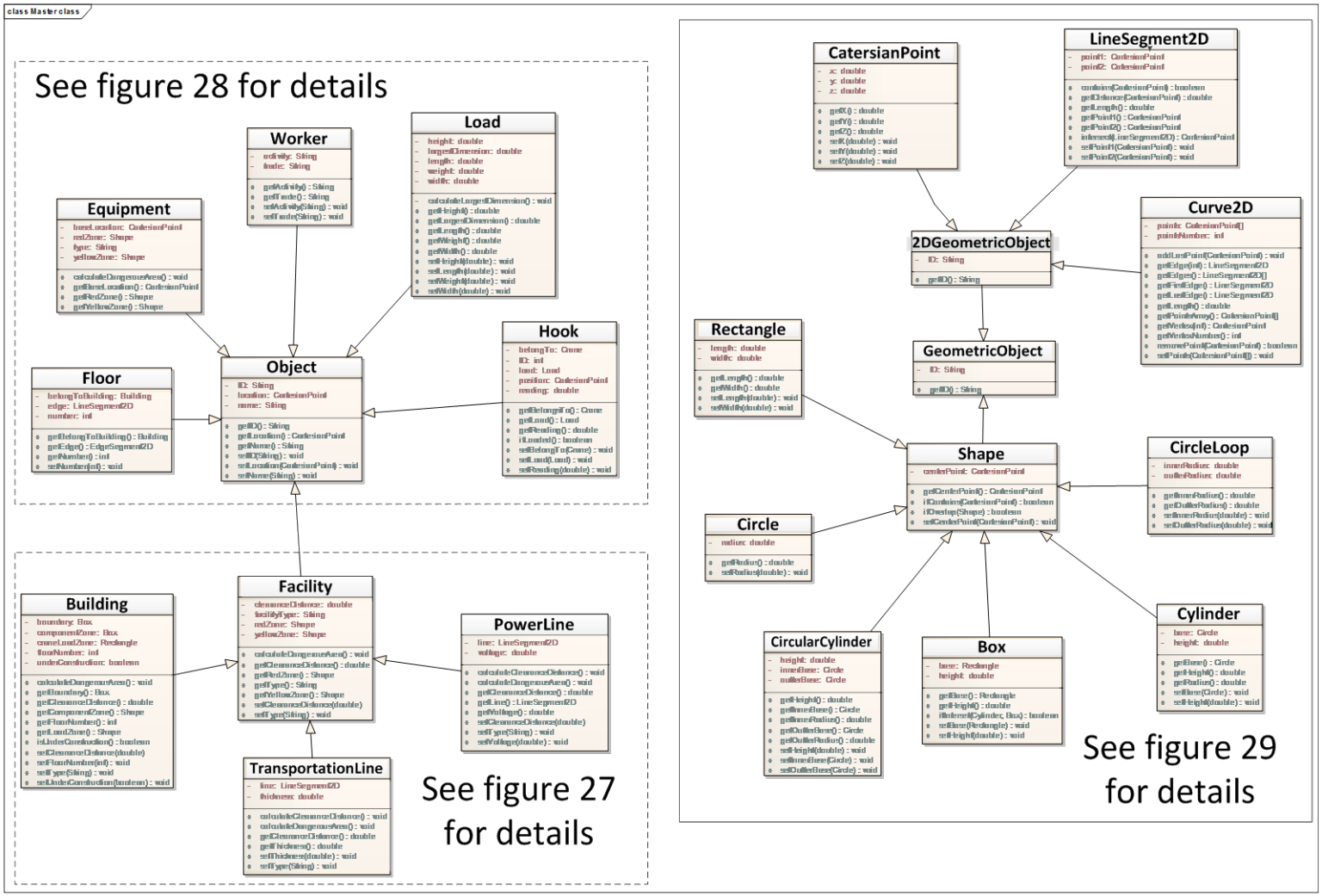


Figure 25 Master Class diagram for the System (Segments are shown in figure 27-29)

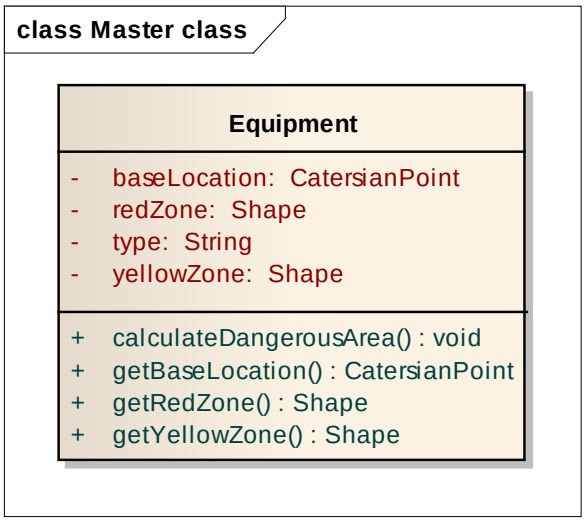


Figure 26 Equipment Class Diagram

- Facility (Figure 27): The facility class is a generic class of all facilities on construction job site, including power lines, buildings, transportation lines and more. The facility class also has the same attributes of yellowZone and redZone as the equipment classes. The specific shape of the dangerous area can be defined in the subclass (e.g., powerlines). For example, the power line class specifically defines the yellowZone as Rectangle and the redZone as Box. New attributes (voltage and clearanceDistance) can be added for the subclasses under the Facility class. The component described in the previous section can be called as a method for those classes.

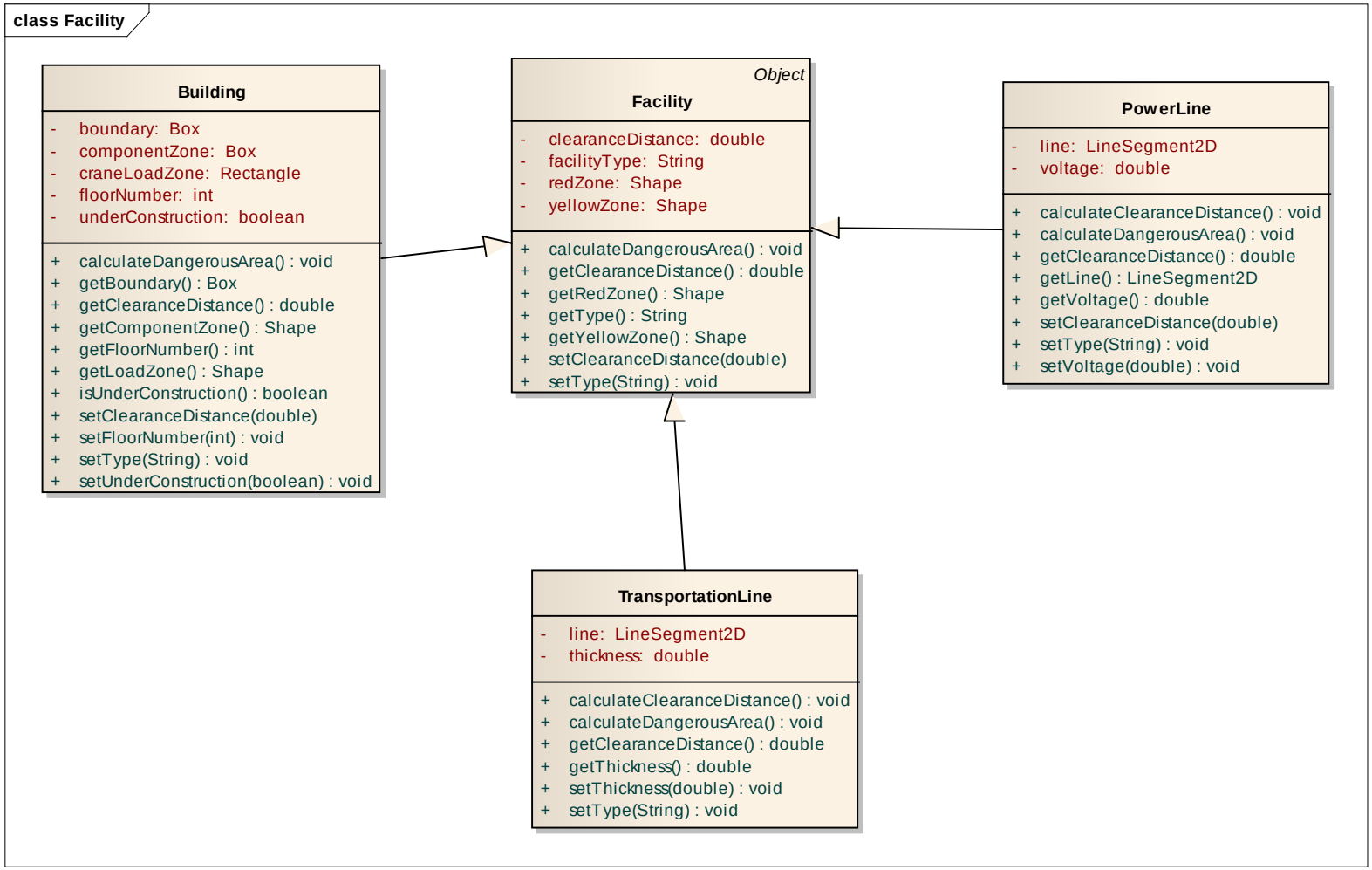


Figure 27 Facility Class Diagram

- Shape (Figure 28): the shape class is used to define the dangerous area. As the class is used to define the dangerous areas in the autonomous jobsite safety monitoring system, it includes the most common shapes (rectangle, circular Cylinder, Cylinder, Box, CircleLoop and Circle) of dangerous areas as its subclasses. The center point of the shape is defined as an attribute in the shape class and an Object's Relationship to Dangerous Area Checking component described in the previous section can be separated into two operations for the shape class. The two operations are implemented for each specific shape.

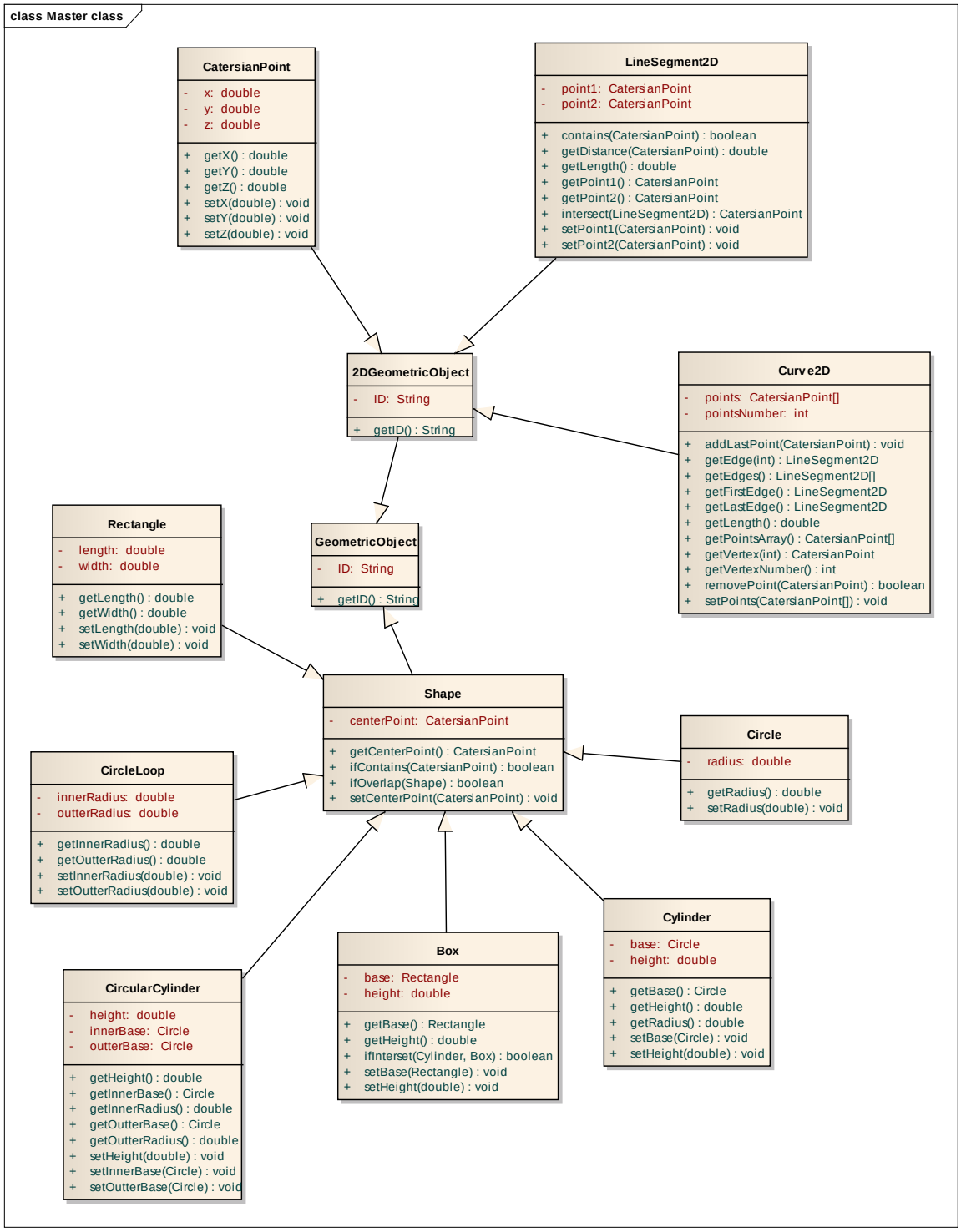


Figure 28 Shape Class Diagram

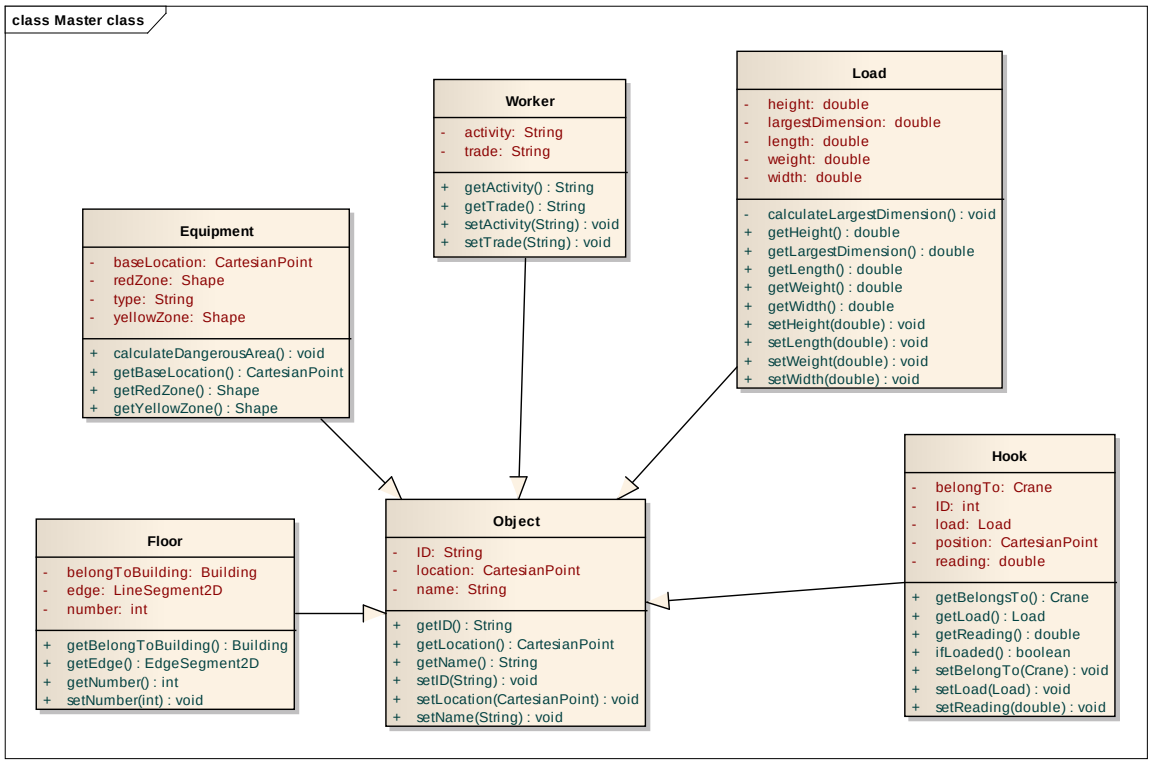


Figure 29 Object Class Diagram

4.6 DEMONSTRATION

4.6.1 Crane Safety Monitoring Application

By analyzing the decision making flowcharts for the crane safety monitoring system, the author decided that a majority of components (listed in Table 5) in the component registry can be used in the crane safety monitoring system for design and developing purposes.

Table 5 Components Used in the Crane Safety Monitoring System

Component	Sub-component	If the component is used
Localization	Distance Calculation	Yes
	Localization based on Triangulation	Yes
Dangerous Area Calculation	Location information retrieval	Yes
	Crane load dimension retrieval	Yes
	Facility parameter acquisition	Yes
	Target type identification	Yes
	Edge information retrieval	No
	Dangerous area generation	Yes
Object's Relationship to Dangerous Area Checking	Point to Point Checking	Yes
	Point to Area Checking	Yes
	Point to Box Checking	Yes
	Area to Area Checking	Yes
	Area to Box Checking	Yes
	Box To Box Checking	Yes
Authorization Checking	Belonging control area calculation	Yes
	Authorization list generation	Yes
	Comparison to the authorization list	Yes
PPE Checking	Required PPE list generation	Yes
	Carried PPE information retrieval	Yes
	Comparison of required and carried PPEs	Yes

Figure 30 shows how the developed decision chunks are reused in the safety monitoring applications decision making process. The green decision chunks are the sub components in Table 5 to fulfill the functions in the decision making flowchart. By integrating the used components together, the autonomous safety application for the areas under the crane load can be developed.

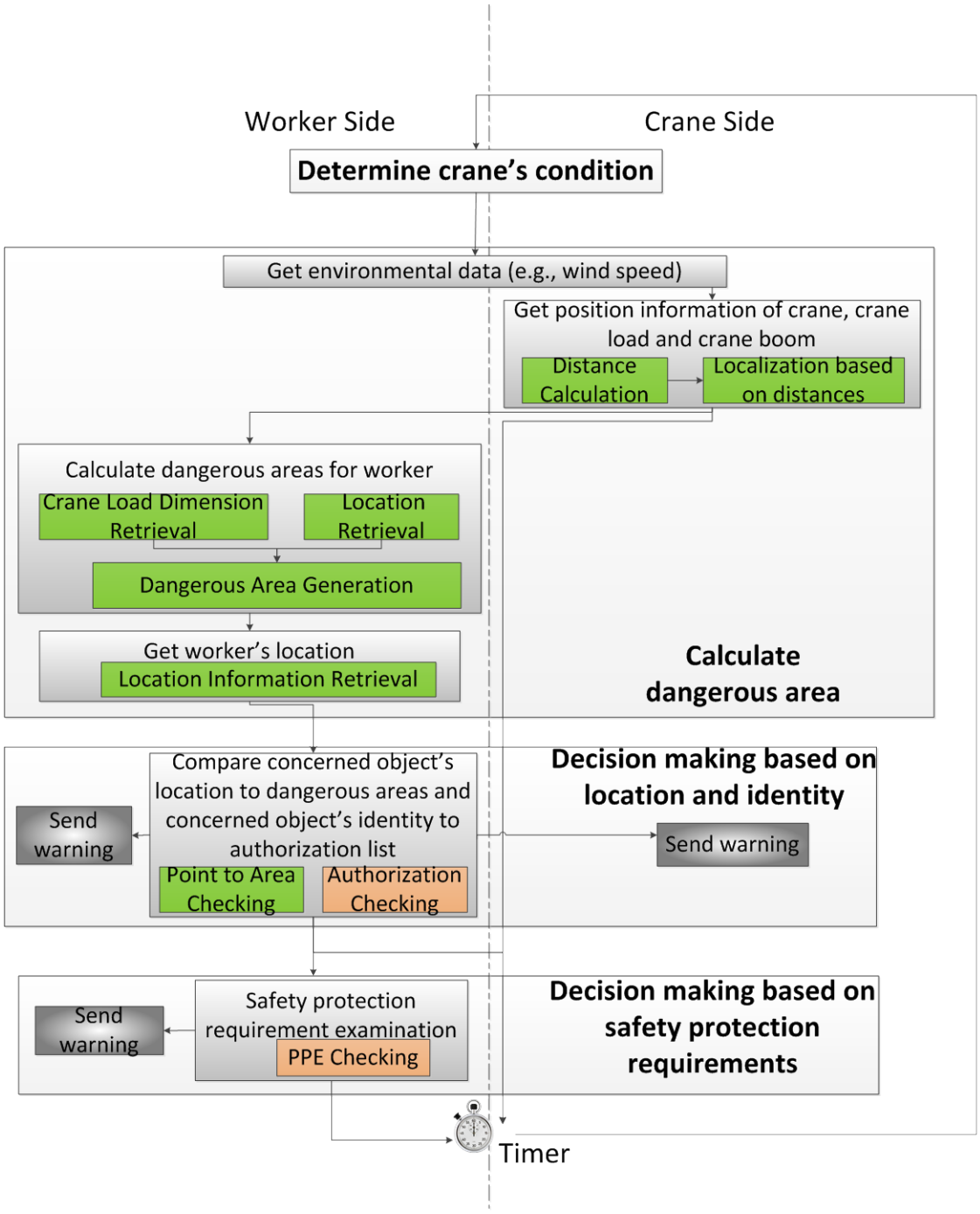


Figure 30 Component Reuse in Safety Monitoring Application for Dangerous Area Under the Crane Load

When designing the classes for the crane safety monitoring system, new classes can be created by extending the existing classes described above. For example, a crane class (Figure 31) is created by extending the equipment class and the tower crane class is created based on the new crane class. Hook as a common element in all types of crane, it is created in the crane class, and related operations are developed in the crane class. In the subclass Tower Crane under Crane class, boom Length and boomAngel are defined as attributes, which can be used for the crane hook's location calculation.

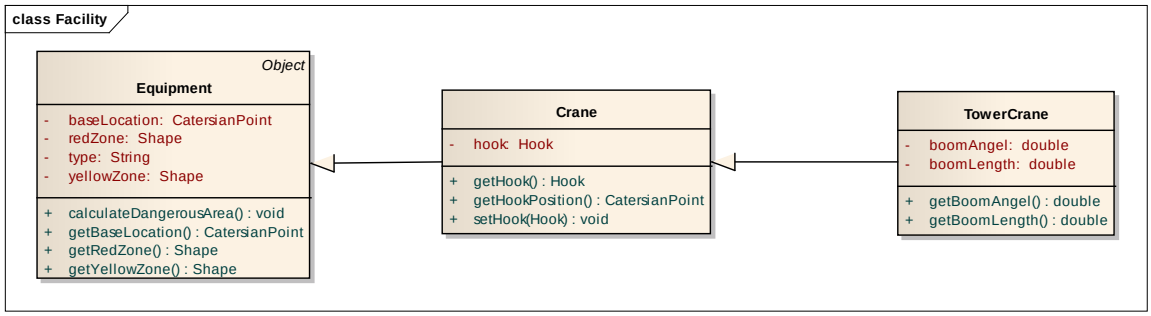


Figure 31 Extending Equipment Class to Tower Crane Class

A sample sequence diagram (Figure 32, the full set can be found in appendix C) consists of four objects participating in safety monitoring under crane load activities (one of the safety monitoring tasks in the system): the worker's handheld device with running safety monitoring applications, the worker with a cricket mote sensor, the crane with a computing device where crane side safety monitoring application runs, and the crane load with a cricket mote sensor for localization. The sequence diagram was developed based on the information flowchart described in the safety requirements of crane safety

monitoring. The messages in the sequence diagram are self-explanatory. It shows how the messages are pushed and pulled across these four objects.

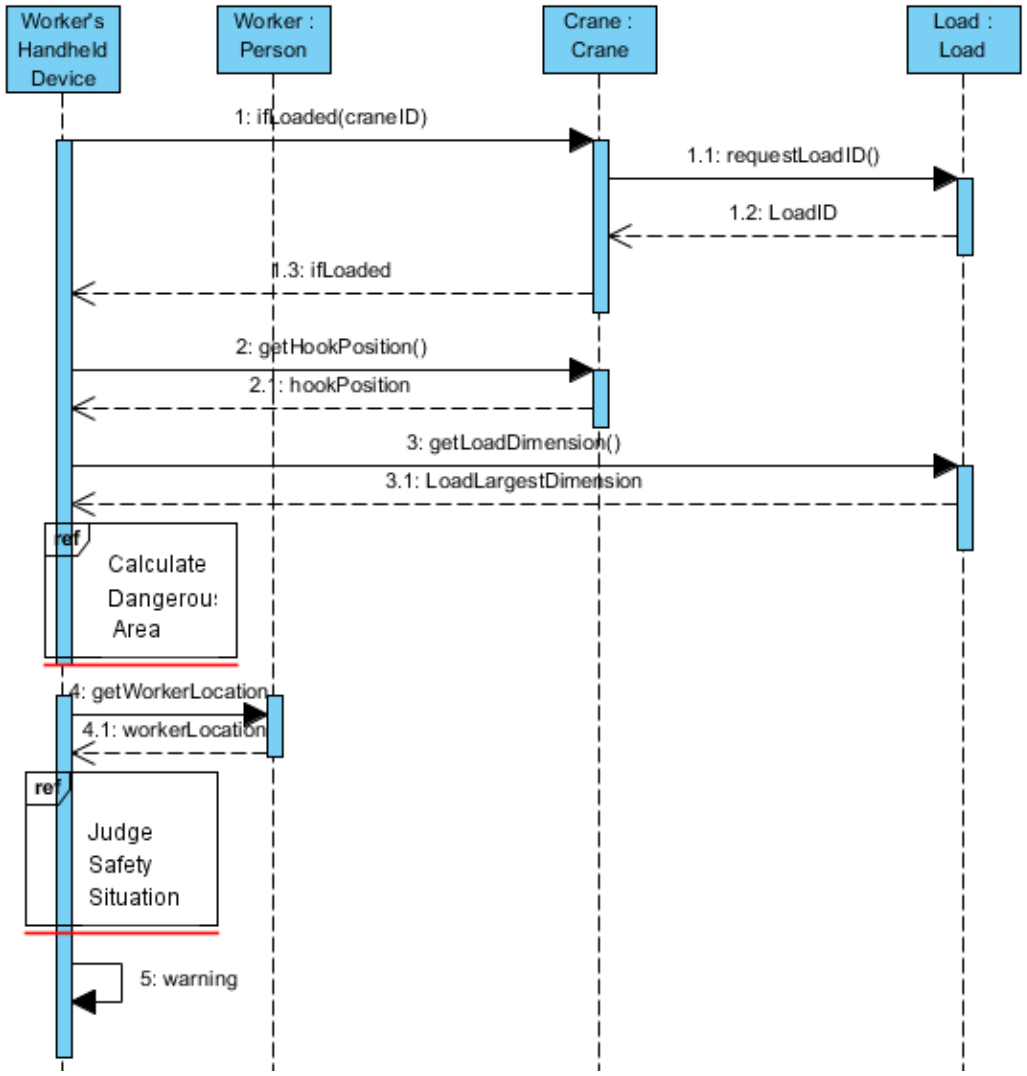


Figure 32 Sequence Diagram for Safety Monitoring Under Crane Load

A sample state diagram (Figure 33, the full set can be found in appendix C) shows the states within the system and transitions among these states. The area control under the crane load state diagram is initiated with starting the safety monitoring application.

During the lifecycle of the application, various actions would change the states of the application and the application would not stop until the user terminates it. The application would reach at least one of the two states (in a safe condition, or warning) during the lifecycle.

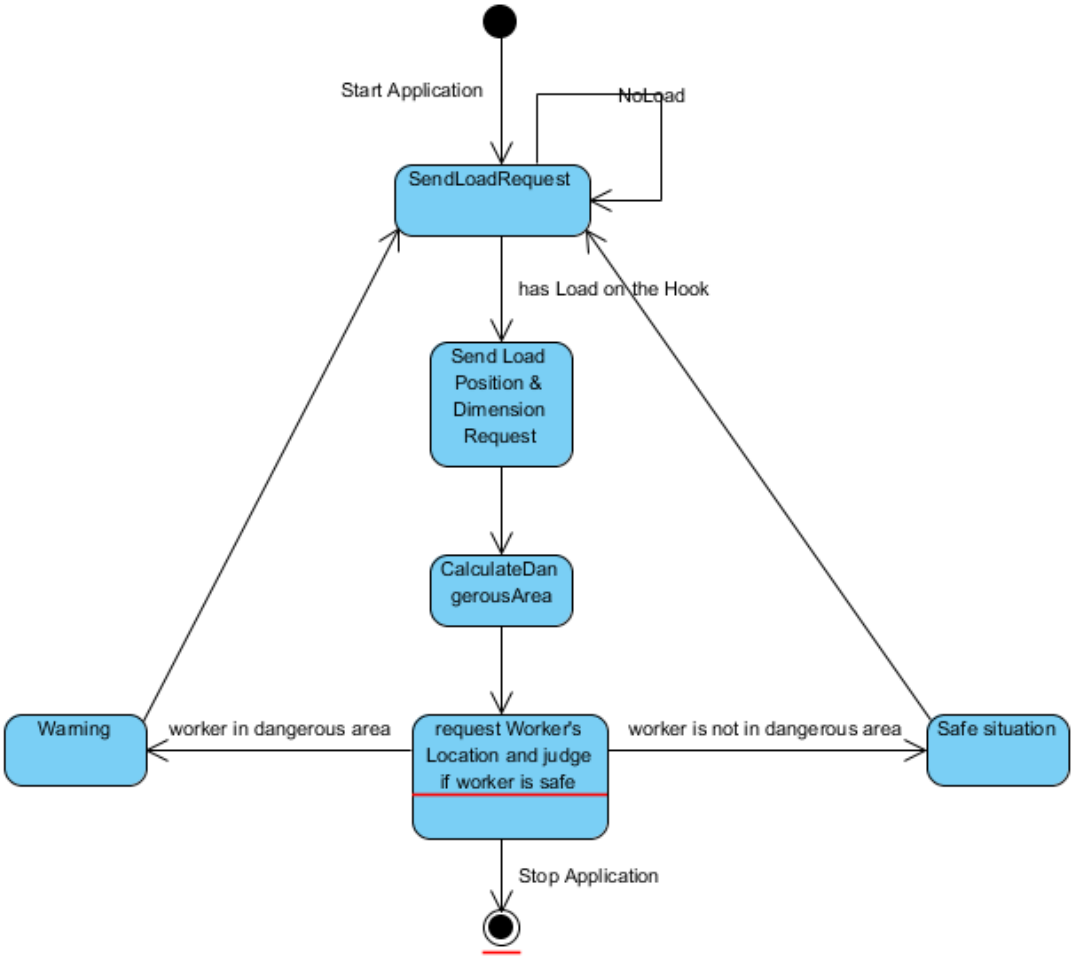
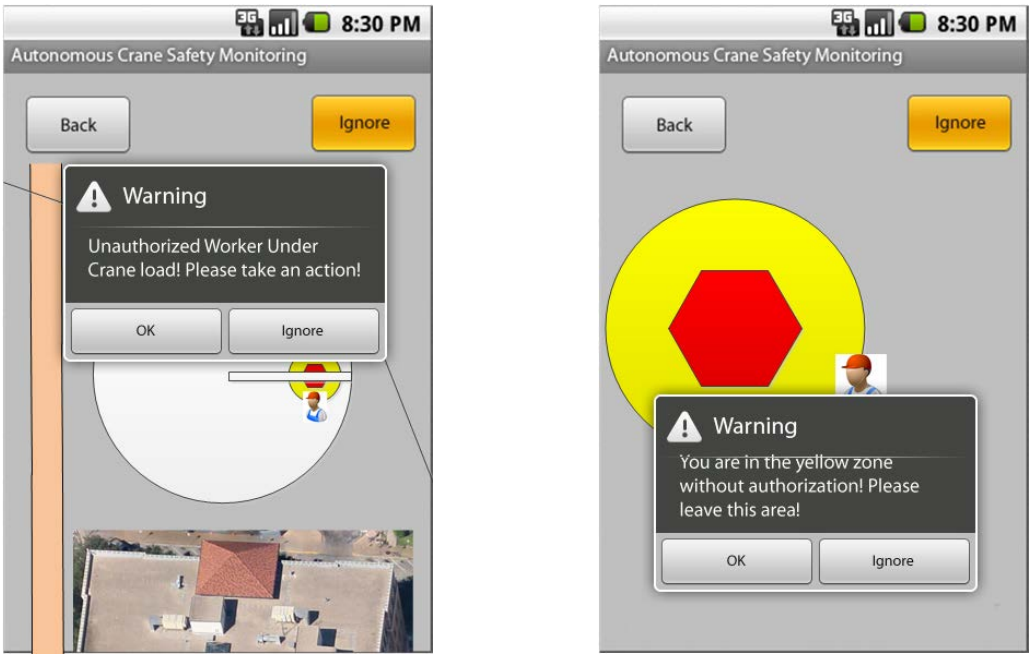


Figure 33 State Diagram for Safety Monitoring Under Crane Load

Based on the system design and decision making algorithms, the crane safety monitoring system was developed for running on the crane cabin's tablet and the worker's handheld tablet (Figure 34).



(a) Crane Cabin Side (b) Worker Handheld Side

Figure 34 GUIs of Crane Safety Monitoring System

4.6.2 Proactive Fall Prevention Application

Some of the components (listed in Table 6) in the component registry (Table 4) can be reused for the proactive fall prevention application. All the components in the registry can be reused, although some of the subcomponents were used to assemble into the upper level components. For example, the dangerous area of the proactive fall prevention system is the proximity of open edges. Hence, for the dangerous area calculation component, only location information retrieval, target type identification,

edge information retrieval and dangerous area generation subcomponents were used to develop the larger dangerous area calculation component.

Table 6 Components Used in the Proactive Fall Prevention System

Component	Sub-component	If the component is used
Localization	Distance Calculation	Yes
	Localization based on Triangulation	Yes
Dangerous Area Calculation	Location information retrieval	Yes
	Crane load dimension retrieval	No
	Facility parameter acquisition	No
	Target type identification	Yes
	Edge information retrieval	Yes
	Dangerous area generation	Yes
Object's Relationship to Dangerous Area Checking	Point to Point Checking	Yes
	Point to Area Checking	Yes
	Point to Box Checking	No
	Area to Area Checking	Yes
	Area to Box Checking	No
	Box To Box Checking	No
Authorization Checking	Belonging control area calculation	Yes
	Authorization list generation	Yes
	Comparison to the authorization list	Yes
PPE Checking	Required PPE list generation	Yes
	Carried PPE information retrieval	Yes
	Comparison of required and carried PPEs	Yes

Figure 35 shows how the developed subcomponents are reused in the safety monitoring applications decision making process.

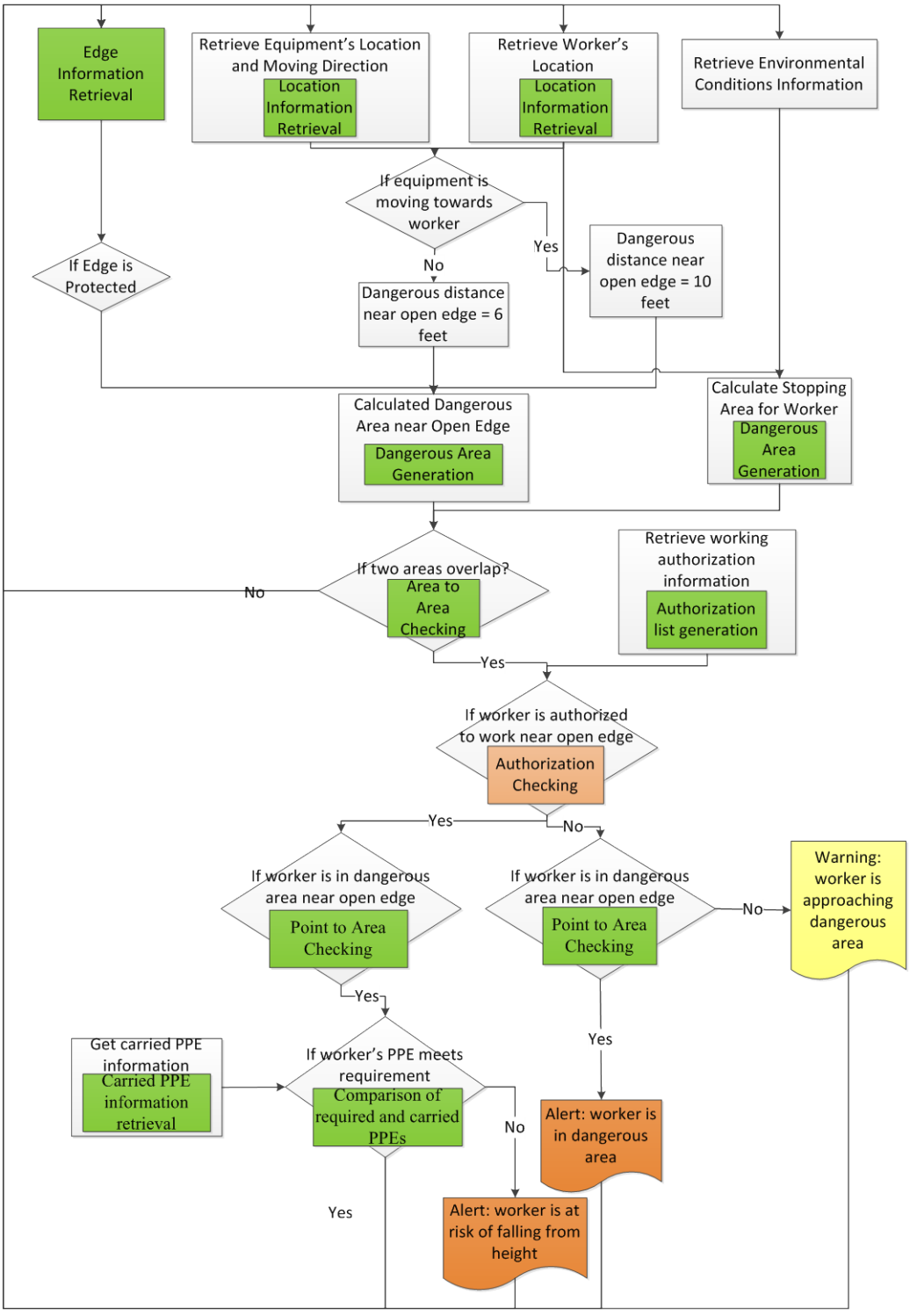


Figure 35 Component Reuse in Proactive Fall Prevention

To implement the component design and develop the system using the designed components, a class diagram is developed by extending the master class diagram in Figure 36. Figure 36 shows an example of developing a class of edgeSegement2D representing edges on the floors. The new class edgeSegement2D extends the master class LineSegment2D by adding new attributes and operations. The new class representing edge on the floor contains the following unique attributes useful in the system: ifWarningline (if the edge has warning line next to it), ifGuardrailSystem (if a guardrail system is erected right next to the open edge), PPERequirements (a list of required personal protection equipment to work in proximity to the open edge), the authorizationList (a list of workers who are authorized to work in proximity to the open edge), the clearanceDistance (the clearance distance an unauthorized worker should be kept away from the open edge), the yellowZone and the redZone (representing dangerous areas next to the open edge). Some decision making subcomponents (e.g., Authorization list generation) listed in Table 6 can be called to implement the methods (e.g., getAuthorization() method) in the class.

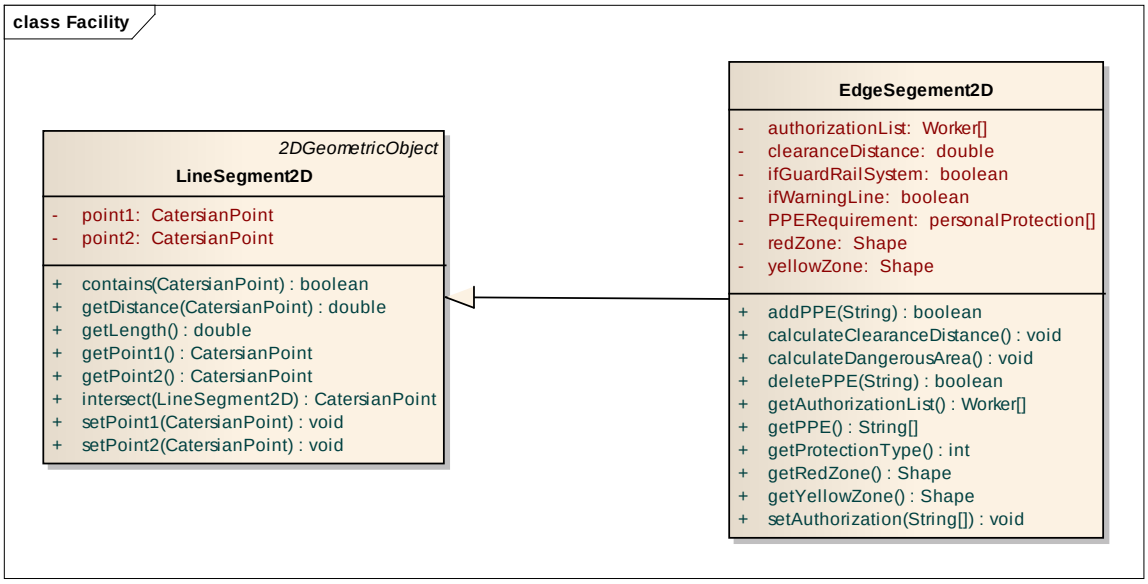


Figure 36 Extending the Master Class to Develop a New Class for Proactive Fall Prevention System

A sequence diagram (Figure 37) was developed based on the decision making flowchart for proactive safety monitoring near the open edge. In the sequence diagram, there are four objects: tablet carried by the worker, localization devices attached to the worker, wireless sensors on the moving equipment and computer database with building information models containing open edge-related information. The sequence diagram shows how the messages flow among the objects, the sequences of pulling and pushing information in the system.

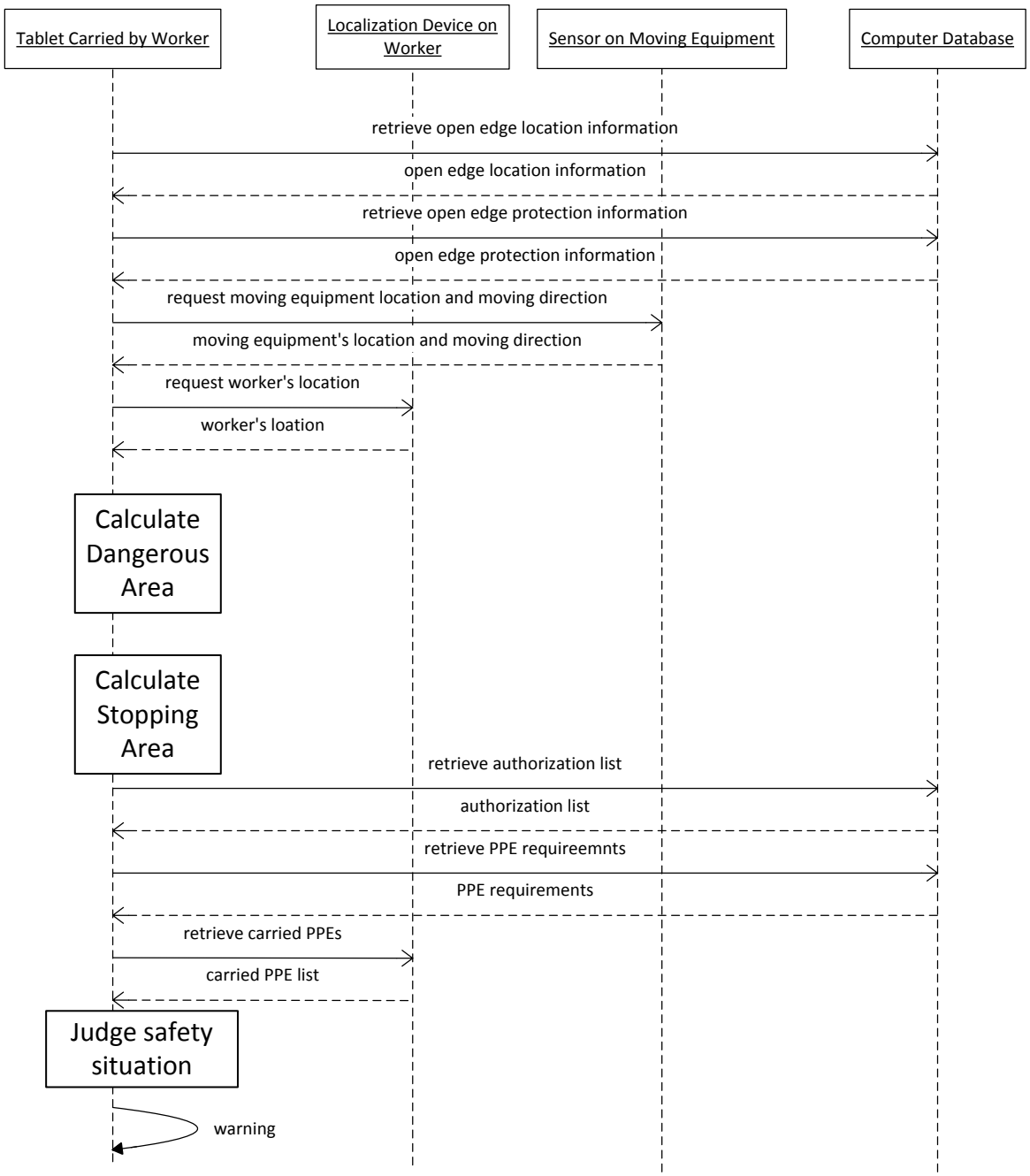
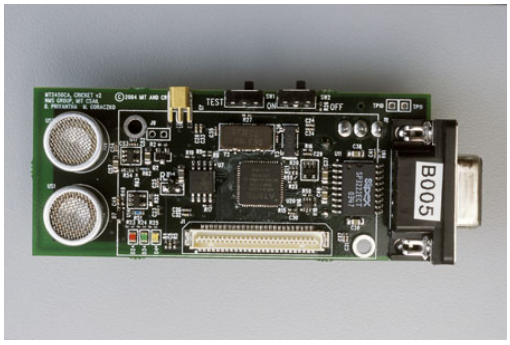


Figure 37 Sequence Diagram for Proactive Fall Prevention

4.6.3 Deploying the safety monitoring system and the testbed description

In this research, cricket motes are selected to build the wireless sensor networks for location data collection. Cricket mote is a mica2-based wireless localization device (Figure 38). The cricket mote contains a mainboard with a 433MHz processing unit, 4kB RAM, 128kB program flash memory and a sensor board with two ultrasonic sensors. The sensor uses a combination of Radio Frequency and ultrasonic technologies for localization. There is a 51pin expansion connector on the mainboard to attach a sensor board for data collection. The add-on sensor board can house a combination of tiny sensors such as light sensors, temperature sensors, 3 axils accelerometer, magnetometer, microphone and GPS.



(a) Cricket mote

(b) add-on sensor board

Figure 38 Wireless Sensor Node

Tablet PC is chosen to run the safety monitoring system for data collection and decision making. A small scale (1:100) construction jobsite with model tower cranes is built in the lab environment to simulate the job site environment to test the crane safety monitoring system. For the proactive fall prevention application, the author used the same

devices but used the lab (1:1 scale to the jobsite open edges) and defined virtual edges and dangerous areas in the lab.

The sensors and computing devices used in the testbed have different various capacities of storage, computing and battery create a distributed mobile computing environment which poses challenges on how to appropriately deploy the system across them. The three-layer architecture for real time decision making development (O'Brien et al., 2008) is used to develop the author's deployment schema for the crane safety monitoring system (Figure 39 and Figure 40).

The crane safety monitoring system is deployed across several devices carried by different objects on the jobsite: 1) location listener attached to a crane's hook, which sends a location services query request to the beacons at fixed positions, receives acknowledgement with a beacon's location and distance information and then uses the collected information to calculate a hook's real time position; 2) location listener attached to the worker handheld device, which acts similarly to the one attached to the crane's hook; 3) computer in a crane's cabin, which registers location services on location listeners attached to relevant objects on the jobsite and received replies with their location information. Location information will be passed from the physical communication layer to the data processing layer and then processed dangerous area information would be passed to the decision layer to do a safety check and give a warning to the crane operator if there exists any dangerous situation regarding crane operations; 4) the worker's handheld devices, which runs crane safety monitoring application (as well as many other applications) to warn the carrier if he/she enters dangerous areas relevant to crane

operations. The working mechanism is as similar as the computer in the crane's cabin. Although the deployment schema only shows a single entity in each category, the schema can be expanded to a large jobsite environment with multiple cranes and workers. The deployment scheme shows how the developed components in Table 5 are deployed across the three layers and different devices in the distributed computing environment.

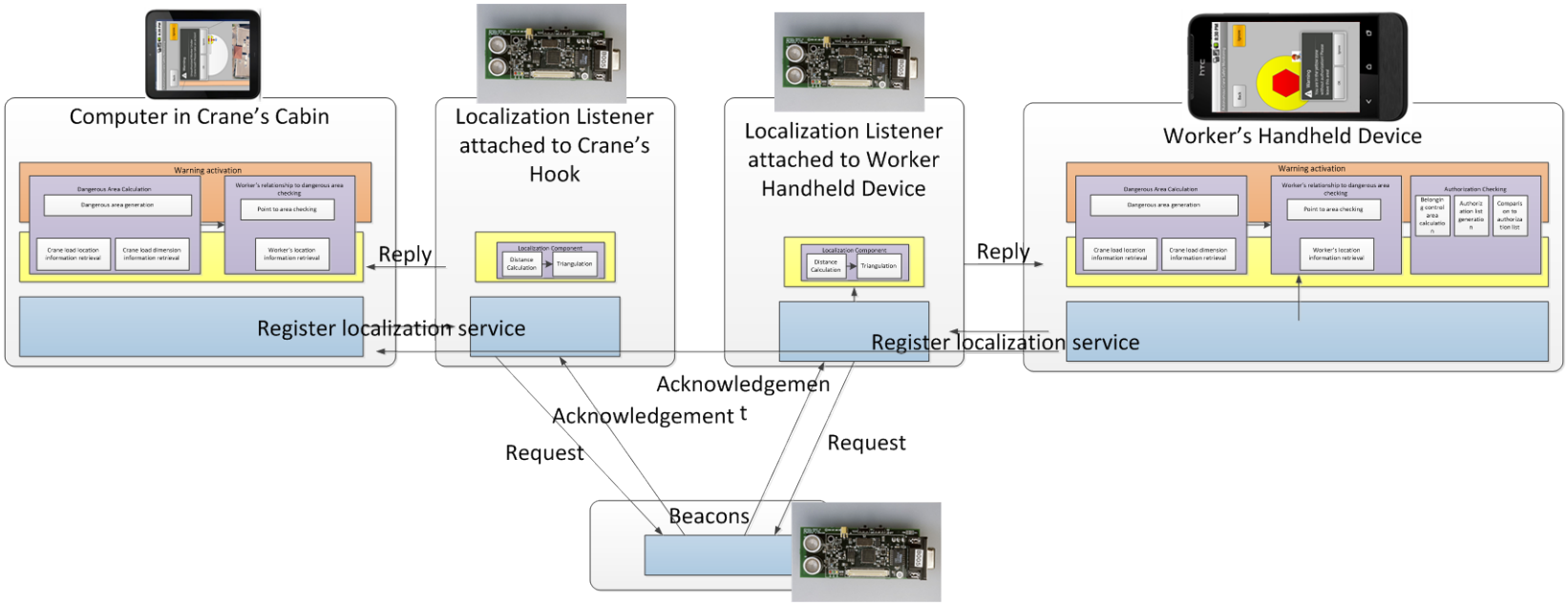


Figure 39 Deployment of Autonomous Crane Safety Monitoring in Distributed Computing Environment

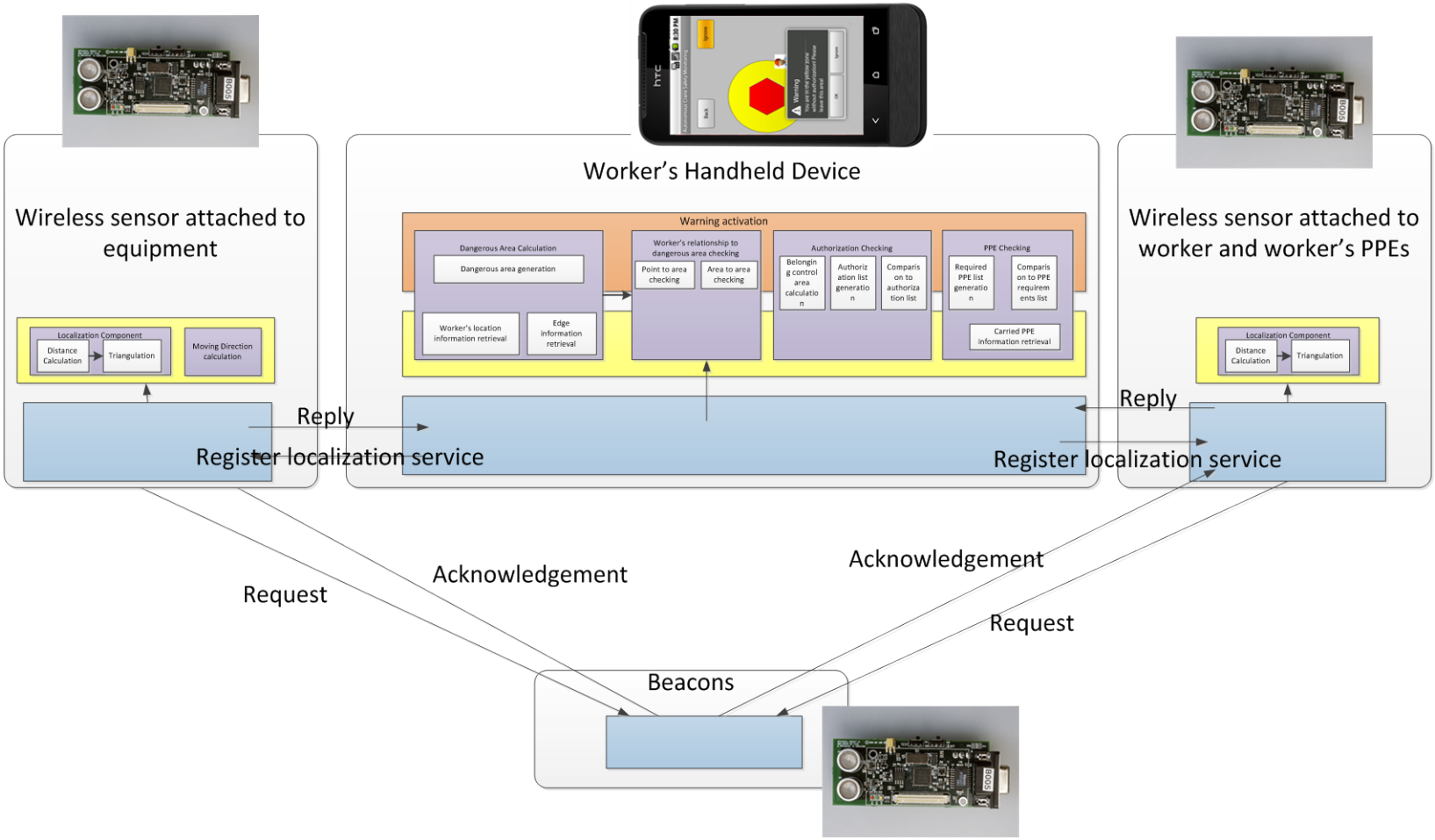


Figure 40 Deployment of Proactive Fall Prevention Application in Distributed Computing Environment

4.7 CUSTOMIZING AND DEPLOYING THE AUTONOMOUS SAFETY MONITORING SYSTEM ON A JOBSITE

In the previous section, the author demonstrated how to apply the three layered distributed computing architecture for system development and deployment in a scaled testbed environment. The system is ready for customization and scaled up to a full size jobsite since the testbed was built based on a typical jobsite to capture its characteristics. In this section, I proposed a process to show how to customize the extracted safety knowledge in the system and deploy the system in a specific jobsite. A general process would be explained and a demonstration would be used to show the applicability of the process.

4.7.1 Proposed a Process for System Deployment on Jobsite

The safety knowledge of proximity control for autonomous jobsite safety monitoring was extracted from the literature and experts (Chapter 2 and Chapter 3), integrated into the safety system described in this chapter. Each construction project is unique and safety attitude may vary according to different safety management teams. Therefore, the extracted safety knowledge in the system might need to be customized to reflect the uniqueness of a specific construction project. The process of the system deployment on jobsite is shown in Figure 41 and explained below:

1) Before physically deploying the autonomous safety monitoring system on the jobsite, the safety management team on the jobsite needs to review the safety rule sets integrated into the system to determine if any rule is inappropriate on this

jobsite or if there is any new safety rule about the proximity controls should be included in the system. If so, the relative rules should be removed from or added to the system.

2) Customize the parameters in the decision rules inside the system. Decision rules in the system define the size, shape, and location of the dangerous areas. The system specific default value to these attributes based on the literature review and expert interviews. Before using the system on the jobsite, the safety management team can review those parameters and decide whether to change those values to reflect the unique situation on this jobsite.
3) Create the instance of objects in the system. Objects regarding facility on and around the construction jobsite need be created in the system and associated required information should be fed in the system before first-time use. Objects described here include buildings under construction on the site, temporary offices/trailers on the site, occupied buildings in proximity of the jobsite, power lines on and around the jobsite, active traffic lines in proximity of the jobsite, tower cranes on the jobsite and others. If there is any change happened to these objects, the corresponding objects existing in the system need to be updated.
4) In the job site, each moving object, which is required to provide its information to the system, needs to be tagged with a localization sensor. The sensor is not necessary to be the Cricket motes used in the demonstrated testbed. It can be any one or a combination of several ones from a wide range of sensors, including but not limited to GPS, RFID and Ultra Wideband Sensor.

5) After tagging the sensors on those components, the system should calibrate and test the localization system to ensure that the localization sensors work appropriately.
6) After tagging the objects on the jobsite and testing the associated localization sensors, the developer can adjust the autonomous safety monitoring system in the jobsite and replace the localization components in the system and change the components in accordance with the requirements of project safety management. At the completion of customizing the system, I can deploy the sensors on the jobsite and integrate the sensors into the system, so a trial can be run on the jobsite for a short time to test its reliability.

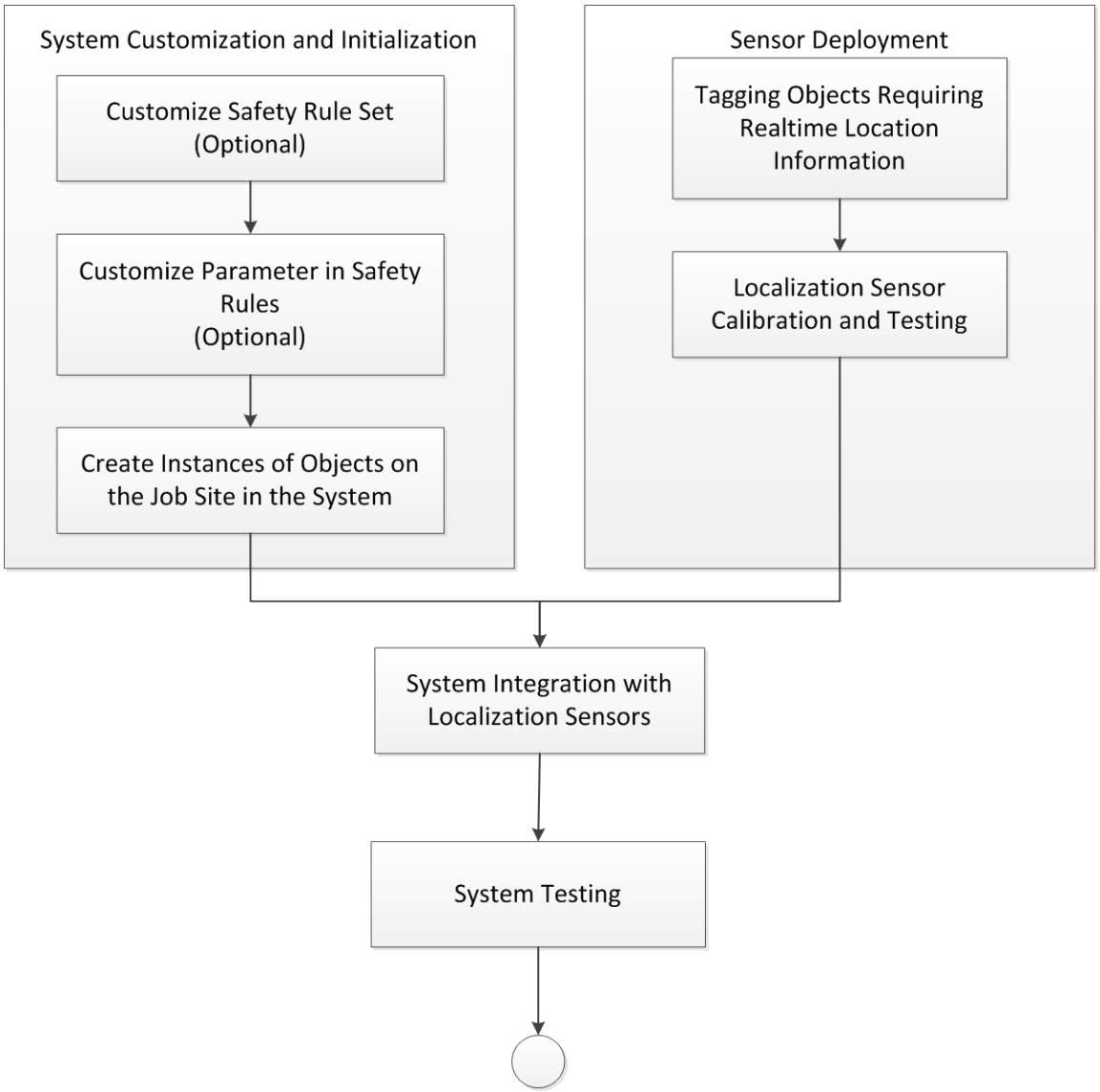


Figure 41 Process Diagram for System Customization and Deployment on Jobsite

4.7.2 Example: Deploying the Autonomous Crane Safety Monitoring System on a Jobsite for Proximity Control under a Crane Load

In this subsection, I used the subsystem of the proximity control under the crane load in the autonomous crane safety monitoring system to create a scenario to show how

the extracted safety knowledge can be customized and how the system can be scaled up to the jobsite following the proposed process in the previous section.

In this scenario, a safety manager decided to implement the autonomous crane safety monitoring system proposed in this chapter to monitor the dangerous areas under the crane load on his jobsite in downtown Austin. When reviewing the safety rules regarding the areas under the crane load, the safety manager confirmed that safety rules for the proximity control under the crane load are comprehensive. The safety manager is risk-averse and would rather increase the chance of workers being in false alarm situations, rather than exposing workers to the hazards of falling objects. Therefore, the clearance distance between the yellow zone and the red zone in the system is set to a value of 3 meters to replace the default value of 2.3 meters.

After customizing the safety knowledge for this construction project, objects of two buildings under construction, two occupied buildings next to the jobsite, a railway running along the south side of the jobsite, two roads with some traffic, and a tower crane were created in the system. The dimension and location information of these objects were also attached to the objects as attributes.

The safety manager's first thought was to see how good the GPS devices might work on the safety monitoring system on this jobsite. Therefore, GPS devices were attached to the crane hook and the workers working on the jobsite. The system was adjusted by replacing the cricket mote localization component with the GPS location retrieval component.

In the next step, the system would be tested to ensure the workability of the system.

4.8 RESULTS AND DISCUSSION

In this section, I tested the autonomous safety monitoring system in a mobile computing environment with Cricket mote localization and a tablet PC. The tests answered research question 2.3 by providing the performance constraints posed by the computing and sensing technologies. Three performance metrics are discussed below:

- Latency

Latency here is defined as the time difference between a moment a mote node sends out a package to the other mote node and the moment that the base node receives a reply from the targeting node. Any package transmission with latency of over one second is considered as a lost package and discarded in our application. The latency ranges from 50 to 300 milliseconds and the average latency of package transmissions between mote nodes is 100 milliseconds. A large data package might result in increased latency and a higher package lost rate. For near real time safety decision-making, it is best to enable communication between a computer and sensors within 1 to 2 hops.

- Computation time

For the jobsite testbed with 2 tower cranes, 5 workers, 7 buildings and 5 sections of power lines, the author ran the safety monitoring application on two tablets with different specifications. On a tablet with Duo Core 1.3GHz CPU and 8G RAM, the running time for one iteration ranges from 0.2 millisecond to 1 millisecond. The average

running time is 0.53 millisecond. On a tablet with Duo Core 2.4GHz CPU and 3G RAM, the running time for one iteration ranges from to 0.1 to 0.33 millisecond. The average running time is 0.15 millisecond. The computation time will increase linearly as the number of entities in the jobsite increases. The results also show that the computation time decrease if a tablet with higher computing capacity is adopted.

- Missing data

Based on the system running in the testbed, the author observed a missing data rate of less than 5% at all points. The missing location data results in the incapacity of judging the safety situation of the worker and the crane. There are two potential solutions for misjudgments due to missing data: 1) use the safety situation of the previous step as the current situation; 2) use the previous location information to predict the current location and use the predicted location to determine the safety situation.

At this moment, the bottleneck for real time decision making is not computing time but network latency. As the number of entities in the system increases, I can still restrict the computing time within a limit by only introducing entities within a predefined distance to the reasoning process.

To reduce the transmitting data package size, the author deployed some of the data processing component in the mote sensor. For example, the localization component can be deployed in the mote node. In this way, the mote node only needs to send back a small localization data package instead of a larger data package with distances to several beacon nodes. However, pushing the data processing functions in mote nodes would

result in decrease freshness of location information. The system developer needs make a tradeoff between transmission latency and information delay when determining what data processing functions to be deployed on the sensor nodes. Another advantage of pushing the data processing functions into sensor nodes is that by reducing the size of the transmission data package, the energy consumption used wireless communication also decreases, resulting in a longer system life with a fixed battery supply.

Since the power supply for the sensors is usually limited, another way to increase the system's life is reducing data sampling and transmission frequency when having no effect on the system accuracy. For example, instead of having a fixed sampling frequency of location information, system can have a self-adaptive sampling frequency: the closer the object is to the center of dangerous area, the higher sampling frequency the system should have.

4.9 CONCLUSIONS

This chapter reviewed the current development and deployment models for sensor applications in a distributed computing environment and answered research question 2.1 by choosing the three layers architecture for the decision making application development and deployment to develop a jobsite autonomous safety monitoring system. The development and deployment process demonstrated that the deployment model met the constraints in a distributed computing environment and provided additional benefits for the system developers. The extracted safety knowledge described in chapter 2 and chapter 3 were translated into the reasoning mechanisms through UML designs to answer

research question 2.2. The reasoning mechanisms were specified in activity diagrams and sequence diagrams. Two applications (crane safety monitoring and proactive fall prevention) were developed on the top of component registry and master class diagrams, and deployed in a jobsite testbed with a distributed computing environment created by wireless sensors and mobile computing devices. The development and deployment of the two safety monitoring applications demonstrated the extensibility and reusability of the distributed approach. After the system development and deployment, computing performance data of the system and devices to show the constraints posed by the distributed computing environment and discussion was presented in the result section to answer research question 2.3.

The reusability and extensibility of the distributed approach indicates that the autonomous jobsite safety monitoring system can be extended to a variety of safety-related applications. For example, location-awareness safety applications (e.g., truck safety monitoring in working zones, transportation facility health monitoring with time-series location data) can be developed using some components in the registry and classes in the master class diagrams. New applications can also enrich the component registry and the master class diagrams to accelerate the development process of other future applications by reusing the existing classes and components.

Future research directions can be developed on the top of the research described in this chapter: 1) enriching and extending the autonomous safety monitoring system with other sensing technologies (e.g., computer vision, environmental sensors); 2) Extending the safety monitoring systems to intelligent safety management by equipping the system a

capacity of responding to the dangerous situations using actuators; 3) collaborative knowledge distributing within the sensor networks, in which the extracted safety knowledge is distributed across the devices in the whole sensor network systems. In this system, the sensing and computing devices collaborate to achieve a larger system goal.

Chapter 5 Exploring Location-aware Sensor Data Imperfections and Their impacts on Autonomous Jobsite Construction Safety Monitoring

During the crane safety knowledge validation described in chapter 2, the safety manager raised a concern about if the proposed autonomous safety monitoring system is trustful because errors always exist in automatic systems. To measure the actual performance of the autonomous safety monitoring system that I proposed in the previous chapters, this chapter explores data imperfections and their impacts on the system's performance to examine the system's reliability. Through the examination, the research question 3.1 (what are the types and sources of information imperfections) and research question 3.2 (what are the impacts of data imperfections on safety monitoring) are answered.

5.1 INTRODUCTION

Emerging sensing technologies offer a solution to improve jobsite safety performance by providing location information to determine workers' safety situation regarding proximity to dangers. However, due to imperfections inherent in real world sensor data, the collected location data might be imperfect (missing, uncertain, imprecise and inconsistent). In many cases, jobsite safety monitoring applications are built on the assumption that the collected location data represents the exact situations which might not be true due to data imperfections. However, data imperfections and their potential impacts on the decisions in autonomous jobsite safety monitoring systems have not been substantially studied. This chapter describes an autonomous jobsite safety monitoring

testbed developed to collect data from location-aware sensors. By comparing the collected location data with the exact ground truth location data, I categorize the types of imperfect data from location-aware sensors. Then, I developed eight jobsite safety monitoring test cases to replicate construction activities on a full scale jobsite and used the collected data, as well as simulated imperfect data at various imperfection levels, to quantify the impacts on decision making performance in terms of precision and recall of workers' dangerous situations. The results indicated that the worst system's performance appears near the transition area of different risk levels (red and yellow, yellow and green) and the performance degrades significantly after the standard deviation of the localization errors reaches 2 cm in the testbed, corresponding to 2 meters in the jobsite. The study provides other researchers with an understanding of how much data imperfections would impact a safety monitoring system's performance and points out future research directions.

My research envisions an autonomous jobsite safety monitoring system, which utilizes distributed data and information collected from various sources (radio frequency identification, localization sensors, accelerometers, load cell sensors and building information models). In chapter 2 and 3, I extracted the safety knowledge and information requirements to serve as the foundation for the autonomous safety monitoring system development in chapter 4. Some experts have doubts about the effectiveness of the system's performance, so they hesitate to adopt such systems until the system's reliability has been proved. Using the autonomous safety monitoring system developed in chapter 4, I evaluated the system's performance in a scaled physical testbed

to present what the expected performance of the system with imperfect data is. This chapter reports the results of evaluating the impacts of data imperfections on autonomous safety monitoring using data from location-aware sensors, which provide the most important information for the autonomous jobsite safety monitoring system.

The remainder of this chapter is organized as follows. In the section 5.2, I provide an overview of the related research by reviewing the studies on safety management based on location data and studies on data imperfections in safety monitoring applications. Next in section 5.3, I describe the detailed research approach for exploring data imperfections in autonomous safety monitoring. Following the proposed research approach, the data is collected and analyzed to provide the results shown in the section 5.4. A further discussion is provided right after the results presentation in section 5.5. The end of this chapter (section 5.6) summarizes the research findings, contributions as well as the limitations of this work.

5.2 BACKGROUND RESEARCH

There have been several localization technologies proposed for collecting location information for construction safety management. From a perspective of cost, accuracy, scalability and reliability perspectives, the most promising technologies for jobsite applications include: Radio Frequency Identification (RFID) which includes Radio Signal Strength Index (RSSI) based algorithms, Ultra Wideband (UWB), Global Positioning System (GPS) and indoor GPS. The provided location information has been used to monitor a target's relative position to dangerous areas. UWB tracking was used for proactive safety management against potential overhead hazards (Carbonari et al., 2011,

Cheng and Teizer) and crane collisions (Hwang, 2012). However, the accurate performance of tens of centimeters provided by UWB requires a direct path between deployed sensors, and the technology has a much higher deployment cost than RSSI and other localization techniques (Khoury and Kamat, 2009, Liu et al., 2007). As such, UWB is found to not be practical for widespread deployment on jobsites. Ultrasonic and Infrared sensors were used in a mobile safety management system to detect when workers are approaching to the fall accident-prone locations to reduce fall-relevant accidents (Lee et al., 2009b), proximity control using RFID has been proposed to prevent falling from height and collision accidents (Chae and Yoshida, 2010, Schneider, 2003). GPS was used for equipment collision detections (Oloufa et al., 2003, Vega, 2001). The performance evaluations (Khoury and Kamat, 2009, Luo et al., 2011c, Maalek and Sadeghpour, 2013) of these sensing technologies have indicated that errors exist in the collected location data. Although the errors can be reduced by as much as 7 centimeters through filtering (Cheng et al., 2011), it is unlikely to eliminate errors completely.

Errors in location sensor data result in imperfect detections on safety situations causing false alarms (Carbonari et al., 2011). Chi and Caldas (Chi and Caldas, 2012) developed a testbed to model several earthmoving operations to evaluate the impact of location tracking errors on safety analyses. Although several studies (Chi and Caldas, 2012, Luo et al., 2011c, Razavi and Haas, 2010, Razavi and Haas, 2011) have addressed the existing data imperfections they still remain in an initial phase with respect to quantifying the impacts of those location data imperfections on safety proximity monitoring decision making.

5.3 RESEARCH APPROACH

To explore data imperfections and their impacts on autonomous safety monitoring applications using location-aware sensors, I built a small-scale testbed instead of conducting a full scale test for autonomous jobsite safety monitoring due to safety issues and difficulties to access to tower cranes. Using the developed testbed, I collected data from sensors, to further explore the categorizations of data imperfections, and study their impacts in a safety monitoring context. After studying the impacts of the collected location data imperfections on the performance of the system I generated the simulated location data to further study the imperfections' impact on the performance of the system at different imperfection levels.

The research process is described in Figure 42. First, I went to an office building construction project with two connected six-floor buildings of 140, 000 square feet to observe the crane operations onsite. Based on my observation, eight representative activities of the tower crane swinging a load were selected to develop the test cases. In the next step, the critical elements on the jobsite involved in the autonomous safety monitoring system were represented in a scaled test bed in a controlled lab environment. The testbed is built using LEGO bricks and mounted with a Cricket indoor localization system, which uses ultrasonic and radio frequency technologies to track the target's location for users. Based on the eight test cases, the discrete test points in each test case were set out in the testbed. Next, the developed crane safety monitoring system was used to collect the crane load's and the worker's localization data at the set out test points. The collected location data was stored in text files for the data processing use. These data was

then fed into the developed crane safety monitoring system as stream data to get the safety situations based the collected data. The coordinates of the set out test points are the actual location where the crane load and the worker are at. Therefore, these coordinates are considered as the ground true location. Feeding the ground true location data into the safety monitoring reasoning mechanism, the safety situations with the ground true locations can be calculated and thus considered as ground truth safety situations. Next, the calculated safety situations were used to compare with the ground truth safety situations to evaluate the system's performance. After that, I generated some sets of location data at all the test points using Microsoft Excel. First, errors are simulated using the random generator function using normal distribution with different standard deviations. Second, the errors were added onto the ground truth location data to get the simulated location data set. I pushed the simulated data set into the safety monitoring reasoning mechanisms, to calculate the safety situations based on the simulated data. Next, these calculated safety situations were used to compare with the ground truth safety situations to evaluate the system's performance at a different imperfection level. Details on the research process are described in the following sub sections.

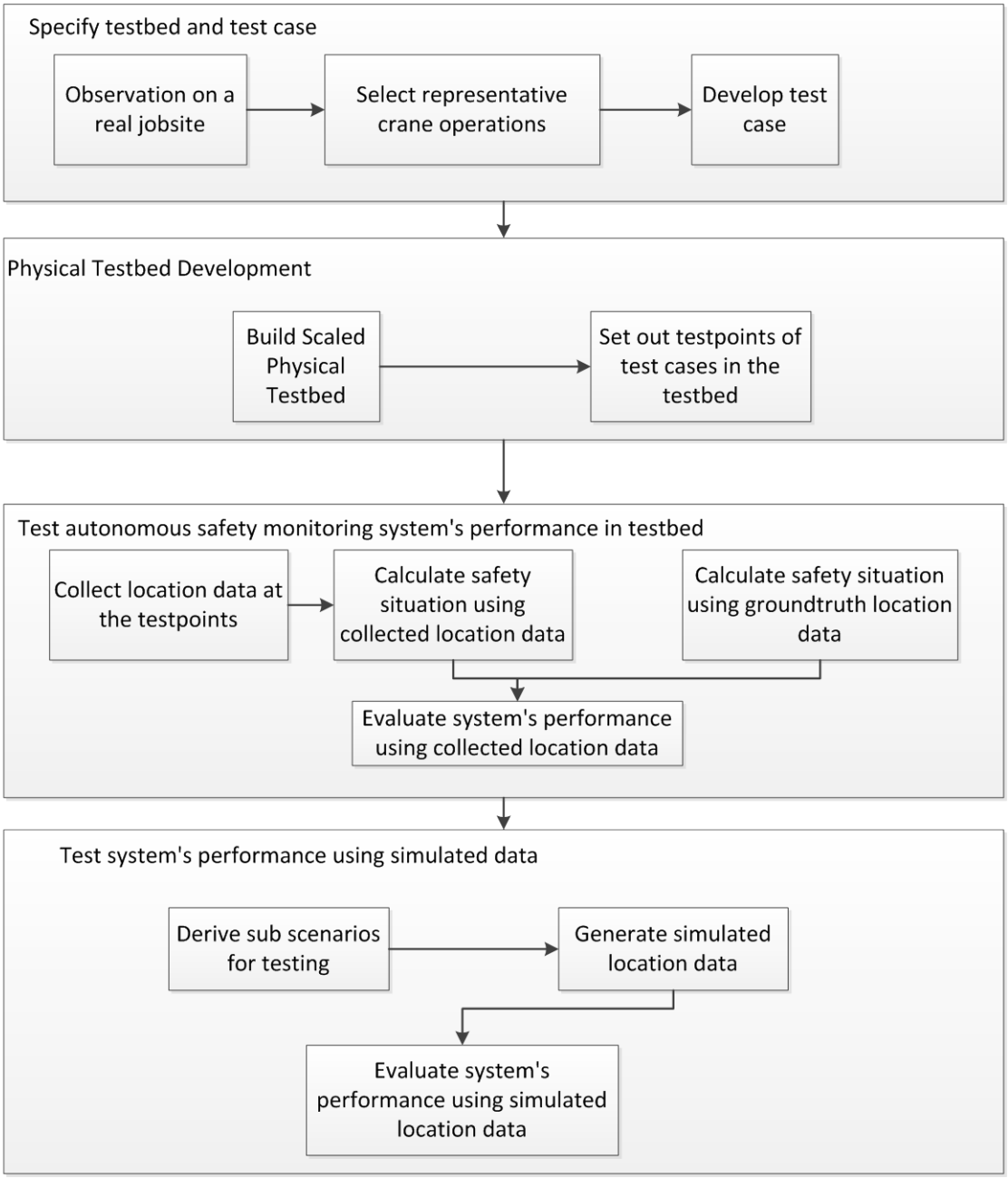


Figure 42 Research Process for the Research

5.3.1 Physical Testbed Development

For a full scale crane safety monitoring system, global positioning system (GPS) is a feasible and mature technology to provide location information for safety monitoring. Previous studies (Weih et al., 2009) indicated that the localization error of GPS is usually in the range of 1 to 13 meters. This range guides the choice of a cricket system for use in the scaled testbed to provide location information. Other Studies (Luo et al., 2011c, Priyantha et al., 2000, Zhou et al., 2009) indicated that the localization error of the cricket system ranges from 1 to 10 centimeters. To better evaluate the location-aware sensor data imperfections on autonomous safety monitoring, the testbed is built using the scale (100:1) between GPS's error and cricket system's error. As shown in Figure 43, the construction project includes two buildings with similar sizes. Two tower cranes are erected on the jobsite (one next to each building under construction) for material transportation and elevation. The jobsite has limited working space and there are three occupied office buildings in close proximity to the jobsite. In addition, a power plant is near the jobsite and a power line runs through the construction jobsite. A road with heavy traffic during peak hours runs to the west side of the jobsite. The limited available spaces on the jobsite and the complex setting surrounding the jobsite have posed challenges for safety operation of tower cranes.

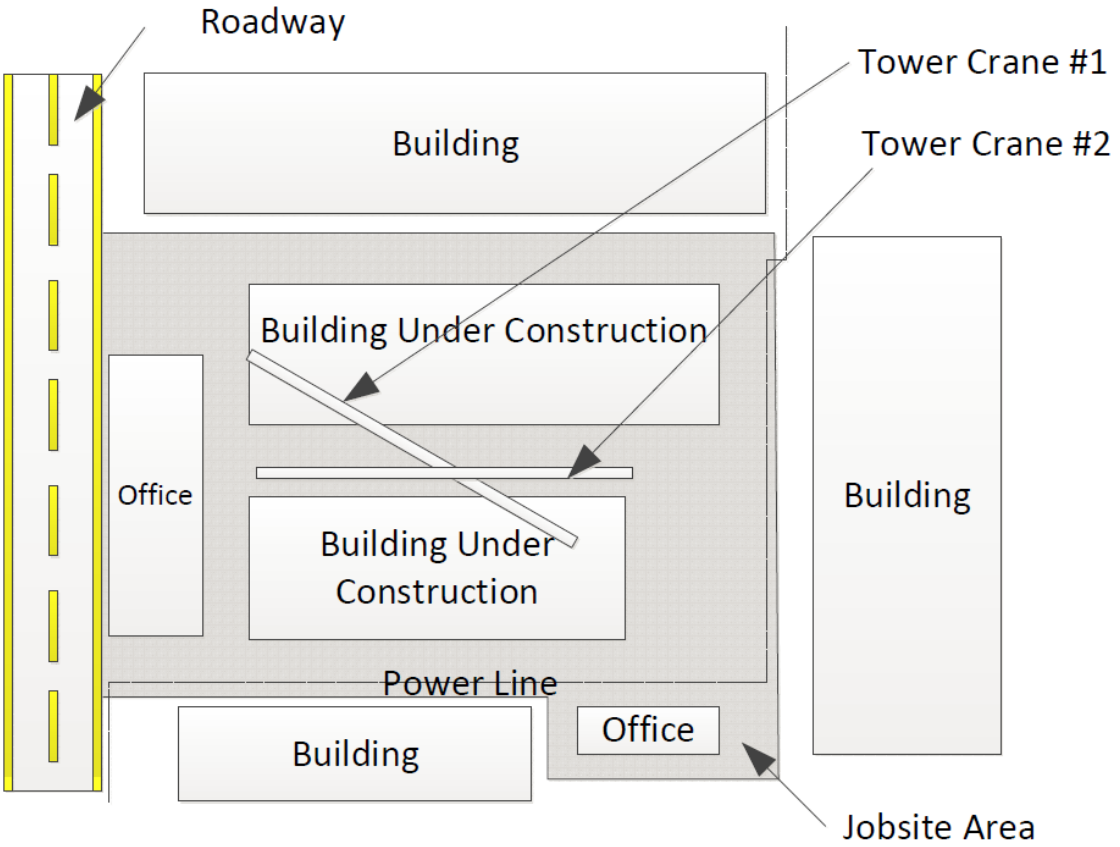


Figure 43 Testbed Layout with Major Construction Components

The small scale testbed (Figure 44) was built based on the aforementioned jobsite using LEGO bricks in a laboratory environment. LEGO blocks and wires were used to represent buildings and power lines on the construction jobsite. Cricket (Priyantha et al., 2000) development kit, a localization system, was deployed on the floor and the ceiling to track the locations of the crane loads and workers. Data collected from the cricket motes was used to explore the data imperfections for autonomous crane safety monitoring. Three cricket mote beacons were mounted on the ceiling, and four beacons were mounted on the ground. The beacons were Crossbow MSC410CA MICA2-based motes with an

ultrasonic transmitter and receiver. The beacons broadcast RF signals and ultrasonic pulses across the testbed. Once the listener, which is attached to a crane component or a laborer, receives an RF signal, it listens to the corresponding ultrasonic pulse to calculate the listener's location. The cricket motes localization system is manufactured by Crossbow Inc. It provides fine-grained location information to applications running on mobile computing devices and sensor nodes. The mote in the system is MSC410CA, using a combination of radio frequency and ultrasonic technologies. The MSC410CA motes in the system can be programmed as beacons with fixed listeners. Beacons with known location information publish information through an RF channel and transmit concurrent ultrasonic pulses. The listener attached to a device listens to RF signals. Once the listener receives the first few fields of an RF message, it listens to the corresponding ultrasonic pulse. When the listener receives the ultrasonic pulse, it estimates the distance for the corresponding beacons using the difference in propagation speed of RF (2.99×10^8 m/s) and ultrasonic (343.2 m/s in dry air at 20°C). The listener computes its position through trilateration (Priyantha et al., 2000) using the distances from multiple beacons and known beacon coordinates.

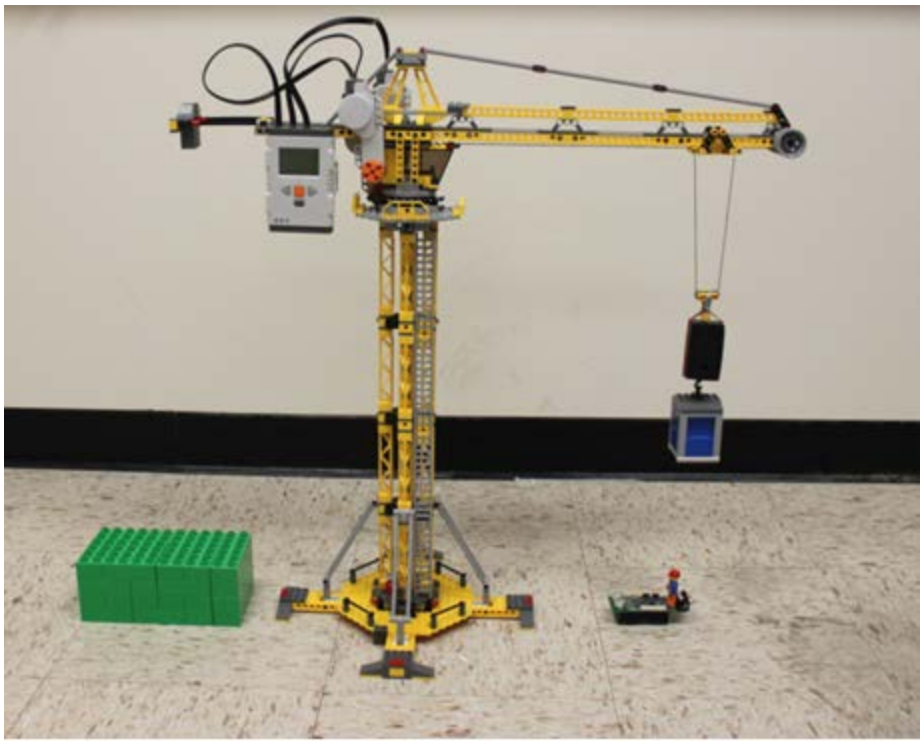


Figure 44 Physical Testbed for Autonomous Tower Crane Proximity Safety Monitoring

5.3.2 Scenarios Used as Test Cases and Data Collection

In this chapter, I used two scenarios (detailed description and results on all the eight test cases can be found in appendix D) of dangerous areas under crane loads as the test cases to explore the data imperfections and their impacts on safety monitoring applications. The fall zone is the control area under a crane load. It is defined as "the area (including but not limited to the area directly beneath the load) in which it is reasonably foreseeable that partially or completely suspended materials could fall in the event of an accident" (OSHA 1926.1401). With the definition of fall zone, the ground area near a crane can be divided into three zones (Figure 45) according to the risk level (Luo et al., 2011a): 1) the red zone is the direct area under a crane load, defined as a circle centered

at the hook's location with a radius of the farthest horizontal distance between any point of the suspended load and the hook's location. No worker should stand under this area. If any worker gets into this area, an alert should be sent to her; 2) the yellow zone, which is a possible fall zone under a crane load. It is the annular region between the red zone and the concentric circle with a radius of a value of the red zone's radius plus a clearance distance. Usually, 1.52 to 3.05 meters is used as the clearance (Luo et al., 2011a), and the experts on each jobsite can determine the clearance distance based on jobsite environments, their risk tolerance and a crane load's characteristics. Only authorized workers can access this area. If any unauthorized worker gets into this area, an alarm should be sent to her; 3) the green zone: other areas where workers are unlikely to be exposed to falling load hazards.

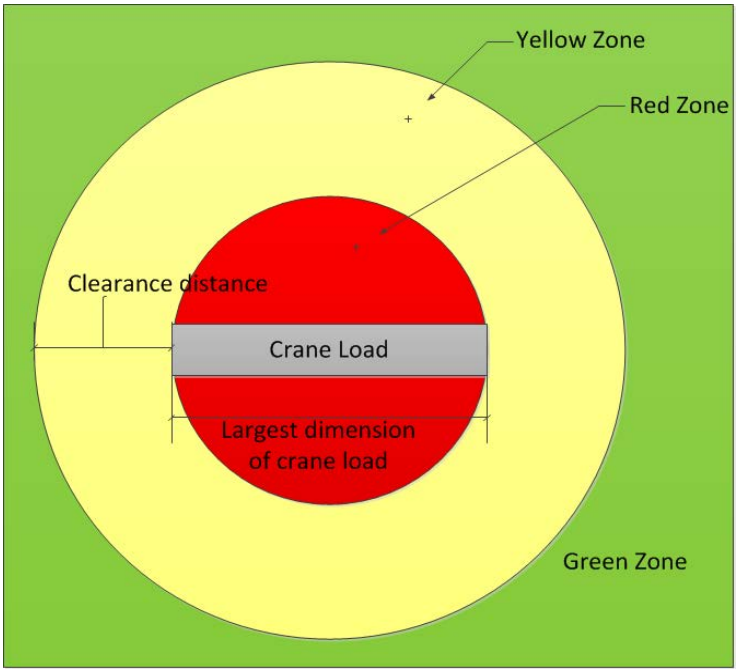


Figure 45 Dangerous Areas Under a Crane Load

Two scenarios were developed based on the dangerous area specifications and decision flowcharts. To simplify the representation, I removed other elements on the jobsite in the figure and only show the tower crane(s) in the representation figures (Figure 46 and Figure 47). Scenario #1 shows a tower crane swinging a load over a worker while the worker is standing still. Scenario #2 shows two tower cranes swinging loads while a worker is changing its location. Scenario #1 is the basic scenario of dangerous area control under the crane load; scenario #2 is a more common case on construction jobsites. In scenario #2, the two dangerous areas are dynamic and might have overlaps.

I selected sixteen discrete points (eight along a worker's moving path and eight along the crane load's moving path) evenly along the paths of the worker and the crane load in scenario #1 and eighteen discrete points (six along crane #1's load's moving path, six along crane #2's load's moving path and six along worker's moving path). For each point in the testbed, I used the cricket motes to retrieve 20 location readings. The ground truth locations of these points were obtained from the testbed coordinate system. By comparing the location readings collected at the same test point, I can find whether the sensor data was consistent. The data missing rate can be calculated through dividing the counts of events with no location reading to the total counts of requests for location data sent to the cricket motes. The errors in location readings are measured by the distance from the sensed locations to the ground truth locations.

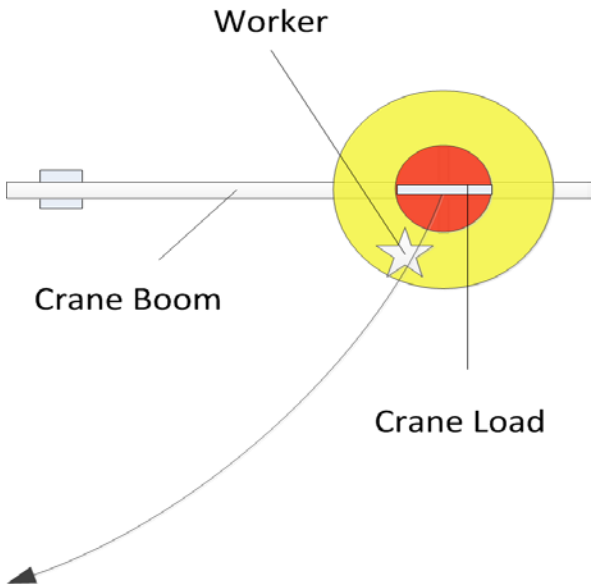


Figure 46 Crane Moving While the Worker is at a Fixed Point

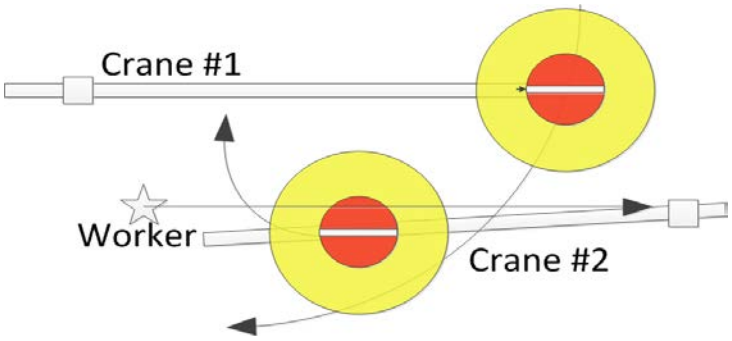


Figure 47 Two Tower Cranes Moving Loads Simultaneously While a Worker is Walking Between Them

5.3.3 Simulation process

To further study the impacts of data imperfections (especially in inaccuracy) on the safety monitoring system, I used simulation to generate the imperfect location data and explore the impacts of data imperfections on the decisions made by the system in a

controlled environment. Figure 48 shows the process that I used to analyze the impact using simulation data. At each test position in a given scenario, I can change the location data's imperfection conditions (standard deviation of error) of a worker and a crane load. If the location data was assumed to be perfect, the simulated location data would be the same as the ground truth location data; if the location data was assumed to be imperfect, a random number was generated following a normal distribution with a given standard deviation. Next, the simulated location data of both the worker and the crane load was passed to the safety monitoring reasoning mechanism (Luo et al., 2011a) in a given test scenario setting to calculate the worker's safety situations. At each test position, 20 location data were generated using the random number generator and 20 safety situations were calculated in correspondence to these simulated location data. By comparing these 20 calculated safety situations to the ground truth safety situations, the precision and recall rates can be calculated at each test position. By changing the standard deviation of errors from 0.5 cm to 5 cm (corresponding to 0.5 meter to 5 meters in a full size test bed), the detailed performance of the autonomous safety monitoring system under different data imperfection levels can be calculated. In the simulation process, I assumed that the errors in location data follow a normal distribution. In the previous two described scenarios, both worker and crane loads provide location information to the autonomous safety monitoring system to support safety decision making. Therefore, there are two combinations of errors in each scenario: 1) either one has error (in this chapter, I assume that only the crane has errors in location information without the loss of generality); or 2)

both have errors. In this way, there are two derivatives (sub scenarios) under each scenario as described below:

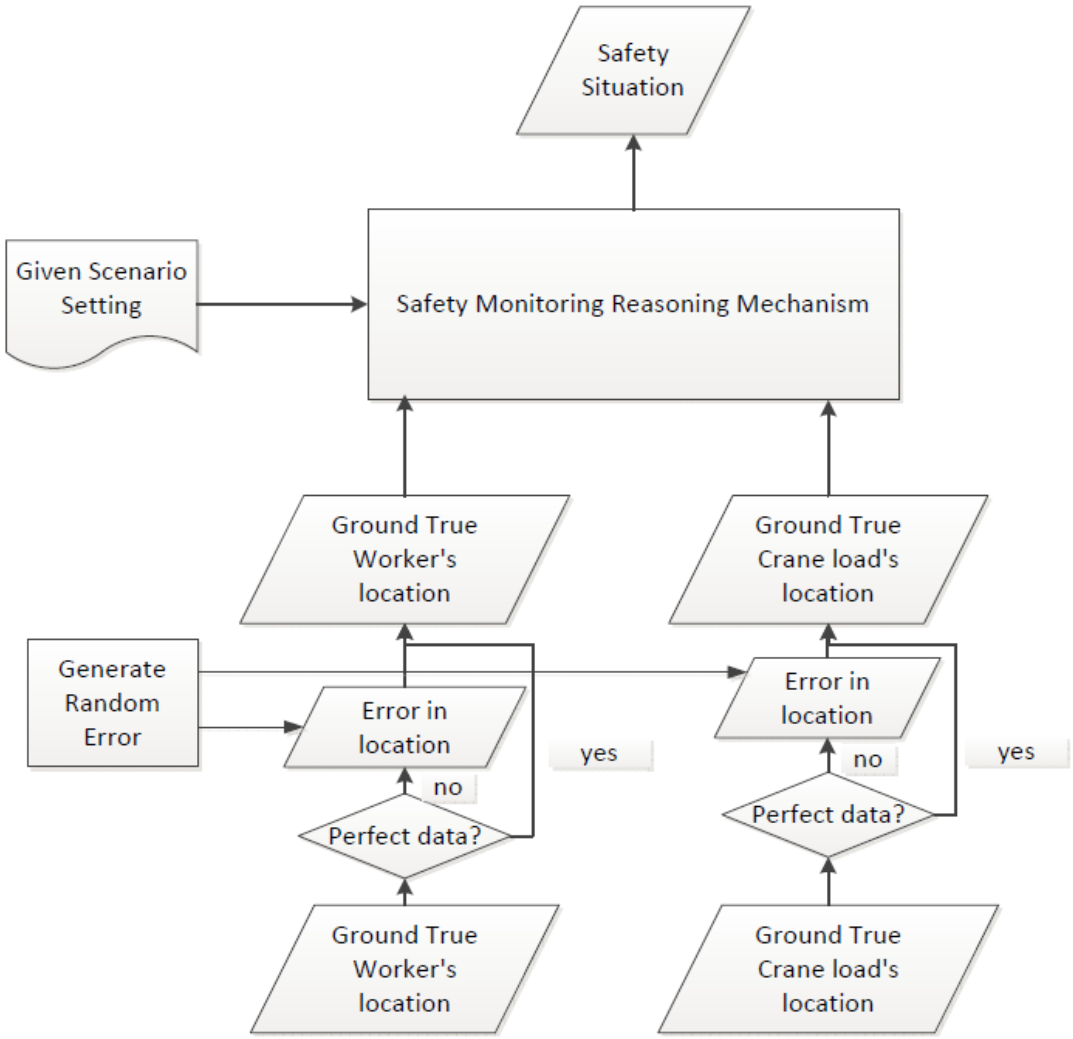


Figure 48 Process for Analyzing Impact with Simulation Data

Sub Scenario 1.1. This case used simulated location data as the input for scenario #1. In this test case, I assumed that the location information of a worker was perfect, and

the errors of location information of a crane load are imperfect. The aforementioned simulation process was used in this test case.

Sub Scenario 1.2. This case used simulated data as the input for scenario #1. I assumed that the localization devices mounted on a crane load and a worker are the same. The errors of location information of both a crane load and a worker had the same level of data imperfections. The simulation process is the same as in case #1.

Sub Scenario 2.1. It used simulated data as the input for scenario #2. I assumed that the location information of a worker is perfect, and the location information of a crane load #2 is imperfect. The simulation process is the same as in case #1.

Sub Scenario 2.2. It used simulated data as the input for scenario #2. I assumed that the localization devices mounted on a crane load and a worker are the same and the errors of location information had the same level of data imperfections. The simulation process is the same as in case #1.

5.4 IMPACTS ON CRANE SAFETY MONITORING

For each scenario in the testbed, there were ground truth safety situations of workers based on her location information. According to this location information, any safety situation judged by the system can be calculated. The three risk level crane safety monitoring system (Red-Yellow-Green) contains three levels of risks, and gives warnings to the worker when she is in the yellow zone and alerts to the worker when she is in the red zone. Ideally, we do not want the worker to be in the red zone, so the transition area between the red zone and the green zone is important. If the worker can be given an alert when entering the transition area (the yellow zone), the worker can have enough time to

respond to alert and the worker be prevented from entering the red zone. Therefore, the red and yellow zones can be combined for analysis, so the workers would get the first alert at the green to yellow boundary. This way, the system is extended into two derivatives: 1) System I (Yellow-Green): crane safety monitoring system with warnings only; and 2) System II (Red-Yellow-Green): crane safety monitoring with both warnings and alerts. In system I, a warning is triggered if the target is in the yellow zone or the red zone. In system II, an alert is triggered if the target is in the red zone and a warning is triggered if the target is in the yellow zone.

For each test point along the crane load's/worker's moving path in each test case, I had the sensed data and the ground truth data. Therefore, the collected location data was used to calculate the imperfectly sensed data situations based on the safety monitoring knowledge and the reasoning mechanism described in chapter 2. At each test point, the ground truth location data is fed into the safety monitoring decision making mechanism to determine the worker's/crane's safety situations (ground truth safety situation), while each sensed data reading was fed into the safety monitoring decision making mechanism to determine the safety situations (measured safety situation based on sensor data) based on sensor data. At a test point at a specific timestamp, if the measured safety situation based on sensor data is not the same as the ground truth safety situations, an error is detected. There are two types of errors: false positive and false negative. In a false positive error, the worker/crane is incorrectly identified to be in a more dangerous situation; in contrast with a false negative error, the worker/crane is incorrectly identified to be in a safer situation. If the measured safety situations based on sensor data is not the

same as the ground truth safety situations, which means the worker/crane is correctly identified in a safe/unsafe situation, it is true positive. The types of error are shown in Table 7.

Table 7 Category of Error in Safety Monitoring System

System	Measured situation by the system / Ground Truth Safety Situation	Green	Yellow	Red
Yellow -Green	Green	True Positive	False Positive	False Positive
	Yellow	False Negative	True Positive	True Positive
	Red	False Negative	True Positive	True Positive
Red-Yellow -Green	Green	True Positive	False Positive	False Positive
	Yellow	False Negative	True Positive	False Positive
	Red	False Negative	False Negative	True Positive

To evaluate the performance of the safety monitoring system, two metrics were used: precision and recall.

Precision is the ratio of True Positive to the sum of True Positive and False Positive. It measures the percentage of actual alerts and warnings that are triggered by the system.

$$Precision = \frac{True\ Positive}{True\ Positive + False\ Positive} \quad (5.1)$$

Recall is the ratio of True Positive to the sum of True positive and False Negative. It measures the percentage of actual dangerous situations that are reported (when an alert or alarm is triggered by the system).

$$Recall = \frac{True\ Positive}{True\ Positive + False\ Negative} \quad (5.2)$$

5.4.1 Results with Data Collected from the Testbed

With the location data collected at the thirty-four points in scenarios #1 and #2, the impacts of data imperfections on the systems' performance in terms of precision and recall can be evaluated. Figure 49 and Figure 50 show precision and recall rates along the worker's movement path in scenario #1 for both systems (using the crane load #1's position as the origin). In the figures, the radius of the red zone is 3 cm and the radius of the yellow zone is 7.5 cm. The average localization error of the crane load is 6.26 cm with a standard deviation of 1.67 cm, and the average localization error of the worker is 2.14 cm with a standard deviation of 0.94 cm. Figure 49 indicates that in the yellow-green system, the inaccurate location only affects the decisions in proximity to the connecting areas between the yellow zone and the green zone (P6 falls into this area). At point P6, the missing data of the crane load's location was observed 6 times. Hence, the system could not provide any judgment on the worker's safety situations. For the remaining 14 readings at point P6, the system concluded that the worker was in the green zone based on the collected location data while the worker was actually in the yellow zone. For points in yellow zone, performance improvement was not observed at points which were at the edge of the yellow zone; while at other points, performance improvement was observed when switching from the red-yellow-green system to the

yellow-green one. For both systems, performance degrades at the transition areas of two safety status (e.g., red to yellow and yellow to green).

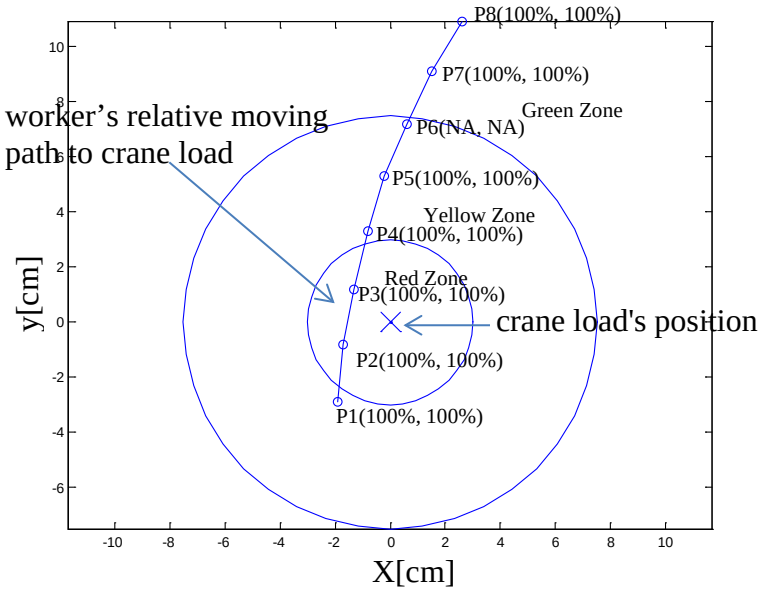


Figure 49 Precision and Recall Rates of Yellow-Green System Along the Worker's Movement Path (Single Tower Crane Involved)

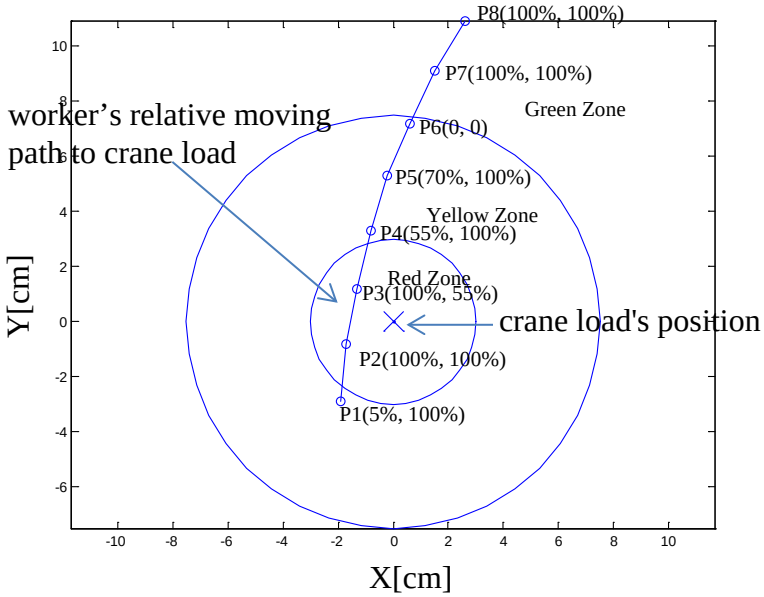


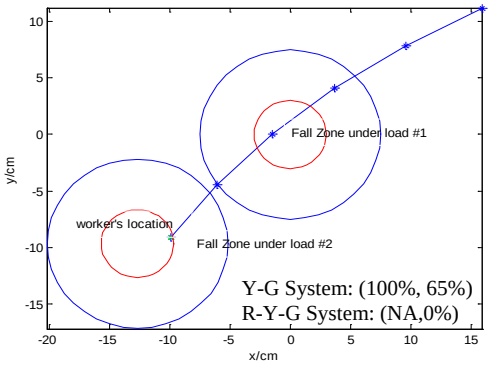
Figure 50 Precision and Recall Rates of Red-Yellow-Green System Along the Worker's Movement Path (Single Tower Crane Involved)

Table 8 shows precision and recall rates for scenario #2, while Figure 51 (using crane #2's load's position as the origin) shows the changes of dangerous area caused by tower crane #1 and tower crane #2. Scenario #2 is a more complex system involving multiple dynamic dangerous area controls and the target is also moving. The results in Table 8 are quite consistent with results of scenario #1:

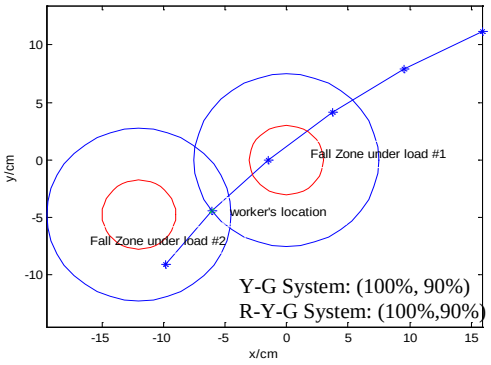
- Performance improves when switching from red-yellow-green system to yellow-green system for points in the red zone (Figure 51a).
- For points in the safe zone (Figure 51e and Figure 51f), there are no changes on precision or recall rates when switching from red-yellow-green system to yellow-green system. Both systems have 100% precision and recall rates.

Table 8 Precision-recall for Scenario #2

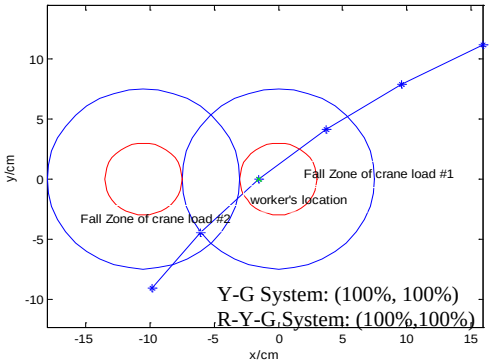
System	Performance	Point					
		P1	P2	P3	P4	P5	P6
Yellow-Green	Precision	100%	100%	100%	100%	100%	100%
	Recall	65%	90%	100%	100%	100%	100%
Red-Yellow-Green	Precision	NA	100%	100%	100%	100%	100%
	Recall	0%	90%	100%	100%	100%	100%



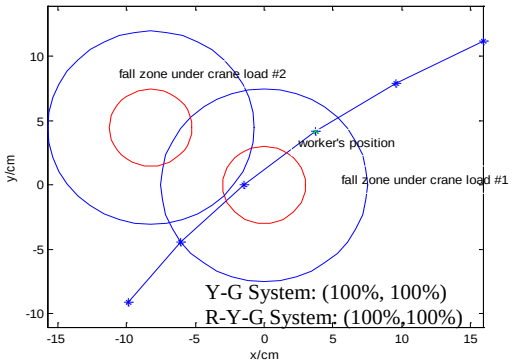
(a) at Point P1



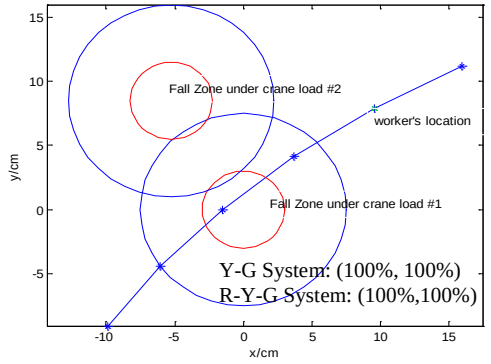
(b) at Point P2



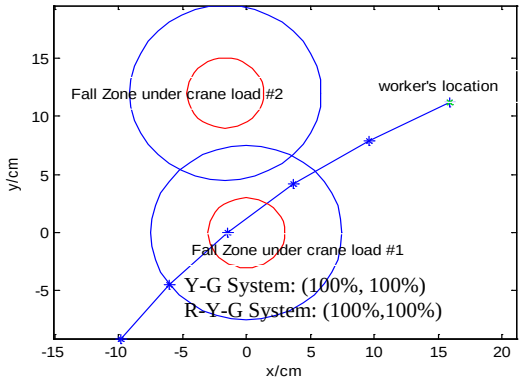
(c) at Point P3



(d) at Point P4



(e) at Point P5



(f) at Point P6

Figure 51 Dangerous Areas as Worker Moves Along the Path (Two Tower Cranes Involved)

5.4.2 Results with Simulation Data

The precision and recall rates for test sub scenario 1.1, 1.2, 2.1 and 2.2 (refers to section 5.3.3 for details) are summarized in tables. Table 9 and Table 10 show the result of test case #1 in the Red-Yellow-Green system and in the Yellow-Green system.

Table 9 Precision and Recall for Simulation Case #1 for Red-Yellow-Green System

Point # / STD/cm		Red-yellow-green system							
		P1	P2	P3	P4	P5	P6	P7	P8
0.5	Precision	95%	100%	100%	70%	85%	100%	100%	100%
	Recall	100%	95%	100%	100%	100%	55%	100%	100%
1	Precision	85%	100%	100%	85%	100%	100%	100%	100%
	Recall	100%	90%	80%	100%	95%	50%	100%	100%
1.5	Precision	70%	100%	100%	70%	100%	100%	100%	100%
	Recall	100%	80%	65%	100%	85%	50%	100%	100%
2	Precision	70%	100%	100%	59%	89%	100%	80%	95%
	Recall	100%	70%	50%	77%	89%	70%	100%	100%
2.5	Precision	94%	100%	100%	81%	80%	90%	70%	90%
	Recall	84%	55%	60%	76%	71%	47%	100%	100%
3	Precision	86%	100%	100%	85%	100%	100%	70%	95%
	Recall	67%	30%	25%	100%	60%	35%	100%	100%
3.5	Precision	86%	100%	100%	88%	80%	75%	80%	90%
	Recall	67%	20%	35%	78%	71%	33%	100%	100%
4	Precision	43%	100%	100%	100%	100%	77%	78%	75%
	Recall	50%	50%	15%	20%	70%	59%	100%	100%
4.5	Precision	88%	100%	100%	67%	85%	90%	47%	85%
	Recall	78%	48%	24%	36%	55%	45%	100%	100%
5	Precision	71%	100%	100%	77%	70%	78%	80%	95%
	Recall	63%	10%	30%	59%	41%	39%	100%	100%

Table 10 Precision and Recall for Simulation Case #1 for Yellow-Green System

Point # / STD/cm		Yellow-Green System							
		P1	P2	P3	P4	P5	P6	P7	P8
0.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	55%	100%	100%
1	Precision	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	95%	50%	100%	100%
1.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	85%	50%	100%	100%
2	Precision	100%	100%	100%	100%	100%	100%	80%	95%
	Recall	100%	100%	100%	85%	90%	70%	100%	100%
2.5	Precision	100%	100%	100%	100%	100%	100%	70%	90%
	Recall	85%	100%	100%	80%	75%	50%	100%	100%
3	Precision	100%	100%	100%	100%	100%	100%	70%	95%
	Recall	84%	95%	90%	100%	60%	35%	100%	100%
3.5	Precision	100%	100%	100%	100%	100%	100%	80%	90%
	Recall	70%	80%	95%	80%	75%	40%	100%	100%
4	Precision	100%	100%	100%	100%	100%	100%	75%	90%
	Recall	70%	75%	90%	70%	65%	45%	100%	100%
4.5	Precision	100%	100%	100%	100%	100%	100%	55%	90%
	Recall	80%	75%	80%	65%	55%	45%	100%	100%
5	Precision	100%	100%	100%	100%	100%	100%	80%	95%
	Recall	70%	60%	65%	65%	50%	45%	100%	100%

Figure 52 and Figure 53 show the average precision and recall rates of points in each area in the red-yellow-green system and the yellow-green system. The tables and the figures indicate that:

- For yellow-green system, the precision was always 100% at points in the yellow zone and the red zone, and recall always reached 100% at points in the green zone.
- For yellow-green system, the closer a point is to the transition area of the yellow zone and the green zone, the worse the performance is. More

specifically, if a target in the yellow zone moves towards the green zone, recall worsens (Figure 54); if a target in the green zone moves towards the yellow zone, precision worsens (Figure 55).

- If the standard deviation of localization error increases, the warning systems' performance (precision and recall) degrades (Figure 56). The system's recall rate remains above 90% when the standard deviation is less than 2.5 cm. In addition, the impact area (a collection of points which show decrease in warning systems' performance) of imperfect data increases. In other words, points in a larger area would lead to a decreased system performance.
- The precision rate increases by up to 10%, resulting in precision rates exceeding 90% by switching the system from the red-yellow-green system to the yellow-green system. Meanwhile, the recall rate also gets increased by up to 15%, resulting in most recall rates exceeding 70% (Figure 57).
- By merging the red area in the red-yellow-green system to the yellow area in the yellow-green system, the performance of the system at points in the yellow zone get improved in terms of precision.

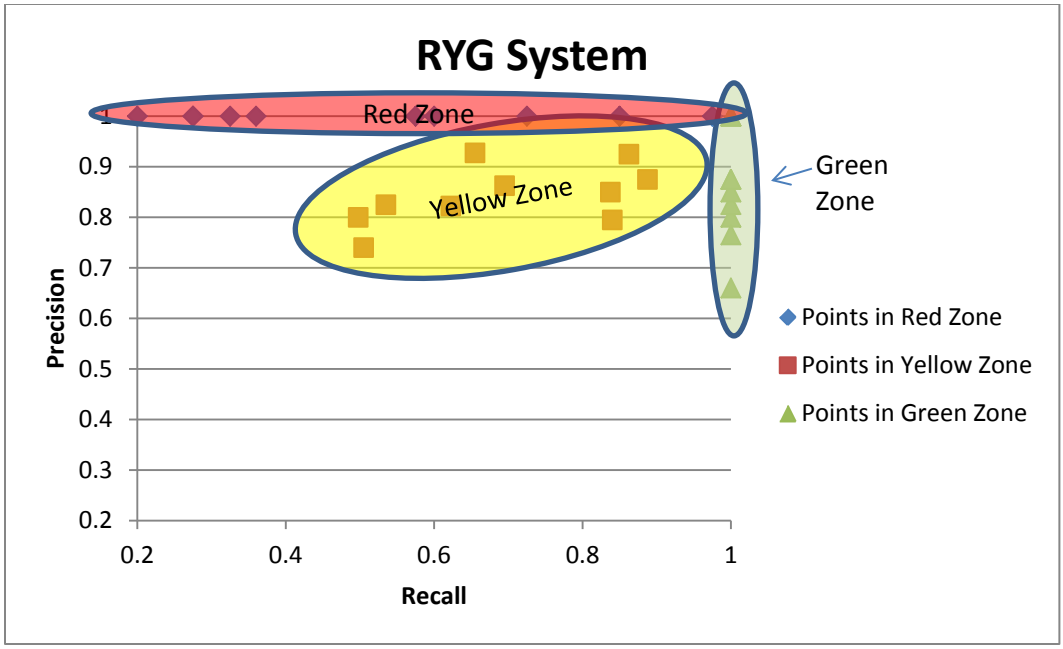


Figure 52 The Average Precision Recall Rates of Points in Each Area with Localization Errors at Different Levels in Red-Yellow-Green System

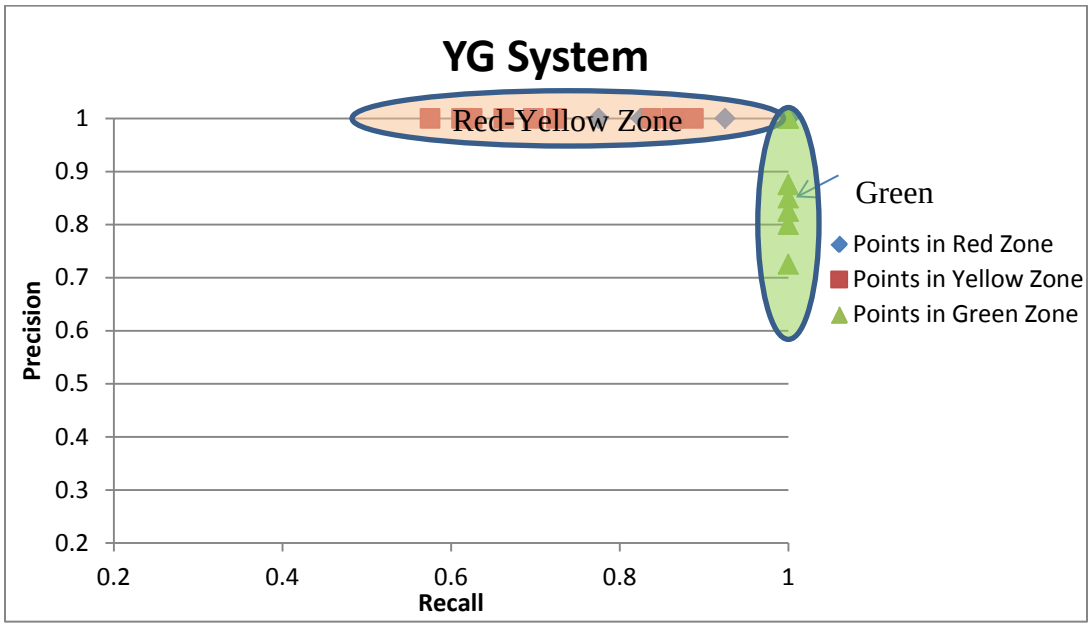


Figure 53 The Average Precision Recall Rates of Points in Each Area with Localization Errors at Different Levels in Yellow-Green System

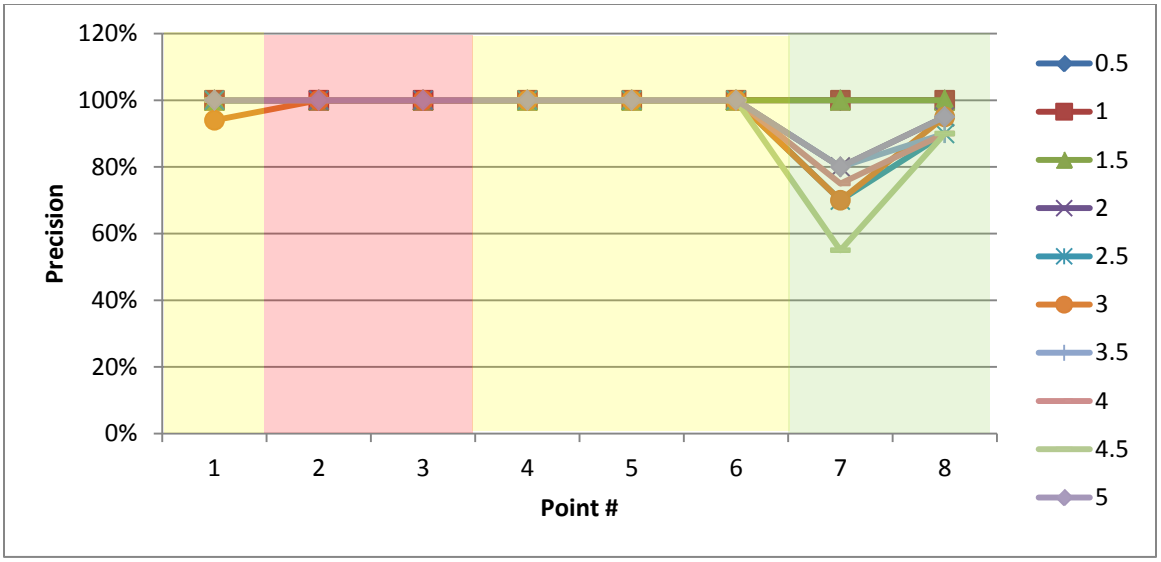


Figure 54 Precision for the Yellow-Green System

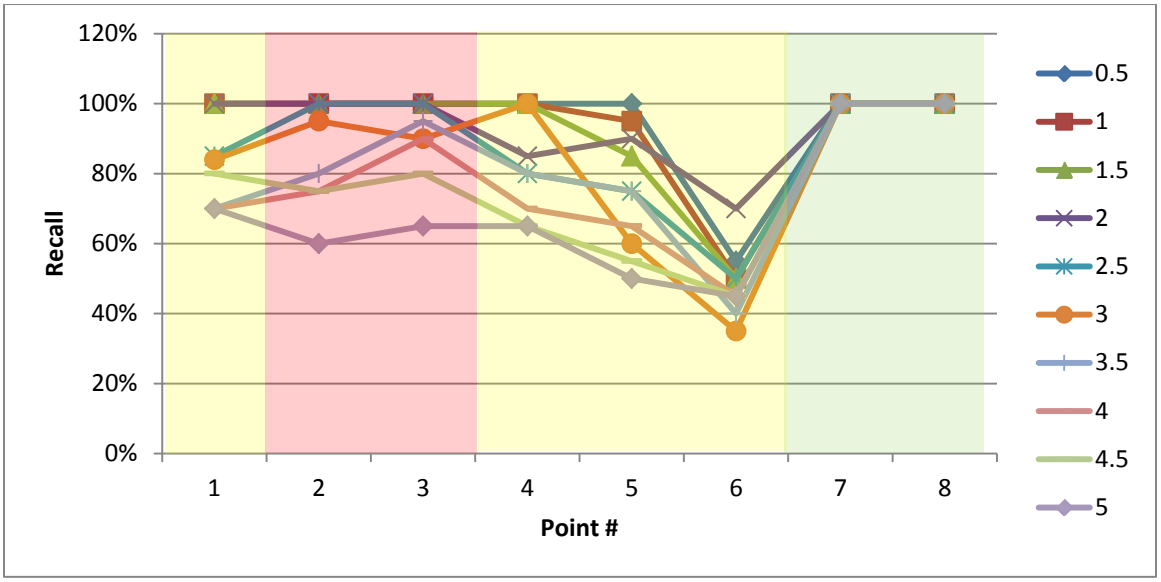


Figure 55 Recall for Yellow-Green System

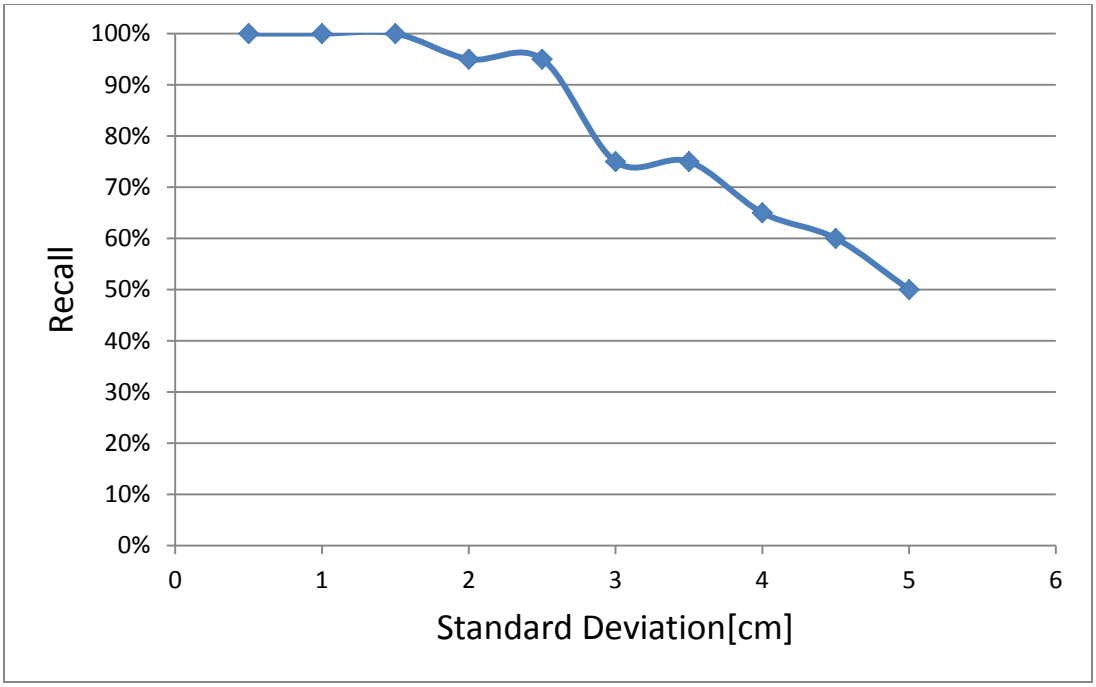


Figure 56 Recall Rates at Point P4 for Yellow-Green System with Various Standard Deviations

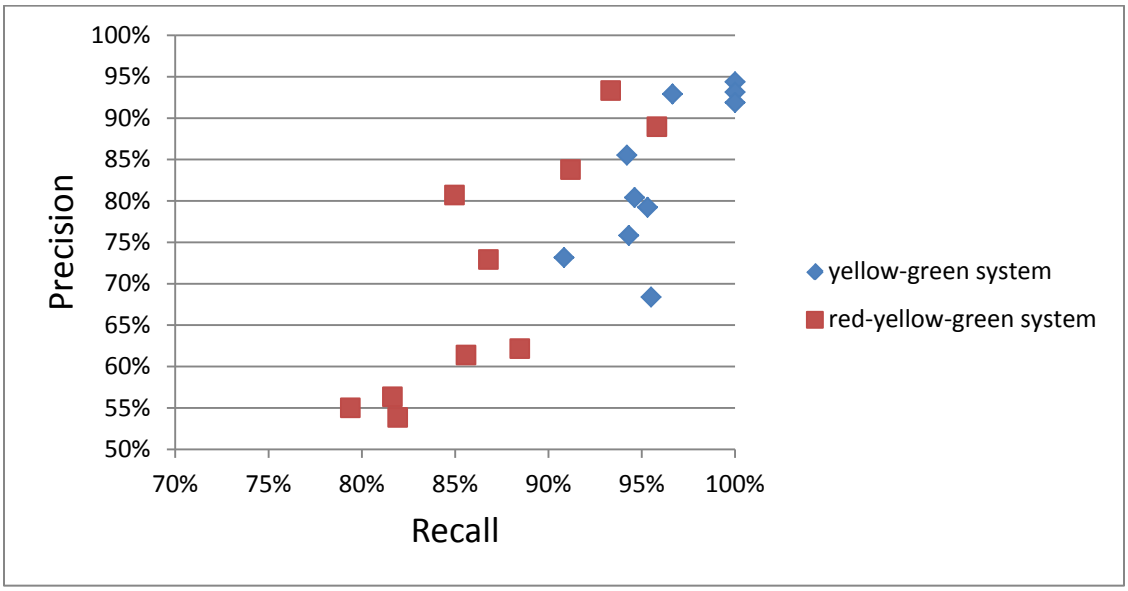


Figure 57 Average Precision and Recall Rates Over All the Eight Points for Sub Scenario 1.1

5.5 DISCUSSION

Results show that the system's performance is improved by merging the red zone into the yellow zone to form a yellow-green system. In the yellow-green system, the worker would receive a warning even if the worker has not entered the red zone yet. In this way, the system can capture actual dangerous situations and trigger alarms to the worker when applicable. Therefore, the system provides a more proactive protection to the worker in proximity of a crane load. In the safety warning system, I want to capture as many dangerous situations as possible and send alarms to the worker, although we do not want to trigger many false alarms. If we had to make a tradeoff between recall and precision, recall rate would be a more important than precision. To improve the system's recall rate, the localization accuracy should be improved for points in the red and yellow zones, while improving the localization accuracy for points in the green zone can improve the system's precision rate. In monitoring dangerous area under a crane load, the three zones are changing continuously; an absolute point can be in the yellow zone at this moment but in the green zone at the other moment. Therefore, there is no priority area whose localization accuracy should be improved first. In some other situations (e.g., monitoring dangerous area near power line and occupied buildings), the dangerous areas are fixed and those dangerous areas can be considered as priority areas to have their localization performance improved first.

This research has shown that in the yellow-green system, the performance worsens as a worker approaches the transition point between the yellow and green zones. Therefore, it would be useful if the location-aware sensors could provide more accurate

location information to achieve better system performance. There are two potential solutions to improve the system's performance: 1) when the worker gets close to the transition point between the yellow and green zones, we can increase the location sensor's sampling frequency to obtain location information closer to the ground truth ones; and 2) obtain data from various sources and fuse the data to obtain more accurate location information. In a scenario of monitoring the dangerous area near open edges, the dangerous area is fixed (unlike the dynamic dangerous area under the crane load). Therefore, if RSSI localization technologies are used, the beacon density can be increased near the transition area between the yellow and green zones to get more accurate location information to achieve a better performance.

In this research, the results indicate that the recall rate for the yellow-green system can be above 90% if the standard deviation of the localization error is less than 2.5 cm. By scaling the error using the scale of the testbed to a real jobsite, when choosing the localization sensors for the system's deployment on jobsite crane safety monitoring, the sensor candidates' localization error's standard deviation should be less than 2.5 meters. A similar simulation process can be conducted for other safety monitoring applications (e.g., monitoring dangerous area near open edges), to obtain the requirements on localization errors in order to get a certain recall rate. The localization accuracy is an important criteria for considering, when selecting the sensor hardware for the safety monitoring system.

5.6 CONCLUSIONS

Wireless sensor networks have been introduced and applied for automating the construction management processes and assisting in decision making for jobsite management. I collected localization data from an automated and intelligent jobsite testbed to help the construction automation research community understand the existence and impacts of data imperfections. This chapter contributes to the body of knowledge by increasing the awareness and knowledge of data imperfections' quantitative impacts on autonomous safety monitoring under an automated and intelligent jobsite by studying a crane safety monitoring system with both testbed data and simulated data. By providing how much the data imperfections may affect the autonomous safety monitoring system, the study can assist the autonomous safety monitoring system developers in selecting appropriate location-aware sensor hardware through estimating the system's performance using different hardware. Also, the study also provides a reference of the hardware requirements on localization errors for sensor manufacturers. Due to the unsatisfactory performance of autonomous safety monitoring with imperfect data collected from location-aware sensors, future research includes exploring potential techniques to deal with imperfect data to improve decision making in a realistic world.

Chapter 6 Minimizing the Impact of Data Imperfections in Autonomous Safety Monitoring: Approach Development and Evaluation

6.1 INTRODUCTION

Construction is a one of the largest industries in the United States. However, the industry is very labor intensive with a high incidence rate of fatalities and injuries. In 2005 (CPWR, 2005), 22% of the nation's work-related deaths is attributed to the construction industry. Researchers in this filed have investigated the causes of the poor construction safety performance on both technical and managerial aspects, such as human factors, attitudes towards safety, safety challenges in a dynamic working environment, safety culture and etc. Among these causes, human factors are the main cause of high accidents in the construction industry, such as human errors, lack of labors, high employee turnover and safety training (Besnard and Hollnagel, 2012, Howell et al., 2002). Although human factors can be managed through safety training and safety management, it is very hard to control all of the human factors that may cause fatalities and injuries in dynamic working environments. The traditional safety protection in the construction industry is very passive because it heavily relies on "human" but human error is inevitable. However, why can we not provide a more active safety protection for construction workers? The construction industry has lagged behind other industries in implementing advanced technologies, limiting its ability to explore innovative approaches to improve the construction safety performance. In particular, being able of autonomously monitor construction workers is more needed for the construction industry.

Since human errors cannot be avoided completely, developing autonomous safety monitoring systems is one of the most promising solutions for improving safety performance in construction.

Several technologies have been applied into the construction industry to achieve autonomous safety monitoring, such as sensing technologies, Ultra Wideband, Radio-Frequency Identification and computer vision based techniques. For example, video based systems (Lee et al. 2006; Shapira et al. 2008) combined with radio-frequency identification (RFID) and wireless communication technologies were developed to minimize the risk of blind lifting for crane operators. Yang (Yang et al., 2011) used image processing techniques on video streams from surveillance cameras to track if the crane enters predetermined blind lifting areas. Navon (Navon and Kolton, 2006) has attempted to autonomously monitor whether guardrail systems were appropriately installed at open edges for preventing fall hazards.

The applications demonstrated the promising benefits of introducing sensing technologies for autonomous safety monitoring; however, the applications were developed under the assumption that the information collected from sensors is perfect, which is not true due to the imperfect nature of sensing devices. Data collected from sensing devices usually lacks of accuracy, precision and robustness. In chapter 5, imperfect information in the autonomous safety monitoring system was studied and the results showed that imperfect information results in unsatisfactory system performance in terms of precision and recall. To improve the system's performance, certain approaches are required and needed to be explored. In this chapter, I conduct an initial exploration of

five approaches to deal with the imperfect data and evaluate their performance based on the data collected from five test cases for tower crane safety monitoring in the miniature testbed. Results on system's performance with those five approaches would be provided and compared with the performance without any imperfect data processing approach.

6.2 RESEARCH APPROACH

6.2.1 Test cases development and data collection

Five test cases were developed to explore various approaches to deal with imperfect data in the autonomous safety monitoring system. For example, there is a tower crane carrying a steel beam and a worker working/traveling in the close proximity of tower crane's work zone. Figure 58 shows the layout of the test case 1, in which the tower crane is lowering a steel beam down to the top floor of the building under construction. A worker is walking along the north side on the top floor of the building as shown in the figure. Based on the extracted safety knowledge described in chapter 2, the dangerous areas (the red zone and the yellow zone) can be determined and shown in Figure 58. The ground true situation is: the worker is in the green zone at point P1 and P6, the worker is in the yellow zone at point P2, P3, P4 and P5.

For each test case, the time interval between each point is 0.5 second and the system attempts to obtain twenty continuous readings at a sampling frequency of 200Hz. Since the sampling frequency of data at each point is small and the worker's/crane load's positions are considered to stay the same for the 20 readings. There are 38 test points in total for the 5 test cases. The collected data of location readings from sensors are stored

in the database as a data set for various evaluation approaches that are introduced in the next sub section.

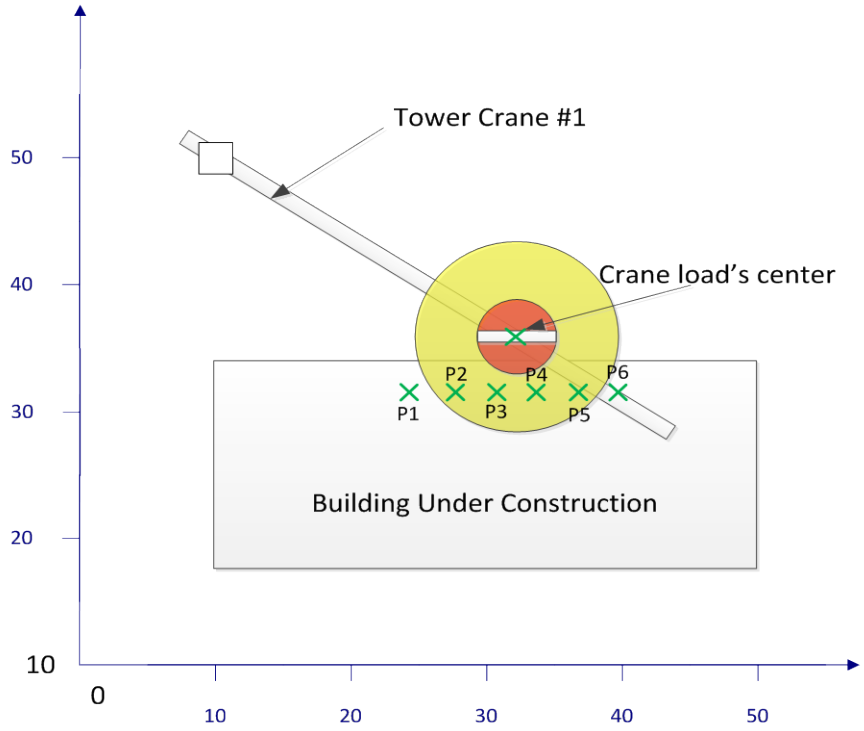


Figure 58 Test Case #1: Tower Crane Lowering the Crane Load While a Worker Passing the Dangerous Areas of the Crane Load

6.2.2 Location Prediction Models

Based on the location data collected from the testbed described in chapter 5, I discovered that the errors in location collected from sensors did not follow a specific patterns and were unpredictable. Therefore, it is difficult to correct the errors in the collected location data and provide more accurate location information to the autonomous safety monitoring system. The safety monitoring system on construction jobsites requires near real time output for workers because their safety situations change very rapidly. So

in this section, I chose location prediction models (Jeung et al., 2008) to provide the predicted location information based on the current and previous location information in a limited time window (to reduce the computing complexity and computation time). The first approach uses the raw data as location data for safety situation calculation; the 2nd approach only uses multiple collected location information at the current position to calculate an average value as to average the localization errors; the 3rd approach use a simple distance vector based on the location data at the previous and current positions to predict the location at the next position; the 4th approach only uses the previous location, the velocity and acceleration at the previous position to predict the current location. These four approaches only use a very limited data at one or two positions hence can provide the predicted location in near real time. The 5th approach uses the average location data at a position as location input for the safety monitoring system. Instead of directly pushing the location data into the safety reasoning mechanism, prior knowledge at previous positions in a limited time window is integrated into safety situation calculation.

6.2.2.1 Raw Data without Data Processing

The worker's position at time T_n in each test case, based on the kth sample/reading is $\overrightarrow{P_{w,T_n,k^{th}}}$;

The crane load's position at time T_n in each test case, based on the kth sample/reading is $\overrightarrow{P_{l,T_n,k^{th}}}$;

Therefore, the distance between the crane load and the worker $D_{T_n,k^{th}}$ at T_n in each test case can be calculated as:

$$D_{T_n,k^{th}} = \begin{cases} \text{null (if either } \overrightarrow{P_{w,T_n,k^{th}}} \text{ or } \overrightarrow{P_{l,T_n,k^{th}}} \text{ is null)} \\ \left|\overrightarrow{P_{w,T_n,k^{th}}} - \overrightarrow{P_{l,T_n,k^{th}}}\right| \text{ (if neither } \overrightarrow{P_{w,T_n,k^{th}}} \text{ nor } \overrightarrow{P_{l,T_n,k^{th}}} \text{ is null)} \end{cases} \quad (6.1)$$

Using the calculated distance between the crane load and the worker at time T_n in each test case, based on the kth sample/reading, the worker's safety situation can be determined as:

$$\text{Safety}(T_n, k^{th}) = f(D_{T_n,k^{th}}) \quad (6.2)$$

6.2.2.2 Simple Averaging

The worker's average position at time T_n in each test case, using the first k samples/readings is

$$\overrightarrow{\widetilde{P_{w,T_n,k}}} = \sum_{j=1}^{k} \vec{P}_{w,T_n} / k \quad (6.3)$$

The crane load's average position at time T_n in each test case, using the first k samples/readings is

$$\overrightarrow{\widetilde{P_{l,T_n,k}}} = \sum_{j=1}^{k} \vec{P}_{l,T_n} / k \quad (6.4)$$

Based on the average position using k samples, the distance between the crane load and the worker at T_n in each test case can be calculated as

$$D_{aver,T_n,k} = \left|\overrightarrow{\widetilde{P_{w,T_n,k}}} - \overrightarrow{\widetilde{P_{l,T_n,k}}}\right| \quad (6.5)$$

Therefore, the worker's safety situation at T_n in each test case can be determined by

$$\text{Safety}(T_n, k) = f(D_{aver,T_n,k}) \quad (6.6)$$

6.2.2.3 Safety Situation Calculation Using the Predicted Location Based on the Previous Two Sensed Location

For each test case,

The worker's location $\overrightarrow{Pp_{w,T_n,k}}$ at T_n (for n >2) can be predicted based on the previous two sensed locations as:

$$\overrightarrow{Pp_{w,T_n,k}} = \overrightarrow{\widetilde{P_{w,T_{n-1},k}}} + \left(\overrightarrow{\widetilde{P_{w,T_{n-1},k}}} - \overrightarrow{\widetilde{P_{w,T_{n-2},k}}}\right) = 2 * \overrightarrow{\widetilde{P_{w,T_{n-1},k}}} - \overrightarrow{\widetilde{P_{w,T_{n-2},k}}} \quad (6.7)$$

The crane load's location $\overrightarrow{Pp_{l,T_n,k}}$ at T_n (for n >2) in each test case can be predicted based on the previous two predicted locations as:

$$\overrightarrow{Pp_{l,T_n,k}} = \overrightarrow{\widetilde{P_{l,T_{n-1},k}}} + \left(\overrightarrow{\widetilde{P_{l,T_{n-1},k}}} - \overrightarrow{\widetilde{P_{l,T_{n-2},k}}}\right) = 2 * \overrightarrow{\widetilde{P_{l,T_{n-1},k}}} - \overrightarrow{\widetilde{P_{l,T_{n-2},k}}} \quad (6.8)$$

Based on the average position using k samples, the distance between the crane load and the worker at T_n $(n > 2)$ in each test case can be calculated as

$$D_{pred,T_n,k} = \left|\overrightarrow{Pp_{w,T_n,k}} - \overrightarrow{Pp_{l,T_n,k}}\right| \quad (6.9)$$

Therefore, the worker's safety situation at $T_n(n > 2)$ in each test case can be determined by

$$Safety(T_n, k) = f(D_{pred,T_n,k}) \quad (6.10)$$

6.2.2.4 Safety Situation Calculation Using the Predicted Location Based on the Previous One Predicted Location, Ideal Velocity and Acceleration

In a general situation, an object's location at T_i can be predicted based on its predicted location, velocity and acceleration at T_{i-1} using the equation below:

$$\overrightarrow{P_{T_i}} = \overrightarrow{P_{T_{i-1}}} + \overrightarrow{v_{T_{i-1}}} * (T_i - T_{i-1}) + 0.5 * \overrightarrow{a_{T_{i-1}}} * (T_i - T_{i-1})^2 \quad (6.11)$$

In the author's testbed, only location information is collected in this phase. Based on the observation on jobsite, the worker's velocity value and the crane load's angular

velocity are approximately constant in the middle of certain activities. Therefore, the author assumes that the value of the worker's linear velocity and the value of the crane load's angular velocity are constant; the worker's linear acceleration and the crane load's angular acceleration are zero. The direction of the simulated velocity reading is set with the value of the previous two sensed locations. Therefore,

The worker's location $\overrightarrow{Pp_{w,T_n,k}}$ at T_n (for n >2) can be predicted based on the previous sensed locations as

$$\overrightarrow{Pp_{w,T_n,k}} = \overrightarrow{P_{T_{n-1}}} + \overrightarrow{v_{T_{n-1}}} * T \quad (6.12)$$

Where,

T is the timer interval between T_n and T_{n-1}(0.5 second in our test cases)

$$\overrightarrow{v_{T_{n-1}}} = * (\overrightarrow{P_{T_{n-1}}} - \overrightarrow{P_{T_{n-2}}})/|\overrightarrow{P_{T_{n-1}}} - \overrightarrow{P_{T_{n-2}}}| \quad (6.13)$$

The crane load's location $\overrightarrow{Pp_{l,T_n,k}}$ at T_n (for n >2) can be predicted based on the previous sensed locations as

$$\overrightarrow{Pp_{l,T_n,k}} = \overrightarrow{P_{T_{n-1}}} + \overrightarrow{v_{T_{n-1}}} * T = \overrightarrow{P_{T_{n-1}}} + \overrightarrow{\omega_{T_{n-1}}} * \frac{|\overrightarrow{r_{T_{n-1}}}|^2}{\overrightarrow{r_{T_{n-1}}}} * T \quad (6.14)$$

Where,

T is the timer interval between T_n and T_{n-1}(0.5 second in our test cases)

Based on the average position using k samples, the distance between the crane load and the worker at T_n $(n > 2)$ in each test case can be calculated as

$$D_{pred,T_n,k} = |\overrightarrow{Pp_{w,T_n,k}} - \overrightarrow{Pp_{l,T_n,k}}| \quad (6.15)$$

Therefore, the worker's safety situation at $T_n(n > 2)$ in each test case can be determined by

$$\text{Safety}(T_n, k) = f(D_{\text{pred},T_n,k}) \qquad (6.16)$$

6.2.2.5 Bayesian Approach[1]

In the extracted safety knowledge for safety situation calculation using predicted location provide by models described in section 6.2.2.1 to 6.2.2.4. In these models, locations were calculated using only information (location, velocity and acceleration) at one or two positions. A more sophisticated way would be to include more information at more points for location prediction and safety situation calculation. One elegant method is the Bayesian approach. This approach uses new information to update prior knowledge based on previous points. Other than using singular data at one or two points, the approach uses multiple data at multiple points aiming towards a better performance.

Bayesian conditional probability (Dempster, 1968) is well known and widely applied in almost every field of science. Figure 59 presents the general principles behind the approach. In a broad context, the prior knowledge $P(H)$ related to a hypothesis (H) is updated $P(H|E)$based upon evidence (E). This process uses evidences in a likelihood function$P(E|H)$.

[1] The author would like to thank Dr. James A. Goulet for his thoughts and recommendations with respect to model-based diagnose Bayesian system.

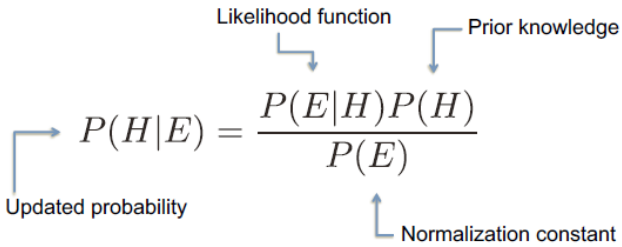


Figure 59 Bayesian Conditional Probability

In the crane safety scenario, the hazard state of the worker can be categorized and her probability of being in any of these states can be described. The three variables describing the worker's safety conditions are:

1. In the green zone
2. In the yellow zone
3. In the red zone

The alarm (if the worker is in the red zone) or warning (if the worker is in the yellow zone) triggering is based on the probability $P(\alpha)$ of the worker being in the safety condition. If $P(\alpha)$ is larger than a threshold$\emptyset$ where $\emptyset \in [0,1]$ (in our test, 50% was chosen as the threshold), a signal would be sent to the worker for notifying her safety situations. In practice, $P(\alpha)$ can be estimated by updating the probability of being in a hazardous situation. $P(\alpha|E)$ conditionally on observations (E) made of the worker's position relative to the hazard.

The Bayesian approach consists of defining and continuously updating the probability $P(\alpha|E)$ in a Bayesian manner, based on the worker's monitored behaviors. The position, velocity and acceleration of both the worker and the crane load are

monitored at a frequencyf ($\frac{1}{T}$). Based on the captured data, three quantities can be obtained at any time step i: the worker's distance to the dangerous area's center ($D_{w,i}$), the worker's velocity towards the dangerous area's center ($v_{w,i}$), and the worker's acceleration towards the dangerous area's center ($a_{w,i}$),. Defining $P(\alpha|E)$ based on these three quantities allows the transient characteristics of a worker's behavior to be included. For instance, if someone is working close to the red zone and is conscious of the danger, no alarm or signal should be given. In another case, if a worker is still relatively far from the red zone, but walking at constant speed towards it with no sign of slowing down, an alarm should be triggered. This heuristic knowledge is encapsulated in a likelihood function $P(E|\alpha) = g(D_{w,i}, v_{w,i}, a_{w,i})$ and is used to update previous knowledge about the hazard state$P(\alpha|E)$. Based on the theory of experimental design (Fisher, 1936, Kuehl, 1999) a set of 45 events $x = [x_1, x_2, \dots, x_{45}]^T$ where $x_n = [D_{w,n}, v_{w,n}, a_{w,n}]$ for $n \in [1,45]$ are defined in a central-composite-design arrangement. The probability of being in an imminent hazardous situation $P(\alpha|E)$ has to be quantified for each point based on a mutual agreement.

The probability $P_n(E|\alpha)$ has to be evaluated for each point n in order to define a second-order polynomial function that can return $P(\alpha|E)$ in the entire domain using Equation 6.17.

$$\vec{P}(E|\alpha) = \beta_0 + \sum_{i=1}^{3} \beta_i x_i + \sum_{i=1,j=1}^{3} \beta_{3i+j-1} x_i x_j + \epsilon_n \quad (6.17)$$

Equation 6.18 is the matrix representation of Equation 6.17 where β_i are parameters determined using Equation 6.20. $\vec{\beta}$ is a vector containing the parameters β_i that minimizes the approximation error ϵ_n.

$$\begin{bmatrix} P_1(E|\alpha) \\ P_2(E|\alpha) \\ \vdots \\ P_{45}(E|\alpha) \end{bmatrix} = \begin{bmatrix} 1 & x_{1,1} & x_{1,2} & \cdots & x_{1,3}^2 \\ 1 & x_{2,1} & x_{2,2} & \cdots & x_{2,3}^2 \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{45,1} & x_{45,2} & \cdots & x_{45,3}^2 \end{bmatrix} \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_9 \end{bmatrix} + \begin{bmatrix} \epsilon_0 \\ \epsilon_1 \\ \vdots \\ \epsilon_{45} \end{bmatrix} \quad (6.18)$$

$$\vec{P}(E|\alpha) = X\vec{\beta} + \vec{\epsilon_r} \quad (6.19)$$

$$\vec{\beta} = (X^T X)^{-1} X^T \vec{P}(E|\alpha) \quad (6.20)$$

The probability of being in an imminent hazardous situation at a time i, $P(\alpha|E)|_{t=i}$ can be obtained by updating the previous state of knowledge $P(\alpha|E)|_{t=i-\xi}^{t=i-1}$ obtained in the last ξ ($\xi \in N$) iterations with the likelihood function $P(E|\alpha)|_{t=i}$ computed from monitored data obtained at time i. ξ can either be defined deterministically or it can be updated recursively using the state of $P(\alpha|E)|_{t=i-1}$ as shown in Equation 6.21. In this equation, κ ($\kappa \in N$) is weighted by $P(\alpha|E)|_{t=i-1}$. When the hazard is low, it is useful to include a large number of previous points in order to avoid potentially misleading outliers. When the hazard is high, the window size should be reduced in order to adapt quickly to changing situations.

$$\xi = \lfloor \kappa / P(\alpha|E)|_{t=i-1} \rfloor \quad (6.21)$$

The equation 6 presents the Bayesian updating procedure where previous knowledge is updated using the likelihood function (Equation. 6.17) translating the relative position, speed and acceleration of a worker into a probability of being in a

hazardous state. In this Equation, P(E) is a normalization constant itself evaluated in Equation 6.23.

$$P(\alpha|E)|_{t=i} = \frac{P(E|\alpha)P(\alpha|E)|_{t=i-\xi}^{t=i-1}}{P(E)} = \frac{1}{P(E)}\prod_{j=i-\xi}^{i} P(E|\alpha)|_{t=j} \quad (6.22)$$

$$P(E) = \left(\left(\prod_{j=i-\xi}^{i} 1 - P(E|\alpha)|_{t=j}\right) + \prod_{j=i-\xi}^{i} P(E|\alpha)|_{t=j}\right)^{-1} \quad (6.23)$$

6.2.3 Performance Metrics

To evaluate the performance of the aforementioned approaches, three performance metrics were chosen.

Accuracy: the accuracy is the percentage of true results in the population.

$$\text{Accuracy} = \frac{\text{number of true positives+ number of true negatives}}{\text{number of true positives+true negatives+false positives+false negatives}} \quad (6.24)$$

Precision is the ratio of True Positive to the sum of True Positive and False Positive. It measures the percentage of actual alerts and warnings that are triggered by the system.

$$\text{Precision} = \frac{\text{True Positive}}{\text{True Positive+False Positive}} \quad (6.25)$$

Recall is the ratio of True Positive to the sum of True positive and False Negative. It measures the percentage of actual dangerous situations that are reported (when an alert or alarm is triggered by the system).

$$\text{Recall} = \frac{\text{True Positive}}{\text{True Positive+False Negative}} \quad (6.26)$$

For both the yellow-green and red-yellow green systems, the values of these three metrics are calculated for the aforementioned approaches and compared with the ones based on

raw data without data processing (See discussion on yellow-green and red-yellow green system in section 5.4 on page 129).

6.3 RESULTS

Figure 60 shows the number of samples used to obtain the average location data for safety situation calculation. By increasing the number of samples used for averaging, the performances of both systems get improved. Based on the figure, when a number between 10 and 13 is chosen as the number of samples used for averaging, the performance reaches a flat platform.

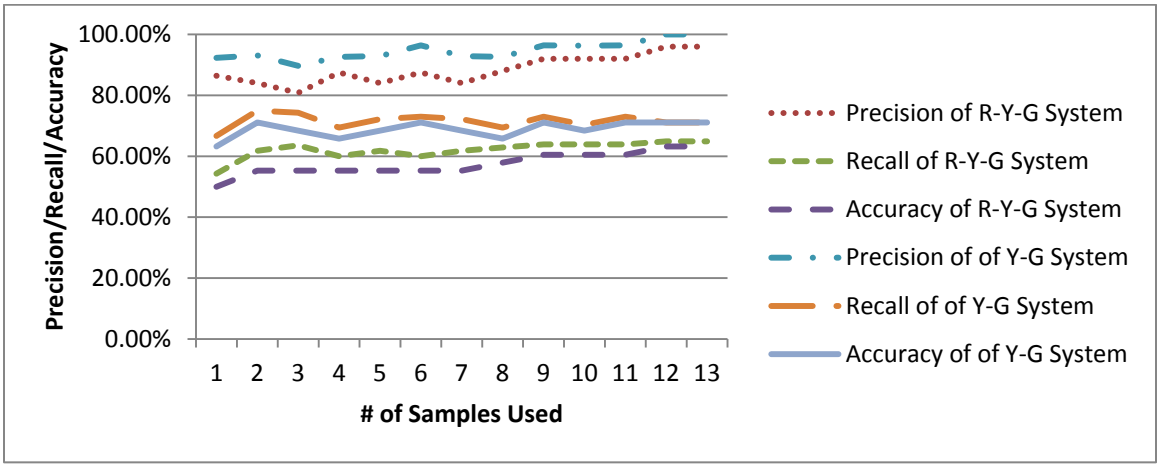


Figure 60 Performance of Simple Averaging with Number of Used Samples Changing

The performances of various approaches are summarized in Table 11 and Figure 61. Because the localization error is large based on the data I collected, as well as the relative path of the worker might not be a straight line, the approach of simple prediction using the vector based on the previous two sensed location does not reach a better performance than simple used the raw data without any data processing approach. Simple

averaging using the first ten readings also averages the localization error down. Therefore, the simple averaging using the first ten readings gets a little better performance than just using raw data for decision making. If additional information (e.g., velocity and acceleration) other than location can be obtained and used to support decision making, the performances of both systems get improved and both systems have performance metrics with value of over 80%.

Table 11 Performance Comparison of Various Approaches to Deal with Imperfect Data

	R/Y/G System			Y/G System		
	Precision	Recall	Accuracy	Precision	Recall	Accuracy
Raw Location Data	87.6%	53.0%	49.3%	94.9%	62.7%	60.7%
Simple averaging using 10 location readings	92.0%	63.9%	60.5%	96.3%	70.3%	68.4%
Prediction using location reading of the previous two points and a vector for prediction	100.0%	35.7%	35.7%	100.0%	39.3%	39.3%
Bayesian Approaches with velocity and acceleration	76.7%	74.2%	60.5%	93.5%	80.6%	76.3%
Prediction using predicted location data at previous point with velocity and acceleration	93.8%	96.8%	90.9%	100.0%	97.0%	97.0%

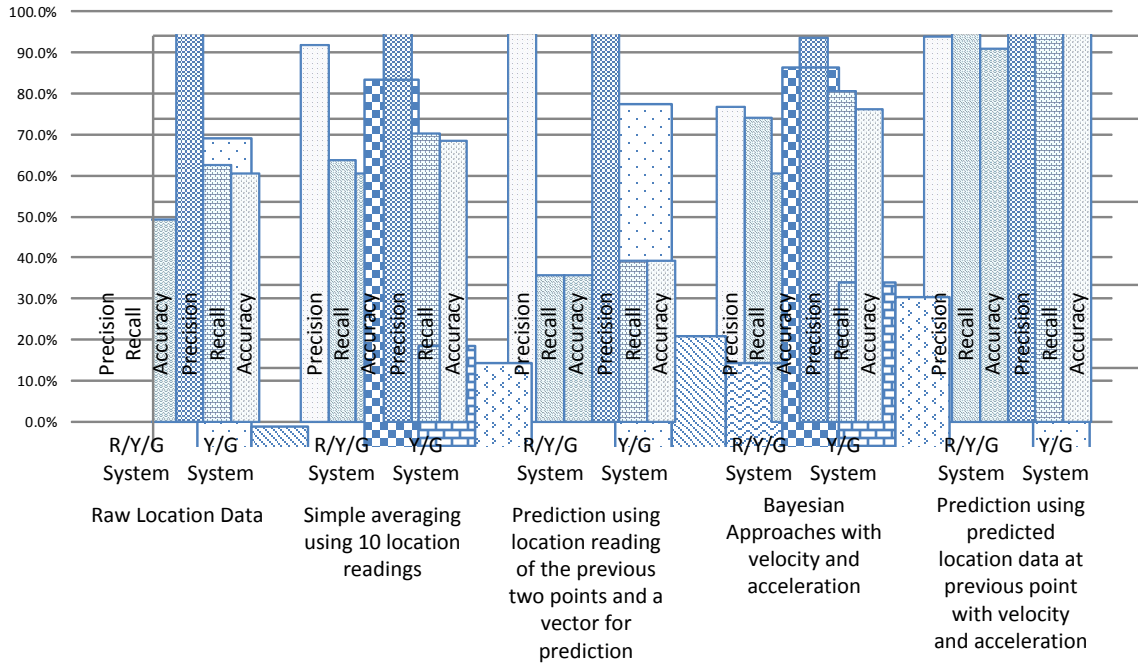
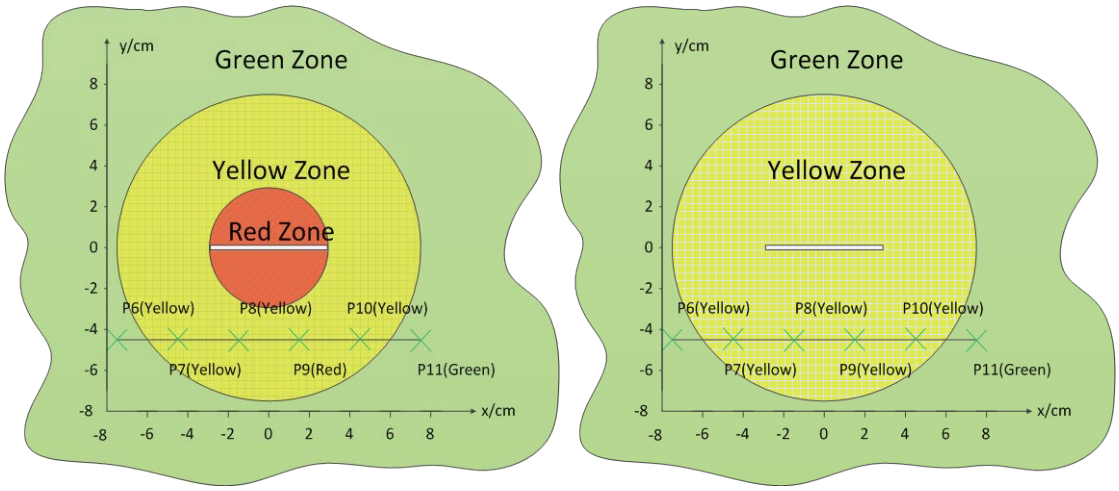


Figure 61 Performance Comparison of Various Approaches

Figure 62 shows the detailed safety decisions made with the Bayesian approach in the R/Y/G system and the Y/G system. In both systems, the calculated safety situations at points in the green zone are the same. The performance would be the same for the same approach at the points in the green zone. False alarms would be raised at some points (e.g., P6) in this area and we want to keep the false alarm rate as low as possible. In this way, the worker's would trust the system and would not turn the system off. In test case #2, the Bayesian approach achieved 100% accuracy at points inside for the yellow zone for the Y/G system (Figure 62b) and only one occurrence (at P9) of false alarm is observed in the R/Y/G system (Figure 62a). At P9 in the R/Y/G system, the system exaggerates the worker's dangerous situations. It's more acceptable than failing to give any warning to the worker and telling her that she is in a safe situation. The result

indicates that switching the system from the R/Y/G system to the Y/G system improves the autonomous safety monitoring system's performance.



(a) R/Y/G System (b) Y/G System

Figure 62 Safety Situation Along the Worker's Moving Path in Test Case #2 Made by Bayesian Approach

Table 12 and Figure 63 show the performance for both systems based on data I collected from the testbed for points in the green zone. Both the Y/G and R/Y/G systems have the same performance in this green zone. For the points in the green zone, the decision making based on raw data reach nearly 86% accuracy and precision, which means the calculated safety situation is also green. The prediction using simple vector and the prediction using predicted data and additional information reach accuracies and precisions of 100%, in which cases all the points have been correctly identified in green zone. For all the other three approaches other than those two with 100% accuracies, although the system incorrectly identifies some points, the decisions are not so bad since no points have been incorrectly identified to be in the red zone. The recall rates of all the

approaches are 100% because all the safe situations were reported. Based on the results, the system might get better performance when applying the approach of prediction with simple vector and the approach of prediction using predicted location and additional information on the sensed data. The other two approaches and decision making with raw data also get an acceptable performance.

Table 12 Systems Performance of Y/G System and R/Y/G System in Green Zone

	Y/G System and R/Y/G System		
Applied Approach	Precision	Recall	Accuracy
Raw Location Data	86.1%	100.0%	86.1%
Simple averaging using 10 location readings	88.9%	100.0%	88.9%
Prediction using location reading of the previous two points and a vector for prediction	100.0%	100.0%	100.0%
Bayesian Approaches with velocity and acceleration	77.8%	100.0%	77.8%
Prediction using predicted location data at previous point with velocity and acceleration	100.0%	100.0%	100.0%

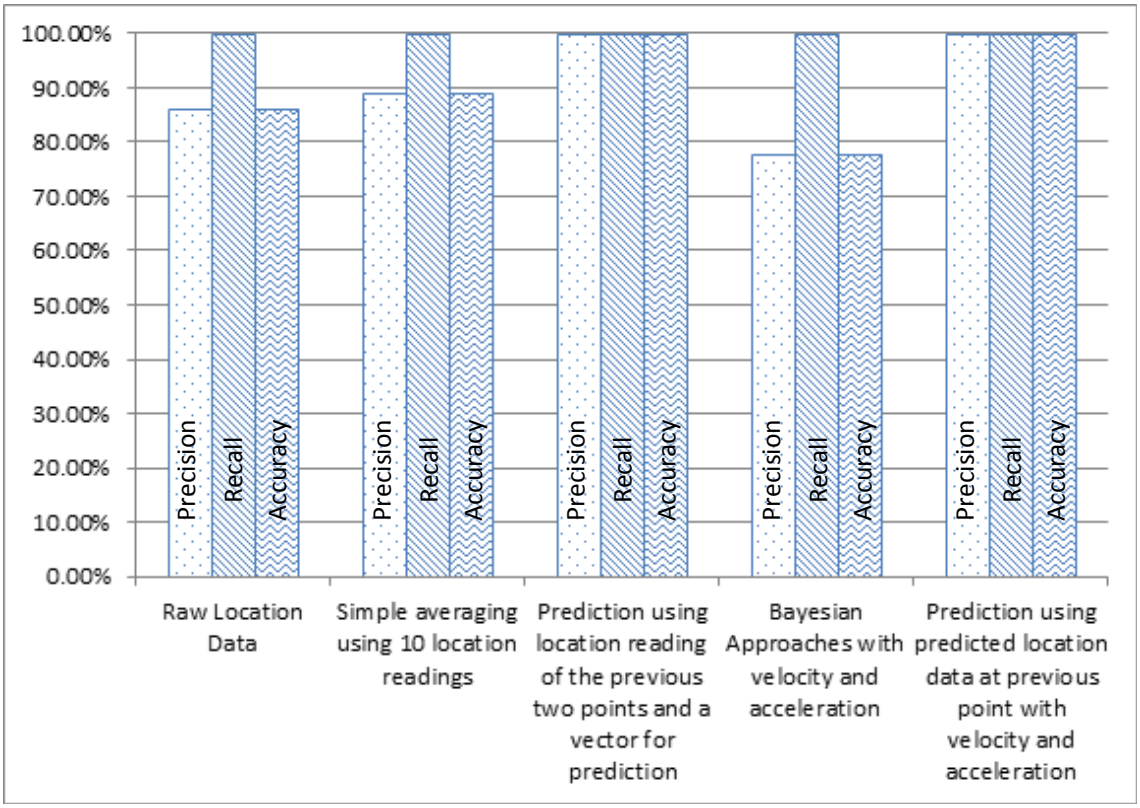


Figure 63 Systems Performance of Y/G System and R/Y/G System in Green Zone

Table 13 and

Figure 64 show the performance for both systems based on data I collected from the testbed for points in the yellow zone. The results are quite consistent with the overall result when considering all the points in different zones as a whole set. For the points in the green zone, the prediction using predicted location data and additional information has the best performances for both the Y/G and R/Y/G systems in terms of precision, recall and accuracy. The Bayesian approach has the 2nd best performance. The results indicate that by introducing additional information (e.g., acceleration and velocity) to support decision making, the performances of both systems get improved and most of the performance metrics have values of over 70%.

Table 13 Systems Performance of Y/G System and R/Y/G System in Yellow Zone

	Y/G System			R/Y/G System		
Applied Approach	Precision	Recall	Accuracy	Precision	Recall	Accuracy
Raw Location Data	100.0%	43.9%	43.9%	85.5%	40.1%	37.5%
Simple averaging using 10 location readings	100.0%	54.6%	54.6%	91.7%	52.4%	50.0%
Prediction using location reading of the previous two points and a vector for prediction	100.0%	25.0%	25.0%	100.0%	25.0%	25.0%
Bayesian Approaches with velocity and acceleration	100.0%	72.7%	72.7%	68.8%	64.7%	50.0%
Prediction using predicted location data at previous point with velocity and acceleration	100.0%	95.0%	95.0%	89.5%	94.4%	85.0%

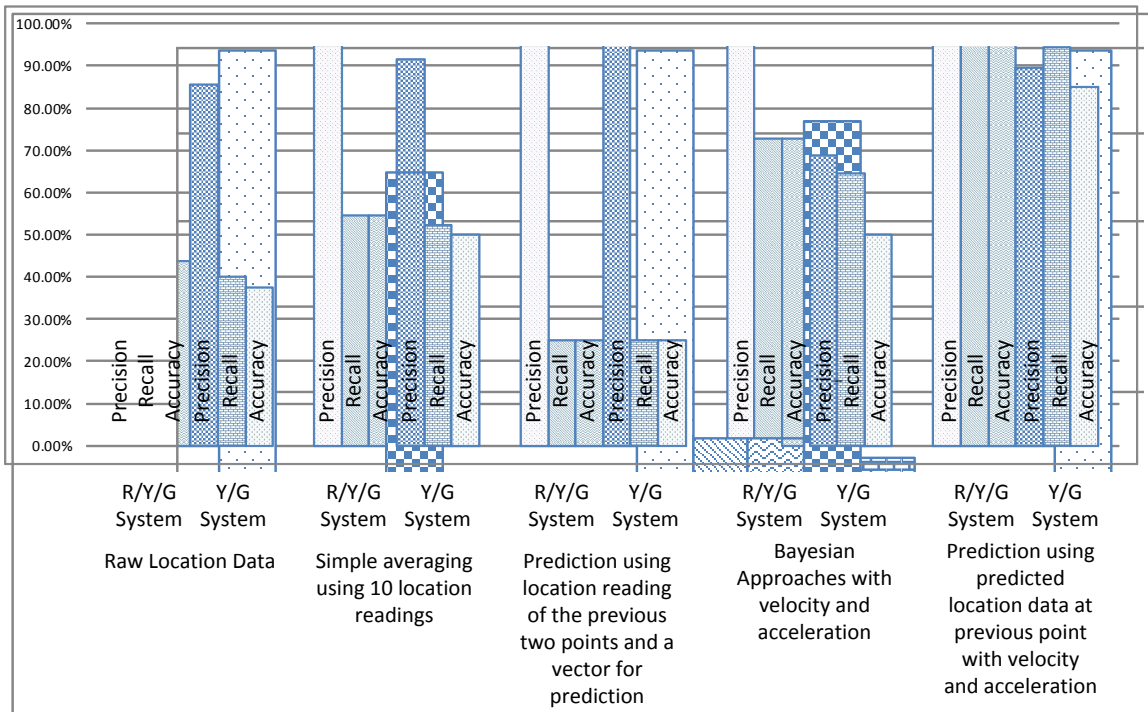


Figure 64 Systems Performance of Y/G System and R/Y/G System in Yellow Zone

Table 14 and Figure 65 show the system's performance (in terms of percentage of points considering to be in a specific safety situation) based on data I collected from the testbed for points in the red zone. For the R/Y/G system, both the simple averaging approach and the approach of prediction using predicted location with velocity and acceleration have the best performance. The Bayesian approach has a similar performance as decision making simply using raw data from the sensors. For the Y/G system, the approach of prediction using predicted location with velocity and acceleration also has the best performance and the Bayesian approach has the 2nd best performance. The prediction approach using simple vector had the worst performance for both systems.

Table 14 Systems Performance of Y/G System and R/Y/G System in Red Zone

	Y/G System			R/Y/G System		
Applied Approach	Precision	Recall	Accuracy	Precision	Recall	Accuracy
Raw Location Data	100.0%	80.7%	80.7%	100.0%	39.3%	39.3%
Simple averaging using 10 location readings	100.0%	100. 0%	100.0%	100.0%	57.1%	57.1%
Prediction using location reading of the previous two points and a vector for prediction	100.0%	28.6%	28.6%	100.0%	14.3%	14.3%
Bayesian Approaches with velocity and acceleration	100.0%	85.7%	85.7%	100.0%	71.4%	71.4%
Prediction using predicted location data at previous point with velocity and acceleration	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

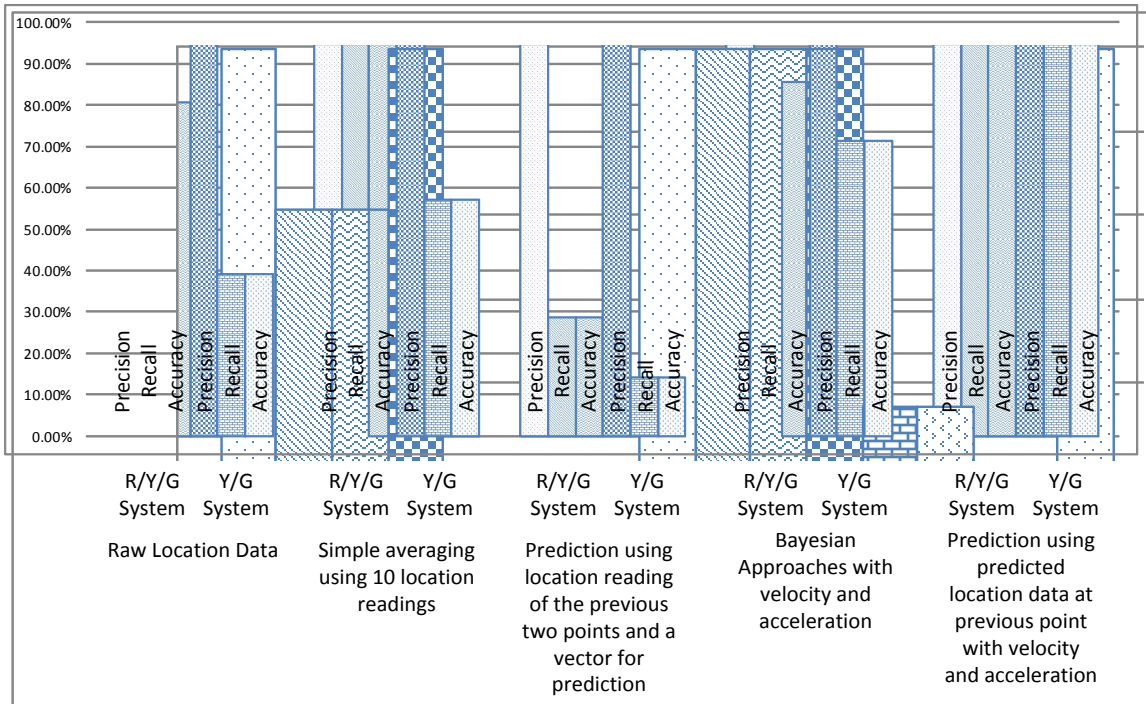


Figure 65 Systems Performance of Y/G System and R/Y/G System in Red Zone

6.4 DISCUSSION

The simple averaging approach used to provide location for safety situation calculation provides a more stable system's performance as the location errors fluctuate less. The system's performance tended to be more stable if more sample location data were used to calculate the average location. Ten to thirteen would be a good number to use as the sample size of location data that should be collected at a specific location in a short period of time. This approach was a simple and effective way to improve the system's performance for a little bit without a need to deploy extra sensors for other types of data.

Deploying extra sensors to collect velocity and acceleration data can greatly improve the system's performance. Both the Bayesian approach and the prediction using

predicate location data, velocity & acceleration utilize that information to provide a more accurate safety situation of the workers. The predication approach using velocity and acceleration in addition to location data achieved the best performance in the test cases used in this chapter. The performance was dependent on the path of worker and crane load. In the test cases described in this chapter, the worker was walking in straight line and the crane load was moving along a circle. This simple pattern of the worker and the crane load's moving path was a possible explanation of why this approach had a very high accuracy in deciding the worker's safety situations. The system's performance might degrade if the worker and crane load's moving path did not have such a clear pattern. Future study would include some test cases with irregular moving paths to test this approach's performance.

The Bayesian approach had the 2nd best performance in the test cases described in this chapter. The Bayesian approach was dependent on its prior knowledge, the size of time windows use to collect prior knowledge for updating, the confidence level used as probability threshold. Therefore, the Bayesian approach approach's performance was variable based on all these factors. An appropriate set of prior knowledge and time windows can improve the autonomous safety monitoring system's performance using the Bayesian approach.

6.5 CONCLUSIONS

In the test cases, the author introduced additional information other than location information for decision making on worker's safety situations. Due to the limitations of data collection, the velocity and acceleration data were simulated and considered no imperfection in their values. The efforts showed that by introducing additional data to adjust the decision making process, the systems can get a much better improvement. Both

Bayesian approach and the prediction using a combination of sensed locations speed and acceleration showed a promising return in terms of performance.

The comparison of various approaches was based on the data collected in a miniature test bed equipped with an indoor localization system, in which the localization error was not so stable due to the environmental conditions. To further analyze the performance of these approaches, simulations as well as additional tests in other deployed test bed with different localization systems should be conducted. In the additional tests, live stream data with more test points in each test case should be collected and used for further analysis.

This chapter attempted to explore different approaches to deal with imperfect data for improving the performance of the autonomous safety monitoring system. The preliminary results showed the promising potentials of approaches introducing additional data in decision making. Future research includes using live stream data collected from different test beds to evaluate the performance of the aforementioned approaches.

Chapter 7 Conclusions and Future Research

The construction industry has a higher injury and fatality rate than most other industries across the globe. One of the causes of the higher accident rate is that the construction workers might not be aware of the dangers when they enter unsafe areas. To increase workers' safety awareness and hence improving safety performance of the construction industry, this research envisions a next generation jobsite safety monitoring of autonomous background monitoring of workers and equipment that will alert workers when entering unsafe areas. During the course of this research, the author picked the top two leading causes of accidents in the construction industry for case studies: crane operations and working at height. The requirements and specifications were developed for autonomous safety monitoring and proactive fall prevention. The requirements and specifications were then integrated into the development and deployment of the autonomous safety monitoring system. The system was evaluated with realistic data imperfection conditions and several approaches were proposed to improve the system's performance.

The system builds on infrastructure developed for an intelligent jobsite, including wireless networks, mobile computing devices, RFID, and other sensors used for productivity analysis and material tracking. The system is generalizable and extensible for safety monitoring in other domains.

7.1 RESEARCH CONTRIBUTIONS

This research was conducted in three phases, each of which answered one of the following research questions raised in the first chapter of this thesis:

RQ1: How to conceptualize safety knowledge in an autonomous monitoring environment?

RQ2: How to formalize the reasoning mechanisms in a distributed computing environment and how to implement autonomous safety monitoring?

RQ3: How do we address information imperfections to better support safety monitoring?

Contributions of each phase are summarized below.

7.1.1 Safety Knowledge Elicitation and Representation

In this phase, a knowledge elicitation and representation process was built and used to extract the safety knowledge for autonomous crane safety monitoring and proactive fall prevention. The extracted safety knowledge for autonomous safety monitoring was explicitly expressed in the form of the defined dangerous areas. The dangerous situations can be expressed in the form of relative locations to the dangerous zones. The rules can be associated to the dangerous zones. In this way, the extracted safety knowledge was rigidly summarized in zones.

In this process, relevant safety regulations, standards and best practices should be comprehensively reviewed and useful decision rules are learnt from these documents. Based on the regulations and standards reviews, knowledge engineers can develop an

interview guideline, which includes some specific safety operation scenarios. The experts with substantial safety knowledge and industrial experience can be invited to go over those scenarios and provide their thoughts on the decision making mechanisms. By integrating the inputs and feedbacks from experts into safety knowledge that is extracted from regulations, the decision making process for jobsite safety monitoring can be represented using decision making flowcharts and the required information inputs are summarized in an information requirements table.

Using this process, I successfully extracted safety knowledge for autonomous crane safety monitoring and proactive fall prevention. The extracted and presented knowledge for autonomous safety monitoring in this phase was technological independence and can be further translated to facilitate the system development with specific technologies.

7.1.2 Extensible Development and Deployment of Autonomous Safety Monitoring System in Mobile Computing Environment

In this phase, the extracted safety knowledge in the previous phases was represented using Unified Modeling Language (UML) to advance the safety monitoring system development. To address the challenges and constraints posed by mobile computing environment, a three-layer architecture was selected for the autonomous safety monitoring system development and deployment. Based on the architecture, the common safety knowledge with decision rules for autonomous safety monitoring was disassembled into single-function decision making chunks in the Decision Support Layer (DSL), so these decision making chunks can be reused, customized, extended and

assembled into a larger decision making chunk to fulfill the functions of a specific safety monitoring application.

To facilitate the development and deployment of the autonomous safety monitoring system, a written process was proposed to guide the developer to build the system by reusing the developed decision making chunks in DSL and customize safety knowledge. Tower crane safety and proactive fall prevention applications were used to demonstrate the reusability and ability of customization of the decision making chunks.

7.1.3 Exploring Data Imperfection in Autonomous Safety Monitoring System

Using the testbed developed in the previous research phase, the author was able to discover the potential issues of deploying such safety monitoring systems in a live jobsite without any potential safety issue. From the data collected from the sensors on the testbed, data imperfections were categorized into three types. The potential impacts on decision making in the safety monitoring system were discussed. To analyze the impacts of data imperfections on the system's performance, the author proposed to use precision and recall for performance assessment. Twelve test cases were developed based on the jobsite activities on a construction project on the University of Texas campus. Data was collected at locations with ground truth information in those test cases. The system performance analysis using the testbed data showed that the data imperfections of localization devices had larger impacts on precision and recall.

To further analyze the impacts on the system performance with imperfect data at different levels, simulation data was generated in Microsoft Excel and pushed into the autonomous monitoring system. The analysis using simulation data showed that the

larger standard deviation, the worse performance of the system might have. Also, by replacing the three dangerous status (red, yellow and green) with the two dangerous status systems (yellow and green), the system performance got apparently improved.

7.2 FUTURE WORK

My dissertation elicited the safety knowledge and information requirements for two construction jobsite safety monitoring applications (tower crane safety monitoring and fall prevention near open edges). Radio frequency and ultrasonic devices were used to provide localization information to support the system development and deployment in a miniature testbed. Data was collected from the testbed to explore the data imperfections and several approaches were proposed to improve the systems' performance with imperfect data. However, my work only covers some aspects of autonomous safety monitoring systems for construction jobsites and presents a preliminary study on imperfect data. Therefore, there are great space for extension and expansion on my research and some following directions are proposed for future research.

7.2.1 Including Other Sensing Technologies to the Systems to Provide Richer Information

Currently, the system introduced in this dissertation uses a radio frequency and ultrasonic localization system to provide location information for safety decision making. There are other sensing technologies available on the market, which can provide location and other information to the system. For example, vision-based tracking technologies, Ultra Wideband, radio signal strength based localization technologies have been

proposed and tested in other research. A future research direction is to include some of these technologies in the system and use them to provide the required information for the modules in my proposed system.

7.2.2 Developing a Full Scale Testbed for System Testing and Evaluation

In my dissertation, I designed a scaled miniature testbed to validate the feasibility of the proposed autonomous system. To further evaluate the feasibility of deploying the system in practice, a full scale test bed should be designed. So the system can be scaled up and fully tested before the actual deployment in practice. Due to the differences between lab environments and jobsite conditions, different sensing devices might be carefully reviewed to choose the appropriate ones for system implementation. Performance evaluation and cost analysis should be conducted for the full scale system to demonstrate the potential and readiness of the system to practitioners in the industries.

7.2.3 Test the Proposed Approaches With Live Stream Data Collected From Sensing Technologies With Different Accuracies

The dissertation explored the impacts of imperfect data and five different approaches to deal with imperfect data in autonomous safety monitoring based on the data collected from the radio frequency and ultrasonic localization system. Localization data was discretely collected in the testbed for the test cases introduced in the dissertation. Simulation data indicated that the performance of localization system would impact the system's performance. To explore which techniques can result in a better performance, sensing technologies with different accuracies should be tested in the

testbed environment. In addition, information on location, velocity and acceleration should be continuously collected in the test cases with more testing points to create a richer data set, which can be used to further evaluate the approaches dealing with imperfect data in a continuous manner. The developed full-scale testbed can also be used to test a full range of conditions including wind and soil conditions for crane safety monitoring.

7.2.4 Extending the Autonomous Safety Monitoring System to Self-response System with Actuators

The autonomous safety monitoring system proposed in this dissertation used the information of surrounding environments to determine the safety situations of workers and equipment. A warning/alarm was sent to the worker and the equipment operator if they were exposed to risks, so they can take appropriate actions to eliminate the risks. For some applications (e.g., monitoring crane safety in proximity of power line) in the system, actuators can be used to control the equipment's operation in such a situation. In this way, the actuator installed on the equipment would be activated to control the movement of the motors on the tower crane and promptly prevent the equipment of being in a higher unsafe situation. In the self-response system with actuators, not all unsafe situations would activate the self-response mechanisms. Rules on under what situations (e.g., the threshold of confidence level of the equipment being in unsafe condition) the self-response mechanisms should be activated need to be carefully studied to improve the system's reliability.

Appendix A Interview Guide on crane related safety working zones and collected data

A.1 Interview Guide on Crane Related Safety Working Zones

The purpose of the interview is to get safety experts opinion on crane related working zones safety and their decision making process during safety monitoring on construction activities around these zones. The information you provide will be only used for research purpose.

Privacy and Confidentiality Protection:

Your participation in this study will be kept confidential to the extent allowed by law. The records of this study will be stored securely and kept confidential. All publications will exclude any information that will make it possible to identify you as a subject.

Name: _____
Job Title: _____
Name of your company: _____
Years of working experience in safety management:_____
Years of working experience in the construction industry:_____

1. What are your major safety concerns on crane (including tower crane, mobile crane and others) operations? (You can list them in priority or no order)

2. Do you agree that worker's access to dangerous working zones (e.g., area under the crane's load) related to cranes and crane component's access to dangerous areas (e.g., proximity to power line) are two important causes of crane related fatalities?
□ Strongly Agree □Moderately Agree □Neutral □Moderately Disagree
□ Strongly Disagree

3. Which of the following regulations/standards are you following regarding working zones under/near cranes? (Please check all that apply)
□ OSHA 1910 Subpart N: Material handling and storage
□ OSHA 1926 Safety and Health Regulations for Construction
□ ANSI/ASME B30 Serials: Covering cranes, hoist, lifting system and derricks
□ OSHA-2007-0066: Cranes and derricks in construction – Proposed Rules (Not yet, comes out in July)

□ Operation manuals from crane manufacturers.
□ Best practice publication from industrial associations/organizations (e.g., best practice published by UK's Construction Plant-hire Association, report published by US's CII), which one?
□ Company's documented safety guideline/rules:_____ _____
□ Others:_____

4. Are you using information technologies (e.g., sensing technology, commercial crane safety management system, GPS and etc.) for crane safety monitoring?
   □ Yes, we use the following technologies (multiple choices):
      □ GPS
      □ RFID
      □ Laser Scanner
      □ Lightening Detector
      □ Commercial safety system from vendors (_____)
      □ Company customized safety system (_____)
      □ Sensors (what types of sensors: _____)
      □ Others (_____)
   □ No

5. What kind of technology might be helpful for safety monitoring on site? In what aspect?

6. What do you need to know to execute safety monitoring on site?

Dangerous area #1 for single tower crane – Under the load and counterweight

Figure A.1 shows the top view and side view of a tower crane. The blue block in side view figure stands for crane load. The shade area is the area under the crane load and is considered to be dangerous for workers. Please answer the questions regarding both situations.

Situation I: load going straight down

Situation II: load is moving from site to site

1-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?

1-2. How do you define the boundary of this dangerous area under the load?

1-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area? Does the action depend on the worker's type? If yes, how?

1-4. How do you define the boundary of dangerous area under the counterweight?

1-5. What actions will you take if target (crane's component or worker) enters/is approaching this area? Do the actions depend on the worker's type? If yes, how?

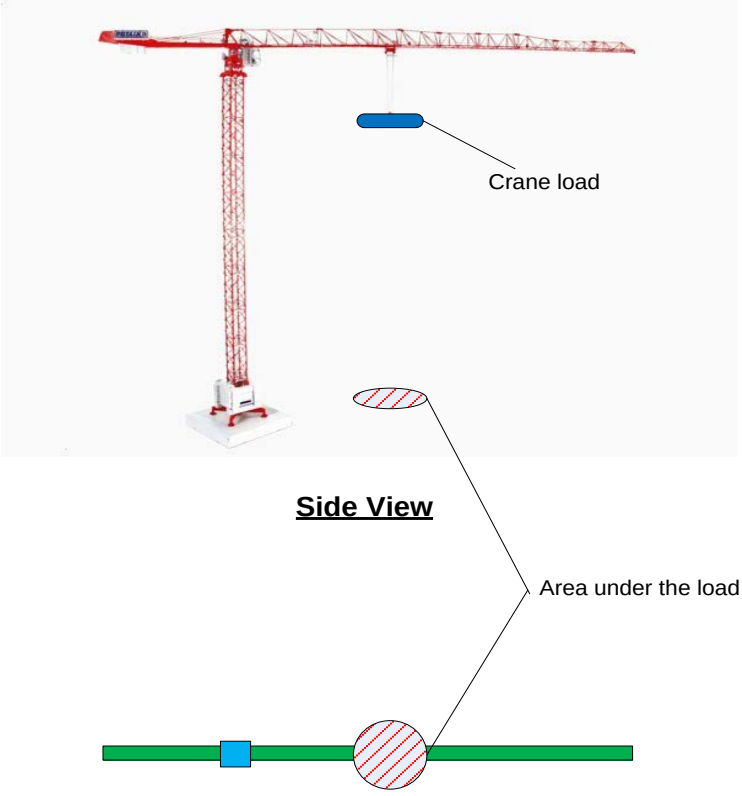


Figure A.1 Area Under the Crane Load

Dangerous area #2 for single tower crane – Area around material stack when crane is pulling material from the stack

Figure A.2 shows the top view and side view of a tower crane. The dark blue block stands for material stack. The shade area is the area around material stack and is considered to be dangerous for workers. Please answer the questions on this page.

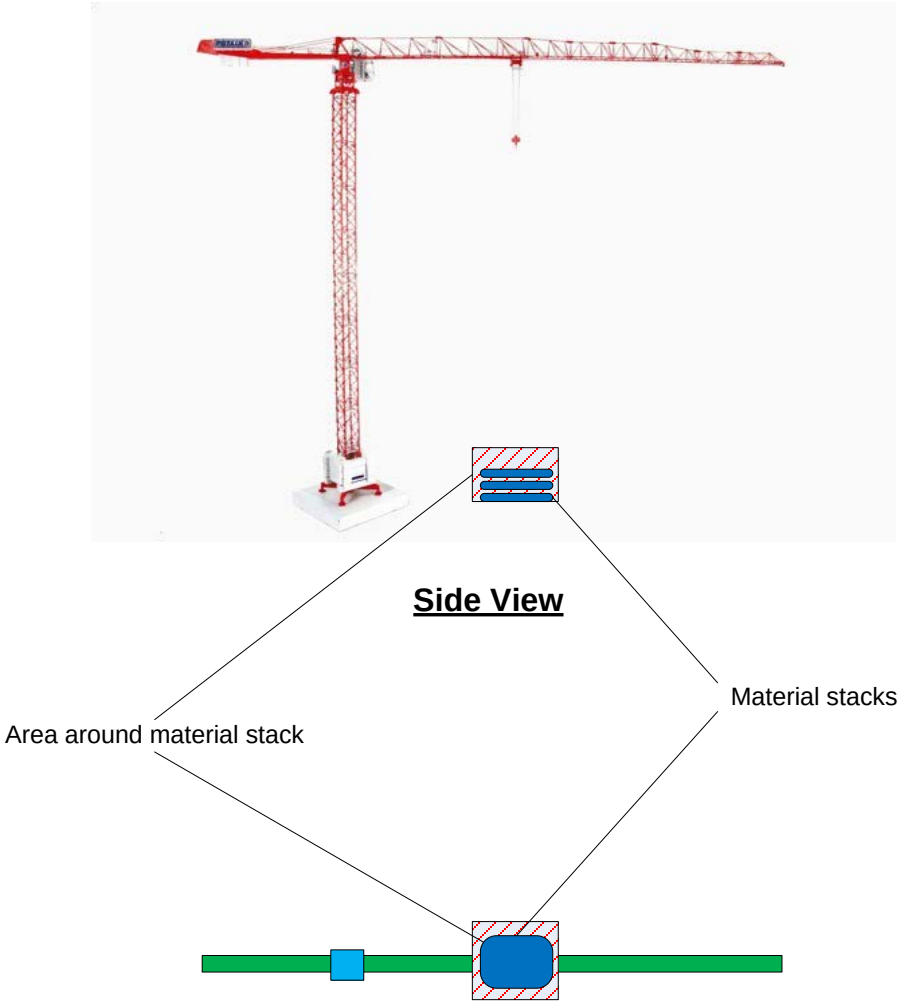


Figure A.2 Area Around Material Stacks

2-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
2-2. How do you define the boundary of this dangerous area?
2-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #3 for single tower crane – Proximity to nearby occupied structures

Figure A.3 shows the top view and side view of a tower crane. The blue block stands for a nearby building. The shade area is the area around the building and is considered to be dangerous area for crane's boom. Please answer the following questions.

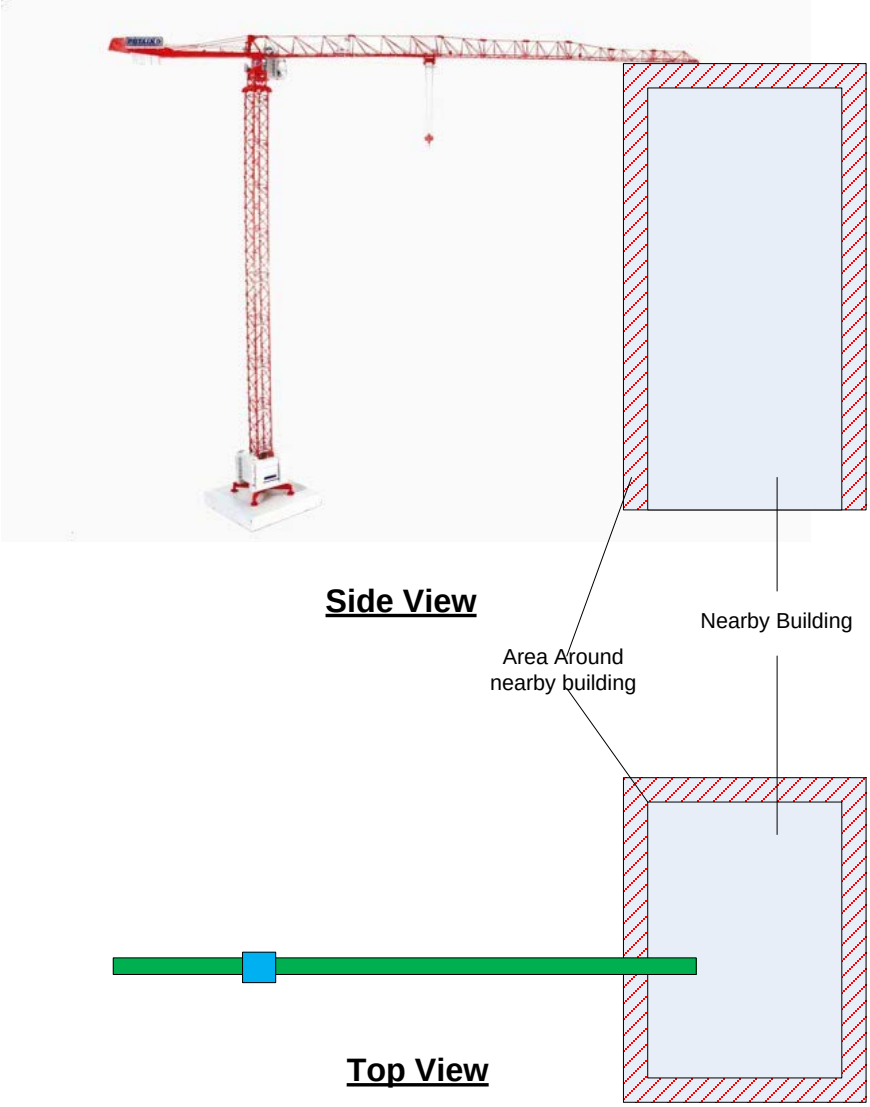


Figure A.3 Area Around Nearby Building

3-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?

3-2. How do you define the boundary of this dangerous area?

3-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #4 for single tower crane – Proximity to nearby roads, highway, railway line or waterway

Figure A.4 shows the top view and side view of a tower crane. The black thin lines stand for a nearby road. The shade area is the area around the road and is considered to be dangerous area for crane's load. Please answer the questions on this page.

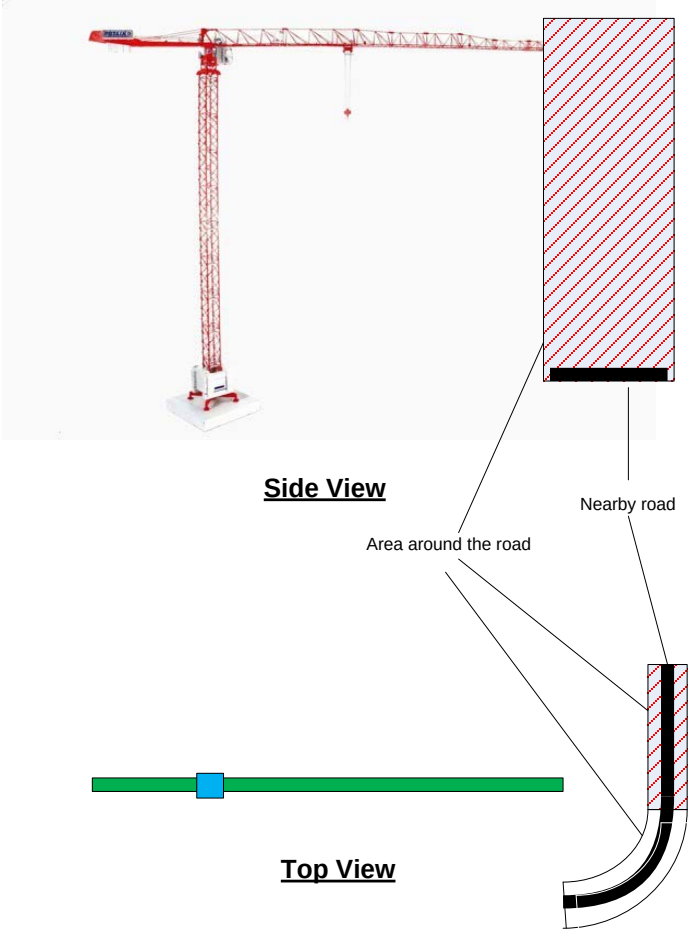


Figure A.4 Area Around Nearby Roads

4-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
4-2. How do you define the boundary of this dangerous area?
4-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #5 for single tower crane – Proximity to nearby power lines

Figure A.5 shows the top view and side view of a tower crane. The black lines stand for nearby power lines. The shade area is the area around the power lines and is considered to be dangerous area for any component (including loads) of crane. Please answer the questions on this page.

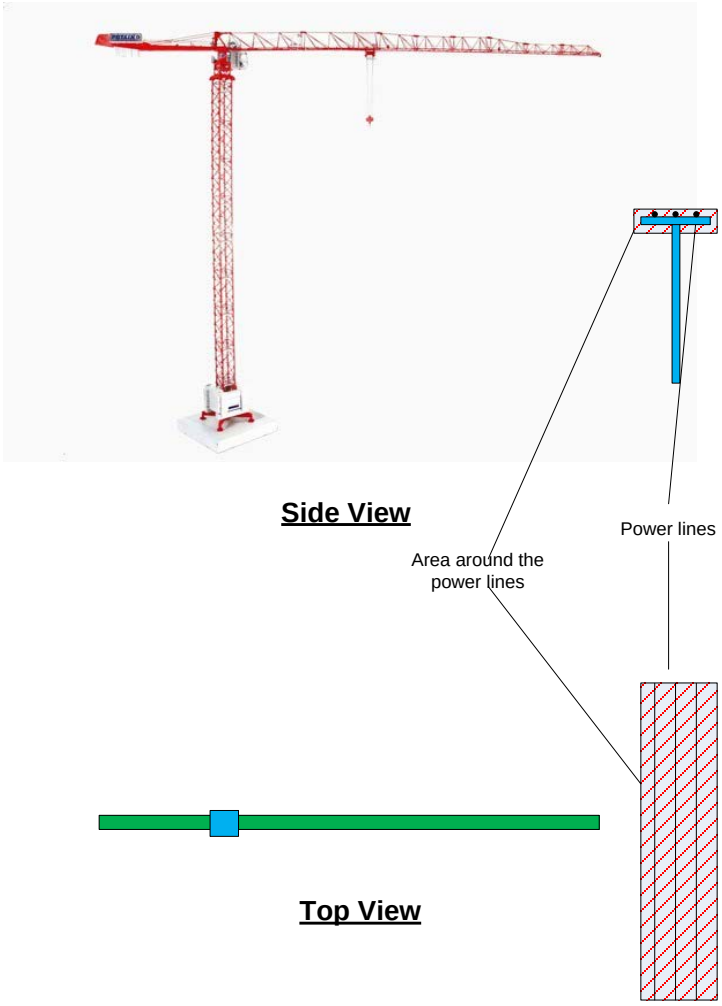


Figure A.5 Area Around Nearby Power Lines

5-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
5-2. How do you define the boundary of this dangerous area?
5-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #6 for single tower crane – Others

Figure A.6 shows the top view and side view of a tower crane. Please mark the dangerous area that is not listed above on the figure.

Side View

Top View

Figure A.6 Other Areas You Considered to be Dangerous

6-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
6-2. How do you define the boundary of this dangerous area?
6-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #7 for single mobile crane – swing radius of rotating upper structure (including counter weight)

Figure A.7 shows the top view and side view of a mobile crane. The blue block stands for rotating base of the crane. The shade area is the swing area of the rotating base and is considered dangerous area for workers. Please answer the questions on this page.

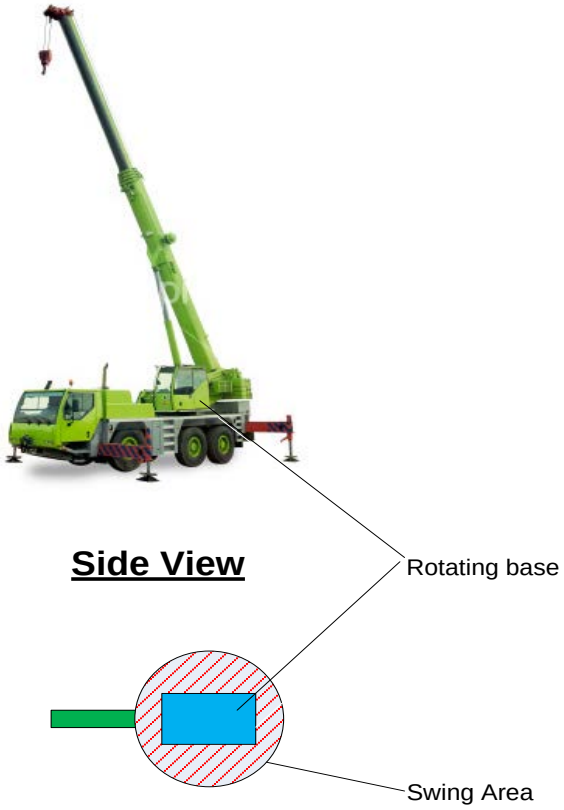


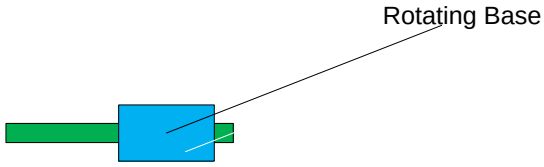
Figure A.7 Swing Area of Rotating Base

7-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
7-2. How do you define the boundary of this dangerous area?
7-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #8 for single mobile crane – Others

Figure A.8 shows the top view and side view of a mobile crane. Please mark the dangerous area that is not listed above on the figure.

Side View



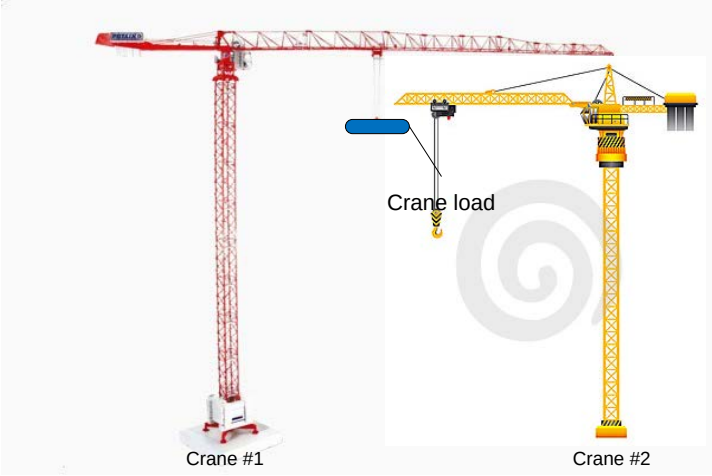
Top View

Figure A.8 Other Areas you Considered to be Dangerous

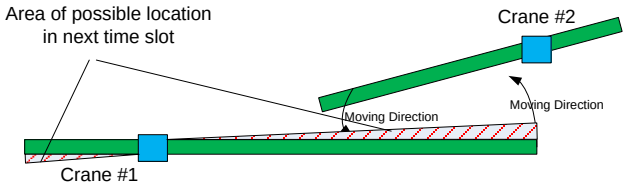
8-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
8-2. How do you define the boundary of this dangerous area?
8-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #9 for two cranes – proximity to the running direction

Figure A.9 shows the top view and side view of two tower cranes. Cranes' booms' moving direction is shown in the top view. The shade area is the proximity area to the running direction of crane #1 and is considered dangerous area for crane #2's boom. Please answer the questions on this page.



Side View



Top View

Figure A.9 Proximity to Running Direction

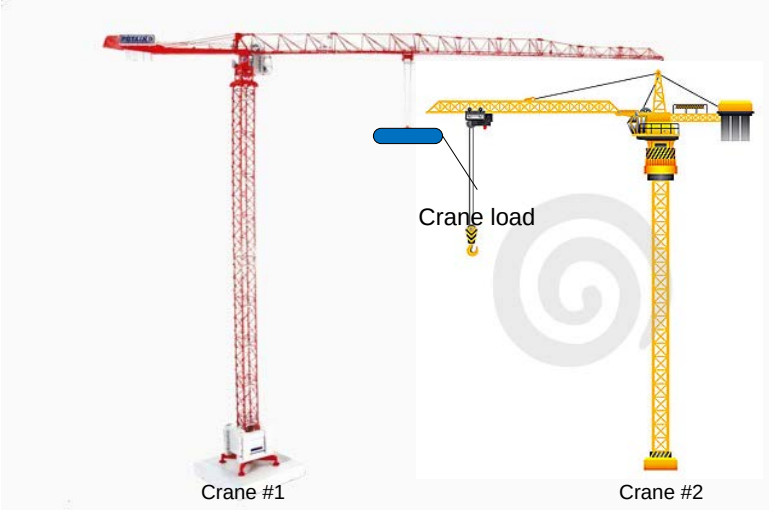
9-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?

9-2. How do you define the boundary of this dangerous area?

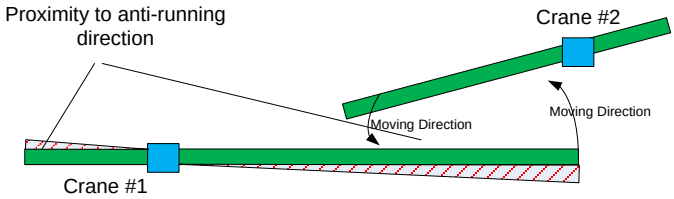
9-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #10 for two cranes – proximity to the anti-running direction

Figure A.10 shows the top view and side view of two tower cranes. Cranes' booms' moving direction is shown in the top view. The shade area is the proximity area to the anti-running direction of crane #1 and is considered dangerous area for crane #2's boom. Please answer the questions on this page.



Side View



Top View

Figure A.10 Proximity to Anti-Running Direction

10-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
10-2. How do you define the boundary of this dangerous area?
10-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #11 for two cranes – proximity to the hook cable and load

Figure A.11 shows the top view and side view of two tower cranes. The blue block stands for crane #1's load. The shade area is proximity area of crane #1's load and hook cable and is considered dangerous area for crane #2's component. Please answer the questions on this page.

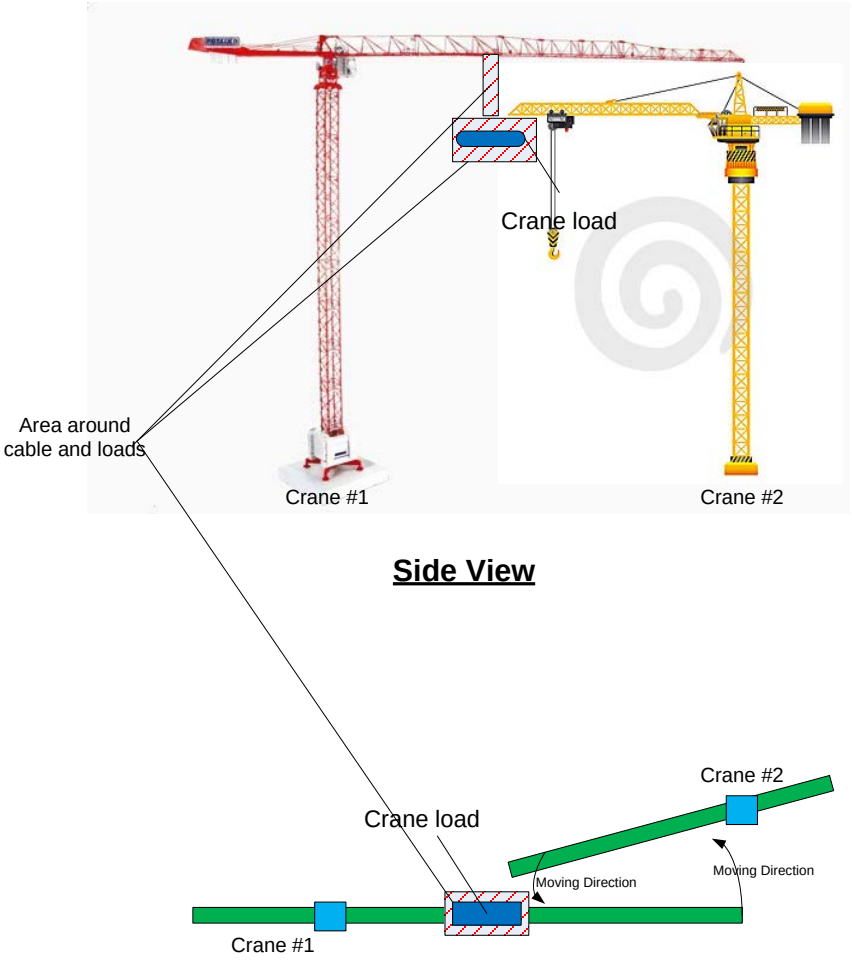
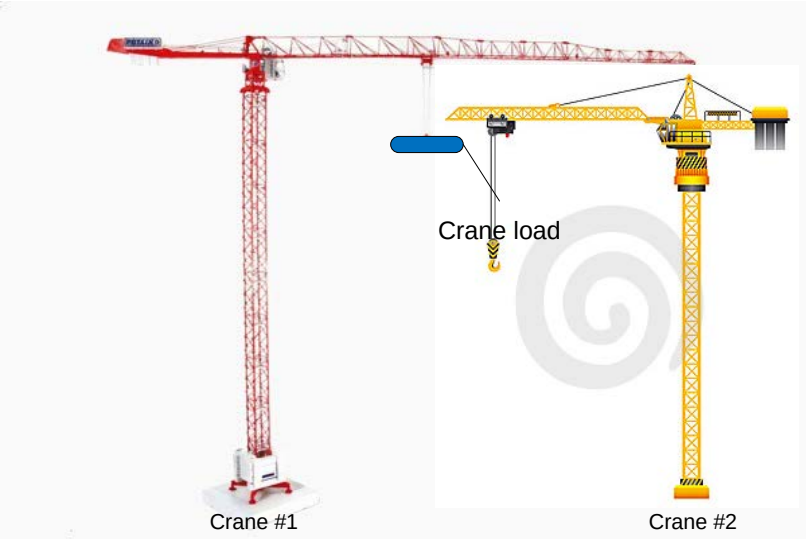


Figure A.11 Proximity to Hook Cable and Load

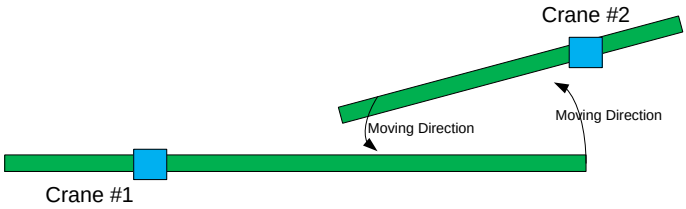
11-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
11-2. How do you define the boundary of this dangerous area?
11-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Dangerous area #12 for two cranes – Others areas you considered to be dangerous

Figure A.12 shows the top view and side view of two tower cranes. Please mark the dangerous area that is not listed above on the figure.



Side View



Top View

Figure A.12 Others Areas You Considered to be Dangerous

12-1. Do you pay attention to this area in daily safety monitoring? If yes, what is your major safety concern for this area?
12-2. How do you define the boundary of this dangerous area?
12-3. What actions will you take if the target (crane's component or worker) enters/is approaching this area?

Wrap up questions

13-1. Below are the top view (Figure A.13) and side view (Figure A.14) pictures of a high rise residential building in downtown Austin area with two tower cranes. Does it remind you any other dangerous areas related to tower crane operations which are not covered above?

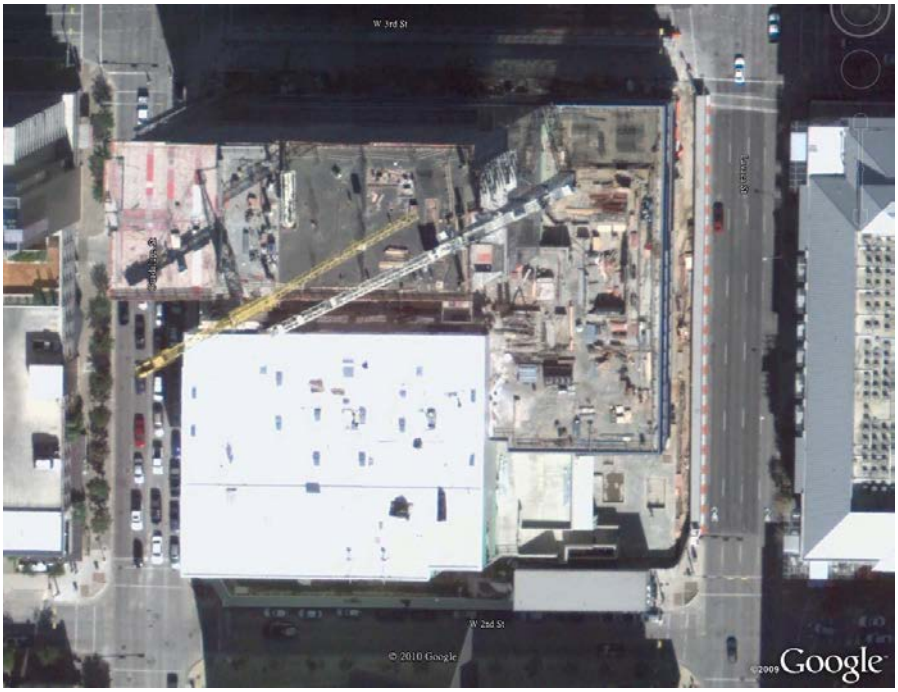


Figure A.13 Top View of a Jobsite in Downtown Austin

Figure A.14 Side View of a Jobsite in Downtown Austin

13-2. Below is a building with a mobile crane on the University of Texas at Austin campus. Does it remind you any dangerous area related to mobile crane operations which are not covered above?

Figure A.15 A Jobsite With Mobile Crane on The University of Texas at Austin Campus

13-3. What other crane related safety concerns do you have, besides dangerous area?
13-4. Do you think the areas have been addressed by existing practice or crane safety systems?
13-5. If not, what is missing and what is the challenge?

A.2 ADDITIONAL DATA COLLECTED FROM THE INTERVIEW

1. Safety concerns regarding crane operations

Crane Type	Safety Concerns
Tower Crane	Crane Collapse Drop materials, for example crane load fall onto labor worker under it Crane collapse, for example boom falls, crane roll over on site (e.g., unstable ground where the crane's triggers/stabilizers are set out)
Mobile Crane	Worker Beijing struck by the counter weight in the swing radius of the crane (like the back end area of the crane). Worker being struck by the load that the crane is handling with

2. Regulations/standards used for crane operations
   - OSHA 1910 Subpart N: Material handling and storage
   - ANSI/ASME B30 Series: Covering cranes, host, lifting system and derricks
   - Operation manuals from the corresponding manufacturers
   - OSHA 1926 in Construction
   - OSHA-2007-0066: Cranes and derricks in construction
   - Incorporate Safety Manuals
   - Other country's regulations depending on where the project is located

3. Information Technologies currently used for Crane Safety Monitoring on the jobsite
   - Lightening detector
   - Electronic scales on crane
   - Load sensor
   - Anti two-blocks sensor
   - Leveler indicator

4. Technology systems that the experts considered to be useful for crane safety monitoring
   - Proximity and voltage sensor to warn operator when the crane is getting too close to the power line
   - Proximity sensor to the structure
   - Proximity system to detect labor working around the swing radius
   - Soil stability
   - Fall protection system
   - Ground condition tracking system

5. Useful Information for crane operation safety monitoring
    - Crane lifting plan, including hazards at each location. For example, if there is any power line nearby, a road nearby, pedestrians nearby, lifting over the buildings, what is the lifting path of the load, how much is the weight and so on.
    - Ground stability (understanding what is there)
    - Obstruction in the area
    - Site conditions and ensure the lift zone is properly barricaded
    - Make sure counterweight is heavy enough

6. Other safety concerns besides the aforementioned ones
    - Qualification and experience of crane operator and rigger
    - Proper crane maintenance
    - Proper rigging specific types of loads

Appendix B Interview Guide on safety working zones at height and collected data

B.1 Interview Guide on Fall Prevention Scenario

The purpose of the interview is to get the knowledge of safe operation in various scenarios to prevent falling from height, as well as the decision rules when unsafe operation appears in these scenarios.

Privacy and Confidentiality Protection

Your participation in this study will be kept confidential to the extent allowed by law. The records of this study will be stored securely and kept confidential. All publications will exclude any information that will make it possible to identify you as a subject.

Name: _____
Title: _____
Name of your company/institute: _____
Years of working experience in safety management:_____
Years of working experience in the construction industry:_____

1. What are the major risks of working at height?

2. Do you agree that worker working too close to open/leading edges might expose himself/herself to the risk of falling from height?
□ Strongly Agree □Moderately Agree □Neutral □Moderately Disagree
□ Strongly Disagree

3. Which of the following regulations/standards are you following to prevent falling from height in US?
□ OSHA 1926 Subpart M Fall Protection
□ ANSI/ASSE Z359 Fall Protection Code Package
□ Best practice publication prepared by industry association or other institute (e.g., Best practice for fall protection in the telecommunication industry prepared by National Telecommunication Safety Panel in 2006). If yes, which one? _____
□ Company's documented safety guideline/rules (_____)
□ Specification of fall protection equipment used on jobsite

□ Others:_____

4. Are you using information technologies (e.g., sensing technology, localization system, computer-aided warning systems) for fall prevention monitoring?

□ Yes, we use the following technologies (multiple choices):

□ GPS

□ RFID

□ Laser Scanner

□ Company customized safety system (_____)

□ Sensors (what types of sensors: _____)

□ Others (_____)

□ No, we use traditional non-IT techniques (e.g., warning lines, manual monitoring)

5. What kind of technology/system that you think might be helpful for safety monitoring regarding fall protection? (You can use your imagination, not necessary to be the ones available in market).

6. What do you need to know for executing safety monitoring regarding fall protection on site? Some examples might be:

- If the fall prevention system is working
- If a worker is getting close to falling area, why they expose themselves to the risk of falling
- The worker's location
- The worker's current work/activity

Scenario #1: Fall protection near open edges

Figure B.1 shows a floor (can be top floor or any floor). There is an opening at the left edge of the floor (see blank section in the figure). Assuming that this floor is at least 6 or 4 feet higher that the adjacent platform/floor. Please answer the questions below:

Figure B.1 Area Near an Open Edge at One Side of the Floor

General Questions

2-1. What are the risks about working near the open edges?

2-2. How do you manage these risks in your practice?

Situation #1-1 Protected open edge

2-3. Do you use a warning line to keep workers away from open edge?

□ Yes. Seldom

□ No. We never use warning line system.

1) In what situation (e.g., working at flat roof) or when do you use a warning line?
2) What is the requirement of distance between the warning line and the edge?
3) Does the worker need to be warned if he/she is approaching the warning line? If yes, how many feet away should he/she be warned?
4) Is there any worker who is allowed to pass the warning line? If so, who?
5) If an authorized person needs to go over the warning line, is there any action (e.g., tie off) he/she needs to take before going over the warning line?
6) Have you observed any unauthorized worker passing the warning line by purpose or by accident? If so, when? What (e.g., give warning to the worker) should he/she or his/her supervisor do immediately?

7) In the area between the warning line and the open edge, is the risk of falling from height the same or there are several areas with different levels of risks?

2-4. Do you use guardrail system to keep worker away from open edge?
□ Yes □ No
1) In what situation or when do you use guardrail system?
2) What is the distance you used to erect the guardrail system away from the open edge?
3) Does the worker need to be warned if he/she is approaching the guardrail system? If yes, how many feet away should he/she be warned?
4) Who is allowed to pass the guardrail system?
5) If an authorized person wants to go over the warning line? Is there any action he/she needs to take before going over the warning line?
6) If an unauthorized person goes over the warning line? What should he/supervisor do immediately?

2-5. Do you use any other systems/techniques to keep the workers away from the open edge?

<u>Situation #1-2 Unprotected open edge</u>

2-6. Is there any situation (e.g., loading materials) that you will put the guardrail system away or don not use guardrail system /warning lines? If yes, in what situation?

2-7. If guardrail system and the warning line are missing around this open edge, do you think that there is a dangerous area around the open edge, which is an unsafe action without any personal protection equipment?
□ Yes.
○The shape and the size of the area remain the same regardless of the size of the opening. Please describe the area shape and its dimension (or mark it in the figure above)
○Do you think this area's size and shape will changes if the opening's size increases or decreases?
□ No.

2-8. Who would be allowed to work in this area? What personal protection measures should h/she take?

<u>Situation #1-3 With Moving Equipment</u>

2-9. Does the use of moving equipment on the floor will affect your answers above?
□ No.
□ Yes.
○Distance between the open edge and warning line will change. How?
○Shape and Size of the dangerous area near the open edge will change. How?

Scenario #2: Fall protection near holes and floor openings

Figure B.2 shows a worker working near a floor opening. The shade area represents the holes/floor opening, assuming that the lower level next to the hole/opening is at least 6 feet lower than the current floor. Please answer the questions below:

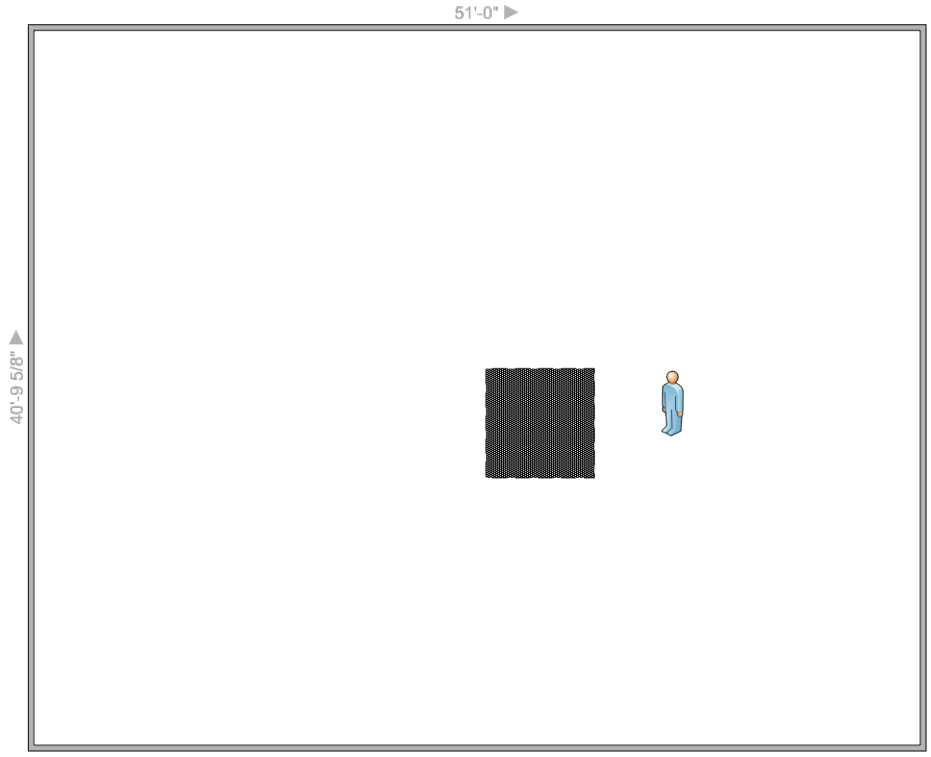


Figure B.2 Area Near a Hole or Floor Opening

Situation #2-1 Hole/floor opening with cover

3-1. When (In what conditions) will you cover the hole/floor opening?

3-2. What are the major risks about working near the covered hole/floor opening?

3-3. How do you mitigate or minimize these risks in your safety practice?

3-4. How to inspect to find that the cover is tightly fixed on the floor? How often do you need to do the inspection?

3-5. Is there any strength requirement for the cover? If yes, what is the strength requirement for the cover? (What is your source?) How do you choose which material to use for the cover?

3-6. Is it allow to step on the cover?

□ Yes.
□ Yes, but not recommended. The worker should avoid stepping on the cover if possible.
□ No. Workers are not allowed to step on the cover.

3-7. Is there any requirement on the elevation of the cover? Or is it required that the cover's top level should be on the same level as the surrounding floor?

□ Yes.
□ No.

Situation #3-2 Floor opening without cover

3-8. When (In what conditions) will you leave the hole/floor opening uncovered?

3-9. What are the major risks about labor working near the uncovered hole/floor opening?

3-10. How do you mitigate or minimize these risks in your safety practice?

3-11. If the hole/floor opening is uncovered, do you use guardrail system, warning line or other fall prevention systems?

□ We use guardrail system.
□ We use warning lines.
□ Others _____
□ None of them.

3-12. Is the requirement of distance between guardrail system/warning line and the opening the same as that of open edge?

□ Yes.
□ No. What is the difference and why there is such a difference?

3-13. Is there any situation that you will put the guardrail system away or don't use guardrail/warning line? If yes, in what situation?

3-14. If guardrail system and warning line is missing around this opening, do you think that there is an area around the opening, entering which is an unsafe action without any personal protection equipment?

□ Yes. If yes, please mark the area in the figure above and note the dimensions of this area

□ No.

3-15. Do you think it would be safe to work in the marked area with appropriate personal protection equipments?

□ Yes. What PPEs should be carried by the worker? _____

□ No. Why?

Situation #3-3 Multiple workers working near the uncovered opening

3-16. Do you think multiple workers working near the uncovered opening (e.g., a worker is handling materials while the other worker is working near him/her) will change the clearance between the edge of the opening and the guardrail system? If yes, what is the change and why there is such a change?

3-17. Do you think multiple workers working near the uncovered opening (e.g., a worker is handling materials while the other worker is working near him/her) will change the restricted area of unauthorized access? If yes, what is the change and why there is such a change?

Situation #3-4 With moving equipments near the uncovered opening

3-18. Do you think moving equipments near the uncovered opening will change the clearance between the edge of the opening and the guardrail system? If yes, what is the change and why there is such a change?

3-19. Do you think moving equipments near the uncovered opening will change the restricted area of unauthorized access? If yes, what is the change and why there is such a change?

Thinking the fall protection from the worker's perspective

Till now, we look at the fall prevention by defining dangerous areas and constrain labor's access to these areas to prevent fall-related accidents. In this section, we propose a different viewpoint to look at the fall prevention by defining a dynamic moving project area around the worker.

More specifically, we define an area as a set of positions that the worker might travel before he/she actually stops after realizing the dangerous situation/hazard. If this area intersects with the opening or open edge, we conclude that the worker might be in an unsafe condition. Otherwise, the worker is in a safe condition.

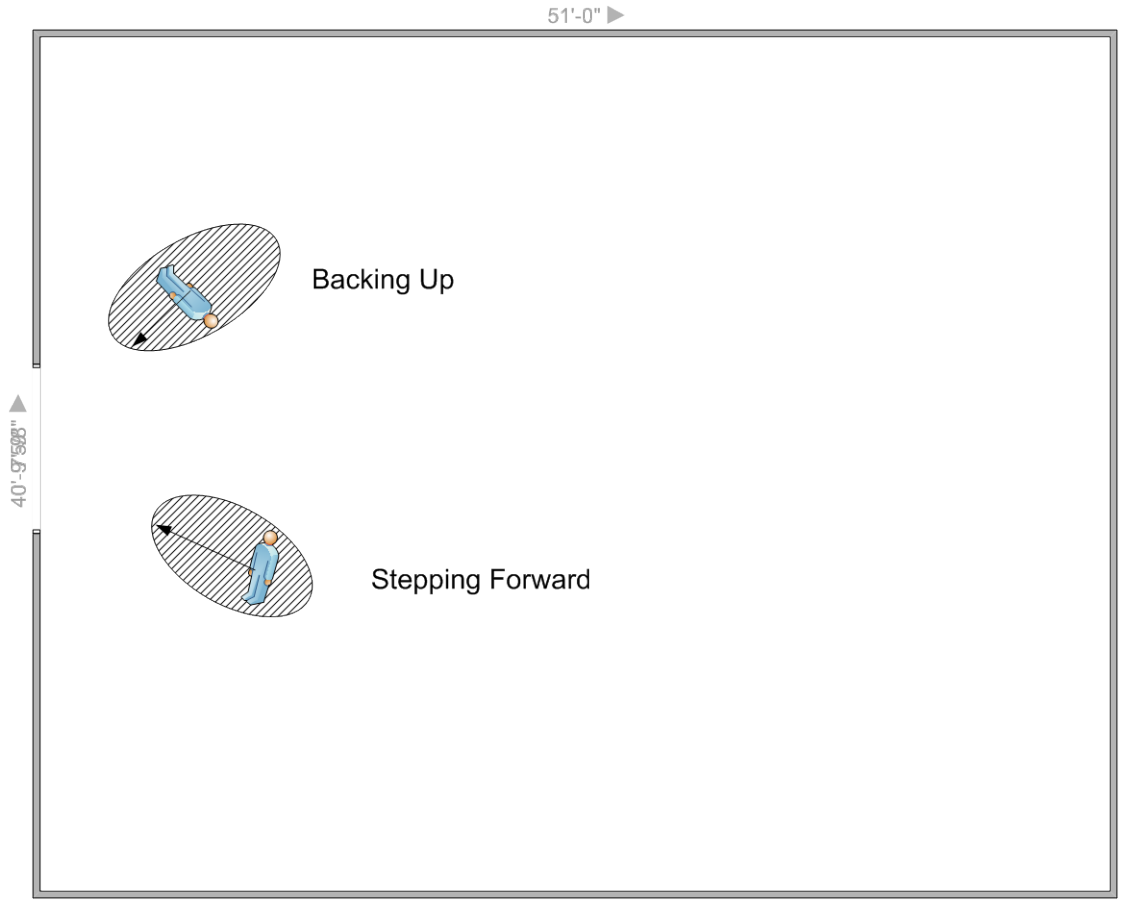


Figure B.3 A Different View of Fall Prevention From Worker's Perspective

4-1. Do you think this approach is appropriate as a supplement to existing physical protection systems (e.g., guardrail system, fall arrest system)?

□ Yes.

□ No. Explain your reason.

4-2. What do you think the shape of the projected area should look like? (e.g., circle, sector, rectangle, triangle…). Or you can draw the shape in figure 4.Please make justification on your answer.

4-3. Which of the following factor(s) do you think might affect the dimension of the area? Why or how does it affect the area's dimension?

□ Worker's current speed
□ Worker's response time (between he sees the danger and the brain is signaled)
□ Worker's stopping time (between the brain signals stop and the worker stops)
□ Worker's height
□ The floor condition (e.g., if the floor is wet or dirty)
□ If there is moving equipment nearby
□ If there is other labor working around
□ Worker's moving direction
□ Others

4-4. If the area you identified does not intersect with the open edge, we conclude that the worker is in a safe condition without any PPEs for fall protection. Do you agree or not?

□ Yes
□ No. Why?

Wrap up questions

5-1. What other risks regarding fall protection do you have besides these mentioned above?

5-2. How do you manage these risks in your current practice?

5-3. Do you see any challenge in your practice? If so, can you give us details?

B.2 OTHER INFORMATION COLLECTED FROM THE INTERVIEW

1. Major Risks of falling from height
   - Failure to tie off
   - Working too close to open edges
   - Working near leading edges
   - Falling from the ladders
   - Worker is not familiar with the safety requirements
   - Worker being unaware of the dangers around or Beijing distracted, loses his/her balance and falls from the points

2. Regulations/Standards followed
   - OSHA 1926 Subpart M Fall Protection and Subpart R Steel Erection
   - ANSI/ASSE Z359 Fall Protection Code Package
   - Company's best practice
   - Country-specific requirements
   - Regulations required by local agencies

3. What techniques you think might be useful for fall protection
   - Self-diagnose system on fall prevention equipment itself, telling that whether it's in proper working condition
   - Audible indoor visible cue, if anyone enter the area that requires fall protection and if he is not connected to retrain/arrest system properly.

4. What information you need to know for fall prevention
   - Type of fall hazards
   - Type of fall prevention equipment
   - Type of training the worker has
   - Culture of the company he works in
   - If there is a union or not
   - Effectiveness of safety supervision
   - Clearance level of fall
   - Location of anchor point
   - Radius that you allow the worker to travel
   - The worker's location and working area

5. Other challenges in fall protection
   - Establishing rescue plan: if someone falls, how to get him/her back

6. Factors affecting the dimension of a worker's stopping area:
    - Worker's current speed
    - Worker's response time
    - Worker's stopping time
    - Worker's height
    - The floor condition
    - If there is moving equipment nearby
    - If there is other labor working around
    - Worker's moving direction
    - Worker's age and experience
    - Company's safety culture

Appendix C Documents for System Development

C.1 COMPONENT REGISTRY

The component registry in this section described the component listed Table 4 (chapter 4) in details. Each component has inputs and outputs. The pseudocode of each component illustrated the reasoning mechanism within the component and is used for component implementation. The components can be extended and customized according to the new requirements.

Table C.1 Common Component Registry in the Autonomous Safety Monitoring System

Component	Sub-component	Page
Localization	Distance Calculation	204
	Localization based on Triangulation	205
	Location information retrieval	205
Dangerous Area Calculation	Crane load dimension retrieval	205
	Facility parameter acquisition	206
	Target type identification	206
	Edge information retrieval	206
	Dangerous area generation	207
Object's Relationship to Dangerous Area Checking	Point to Point Checking	207
	Point to Area Checking	208
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Distance Calculation

Input:

Timestamp of the start of the RF message; timestamp of the arrival of Ultra Sonic signal at the listener; temperature sensed at the listener; temperature sensed at the beacon

Output:

Distance between the listener and the beacon

Pseudocode:

The intent of this component is to calculate the distance between the cricket mote and the beacon.

Initialize the component and reset all variables to default value
T = the average temperature of listener's reading and beacon's reading
Calculate the time interval (Δ_t) between the start of the RF message and the arrival of the Ultra Sonic signal at the listener
Distance = 20.5 x $\sqrt{T}x\Delta_t$
End Distance Calculation

Localization based on Triangulation

Input:
List of 2-tuple (beacon's id, distance between beacon and listener)
Output:
Listener's coordinate
Pseudocode:
The intent of this component is to calculate the listener's coordinate using triangulation algorithm, the component can be customized with other localization algorithms.
Initialize the component and reset all variables to default value
Scan the points in the grid and records the counts of its appearance within the detected distance to the beacons.
If the max count is less than 3, output missing dat;
Otherwise, set k = max of counts;
Average the coordinates for points with counts = k;
Listerner's coordinate = average value.
End Triangulation.

Location information retrieval

Input:
Target's id
Output:
Target's location
Pseudocode:
The intent of this component is to retrieve the target's location information.
Get the target's class type using target's id;
Return target's location information;
End location information retrieval component

Crane load dimension retrieval

Input:
Crane id
Output:
Crane load's largest dimension
Pseudocode:
The intent of this component is to retrieve the largest dimension of the crane load.
Initialize the component and reset all variables to default value;
Retrieve the hook id based on the crane id;
Retrieve the load id based on hook id;

Get the three dimensions (a,b,c) of the load and return the max(a,b,c);
End crane load dimension retrieval component.

Facility parameter acquisition

Input:
Facility id
Output:
Varies depending on facility's type
Pseudocode:
The intent of this component is to retrieve the facility's paramter.
Initialize the component and reset all variables to default value;
Retrieve the facility's type using facility id;
switch (facility type){
case that facility is power line: return voltage;
case that facility is transportation line: return thickness;
case that facility is building: return if underconstruction;
}
End facility parameter acquisition component;

Target type identification

Input:
Target's id
Output:
Target's type
Pseudocode:
The intent of this component is to identify the target's type (e.g., crane load, crane component or worker).
Initialize the component and reset all variables to default value;
Retrieve target's id;
Return target's type;
End target type identification component.

Edge information retrieval

Input:
Floor id;
Output:
Open edges;
Pseudocode:
The intent of this component is to calculate the open edges on a given floor;
Initialize the component and reset all variables to default value;
Retrieve the boundary of the floor;
Retrieve the protection information of each line segment on the floor boundary;
Append the line segments without proper protection measures to the unprotected edge variable;
Return the value of unprotected edge variable;
End edge information retrieval component.

Dangerous area generation

Input:

Crane id, facility id, floor id

Output:

Red zones and yellow zones

Pseudocode:

The intent of this component is to calculate the dangerous area;
Initialize the component and reset all variables to default value;
// For dangerous area under crane load
Retrieve the crane load's location, load's largest dimension;
Radius of redzone = load's largest dimension;
Radius of yellowzone = radius of redzone + clearance distance;
// For dangerous area in proximity to power line
Retrieve the clearance distance and center line of power line;
Use the center line as central axis and the clearance distance as the width and height to create a box as red zone for crane component and crane load;
Use the center line as the center line of rectangle base, clearance distance as the width of rectangle base, and a large enough number (e.g., 9999) as the height to create a box as the yellow zone for crane load.
// For dangerous area in proximity to transportation line
Retrieve the center line and thickness of transportation line;
Create a rectangle with the transportation line's center line and thickness as width;
Use the rectangle as base and a large enough number (e.g., 9999) as the height to create a box as red zone for crane load;
*Create a rectangle b with the transportation line's center line and (thickness + 2*clearance distance) as width;*
Use the rectangle b as base and a large enough number (e.g., 9999) as the height to create a box as yellow zone for crane load;
// For dangerous area in proximity to occupied building
Retrieve the bounding box of occupied building;
Create a box with a clearance distance to the retrieved building's bounding box and set it as the red zone for crane's component;
Create a rectangle the same as the building's base and set it as the red zone for crane load;
Extend a clearance distance out of the building's base and set it as the yellow zone for crane load;
End dangerous areas generation component.

Point to Point Checking

Input:

Point 1, point 2, and clearance distance

Output:

Safety status

Pseudocode:

The intent of this component is to test if two points are getting too close and create an unsafe situation;

Initialize the component and reset all variables to default value;

Calculate the distance between these two points;

If distance <= clearance distance, return dangerous situation message;

Otherwise, return safe situation message;

End point to point checking component.

Point to Area Checking

Input:

Point, area

Output:

Safety situation

Pseudocode:

The intent of this component is to test if a point falls into a dangerous area;

Initialize the component and reset all local variables to default value;

Switch (area type){

case that area is rectangle {

use the four corner (A,B,C,D) of the rectangle and the known point (O) to create triangle AOB, BOC, COD, DOA;

Calculate the sum(S) of areas of those four triangles;

Calculate the area of the rectangle;

If the S == area of the rectangle, point is inside the area, return dangerous message;

Otherwise, return safe message;

}

case that area is circle{

Retrieve the center point of the circle and the radius of the circle;

Use the point to point checking component;

}

case that area is circular loop{

Retrieve the center point (CP) of the circle, internal radius (r) and external radius (R);

Calculate the distance (d) from the known point to CP;

If R>d>r, return dangerous message;

Otherwise, return safe message;

}

}

End point to point checking component.

Point to Box Checking

Assumption:

The box's base is in the X-Y coordinate level

Input:

Point, box

Output:

Safety situation

Pseudocode:

The intent of this component is to test if a point falls into a dangerous area of a box;
Initialize the component and reset all local variables to default value;
Retrieve the box's base;
Copy the point's coordinate to a temporary point and replace the z value with the one of the box's base;
Call point to area checking component;
If the temporary point is outside the box's base, return safe situation;
Otherwise, retrieve the z value (Z_{box}) of the box's base and the height (H) of the box;
If (the z value is between Z_{box} and Z_{box} + H, return dangerous situation;
Otherwise, return safe message.
End point to box checking component.

Area to Area Checking

Input:

Area1, Area2 (Assuming Area 1 and Area 2 are on the same X-Y level)

Output:

Intersection message

Pseudocode:

The intent of this component is to test if two areas intersect;
Initialize the component and reset all local variables to default value;
Create a new Boolean type variable intersect;
If both Area1 and Area 2 are rectangles;
Retrieve the different normal vectors (V1, V2, V3, V4) of the edge of area 1 and area 2;
Project all corner points of area 1 and area 2 onto V1, get the reading of those projected points on V1;
For projected points from area 1, get the min value as Min1 and max value as Max1;
For projected points from area 2, get the min value as Min2 and max value as Max2;
if (Min1<Max1<Min2<Max2 or Min2<Max2<Min1<Max1), intersect = false;
Otherwise intersect = true;
Repeat the V2, V3, V4;
If intersect = true, they intersect;
Else they do no intersect.
Else if both areas are circles;
Retrieve the center of these two circles and the radius of these two circles;
Calculate the distance of these two centers;
If distance < sum of two radius, intersect;
Else they do not intersect;
Else if one is rectangle and the other is circle.
Similar to the comparison of two rectangles collision checking.
End area to area checking.

Area to Box Checking

Input:

Area, Box

Output:

Intersection message

Pseudocode:

The intent of this component is to test if the area intersects with the box;
Initialize the component and reset all local variables to default value;
Get the base rectangle of the box;
Call area to area checking component;
End area to box checking component.

Belonging control area calculation

Input:

Worker id

Output:

The control area that the worker is located.

Pseudocode:

The intent of this component is to judge which control area the worker is in now;
Initialize the component and reset all local variables to default value;
Retrieve all the dangerous areas near open edges and dangerous areas under crane loads;
Call point to area checking component;
If the worker is within any of the dangerous area, return the dangerous area's affiliation's id;
Else return null;
End Belonging control area calculation.

Authorization list generation

Input:

Dangerous area

Output:

Authorization worker's list

Pseudocode:

The intent of this component is to retrieve or develop the authorized worker list in this area;
Initialize the component and reset all local variables to default value;
Retrieve the dangerous area's ID;
Retrieve the authorized worker's list or authorized worker's type;
If authorized worker's list is not predefined, retrieve the activities id in this area and retrieve the list of workers who are assigned with those activities.
End authorization list generation component.

Comparison to the authorization list

Input:

Worker's id, authorization list

Output:

Message indicating if the worker is authorized

Pseudocode:

The intent of this component is to compare the worker to the authorization list to determine if the worker is on the authorization list;

Initialize the component and reset all local variables to default value;

Traverse the values in the authorization list and compare them with the worker's id;

If a match is found, the worker is on authorization list;

Else the worker is not on the authorization list;

End comparison to the authorization list component.

Required PPE list generation

Input:

Area id

Output:

Required PPE list

Pseudocode:

The intent of this component is to retrieve the required PPE list;

Initialize the component and reset all local variables to default value;

Retrieve the required PPE list attached to the dangerous area;

Return the required PPE list;

End Required PPE list generation component.

Carried PPE information retrieval

Input:

Worker's id

Output:

Carried PPE list

Pseudocode:

The intent of this component is to retrieve the list of PPEs carried by the worker;

Initialize the component and reset all local variables to default value;

Send out a query to the nearby PPEs;

Filters the return message with signal strength less than a threshold value;

Retrieve the PPEs id from the remaining messages.

Return the PPE list.

End carried PPE information retrieval component.

Comparison of required and carried PPEs

Input:

Required PPE list, carried PPE list

Output:

Missing PPE list

Pseudocode:

The intent of this component is to compare the required PPEs and the PPEs carried by the worker and warn the worker of the missing PPEs;

Initialize the component and reset all local variables to default value;
Traverse the values in the authorization list and compare them with the carried PPEs list;
If any value is not found on the carried PPEs list, print out the missing PPEs.
Else return null;
End comparison of required and carried PPEs component.

C.2 MASTER CLASS DESCRIPTION

The master classes in figure C.1 (described in chapter 4) are described in the following tables. Each table represents a master class corresponding to the one in the figure. The critical fields and methods are given in the tables.

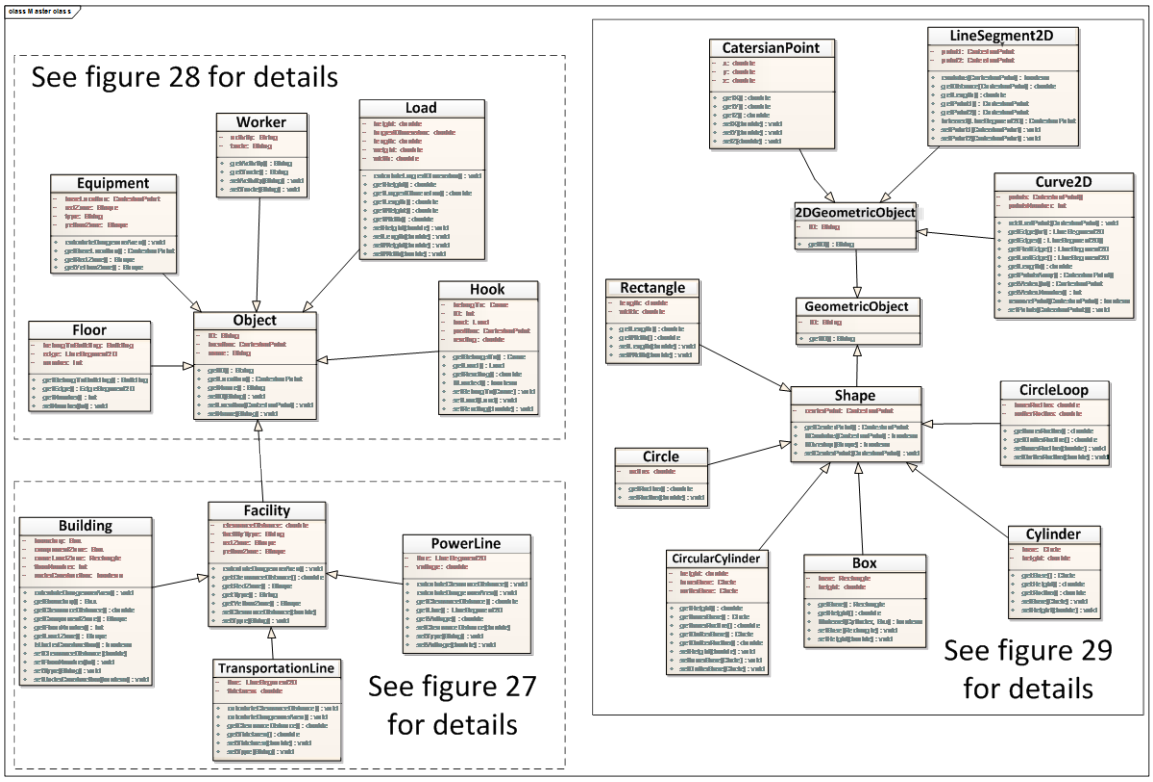

Figure C.1 Master Class Diagram for the System

Table C.2. List of Classes in This Appendix

Class Name	Page
Object	214
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Worker	214
Load	215
Hook	215
Floor	216
Facility	216
PowerLine	216
Building	217
TransportationLine	217
Shape	218

Box	218
CircularCylinder	218
Cylinder	218
CircleLoop	219
Circle	219
Rectangle	219
CartesianPoint	219
LineSegment2D	220
Cuve2D	220

	Value	Description
Class Name	Object	Object is the root of all object classes on the jobsite.
Fields	id	Unique identification of the object
	name	Object's name
	location	The coordinate of the object's centroid
Methods	setID(string)	Set the id of the object to the specific value.
	getID()	Return the id of the object.
	getName()	Return the name of the object.
	getLocation()	Return the coordinate of the object's centroid.
	setLocation(CartesianPoint)	Set the location of the object to the specific coordinate.

	Value	Description
Class Name	Equipment	Equipment representing the machines designed for executing construction tasks on the jobsite.
Fields	type	Equipment's type (e.g., crane, truck)
	yellowZone	The yellow zone of this equipment, if any.
	redZone	The red zone of this equipment, if any.
	basePosition	The coordinate of the centroid of equipment’s base
Methods	calculateDangerousArea()	Calculate the dangerous area related to the equipment
	getYellowZone()	Return the yellow zone of the equipment, if any.
	getRedZone()	Return the red zone of the equipment, if any.
	getBasePosition()	Return the coordinate of the centroid of the equipment's base

	Value	Description
Class Name	Worker	A worker representing a human body on the jobsite.
Fields	trade	The trade that the worker belongs to, the value should be one of the value in a trade table predefined by the jobsite
	activity	The activity that the worker is assigned to.
Methods	setTrade(string)	Set the value of trade the worker belongs to.
	getTrade()	Return the worker's trade.
	setActivity(string)	Assign an activity to the worker
	getActivity()	Return the activity assigned to the worker

	Value	Description
Class Name	Load	A load representing the objects carried by the crane's hook. For simplification, a bounding box is used to represent the boundary of the load.
Fields	weight	The weight of the load.
	length	The longest horizontal dimension of the load's bounding box.
	width	The shortest horizontal dimension of the load's bounding box.
	height	The vertical dimension of the load's bounding box.
	largest dimension	The largest horizontal distance from any point of the load to the connection point to the hook.
Methods	setWeight(double)	Set the value of the load's weight as the specific value.
	getWeight()	Return the load's weight.
	setLength(double)	Set the value of the load's length as the specific value.
	getLength()	Return the load's length.
	setWidth(double)	Set the value of the load's width as the specific value.
	getWidth()	Return the load's width.
	setHeight(double)	Set the value of the load's height as the specific value.
	getHeight()	Return the load's height.
	getLargestDimension()	Return the load's largest horizontal dimension.
	calculateLargestDimension()	Calculate the largest horizontal dimension based on the load's geometry parameters.

	Value	Description
Class Name	Hook	A hook representing the device attached to the crane, used to carry the load.
Fields	belongsTo	The crane that this hook belongs to.
	load	The load that this hook carries.
	reading	The hook's reading of the load it carries.
	position	The 3D coordinates of the hook.
	id	The unique id of the hook.
Methods	setBelongsTo(Crane)	Set the value of crane that the hook associates to.
	getBelongsTo()	Return the instance of crane that the hook associates to.
	setLoad(Load)	Set the value of the load that the hook is carrying.
	getLoad()	Return the instance of load that the hook is carrying.
	setPosition(CartesianPoint)	Set the position of the hook to a specific Cartesian point.
	getPosition()	Return the coordinate of this hook.
	setReading(double)	Set the load reading at the hook to the specific value.
	getReading()	Return the load reading from this hook.
	ifLoaded()	Return the Boolean value indicating if the hook is loaded or not.
	setID(string)	Set the id of this hook to the specific value.
	getID()	Return the unique id of this hook.

	Value	Description
Class Name	Floor	A floor representing the story in a building that could be used by people.
Fields	belongsToBuilding	The building that this floor belongs to.
	number	The floor number that this floor located in the building.
	edge	The boundary of the floor.
Methods	getBelongsToBuilding()	Return the building that this floor belongs to.
	setNumber(int)	Set the floor number of this level to the specific value.
	getNumber()	Return the floor number of this level.
	getEdge()	Return the boundary (series of EdgeSegement2D) of this floor.

	Value	Description
Class Name	Facility	A facility representing fixed, mobile, or transportable structure on the jobsite.
Fields	facilityType	Facility's type (e.g., power line, railway)
	yellowZone	The yellow zone of this equipment, if any.
	redZone	The red zone of this equipment, if any.
Methods	getType()	Return the facility's type.
	getYellowZone()	Return the yellow zone of the equipment, if any.
	getRedZone()	Return the red zone of the equipment, if any.
	calculateDangerousArea()	Calculate the dangerous area related to the equipment

	Value	Description
Class Name	PowerLine	A powerline representing an electric power transmission line suspended by tower or utility poles.
Fields	voltage	The nominal voltage of this power line (in kV).
	line	The center line of the power line.
	clearanceDistance	The safety distance that the crane component should keep away from this power line.
	yellowZone	The yellow zone of this equipment, if any.
	redZone	The red zone of this equipment, if any.
Methods	setVoltage(double)	Set the nominal voltage of this power line to the specific value.
	getVoltage()	Return the nominal voltage of this power line.
	setClearanceDistance(double)	Set the clearance distance of this power line to the specific value.
	getClearanceDistance()	Return the clearance distance of this power line.
	calculateClearanceDistance()	Calculate the clearance distance of this power line based on its voltage.
	getYellowZone()	Return the yellow zone of the equipment, if any.
	getRedZone()	Return the red zone of the equipment, if any.
	getLine()	Return series of LineSegement2D representing the power line's geometry characteristics.

	Value	Description
Class Name	Building	A building representing the structure used to support occupancy, including site offices, buildings under construction and buildings in operation.
Fields	floorNumber	The count of floors in this building.
	underConstruction	A Boolean value indicating if this building is under construction or not.
	clearanceDistance	The clearance distance between the crane component and the building.
	boundary	The projection of the building's bounding box on horizontal level.
	componentZone	The dangerous zone for crane component. Crane component may not enter this area.
	craneLoadZone	The dangerous zone for crane load. Crane load may not enter this area
Methods	setFloorNumber(int)	Set the count of floors in this building to the specific value.
	getFloorNumber()	Return the count of floors in this building.
	setUnderConstruction(boolean)	Define if the building is under construction according to the specific value.
	isUnderConstruction()	Return if the building is under construction.
	setClearanceDistance(double)	Set the clearance distance to the specific value.
	getClearanceDistance()	Return the clearance distance of this building.
	calculateDangerousArea()	Calculate the dangerous areas for crane load and crane component in proximity to this building.
	getLoadZone()	Return the dangerous area for the crane load.
	getComponentZone()	Return the dangerous area for the crane component.
	getBoundary()	Return the boundary of this building.

	Value	Description
Class Name	TransportationLine	A transportationline representing the fixed installation for transporting people, including roads, railways and water ways.
Fields	line	The center line of this transportation line.
	thickness	The width of this transportation line.
	type	The type of this transportation line. For example, roads, railway and water way.
	clearanceDistance	The clearance distance between the crane component and this transportation line.
	yellowZone	The yellow zone of this equipment, if any.
	redZone	The red zone of this equipment, if any.
Methods	setThickness(double)	Set the width of this transportation line to the specific value.
	getThickness()	Return the width of this transportation line.
	setClearanceDistance(double)	Set the clearance distance of crane operation in proximity to this transportation line to the specific value.
	getClearanceDistance()	Return the clearance distance of this transportation line.
	calculateClearanceDistance()	Calculate the clearance distance for crane operation in proximity to this transportation line.
	calculateDangerousArea()	Calculate the dangerous area for crane component using clearance distance and this transportation line’s geometry parameters.
	getRedZone()	Return the yellow zone of the equipment, if any.
	getYellowZone()	Return the red zone of the equipment, if any.

	Value	Description
Class Name	Shape	The shape provides definitions for objects that represent some form of geometric shape.
Fields	centerPoint	The coordinate of the center of the shape.
Methods	getCenterPoint()	Return the coordinate of the center of this shape.
	setCenterPoint(CartesianPoint)	Set the coordinate of the center of this shape to a specific position.
	ifContains(CartesianPoint)	Test if the specific Cartesian point is inside the boundary of this shape.
	ifOverlap(Shape)	Test if this shape overlaps with the other specific shape.

	Value	Description
Class Name	Box	A box representing a rigid geometry container with a given length, width, and height.
Fields	base	The bottom side of this box.
	height	The height of this box.
Methods	setBase(Rectangle)	Set the base of this box to a specific rectangle.
	getBase()	Return the base of this box.
	setHeight(double)	Set the height of this box to a specific number.
	getHeight()	Return the height of this box.
	ifIntersect(Box, Cylinder)	Test if a specific box intersects with a specific cylinder.

	Value	Description
Class Name	CircularCylinder	A circularcylinder representing a hollow cylinder.
Fields	innerBase	The base of the internal cylinder.
	outterBase	The base of the external cylinder.
	height	The height of this hollow cylinder.
Methods	setOutterBase(Circle)	Set the base of the external cylinder to the specific Circle.
	setInnerBase(Circle)	Set the base of the internal cylinder to the specific Circle.
	setHeight(double)	Set the height of this hollow cylinder to the specific value.
	getInnerBase()	Return the Circle base of the internal cylinder.
	getOutterBase()	Return the Circle base of the external cylinder.
	getHeight()	Return the height of this hollow cylinder.
	getInnerRadius()	Return the radius of the internal cylinder.
	getOutterRadius()	Return the radius of the external cylinder.

	Value	Description
Class Name	Cylinder	A cylinder representing a curvilinear geometry shape with a radius and a height.
Fields	base	The circle as a base of this cylinder.
	height	The height of this cylinder.
Methods	setBase(Circle)	Set the base of this cylinder to a specific Circle.
	setHeight(double)	Set the height of this cylinder to a specific value.
	getBase()	Return the base of this cylinder.
	getHeight()	Return the height of this cylinder.
	getRadius()	Return the radius of this cylinder.

	Value	Description
Class Name	CircleLoop	A circleloop representing an annulus, a ring-shaped geometric object.
Fields	innerRadius	The radius of the internal concentric circle.
	outterRadius	The radius of the external concentric circle.
Methods	setInnerRadius(double)	Set the radius of the internal concentric circle to a specific value.
	setOutterRadius(double)	Set the radius of the external concentric circle to a specific value.
	getInnerRadius()	Return the radius of the internal concentric circle.
	getOutterRadius()	Return the radius of the external concentric circle.

	Value	Description
Class Name	Circle	A circle representing a round shape with a specific radius and center point.
Fields	radius	The radius of this circle.
Methods	setRadius(double)	Set the radius of this circle to a specific value.
	getRadius()	Return the radius of this circle.

	Value	Description
Class Name	Rectangle	A rectangle representing a quadrilateral with four right angles.
Fields	width	The width of this rectangle.
	length	The length of this rectangle.
Methods	setWidth(double)	Set the width of this rectangle to a specific value.
	setLength(double)	Set the length of this rectangle to a specific value.
	getLength()	Return the length of this rectangle.
	getWidth()	Return the width of this rectangle.

	Value	Description
Class Name	CartesianPoint	A CartesianPoint representing a location in (x,y,z) coordinate space.
Fields	x	The x coordinate.
	y	The y coordinate.
	z	The z coordinate.
Methods	setX(double)	Set the x coordinate to a specific value.
	setY(double)	Set the y coordinate to a specific value.
	setZ(double)	Set the z coordinate to a specific value.
	getX()	Returns the x coordinate of this point.
	getY()	Returns the y coordinate of this point.
	getZ()	Returns the z coordinate of this point.

	Value	Description
Class Name	LineSegment3D	A lineSegment3D representing a line segment in (x,y,z) coordinate space.
Fields	point1	The coordinates of the 1st point of this line segment.
	point2	The coordinates of the 2nd point of this line segment.
Methods	setPoint1(CartesianPoint)	Set the 1st point of this line segment to a specific position.
	setPoint2(CartesianPoint)	Set the 2nd point of this line segment to a specific position.
	getPoint1()	Return the 1st point's coordinate.
	getPoint2()	Return the 2nd point's coordinate.
	Contains(CartesianPoint)	Test if the linesegment contains a specific point.
	getDistance(CartesianPoint)	Calculate and return the distance from a specific point to this line segment.
	getLength()	Calculate and return the length of this line segment.
	getMidPoint()	Calculate and return the middle point of this line segment.
	Intersect(LineSgement3D)	Return the intersection point of this line segment to the other specific line segment. If these two line segment don't intersect, return null.

	Value	Description
Class Name	Cuve3D	A curve3D representing a curve making up with several continuous line segments.
Fields	points	List of the start point, turning points and end point in order.
	pointNumber	The counts of curve points in this curve.
Methods	getPointArray()	Return the array of vertex of this curve.
	setPoints(CartesianPoint[])	Set the curve points of this curve to a specific array of Cartesian points.
	addLastPoint(CartesianPoint)	Add a specific Cartesian point to the curve as a new ending point.
	removePoint(CartesianPoint)	Remove the specific point from the curve.
	getEdges()	Return the array of line segments of this curve in order.
	getVertexNumber()	Return the count of vertex on this curve.
	getVertex(int)	Return the nth vertex of this curve.
	getEdge(int)	Return the nth line segment of this curve.
	getFirstEdge()	Return the first line segment of this curve.
	getLastEdge()	Return the last line segment of this curve.
	getLength()	Calculate and return the total length of this curve.

C.3 USE CASE DIAGRAMS

Figure C.2 shows the use case diagram for crane safety monitoring sub-system in the autonomous jobsite safety monitoring system. There are three actors in the use case diagram: safety manager, worker and crane operator. The safety manager is involved in configuring the sensors and system parameter (e.g., setting clearance distance and size of dangerous area, setting sensor sampling frequency), activating and deactivating the safety monitoring system, and reviewing safety reports. The crane operator and the worker are the main actors of the system who benefit most from the system. The crane operator and the worker are involved in monitoring the safety situation and responding to an alarm. The *Monitoring Safety Situation* use case can be decomposed into smaller and more detailed use cases as shown in figure C.3.

The detailed descriptions for the use cases shown in figure C.2 and C.3 are listed below.

Use Case	Configure Sensors and System Parameters
Primary actor	Safety Manager
Goal in context	To set the sensor sampling frequency, revise the system's parameter according to the safety manager's judgment on the jobsite environment
Trigger	The safety manager decided to customize the system to reflect the jobsite's uniqueness
Scenario	1. Safety manager: log in the system administration module. 2. Safety manager: select "sensor configuration" or "customize system parameters" 3. Safety manager: choose the parameter and enter the new value 4. Safety manager: save changes or discard changes 5. Safety manager: log off the system administration module.

Figure C.2 Use Case Diagram for Crane Safety Monitoring System

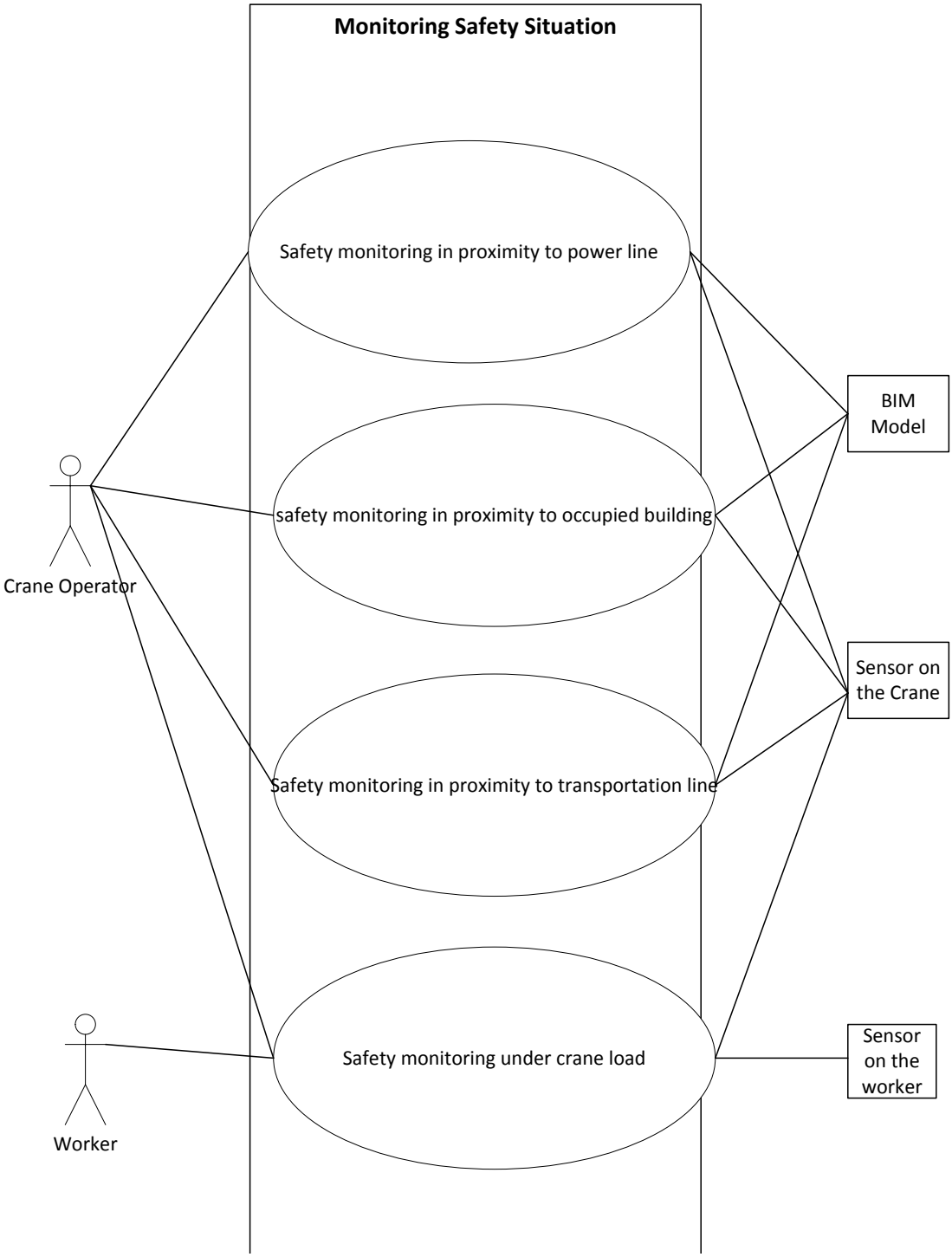


Figure C.3 Use Case Diagram for Monitoring Safety Situation

Figure C.4 shows the use case diagram for proactive fall prevention sub-system in the autonomous jobsite safety monitoring system. There are two actors in the use case diagram: safety manager, and worker. The safety manager is involved in configuring the sensors and system parameter (e.g., setting clearance distance and size of dangerous area, setting sensor sampling frequency), activating and deactivating the safety monitoring system, and reviewing safety reports. The crane worker is the main actor of the system who benefits most from the system.

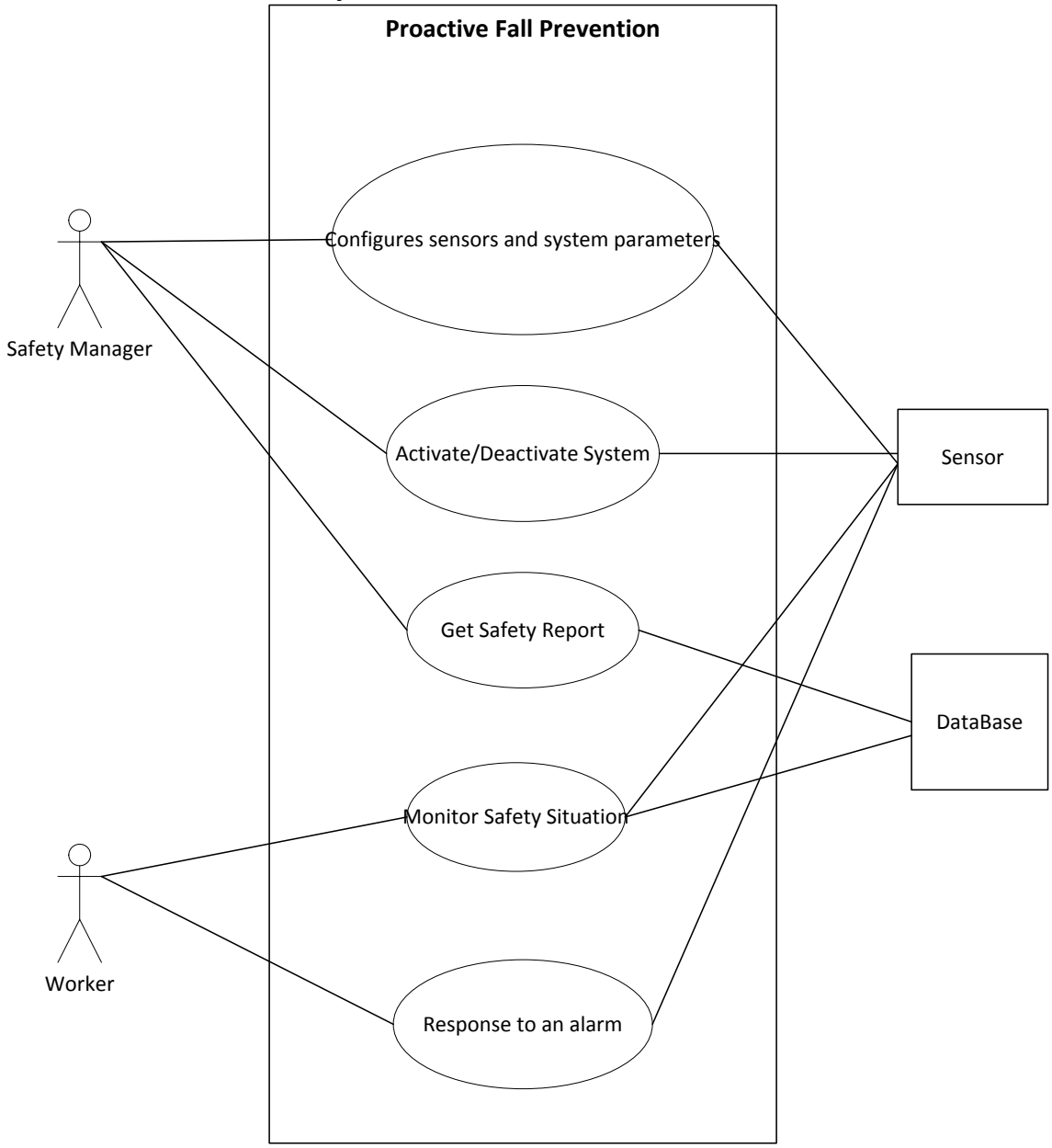


Figure C.4 Use Case Diagram for Proactive Fall Prevention Sub-system

C.4 ACTIVITY DIAGRAMS

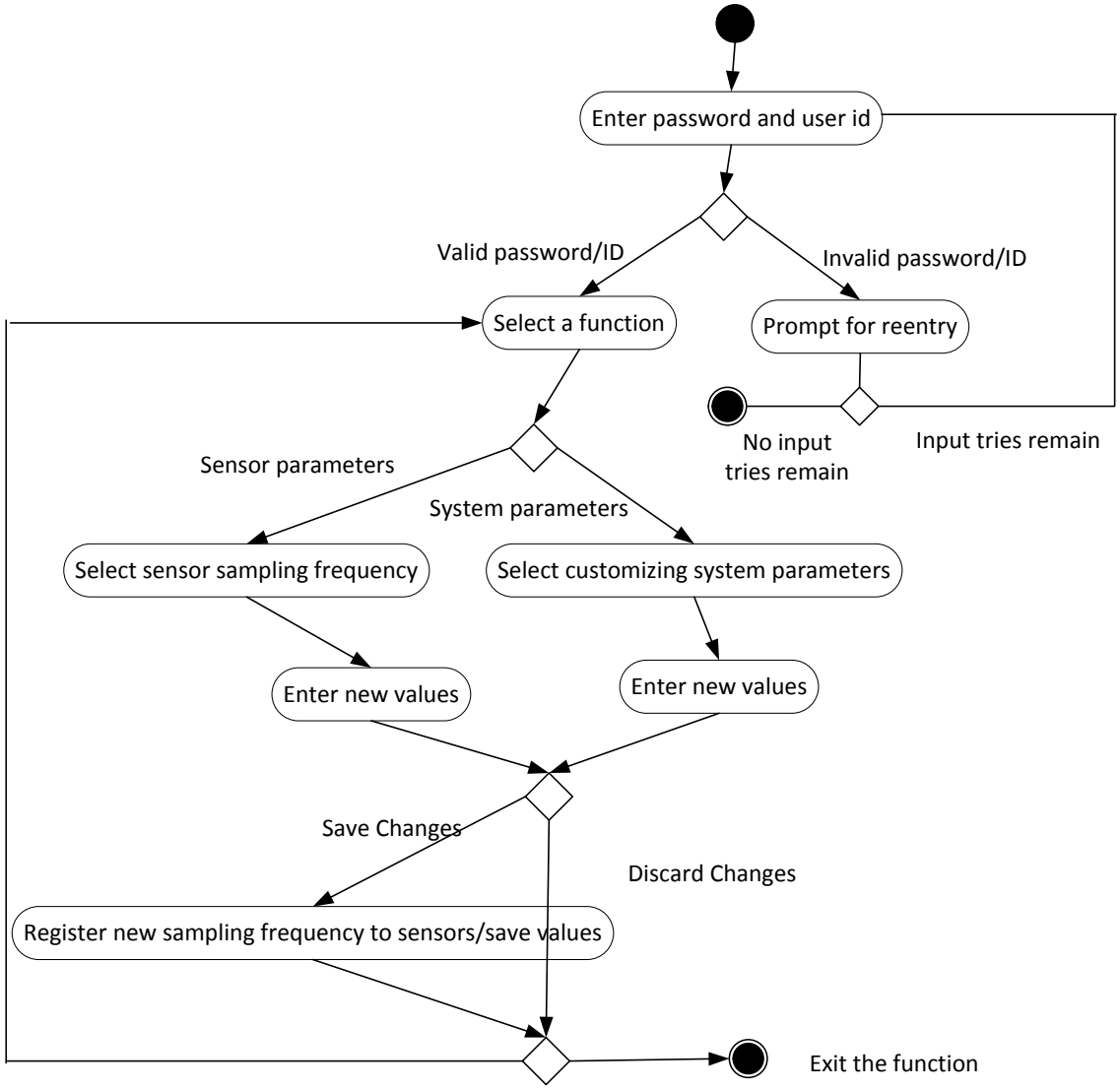


Figure C.5 Activity Diagram for Configuring Sensor and System Parameters

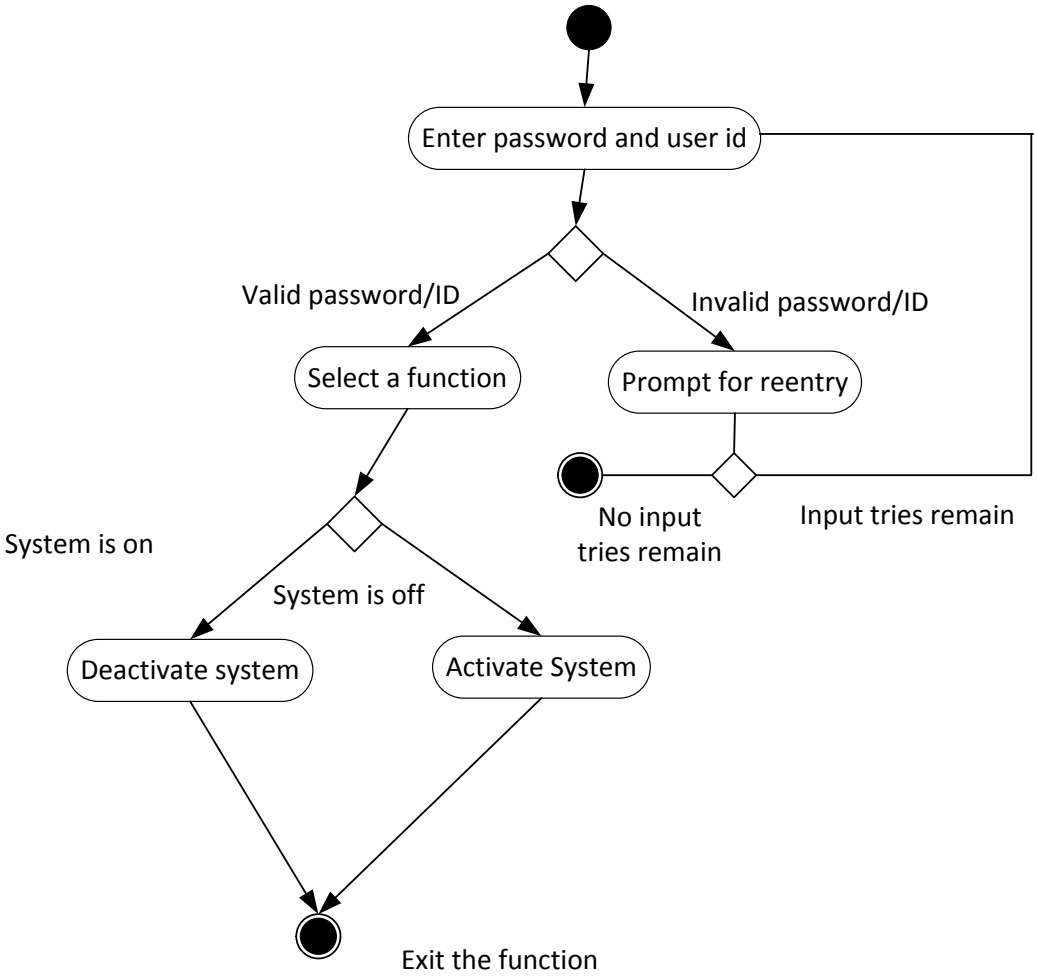


Figure C.6 Activity Diagram for Activating/Deactivating System

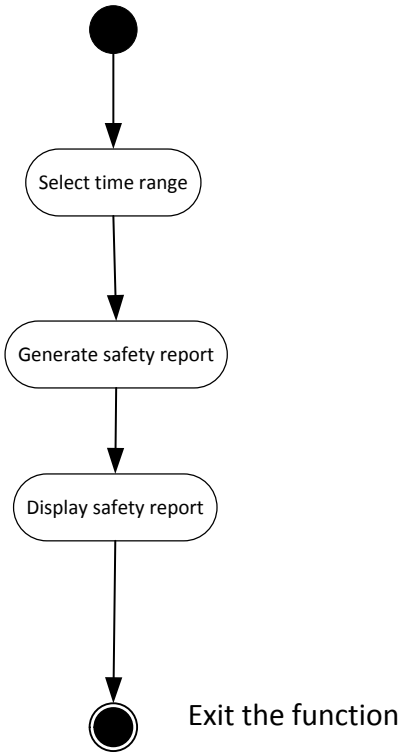


Figure C.7 Activity diagram for getting safety report

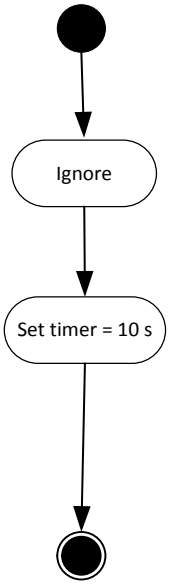


Figure C.8 Activity Diagram for Crane Operator Responding to an Alarm

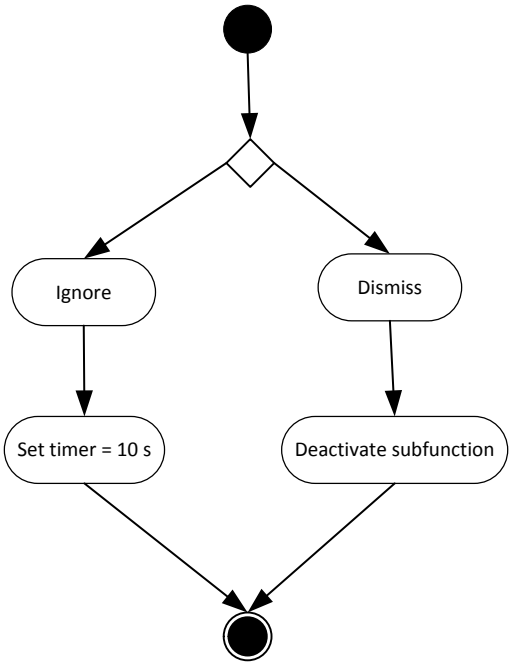


Figure C.9 Activity Diagram for Worker Responding to an Alarm

Figure C.10 Activity Diagram for Safety Monitoring in Proximity of Power Line

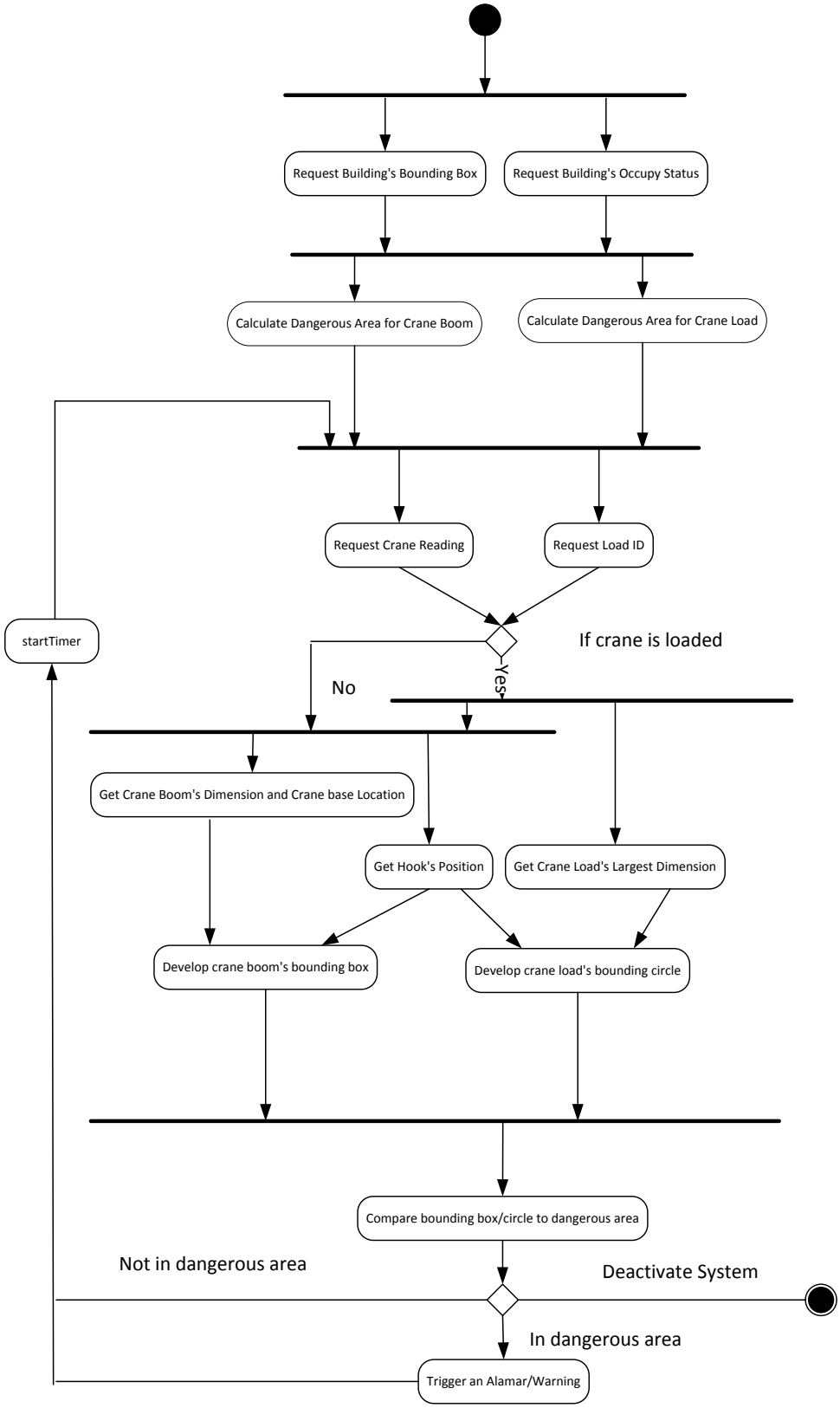


Figure C.11 Activity Diagram for Safety Monitoring in Proximity to Occupied Buildings

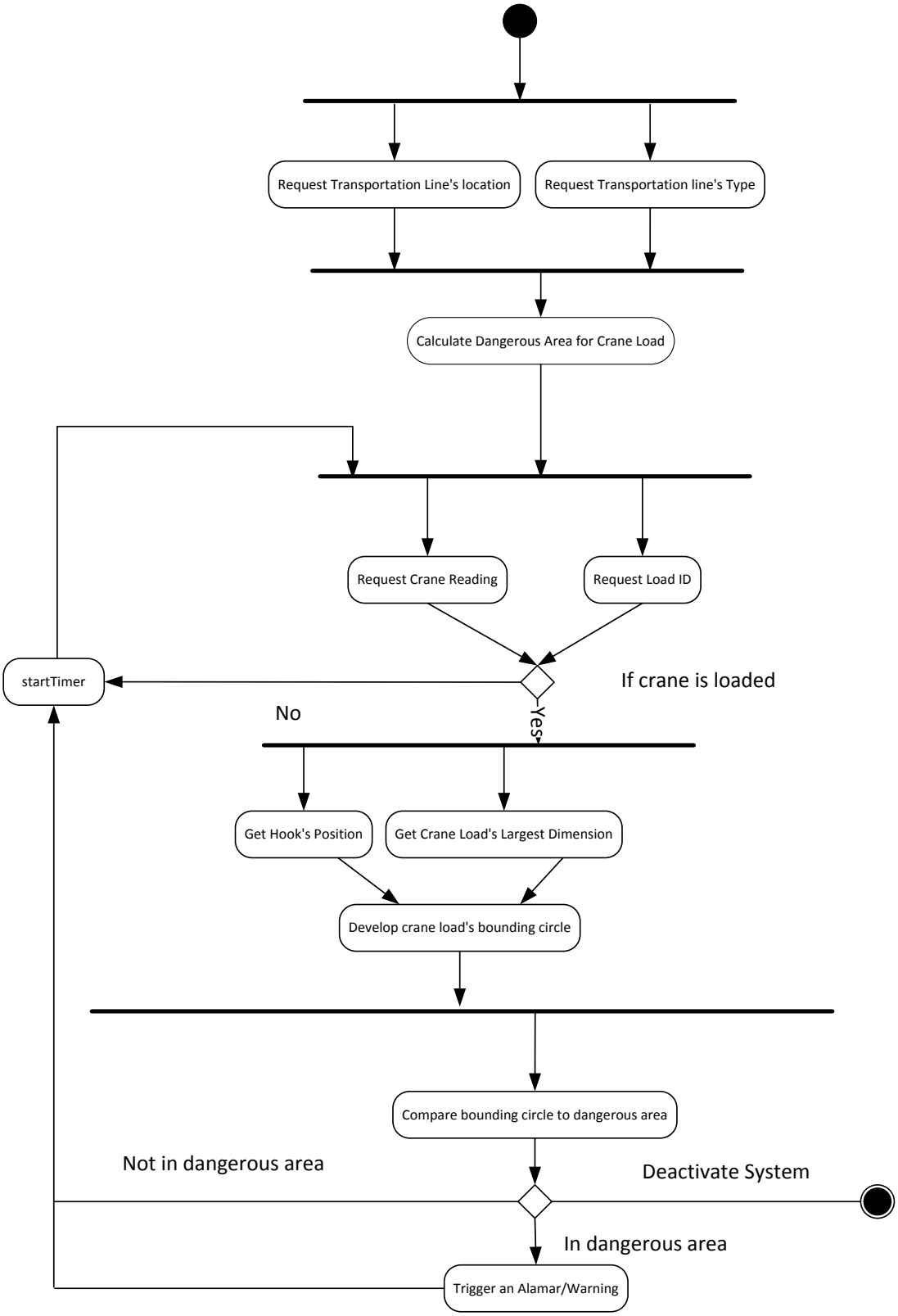


Figure C.12 Activity Diagram for Safety Monitoring in Proximity to Transportation Line

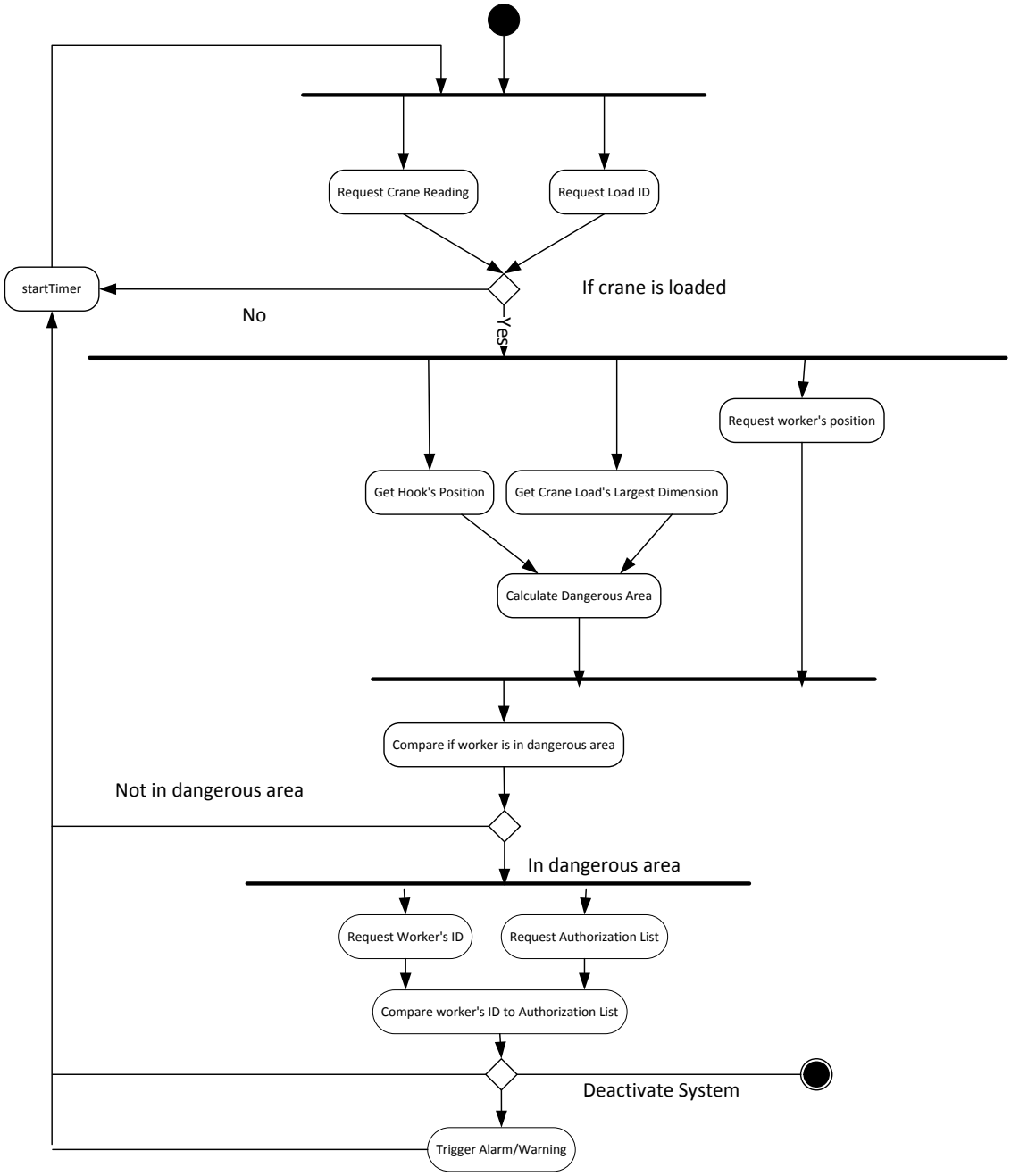


Figure C.13 Activity Diagram for Safety Monitoring Under Crane Load

C.5 SEQUENCE DIAGRAM

Three interaction diagrams are presented here as a supplement to the sample sequence diagram presented in chapter 5. They consists of four objects participating in the three safety monitoring activities: computer mounted on the crane to run crane safety monitoring system, crane hook with localization sensor, crane load with RFID, and the building information models (BIM) stored in the computer database. The sequence diagram was developed based on the information flowchart described in the safety requirements of crane safety monitoring. The messages in the interaction diagram are self-explanatory. It shows how the messages are pushed and pulled across these four objects.

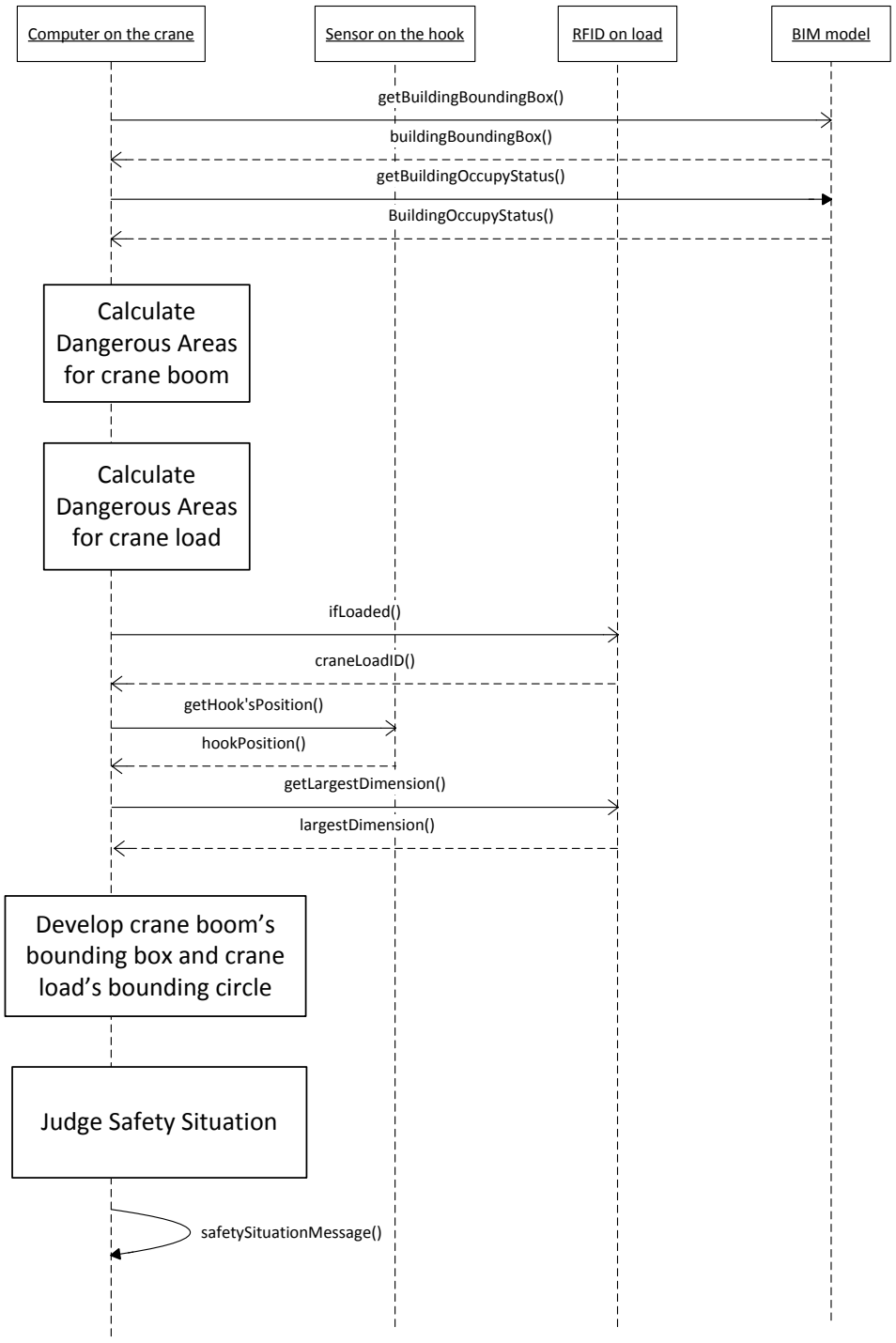


Figure C.14 Sequence Diagram for Crane Safety Monitoring in Proximity of Occupied Building

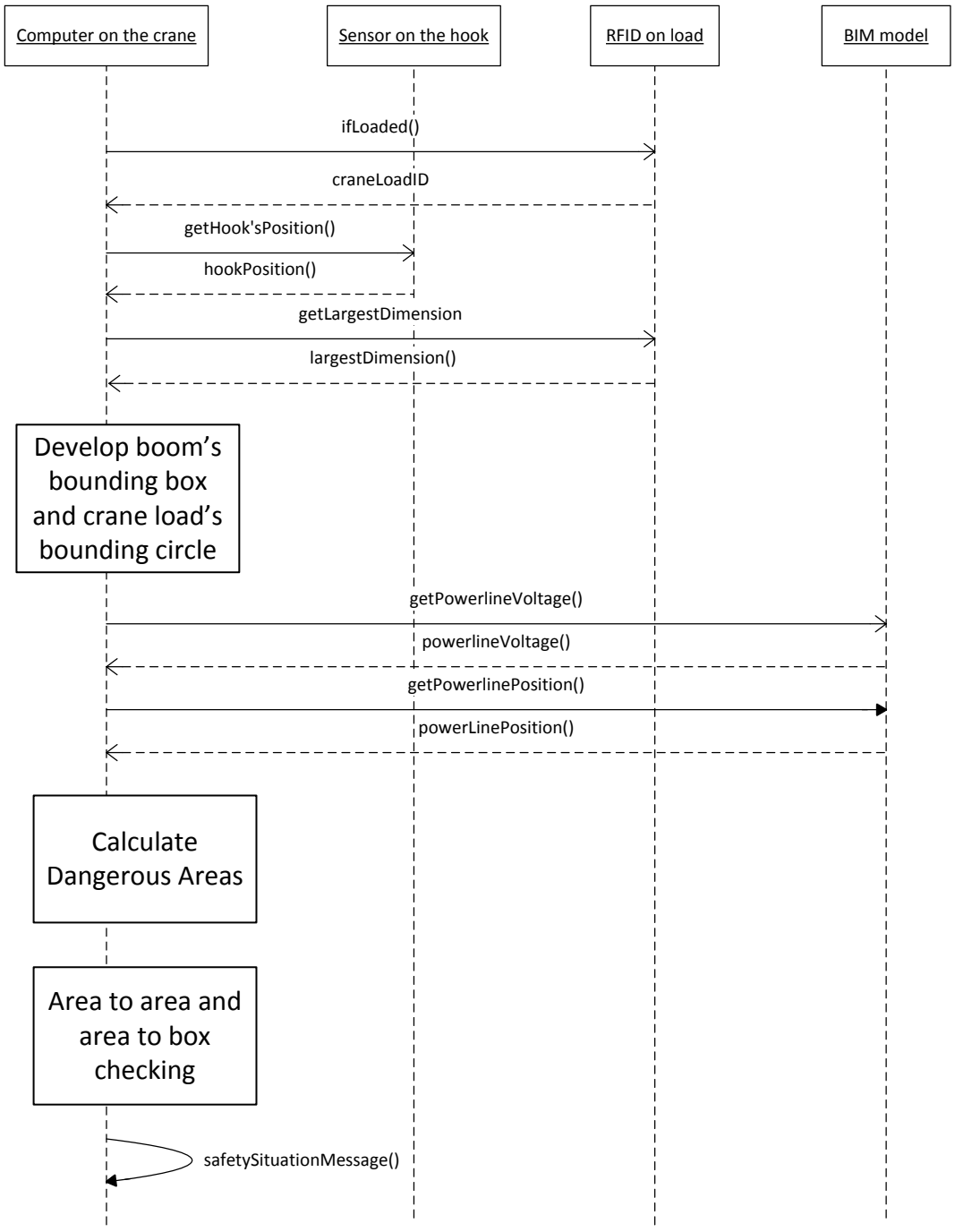


Figure C.15 Sequence Diagram for Crane Safety Monitoring in Proximity of Power Line

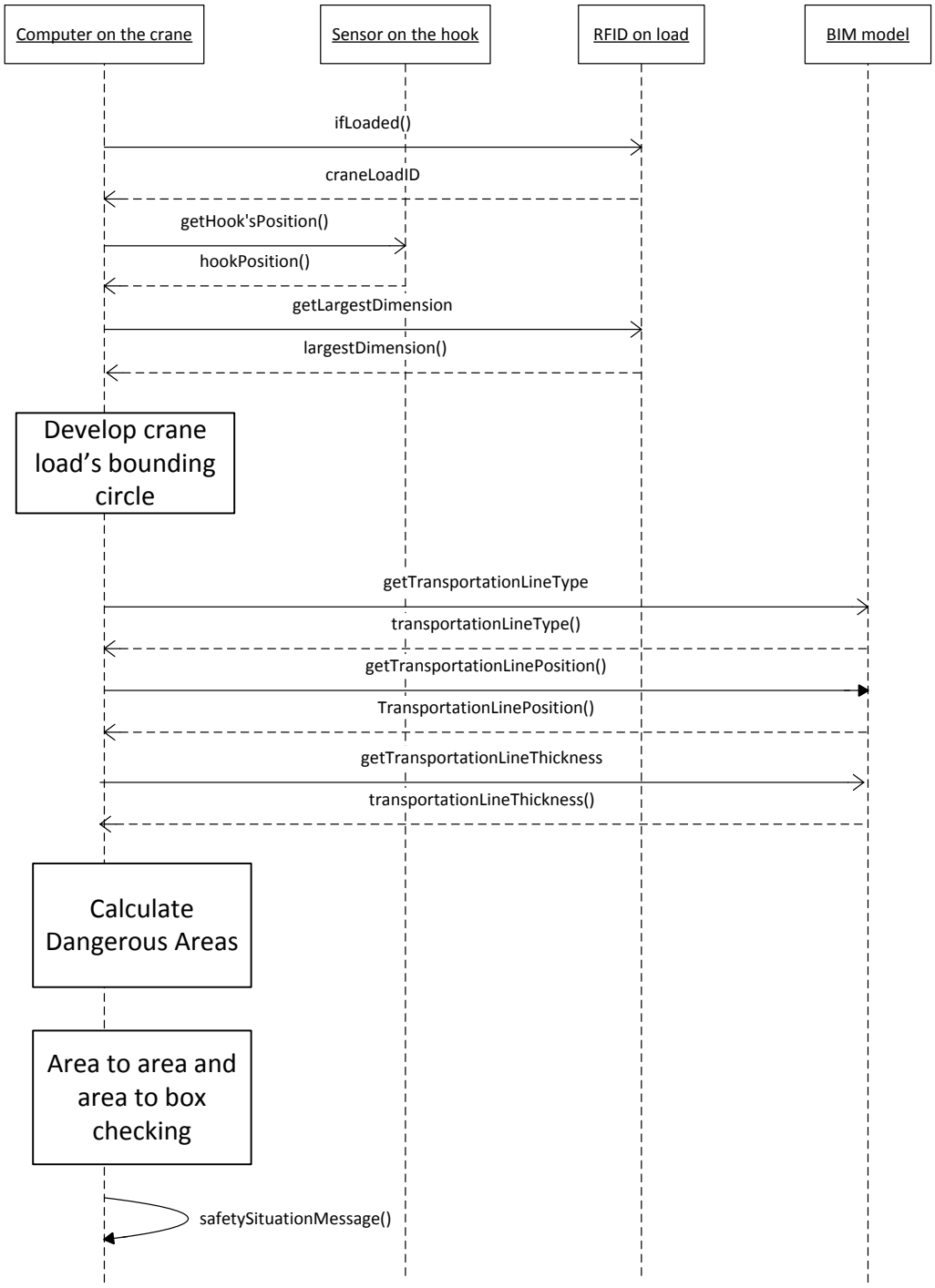
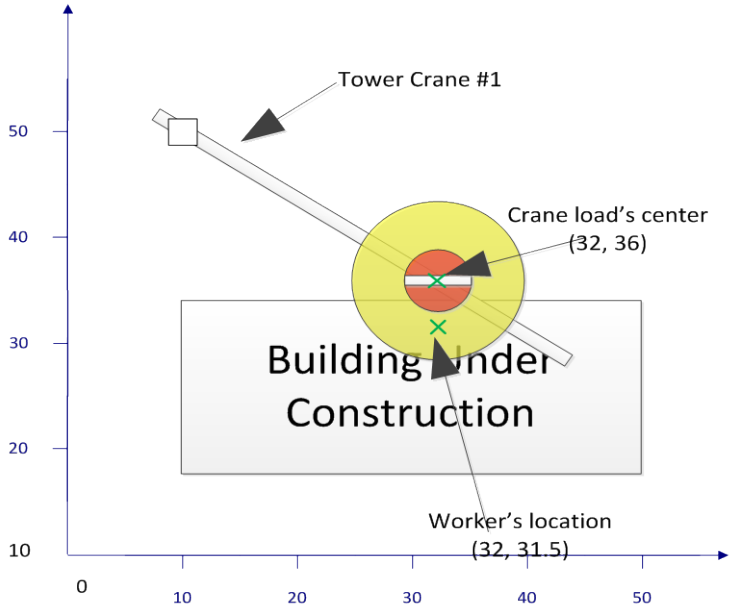


Figure C.16 Sequence Diagram for Crane Safety Monitoring in Proximity of Transportation Line

Appendix D Test cases for Crane Safety Monitoring and Proactive Fall Prevention

D.1 TEST CASE #1

In test case #1, tower crane is lowering a beam with a size of 6 cm x 1 cm down to the top floor of the building under construction and a worker is working at the north side of the roof of the same building. The initial position of the beam's center is (32.0,36.0) and the position of the worker is (32.0,31.5). According to the safety knowledge presented in chapter #2, the radius of the red zone is 3 and the radius of the yellow zone is 7.5. Based on the dangerous zone specification described in chapter 2, the worker's ground true safety situation is that the worker is in the yellow zone.



Precision and Recall with testbed data

At each point, 20 readings are collected for calculating the performance of the system. The position data is stored in a txt file. Each line in the file has three values, as x, y, and z. A sample record for location reading of the crane load is shown below:

19.38390363825446 31.55450386135964 38.51613117296637
19.89686232589606 30.20957072624654 39.4020838190174
19.72430451847397 31.70795616085068 38.50747607829095
19.89686232778222 30.20957072160384 39.42928886132322
19.79280586126755 31.43086921976873 39.37076467832702
19.89686232778222 30.20957072160384 39.42928886132322
19.79554779808534 31.42512257223686 39.39282619485056
19.89686232778222 30.20957072160384 39.42928886132322
19.79756339604258 31.41838338395681 39.39961962181917
19.89686232778222 30.20957072160384 39.42928886132322
19.79907176993549 31.41242399711458 39.46016195387227
19.89686232778222 30.20957072160384 39.42928886132322
19.80021228920661 31.40750044092677 39.66380444630994
19.89686232606241 30.20957072225547 39.37108417014508
19.65216381945294 31.77439544133322 39.72752228373542
19.82136989606241 32.22694888225547 39.37108417014508
19.82136986808096 31.62326745391582 39.75288025320907
19.63273168606241 32.22694888225547 39.37108417014508
19.82136980721876 31.78037133865759 39.76451367144867

Point #		1	2	3	4	5
Yellow-Green System	Precision	100%	NA	NA	NA	NA
	Recall	0%	0%	0%	0%	0%
Red-Yellow-Green System	Precision	100%	NA	NA	NA	NA
	Recall	0%	0%	0%	0%	0%

In the table, NA appears several times in the precision box because at these points, the system determines that the worker is in the green zone and no alert or alarm is triggered. So the precision is NA (non-applicable). The Recalls at those points are quite low because most of the time the system determines that the worker is in the green zone while she is actually in the yellow zone.

Precision and Recall with simulation data (only crane load's position reading is imperfect)

Point # / STD/cm		yellow-green system					Red-Yellow-Green System				
		P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	100%	100%	100%	95%	95%	100%	100%	100%	95%	95%
1	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	100%	100%	100%	100%	100%	90%	89%	84%	90%	94%
1.5	Recall	100%	80%	95%	100%	85%	100%	89%	94%	100%	84%
	Precision	100%	100%	100%	100%	100%	68%	85%	72%	80%	94%
2	Recall	95%	100%	90%	100%	90%	93%	100%	87%	100%	89%
	Precision	100%	100%	100%	100%	100%	89%	72%	62%	95%	59%
2.5	Recall	95%	90%	65%	95%	85%	94%	87%	53%	95%	77%
	Precision	100%	100%	100%	100%	100%	88%	94%	87%	82%	87%
3	Recall	85%	80%	75%	85%	75%	83%	79%	72%	82%	72%
	Precision	100%	100%	100%	100%	100%	93%	92%	79%	79%	79%
3.5	Recall	75%	60%	70%	70%	70%	74%	58%	65%	65%	65%
	Precision	100%	100%	100%	100%	100%	86%	71%	56%	73%	75%
4	Recall	70%	85%	45%	55%	60%	67%	80%	31%	47%	53%
	Precision	100%	100%	100%	100%	100%	90%	88%	90%	83%	82%
4.5	Recall	50%	40%	50%	60%	55%	47%	37%	47%	56%	50%
	Precision	100%	100%	100%	100%	100%	88%	100%	82%	83%	83%
5	Recall	40%	60%	55%	60%	60%	37%	60%	50%	56%	56%

Precision and Recall with simulation data (both worker's and crane load's position readings are imperfect)

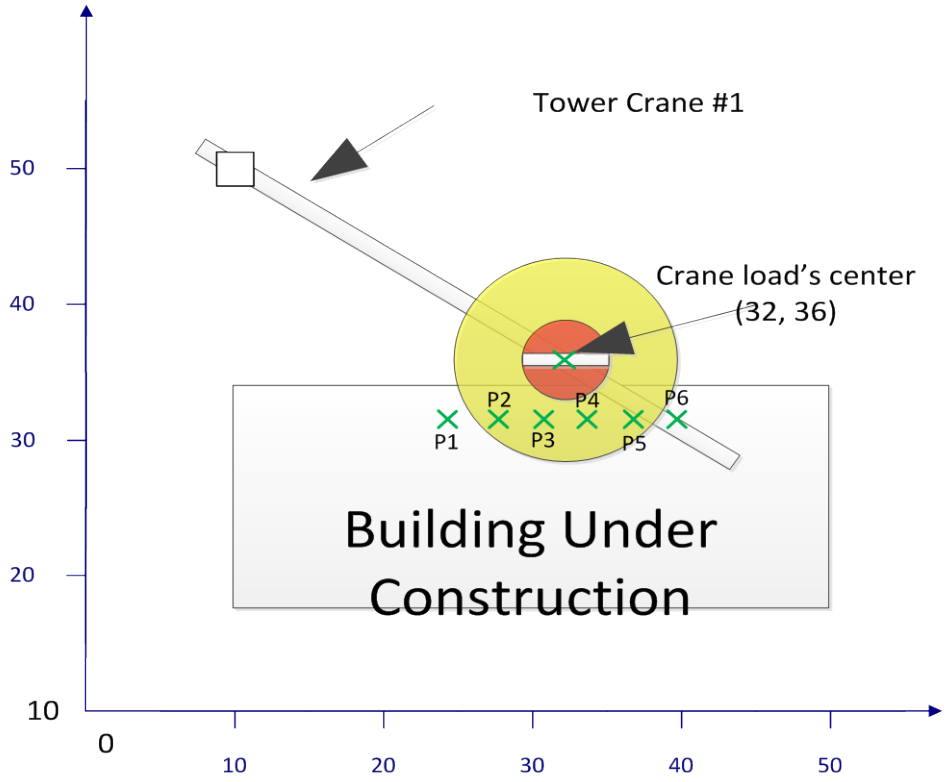
Point # / STD/cm		yellow-green system					Red-Yellow-Green System				
		P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
0.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1	Precision	100%	100%	100%	100%	100%	89%	90%	78%	95%	80%
	Recall	95%	100%	90%	100%	100%	94%	100%	88%	100%	100%
1.5	Precision	100%	100%	100%	100%	100%	79%	82%	89%	89%	81%
	Recall	95%	85%	90%	95%	80%	94%	82%	89%	94%	76%
2	Precision	100%	100%	100%	100%	100%	71%	92%	86%	69%	89%
	Recall	85%	65%	70%	80%	95%	80%	63%	67%	73%	94%
2.5	Precision	100%	100%	100%	100%	100%	86%	79%	69%	77%	100%
	Recall	70%	70%	65%	65%	65%	67%	65%	56%	59%	65%
3	Precision	100%	100%	100%	100%	100%	80%	92%	69%	71%	94%
	Recall	50%	65%	65%	35%	80%	44%	63%	56%	28%	79%
3.5	Precision	100%	100%	100%	100%	100%	75%	67%	81%	64%	54%
	Recall	60%	60%	80%	55%	65%	53%	50%	76%	44%	50%
4	Precision	100%	100%	100%	100%	100%	75%	79%	89%	73%	93%
	Recall	40%	70%	45%	55%	70%	33%	65%	42%	47%	68%
4.5	Precision	100%	100%	100%	100%	100%	89%	75%	71%	88%	70%
	Recall	45%	40%	35%	40%	50%	42%	33%	28%	37%	41%
5	Precision	100%	100%	100%	100%	100%	67%	67%	100%	83%	100%
	Recall	30%	45%	50%	30%	40%	22%	35%	50%	26%	40%

The tables indicate that:

- By switching the system from Red-yellow-green one to yellow-green one, the system gets better performance.
- The higher error the system has, the worst performance the system has.

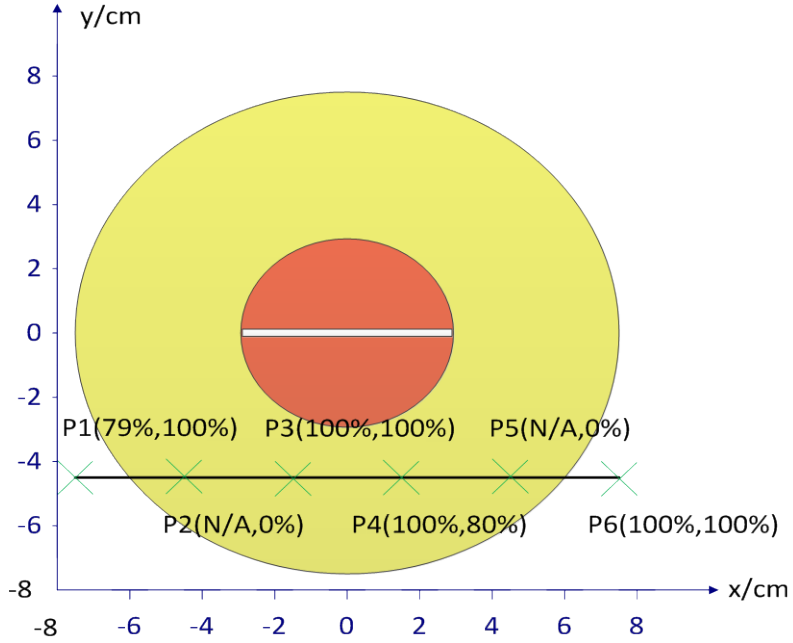
D.2 TEST CASE #2

In test case #2, the tower crane is lowering a beam with a size of 6 cm x 1 cm down to the top floor of the building under construction and a worker is walking along the north side of the roof of the same building. The initial position of the beam's center is (32.0,36.0) and the position of the worker is (24.5,31.5). The ending position of the worker is (39.5, 31.5). According to the safety knowledge presented in chapter #2, the radius of the red zone is 3 and the radius of the yellow zone is 7.5. Based on the dangerous zone specifications described in chapter 2, the worker's ground true safety situation is that the worker is in the green zone at point #1 (24.5, 31.5) and point #6(39.5, 31.5) and the worker is in the yellow zone at point #2 (27.5, 31.5), point #3 (30.5, 31.5), point #4 (33.5, 31.5) and point #5 (36.5, 31.5).

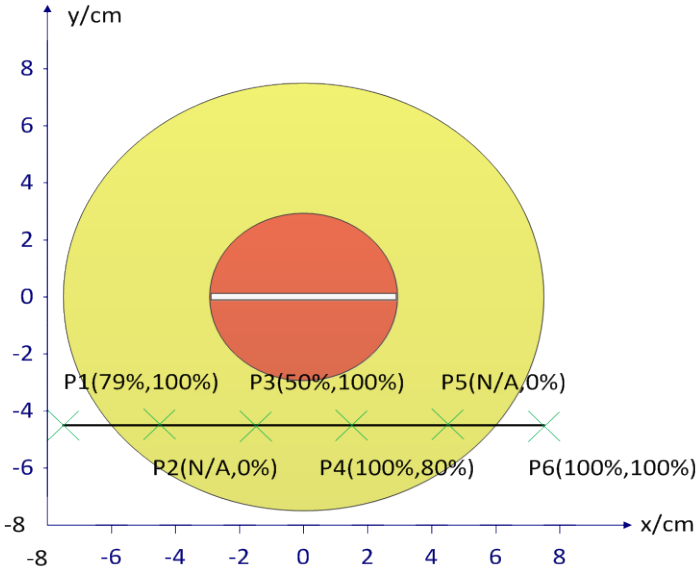


Precision and Recall with testbed data

Point #		1	2	3	4	5	6
Yellow-Green System	Precision	79%	NA	100%	100%	NA	100%
	Recall	100%	0%	100%	80%	0%	100%
Red-Yellow-Green System	Precision	79%	NA	50%	100%	NA	100%
	Recall	100%	0%	100%	80%	0%	100%



Precision and Recall of Yellow-Green System Along the Worker's Path



Precision and Recall of Red-Yellow-Green System Along the Worker's Path

Precision and Recall with simulation data (only crane load's position reading is imperfect)

Point # / STD/cm		yellow-green system						Red-Yellow-Green System					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
	Precision	100%	95%	90%	25%	10%	0%	100%	95%	90%	25%	10%	0%
0.5	Recall	100%	100%	100%	100%	100%	N/A	100%	100%	100%	100%	100%	N/A
	Precision	95%	80%	70%	45%	15%	10%	95%	80%	70%	45%	15%	10%
1	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	95%	75%	55%	45%	40%	25%	95%	75%	55%	45%	40%	25%
1.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	65%	80%	60%	60%	55%	15%	65%	80%	60%	60%	55%	15%
2	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	70%	65%	70%	60%	40%	35%	70%	65%	70%	60%	40%	35%
2.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	80%	65%	55%	40%	60%	25%	80%	65%	55%	40%	60%	25%
3	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	75%	85%	50%	50%	55%	40%	75%	85%	50%	50%	55%	40%
3.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	70%	45%	60%	45%	50%	30%	70%	45%	60%	45%	50%	30%
4	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	45%	65%	60%	65%	40%	35%	45%	65%	60%	65%	40%	35%
4.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	65%	75%	70%	35%	55%	40%	65%	75%	70%	35%	55%	40%
5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

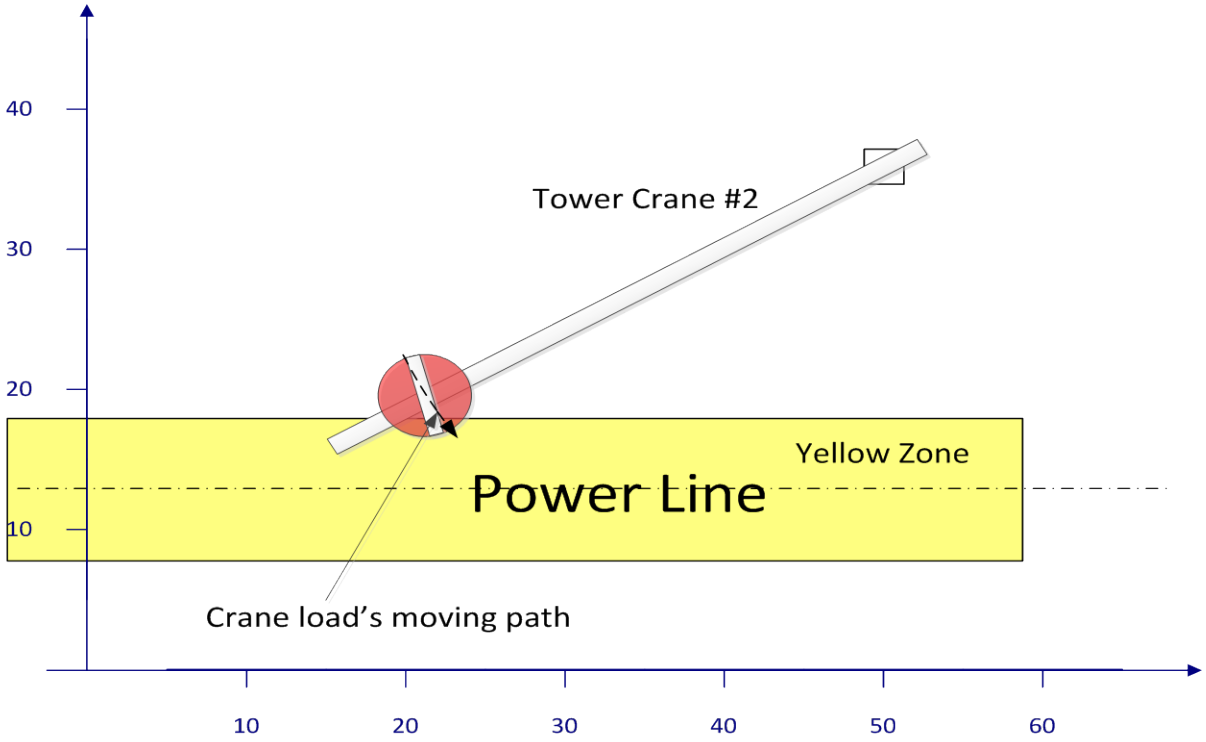
Precision and Recall with simulation data (both change)

Point # / STD/cm		yellow-green system						Red-Yellow-Green System					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
	Precision	100%	100%	100%	100%	100%	95%	100%	100%	100%	100%	100%	95%
0.5	Recall	100%	90%	100%	100%	95%	100%	100%	90%	100%	100%	95%	100%
	Precision	85%	100%	100%	100%	100%	90%	85%	100%	100%	90%	94%	90%
1	Recall	100%	80%	95%	100%	90%	100%	100%	80%	95%	100%	89%	100%
	Precision	85%	100%	100%	100%	100%	90%	85%	100%	85%	89%	86%	90%
1.5	Recall	100%	45%	100%	90%	70%	100%	100%	45%	100%	89%	67%	100%
	Precision	75%	100%	100%	100%	100%	70%	75%	100%	82%	88%	83%	70%
2	Recall	100%	70%	85%	80%	60%	100%	100%	70%	82%	78%	56%	100%
	Precision	75%	100%	100%	100%	100%	75%	75%	100%	100%	79%	91%	75%
2.5	Recall	100%	50%	65%	70%	55%	100%	100%	50%	65%	65%	53%	100%
	Precision	65%	100%	100%	100%	100%	80%	65%	82%	81%	82%	73%	80%
3	Recall	100%	55%	80%	55%	55%	100%	100%	50%	76%	50%	47%	100%
	Precision	80%	100%	100%	100%	100%	45%	80%	82%	60%	69%	89%	45%
3.5	Recall	100%	55%	50%	65%	45%	100%	100%	50%	38%	56%	42%	100%
	Precision	90%	100%	100%	100%	100%	70%	90%	63%	82%	78%	80%	70%
4	Recall	100%	40%	55%	45%	25%	100%	100%	29%	50%	39%	21%	100%
	Precision	65%	100%	100%	100%	100%	75%	65%	83%	80%	80%	67%	75%
4.5	Recall	100%	60%	25%	50%	45%	100%	100%	56%	21%	44%	35%	100%
	Precision	65%	100%	100%	100%	100%	90%	65%	78%	57%	67%	100%	90%
5	Recall	100%	45%	35%	15%	20%	100%	100%	39%	24%	11%	20%	100%

- By switching the system from red-yellow-green one to yellow-green one, the system gets better performance.
- The higher error the system has, the worst performance the system has.

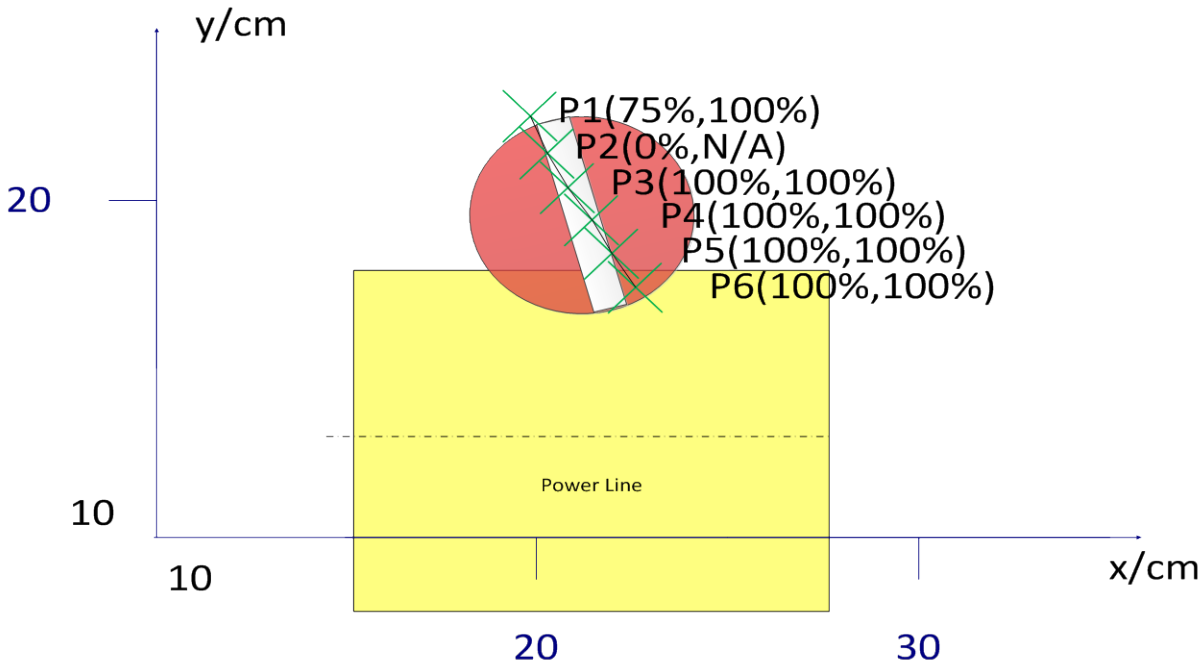
D.3 TEST CASE #3

In test case #3, a power line of 30kV is running between point (-8,13,20) to (68,13,20). The tower crane is swinging a load of 6 by 1 anti-clockwise in proximity to the power line. The initial position of the crane load's center is P1 (19.9, 22.57, 60) and the ending position of the crane load is P6 (22.6,17.5, 60). The other points along the crane load's moving path are P2 (20.3,21.5, 60), P3 (20.9,20.5, 60), P4 (21.4,19.5, 60), and P5 (22.0,18.5,60). Based on the dangerous zone specifications described in chapter 2, the crane boom and the load line are always in a safe situation and the crane load is in a safe situation at location P1and P2. The crane load is in the yellow zone of power line at location P3, P4, P5 and P6.



Precision and Recall with testbed data

Point #		1	2	3	4	5	6
Yellow-Green System	Precision	75%	0%	100%	100%	100%	100%
	Recall	100%	N/A	100%	100%	100%	100%
Red-Yellow-Green System	Precision	75%	0%	100%	100%	100%	100%
	Recall	100%	N/A	100%	100%	100%	100%



Precision and Recall of Both Systems Along the Crane Load's Path

Precision and Recall with simulation data (only crane load's position reading is imperfect)

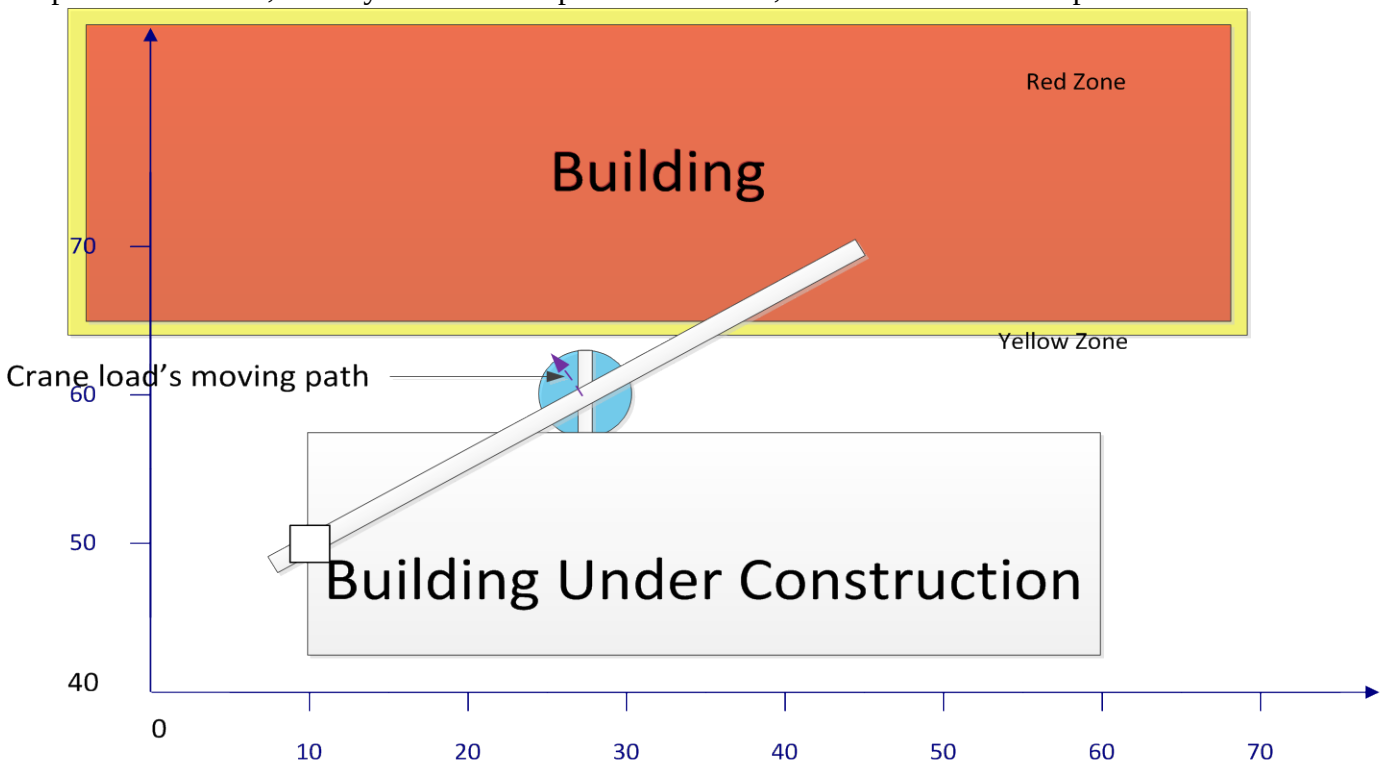
Point # / STD/cm		yellow-green system						Red-Yellow-Green System					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
0.5	Precision	90%	45%	100%	100%	100%	100%	90%	45%	100%	100%	100%	100%
	Recall	100%	100%	90%	100%	100%	100%	100%	100%	90%	100%	100%	100%
1	Precision	55%	60%	100%	100%	100%	100%	55%	60%	100%	100%	100%	100%
	Recall	100%	100%	65%	75%	90%	100%	100%	100%	65%	75%	90%	100%
1.5	Precision	70%	60%	100%	100%	100%	100%	70%	60%	100%	100%	100%	100%
	Recall	100%	100%	55%	60%	80%	100%	100%	100%	55%	60%	80%	100%
2	Precision	70%	40%	100%	100%	100%	100%	70%	40%	100%	100%	100%	100%
	Recall	100%	100%	70%	60%	80%	85%	100%	100%	70%	60%	80%	85%
2.5	Precision	50%	40%	100%	100%	100%	100%	50%	40%	100%	100%	100%	100%
	Recall	100%	100%	50%	70%	80%	80%	100%	100%	50%	70%	80%	80%
3	Precision	60%	50%	100%	100%	100%	100%	60%	50%	100%	100%	100%	100%
	Recall	100%	100%	65%	55%	80%	90%	100%	100%	65%	55%	80%	90%
3.5	Precision	60%	60%	100%	100%	100%	100%	60%	60%	100%	100%	100%	100%
	Recall	100%	100%	50%	55%	55%	75%	100%	100%	50%	55%	55%	75%
4	Precision	45%	65%	100%	100%	100%	100%	45%	65%	100%	100%	100%	100%
	Recall	100%	100%	65%	35%	65%	80%	100%	100%	65%	35%	65%	80%
4.5	Precision	60%	55%	100%	100%	100%	100%	60%	55%	100%	100%	100%	100%
	Recall	100%	100%	40%	50%	60%	60%	100%	100%	40%	50%	60%	60%
5	Precision	55%	45%	100%	100%	100%	100%	55%	45%	100%	100%	100%	100%
	Recall	100%	100%	55%	55%	75%	60%	100%	100%	55%	55%	75%	60%

The tables prove that:

- By switching the system from red-yellow-green one to yellow-green one, the system gets a better performance
- The higher error the system has, the worst performance the system has.

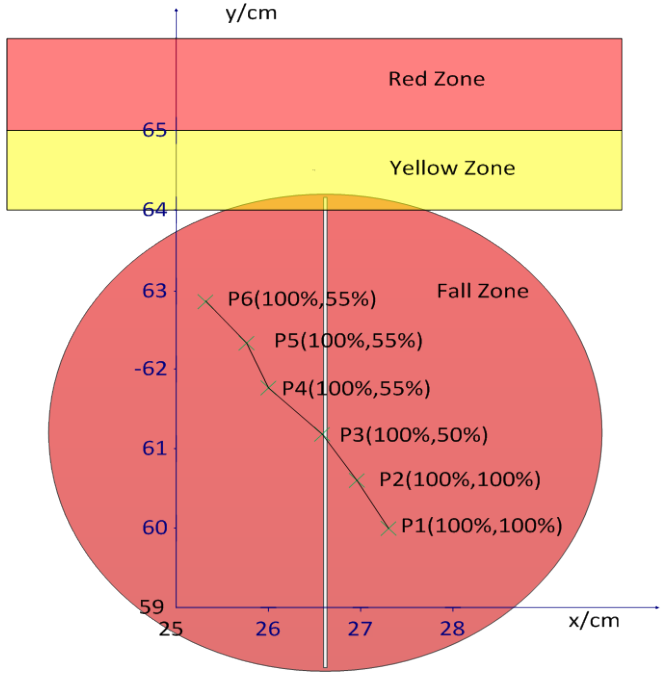
D.4 TEST CASE #4

In test case #4, the positions of the four corners of the occupied buildings are (-4.0,65.0,50.0), (68.0,65.0,50.0), (68.0,85.0,50.0),(-4.0,85.0,50.0). The crane is swinging a steel beam of 6 by 1 in clockwise. The initial starting point of the crane load's center is P 1(27.3, 60.0, 70.0) and the ending point is P6 (25.3, 62.9, 70). Four points are evenly distributed along the crane load's moving path for collecting the location information: P2 (27.0, 60.6, 70.0), P3 (26.6, 61.2, 70.0), P4 (26.2, 61.8, 70.0), and P5 (25.8, 62.3, 70.0). Based on the safety knowledge presented in chapter 2, the crane load is in the dangerous green zone at points P1 and P2, in the yellow zone at points P3 and P4, and in the red zone at points P5 and P6.

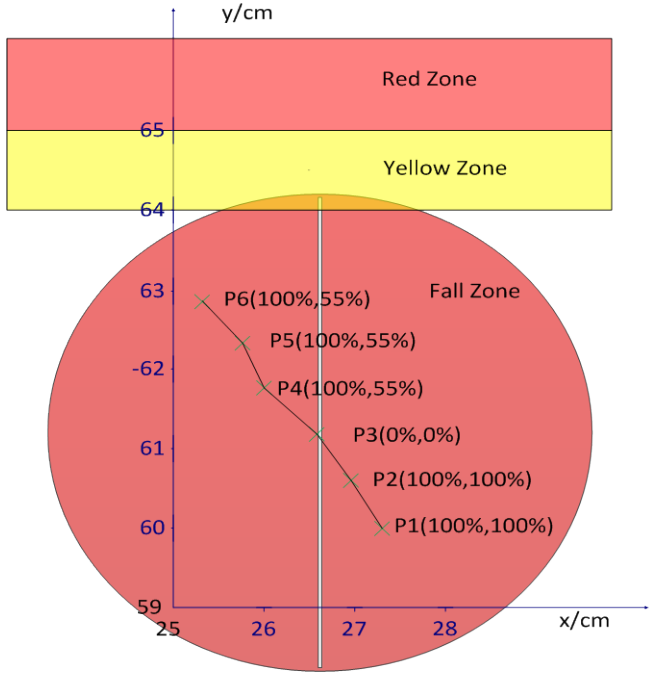


Precision and Recall with testbed data

Point #		1	2	3	4	5	6
Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	50%	55%	55%	55%
Red-Yellow-Green System	Precision	100%	100%	0%	100%	100%	100%
	Recall	100%	100%	0%	55%	55%	55%



Precision and Recall of Yellow-Green System Along the Crane Load's Path



Precision and Recall of Red-Yellow-Green System Along the Crane Load's Path

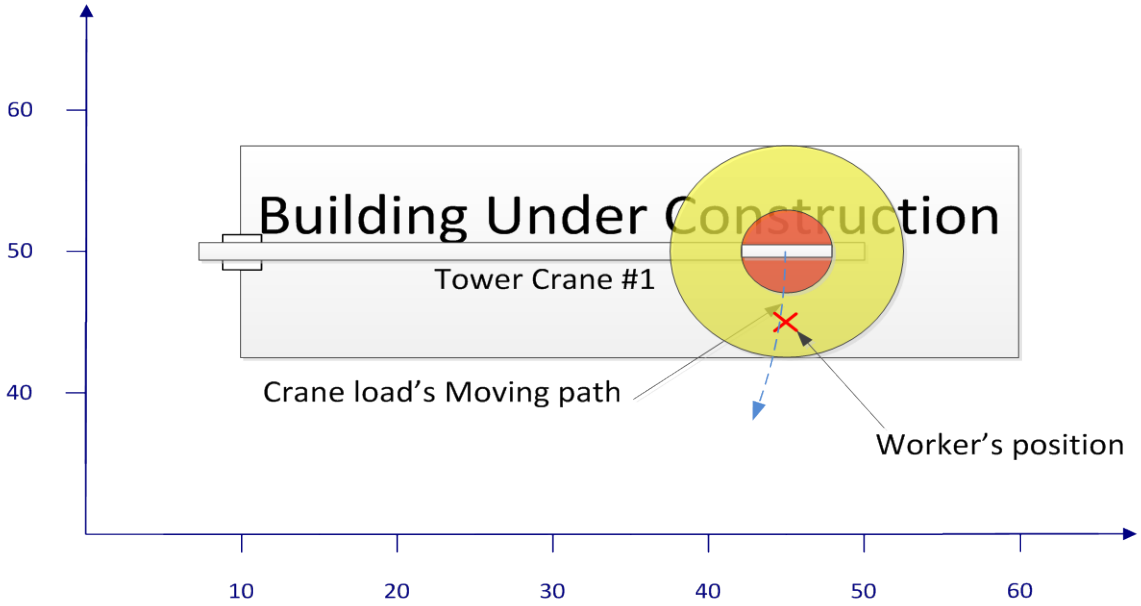
Precision and Recall with simulation data(only crane load's position reading is imperfect)

Point # / STD/cm		yellow-green system						Red-Yellow-Green System					
		P1	P2	P3	P4	P5	P6	P1	P2	P3	P4	P5	P6
	Precision	90%	65%	100%	100%	100%	100%	90%	65%	100%	53%	100%	100%
0.5	Recall	100%	100%	75%	95%	100%	100%	100%	100%	75%	91%	95%	95%
	Precision	80%	45%	100%	100%	100%	100%	80%	45%	85%	33%	100%	100%
1	Recall	100%	100%	65%	90%	100%	100%	100%	100%	61%	75%	60%	80%
	Precision	65%	65%	100%	100%	100%	100%	65%	65%	33%	36%	100%	100%
1.5	Recall	100%	100%	45%	70%	90%	85%	100%	100%	21%	45%	60%	65%
	Precision	40%	40%	100%	100%	100%	100%	40%	40%	23%	27%	100%	100%
2	Recall	100%	100%	65%	75%	65%	70%	100%	100%	30%	44%	35%	55%
	Precision	50%	50%	100%	100%	100%	100%	50%	50%	23%	0%	100%	100%
2.5	Recall	100%	100%	65%	60%	80%	75%	100%	100%	30%	0%	60%	55%
	Precision	75%	20%	100%	100%	100%	100%	75%	20%	17%	36%	100%	100%
3	Recall	100%	100%	60%	55%	65%	65%	100%	100%	20%	31%	50%	50%
	Precision	65%	50%	100%	100%	100%	100%	65%	50%	18%	45%	100%	100%
3.5	Recall	100%	100%	55%	55%	65%	60%	100%	100%	18%	36%	45%	50%
	Precision	80%	60%	100%	100%	100%	100%	80%	60%	27%	0%	100%	100%
4	Recall	100%	100%	55%	70%	70%	65%	100%	100%	25%	0%	50%	55%
	Precision	30%	70%	100%	100%	100%	100%	30%	70%	25%	17%	100%	100%
4.5	Recall	100%	100%	60%	60%	30%	65%	100%	100%	27%	20%	25%	65%
	Precision	65%	60%	100%	100%	100%	100%	65%	60%	13%	11%	100%	100%
5	Recall	100%	100%	40%	45%	60%	75%	100%	100%	8%	8%	55%	70%

- By switching the system from red-yellow-green one to yellow-green one, the system gets a better performance.
- The higher error the system has, the worse performance the system has.

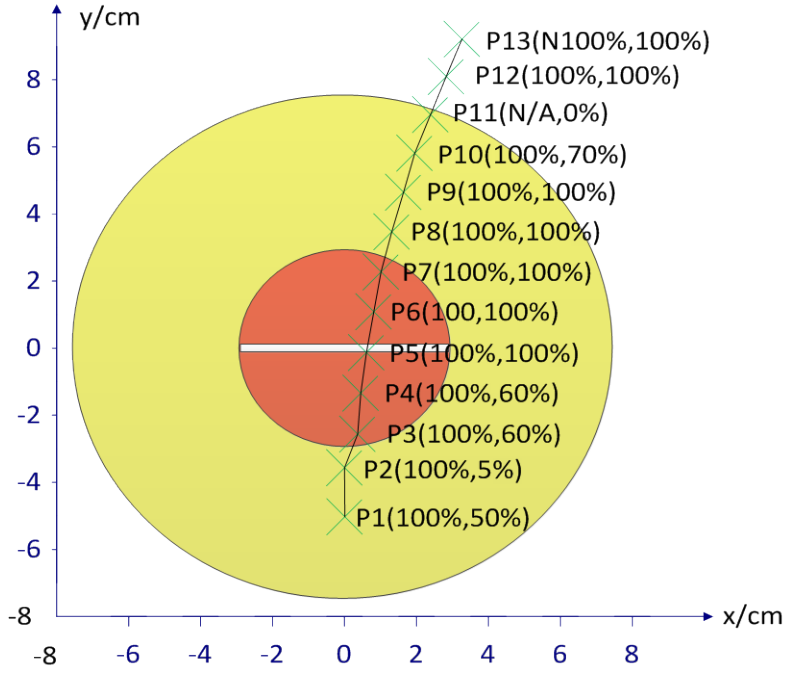
D.5 TEST CASE #5

In test case #5, the tower crane is swinging a beam with a size of 6 cm x 1 cm clockwise along the path shown in the figure below and a worker is standing on the top roof of the building under construction. The initial position of the beam's center is P1(45.0,50.0) and the position of the worker is (45.0,45.0). The ending position of the crane load's center along the path is P13(42.0, 35.8). According to the safety knowledge presented in chapter #2, the radius of the red zone is 3 and the radius of the yellow zone is 7.5. Based on the dangerous zone specifications described in chapter 2, the worker's ground true safety situation is that the worker is in the green zone while load's center is at P12(42.5,36.9) and P13(42.0, 35.8) and the worker is in the yellow zone while the crane load's center is at P1 (45.0, 50.0), P2(45.0,48.8), P8(44.0,41.5), P9(43.0,40.4), P10(43.3, 39.2) and P11(42.9, 38.0), and the worker is in red zone while the crane load's center is at P3(44.9,47.6), P4(44.8,46.3), P5(44.7,45.1), P6(44.5,43.9), and P7(44.2,42.7).

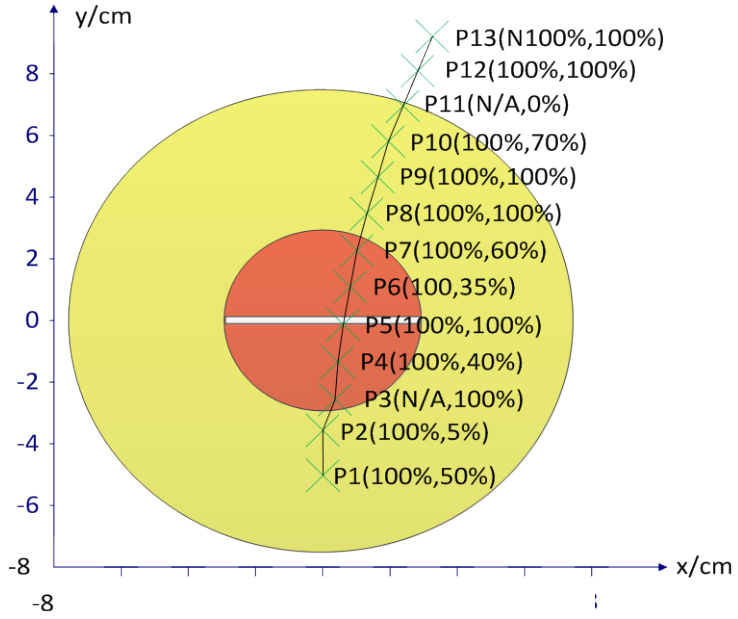


Precision and Recall with testbed data

Point #		1	2	3	4	5	6	7	8	9	10	11	12	13
Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	N/A	100%	100%
	Recall	50%	5%	60%	60%	100%	100%	100%	100%	100%	70%	0%	100%	100%
Red-Yellow-Green System	Precision	100%	100%	N/A	100%	100%	100%	100%	100%	100%	100%	N/A	100%	100%
	Recall	50%	5%	0%	40%	100%	35%	60%	100%	100%	70%	0%	100%	100%



Precision and recall of yellow-green system along the worker's path



Precision and recall of red-yellow-green system along the worker's path

Precision and Recall with simulation data(only crane load's position reading is imperfect)

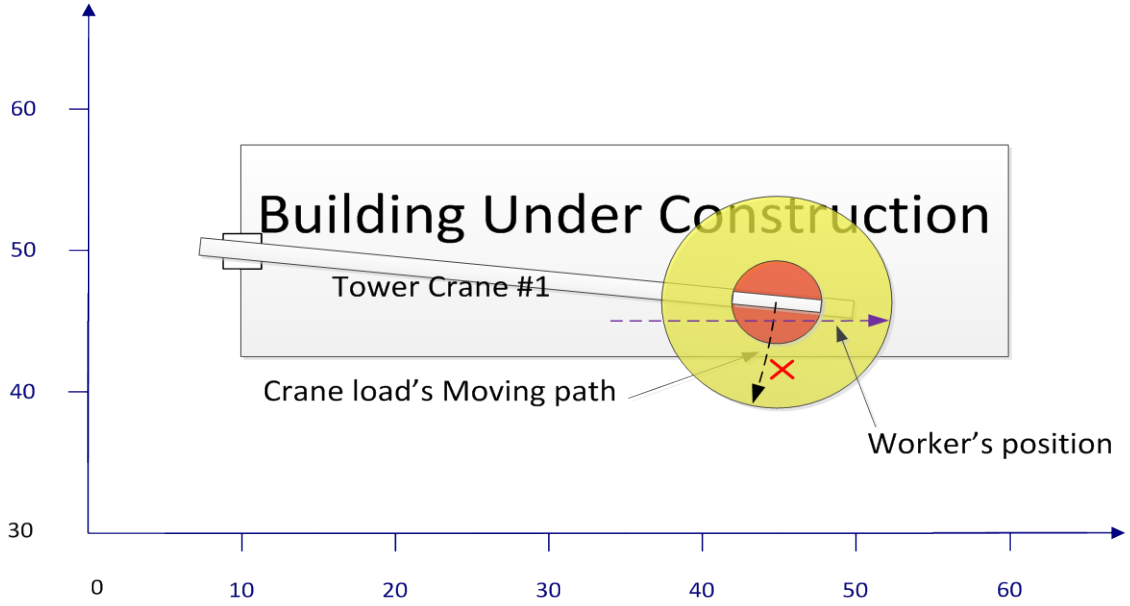
Point # / STD/cm		yellow-green system													Red-Yellow-Green System											
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	95%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	80%	100%	100%	100%	100%	90%	100%	100%	100%	80%	100%	100%	100%	80%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	70%	100%	100%	100%	100%	100%	75%	100%	100%	100%	100%	100%
1	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	95%	55%	100%	100%	100%	100%	30%	95%	100%	95%	70%	100%	100%	95%	55%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	80%	90%	84%	85%	100%	100%	100%	100%	100%	75%	95%	100%	100%	80%	90%
1.5	Recall	95%	100%	100%	100%	100%	100%	100%	100%	95%	90%	75%	100%	100%	94%	100%	60%	70%	75%	95%	50%	100%	95%	90%	75%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	65%	90%	83%	85%	100%	100%	100%	100%	100%	42%	100%	86%	92%	65%	90%
2	Recall	90%	100%	100%	100%	100%	100%	100%	95%	75%	70%	65%	100%	100%	88%	100%	65%	80%	75%	65%	40%	89%	75%	67%	63%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	70%	90%	71%	71%	100%	100%	100%	100%	100%	70%	89%	91%	89%	70%	90%
2.5	Recall	85%	85%	95%	100%	100%	100%	95%	100%	90%	55%	45%	100%	100%	80%	80%	65%	60%	55%	55%	40%	100%	89%	53%	42%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	85%	87%	47%	100%	100%	100%	100%	100%	88%	67%	90%	90%	60%	85%
3	Recall	75%	95%	85%	95%	100%	100%	70%	85%	75%	50%	50%	100%	100%	72%	90%	10%	45%	35%	25%	25%	83%	67%	47%	47%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	65%	75%	82%	71%	100%	100%	100%	100%	100%	69%	77%	100%	71%	65%	75%
3.5	Recall	55%	85%	80%	90%	90%	80%	70%	80%	65%	55%	35%	100%	100%	50%	80%	20%	35%	25%	35%	20%	73%	59%	55%	28%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	75%	91%	50%	100%	100%	100%	100%	N/A	77%	100%	100%	67%	60%	75%
4	Recall	55%	80%	85%	85%	90%	95%	55%	65%	45%	40%	45%	100%	100%	53%	67%	20%	30%	15%	15%	0%	59%	45%	40%	35%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	90%	67%	78%	100%	100%	100%	100%	100%	67%	69%	70%	88%	75%	90%
4.5	Recall	60%	90%	70%	65%	85%	70%	60%	60%	65%	50%	40%	100%	100%	50%	88%	15%	35%	10%	20%	20%	50%	56%	41%	37%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	70%	80%	89%	92%	100%	100%	100%	100%	100%	79%	77%	90%	78%	70%	80%
5	Recall	45%	60%	55%	75%	85%	60%	55%	70%	65%	50%	45%	100%	100%	42%	58%	5%	10%	20%	20%	5%	65%	59%	47%	39%	100%	100%

Precision and Recall with simulation data (both worker's and crane load's position readings are imperfect)

Point # / STD/cm		yellow-green system													Red-Yellow-Green System											
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
0.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	85%	100%	100%	90%	100%	100%	100%	100%	100%	85%	100%	100%	100%	85%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	90%	50%	100%	100%	100%	100%	80%	100%	100%	100%	65%	100%	100%	90%	50%	100%	100%
1	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	90%	100%	95%	90%	100%	100%	100%	100%	100%	100%	95%	100%	100%	90%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	95%	50%	100%	100%	100%	100%	80%	90%	95%	90%	65%	100%	100%	95%	50%	100%	100%
1.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	90%	94%	85%	100%	100%	100%	100%	100%	79%	83%	94%	100%	60%	90%
	Recall	90%	100%	100%	100%	100%	100%	100%	95%	90%	85%	65%	100%	100%	89%	100%	55%	80%	75%	65%	50%	94%	88%	84%	65%	100%	100%
2	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	90%	65%	58%	100%	100%	100%	100%	100%	68%	84%	94%	93%	75%	90%
	Recall	85%	95%	100%	100%	100%	100%	100%	95%	95%	85%	75%	100%	100%	79%	92%	50%	75%	90%	60%	70%	93%	94%	84%	74%	100%	100%
2.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	75%	85%	68%	100%	100%	100%	100%	100%	76%	73%	87%	88%	60%	75%
	Recall	65%	95%	100%	100%	100%	100%	90%	85%	75%	75%	40%	100%	100%	61%	93%	35%	50%	40%	45%	35%	81%	69%	72%	37%	100%	100%
3	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	65%	90%	78%	94%	100%	100%	100%	100%	100%	80%	86%	80%	71%	65%	90%
	Recall	45%	90%	90%	90%	100%	95%	95%	75%	70%	50%	35%	100%	100%	39%	89%	30%	55%	40%	45%	30%	71%	67%	44%	28%	100%	100%
3.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	70%	80%	93%	79%	100%	100%	100%	100%	100%	73%	94%	79%	100%	70%	80%
	Recall	75%	70%	65%	90%	85%	90%	90%	75%	80%	70%	40%	100%	100%	74%	65%	15%	10%	20%	35%	40%	69%	79%	65%	40%	100%	100%
4	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	75%	65%	78%	67%	100%	100%	100%	100%	100%	82%	86%	91%	90%	75%	65%
	Recall	45%	75%	90%	90%	75%	85%	75%	55%	70%	55%	50%	100%	100%	39%	67%	40%	30%	20%	15%	30%	50%	67%	53%	47%	100%	100%
4.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	60%	85%	70%	86%	N/A	100%	100%	100%	100%	81%	91%	80%	50%	60%	85%
	Recall	50%	70%	55%	75%	80%	70%	60%	80%	55%	50%	20%	100%	100%	41%	67%	0%	15%	15%	25%	20%	76%	53%	44%	11%	100%	100%
5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	50%	70%	75%	38%	100%	100%	100%	100%	100%	82%	67%	75%	100%	50%	70%
	Recall	60%	40%	70%	55%	70%	65%	50%	55%	45%	40%	40%	100%	100%	53%	20%	5%	10%	25%	10%	10%	50%	35%	33%	40%	100%	100%

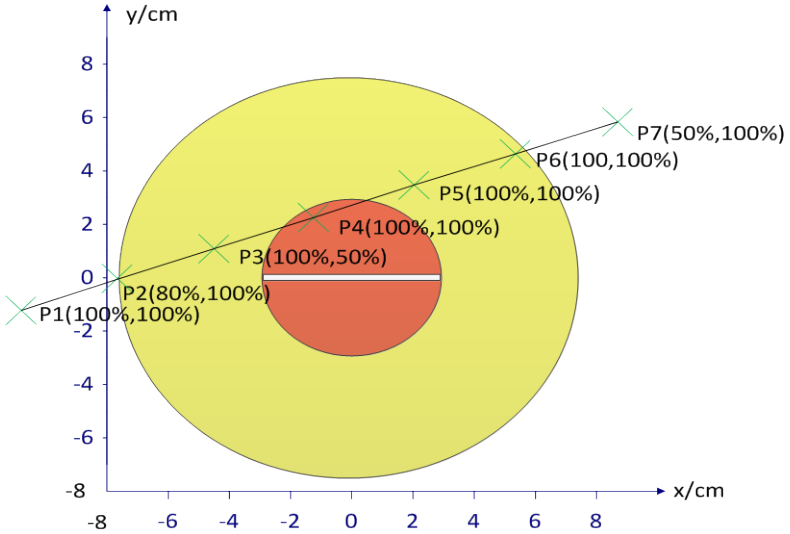
D.6 TEST CASE #6

In test case #6, the tower crane is swinging a beam with a size of 6 cm x 1 cm clockwise along the path shown in the figure below and a worker is walking along the Southside of the top floor of the building under construction. The initial position of the beam's center is P1(44.8,46.3) and the initial position of the worker is P'1(34,45). The ending position of the crane load's center along the path is P7(43.3, 39.2) and the ending position of the worker is P'7(52.0,45.0). The other five points along the crane load's moving path are: P2 (44.7, 45.1), P3(44.5, 43.9), P4(44.2, 42.7), P5(44.0, 41.5) and P6(43.6, 40.4), while the other five points along the worker's moving path are: P'2(37.0,45.0), P'3(40.0,45.0), P'4(43.0,45.0), P'5(46.0,45.0) and P'6(49.0, 45.0). According to the safety knowledge presented in chapter 2, the worker is in a safe situation at P1and P2, the worker is in the yellow zone at P3 and P5, and the worker is in the red zone at P4.

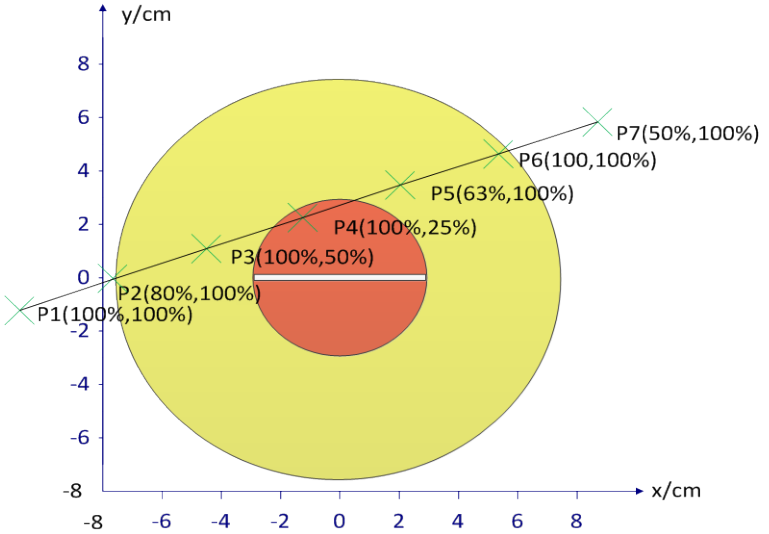


Precision and Recall with testbed data

Point #		1	2	3	4	5	6	7
Yellow-Green System	Precision	100%	80%	100%	100%	100%	100%	50%
	Recall	100%	100%	50%	100%	100%	100%	100%
Red-Yellow-Green System	Precision	100%	80%	100%	100%	63%	100%	50%
	Recall	100%	100%	50%	25%	100%	100%	100%



Precision and Recall of Yellow-Green System Along the Worker's Path



Precision and Recall of Red-Yellow-Green System Along the Worker’s Path

Precision and Recall with simulation data(only crane load's position reading is imperfect)

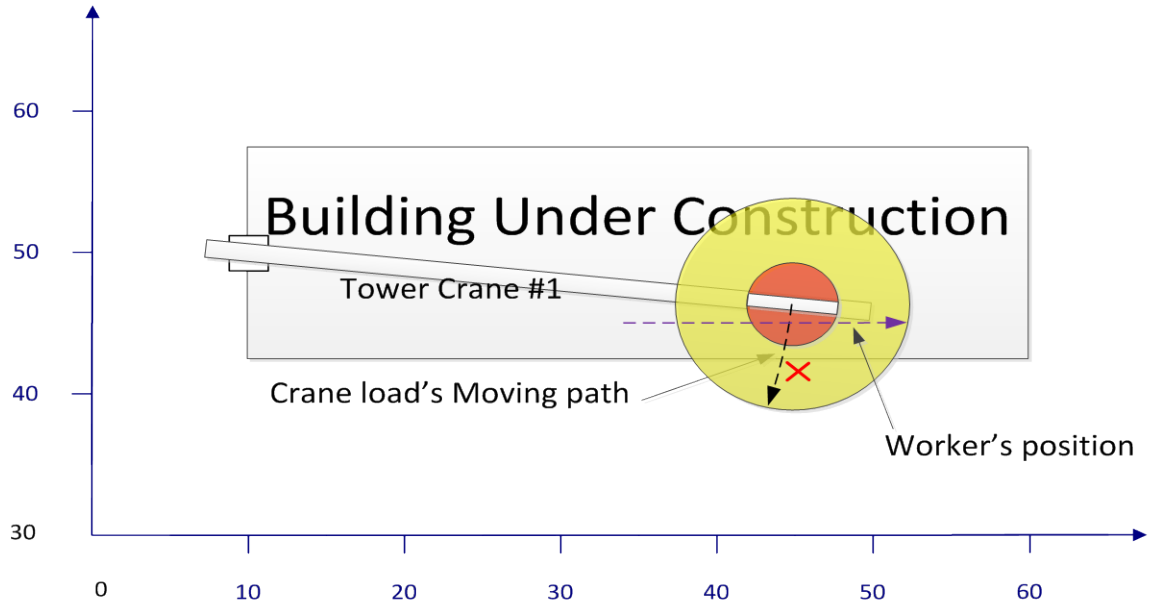
Point # / STD/cm		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
	Precision	100%	70%	100%	100%	100%	100%	100%	100%	70%	100%	100%	95%	100%	100%
0.5	Recall	100%	100%	100%	100%	100%	70%	100%	100%	100%	100%	70%	100%	70%	100%
	Precision	100%	75%	100%	100%	100%	100%	100%	100%	75%	100%	100%	90%	100%	100%
1	Recall	100%	100%	100%	100%	100%	75%	100%	100%	100%	100%	35%	100%	75%	100%
	Precision	100%	65%	100%	100%	100%	100%	95%	100%	65%	89%	100%	85%	100%	95%
1.5	Recall	100%	100%	95%	100%	100%	65%	100%	100%	100%	94%	55%	100%	65%	100%
	Precision	95%	60%	100%	100%	100%	100%	100%	95%	60%	94%	100%	85%	100%	100%
2	Recall	100%	100%	90%	100%	100%	65%	100%	100%	100%	89%	55%	100%	65%	100%
	Precision	90%	50%	100%	100%	100%	100%	100%	90%	50%	88%	100%	84%	100%	100%
2.5	Recall	100%	100%	80%	100%	95%	25%	100%	100%	100%	78%	30%	94%	25%	100%
	Precision	85%	40%	100%	100%	100%	100%	85%	85%	40%	80%	100%	88%	100%	85%
3	Recall	100%	100%	75%	75%	85%	40%	100%	100%	100%	71%	15%	83%	40%	100%
	Precision	95%	60%	100%	100%	100%	100%	90%	95%	60%	75%	100%	73%	100%	90%
3.5	Recall	100%	100%	80%	90%	75%	30%	100%	100%	100%	75%	40%	69%	30%	100%
	Precision	75%	70%	100%	100%	100%	100%	80%	75%	70%	82%	100%	82%	63%	80%
4	Recall	100%	100%	55%	60%	55%	40%	100%	100%	100%	50%	15%	50%	29%	100%
	Precision	90%	65%	100%	100%	100%	100%	80%	90%	65%	67%	100%	67%	80%	80%
4.5	Recall	100%	100%	60%	80%	60%	50%	100%	100%	100%	50%	10%	50%	44%	100%
	Precision	85%	65%	100%	100%	100%	100%	90%	85%	65%	83%	100%	73%	80%	90%
5	Recall	100%	100%	60%	85%	55%	25%	100%	100%	100%	56%	25%	47%	21%	100%

Precision and Recall with simulation data (both worker's and crane load's position readings are imperfect)

Point # / STD/cm		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
	Precision	100%	70%	100%	100%	100%	100%	100%	100%	70%	90%	100%	95%	100%	100%
0.5	Recall	100%	100%	100%	100%	100%	70%	100%	100%	100%	100%	65%	100%	70%	100%
	Precision	100%	70%	100%	100%	100%	100%	100%	100%	70%	89%	100%	85%	100%	100%
1	Recall	100%	100%	90%	100%	100%	45%	100%	100%	100%	89%	50%	100%	45%	100%
	Precision	95%	70%	100%	100%	100%	100%	90%	95%	70%	94%	100%	61%	89%	90%
1.5	Recall	100%	100%	90%	100%	90%	45%	100%	100%	100%	89%	20%	85%	42%	100%
	Precision	85%	55%	100%	100%	100%	100%	95%	85%	55%	72%	100%	73%	100%	95%
2	Recall	100%	100%	90%	85%	75%	65%	100%	100%	100%	87%	25%	69%	65%	100%
	Precision	95%	55%	100%	100%	100%	100%	85%	95%	55%	83%	100%	72%	86%	85%
2.5	Recall	100%	100%	60%	95%	90%	35%	100%	100%	100%	56%	30%	87%	32%	100%
	Precision	75%	65%	100%	100%	100%	100%	85%	75%	65%	92%	100%	79%	100%	85%
3	Recall	100%	100%	65%	60%	70%	30%	100%	100%	100%	63%	20%	65%	30%	100%
	Precision	65%	65%	100%	100%	100%	100%	85%	65%	65%	90%	100%	88%	75%	85%
3.5	Recall	100%	100%	50%	65%	40%	40%	100%	100%	100%	47%	15%	37%	33%	100%
	Precision	80%	70%	100%	100%	100%	100%	65%	80%	70%	86%	100%	86%	83%	65%
4	Recall	100%	100%	35%	45%	35%	30%	100%	100%	100%	32%	10%	32%	26%	100%
	Precision	65%	65%	100%	100%	100%	100%	70%	65%	65%	N/A	100%	89%	71%	70%
4.5	Recall	100%	100%	55%	70%	45%	35%	100%	100%	100%	53%	20%	42%	28%	100%
	Precision	80%	65%	100%	100%	100%	100%	70%	80%	65%	100%	100%	100%	75%	70%
5	Recall	100%	100%	30%	50%	30%	40%	100%	100%	100%	30%	5%	30%	33%	100%

D.7 TEST CASE #7

In test case #7, the tower crane is swinging a beam with a size of 6 cm x 1 cm clockwise along the path shown in the figure below and a walking along the southside of the 3rd floor of the building under construction. The initial position of the beam's center is P1(44.8,46.3) and the initial position of the worker is P'1(34.0,45.0). The ending position of the crane load's center along the path is P7(43.3, 39.15) and the ending position of the worker is P'7(52,45). The other five points along the crane load's moving path are: P2 (44.7, 45.1), P3(44.5, 43.9), P4(44.2, 42.7), P5(44.0, 41.5) and P6(43.6, 40.4), while the other five points along the worker's moving path are: P'2(37.0,45.0), P'3(40.0,45.0), P'4(43.0,45.0), P'5(46.0,45.0) and P'6(49.0, 45.0). According to the safety knowledge presented in chapter 2, the worker is in a safe situation since he/she is not exposed directly under the crane load.



Precision and Recall with testbed data

Point #		1	2	3	4	5	6	7
Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%
Red-Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%

Precision and Recall with simulation data (only crane load's position reading is imperfect)

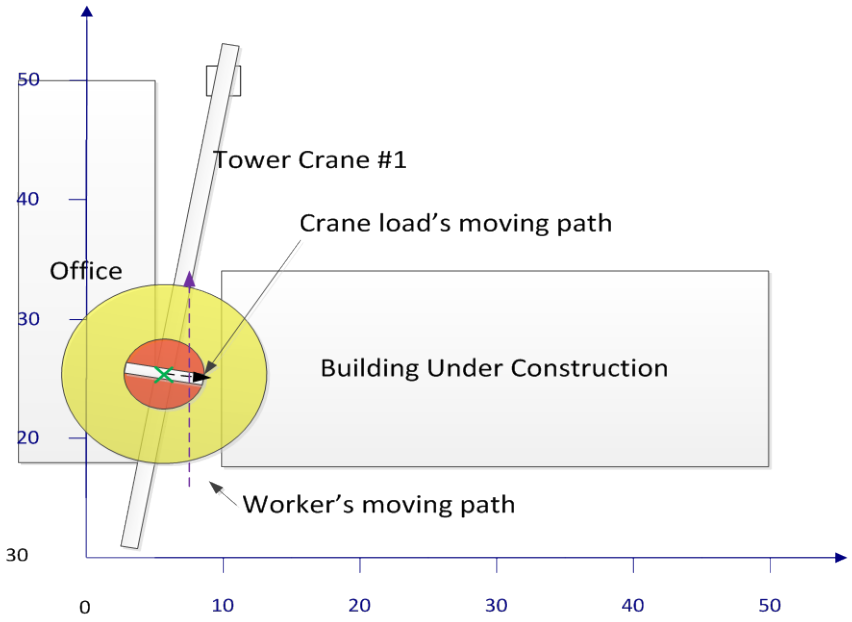
Point # / STD/cm		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
0.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
3	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
3.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
4	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
4.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Precision and Recall with simulation data (both worker's and crane load's position readings are imperfect)

Point # / STD/cm		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
0.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
1.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
2.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
3	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
3.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
4	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
4.5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
5	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

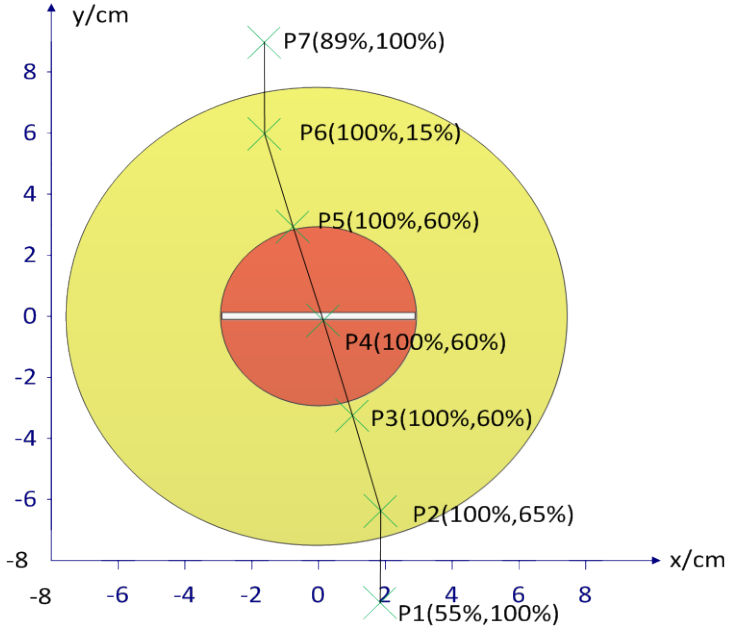
D.8 TEST CASE #8

In test case #8, the tower crane is swinging a beam with a size of 6 cm x 1 cm anticlockwise along the path shown in the figure below and a worker is walking northward on the ground between the site office and the building under construction. The initial position of the beam's center is P1(5.7,25.4) and the initial position of the worker is P'1(7.5,16.0). The ending position of the crane load's center along the path is P7 (9.1, 25.0) and the ending position of the worker is P'7(7.5,34.0). The other five points along the crane load's moving path are: P2(5.7,25.4), P3(6.5,25.2), P4(7.4,25.1), P5(8.3,25.1) and P6(9.1,25.0), while the other five points along the worker's moving path are: P'2(7.5,19.0), P'3(7.5,22.0), P'4(7.5,25.0), P'5(7.5,28.0) and P'6(7.5,31.0). According to the safety knowledge presented in chapter 2, the worker is in the green zone at P1 and P7, in the yellow zone at P2, P3, P5 and P6, in red zone at P4.

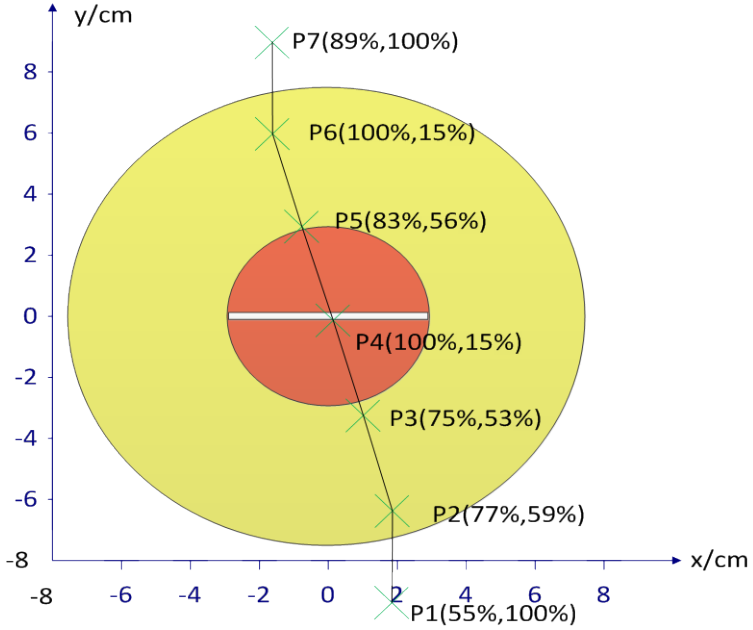


Precision and Recall with testbed data

Point #		1	2	3	4	5	6	7
Yellow-Green System	Precision	55%	100%	100%	100%	100%	100%	89%
	Recall	100%	65%	60%	60%	60%	15%	100%
Red-Yellow-Green System	Precision	55%	77%	75%	100%	83%	100%	89%
	Recall	100%	59%	53%	15%	56%	15%	100%



Precision and Recall of Yellow-Green System Along the Worker's Path



Precision and Recall of Red-Yellow-Green System Along the Worker's Path

Precision and Recall with simulation data(only crane load's position reading is imperfect)

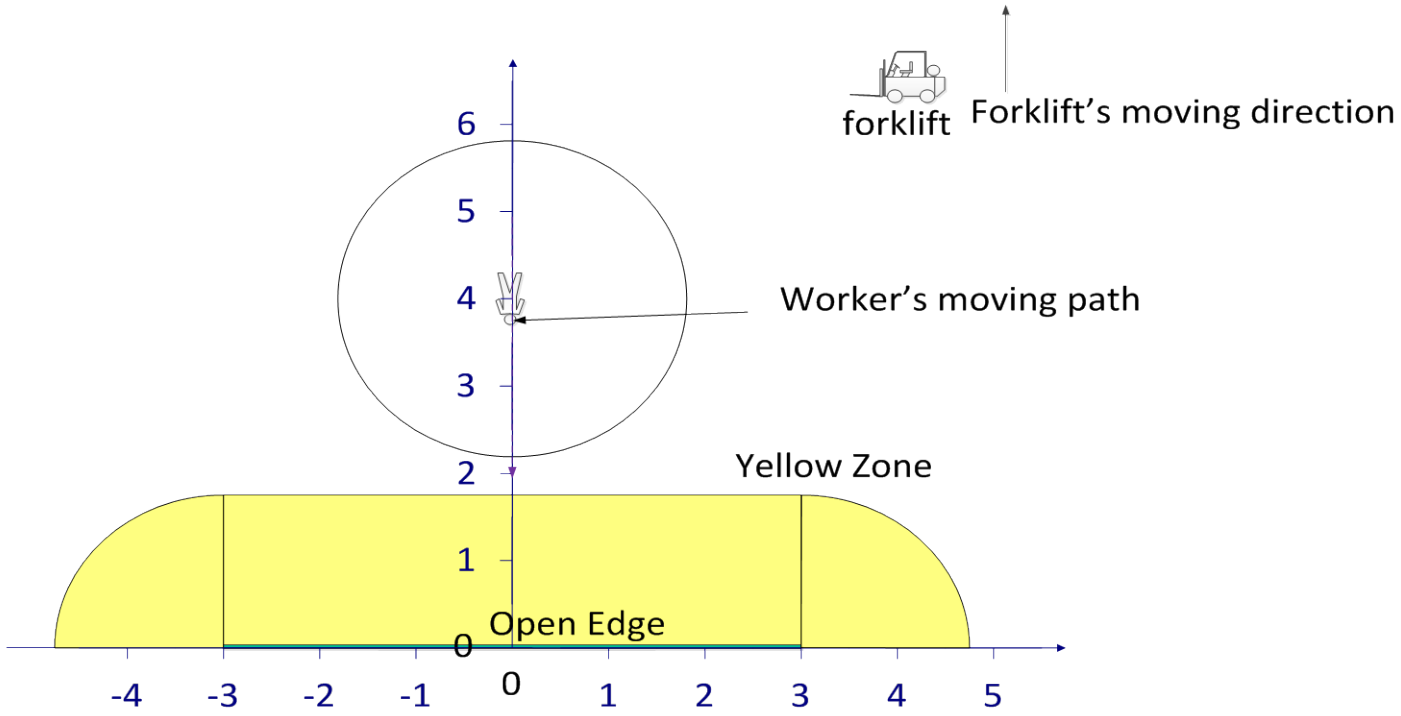
Point # / STD/cm		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	85%	100%	60%	100%	100%
0.5	Recall	100%	95%	100%	100%	100%	100%	100%	100%	95%	100%	100%	100%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	90%	100%	100%	65%	100%	55%	100%	90%
1	Recall	100%	60%	100%	100%	100%	100%	100%	100%	60%	100%	95%	100%	100%	100%
	Precision	95%	100%	100%	100%	100%	100%	85%	95%	100%	60%	100%	55%	100%	85%
1.5	Recall	100%	55%	100%	100%	100%	80%	100%	100%	55%	100%	85%	100%	80%	100%
	Precision	95%	100%	100%	100%	100%	100%	80%	95%	100%	58%	100%	50%	100%	80%
2	Recall	100%	60%	95%	100%	90%	60%	100%	100%	60%	92%	75%	82%	60%	100%
	Precision	85%	100%	100%	100%	100%	100%	80%	85%	82%	68%	100%	50%	100%	80%
2.5	Recall	100%	55%	95%	100%	90%	60%	100%	100%	50%	93%	50%	82%	60%	100%
	Precision	90%	100%	100%	100%	100%	100%	90%	90%	100%	83%	100%	72%	85%	90%
3	Recall	100%	60%	90%	90%	90%	65%	100%	100%	60%	88%	40%	87%	61%	100%
	Precision	75%	100%	100%	100%	100%	100%	90%	75%	89%	67%	100%	87%	100%	90%
3.5	Recall	100%	45%	90%	90%	75%	55%	100%	100%	42%	86%	45%	72%	55%	100%
	Precision	90%	100%	100%	100%	100%	100%	60%	90%	67%	81%	100%	77%	100%	60%
4	Recall	100%	45%	80%	80%	65%	45%	100%	100%	35%	76%	15%	59%	45%	100%
	Precision	60%	100%	100%	100%	100%	100%	60%	60%	100%	83%	100%	80%	73%	60%
4.5	Recall	100%	45%	60%	80%	75%	55%	100%	100%	45%	56%	25%	71%	47%	100%
	Precision	85%	100%	100%	100%	100%	100%	70%	85%	88%	93%	100%	70%	73%	70%
5	Recall	100%	40%	75%	75%	50%	55%	100%	100%	37%	74%	25%	41%	47%	100%

Precision and Recall with simulation data (both worker's and crane load's position readings are imperfect)

Point # / STD/cm		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
	Precision	100%	100%	100%	100%	100%	100%	95%	100%	100%	80%	100%	60%	100%	95%
0.5	Recall	100%	100%	100%	100%	100%	95%	100%	100%	100%	100%	100%	100%	95%	100%
	Precision	95%	100%	100%	100%	100%	100%	90%	95%	100%	65%	100%	55%	100%	90%
1	Recall	100%	70%	100%	100%	100%	95%	100%	100%	70%	100%	80%	100%	95%	100%
	Precision	95%	100%	100%	100%	100%	100%	80%	95%	100%	70%	100%	63%	93%	80%
1.5	Recall	100%	65%	100%	100%	95%	70%	100%	100%	65%	100%	50%	92%	68%	100%
	Precision	80%	100%	100%	100%	100%	100%	70%	80%	100%	79%	100%	60%	100%	70%
2	Recall	100%	35%	95%	100%	100%	60%	100%	100%	35%	94%	20%	100%	60%	100%
	Precision	80%	100%	100%	100%	100%	100%	80%	80%	88%	69%	100%	63%	86%	80%
2.5	Recall	100%	40%	65%	90%	95%	35%	100%	100%	37%	56%	15%	92%	32%	100%
	Precision	70%	100%	100%	100%	100%	100%	70%	70%	67%	94%	100%	73%	100%	70%
3	Recall	100%	60%	80%	85%	75%	45%	100%	100%	50%	79%	25%	69%	45%	100%
	Precision	80%	100%	100%	100%	100%	100%	70%	80%	88%	89%	100%	92%	90%	70%
3.5	Recall	100%	40%	45%	65%	60%	50%	100%	100%	37%	42%	35%	58%	47%	100%
	Precision	80%	100%	100%	100%	100%	100%	85%	80%	67%	75%	100%	75%	88%	85%
4	Recall	100%	15%	60%	65%	60%	40%	100%	100%	11%	53%	10%	53%	37%	100%
	Precision	70%	100%	100%	100%	100%	100%	80%	70%	75%	88%	100%	91%	60%	80%
4.5	Recall	100%	40%	40%	40%	55%	25%	100%	100%	33%	37%	10%	53%	17%	100%
	Precision	70%	100%	100%	100%	100%	100%	85%	70%	75%	67%	100%	75%	100%	85%
5	Recall	100%	40%	30%	40%	20%	40%	100%	100%	33%	22%	10%	16%	40%	100%

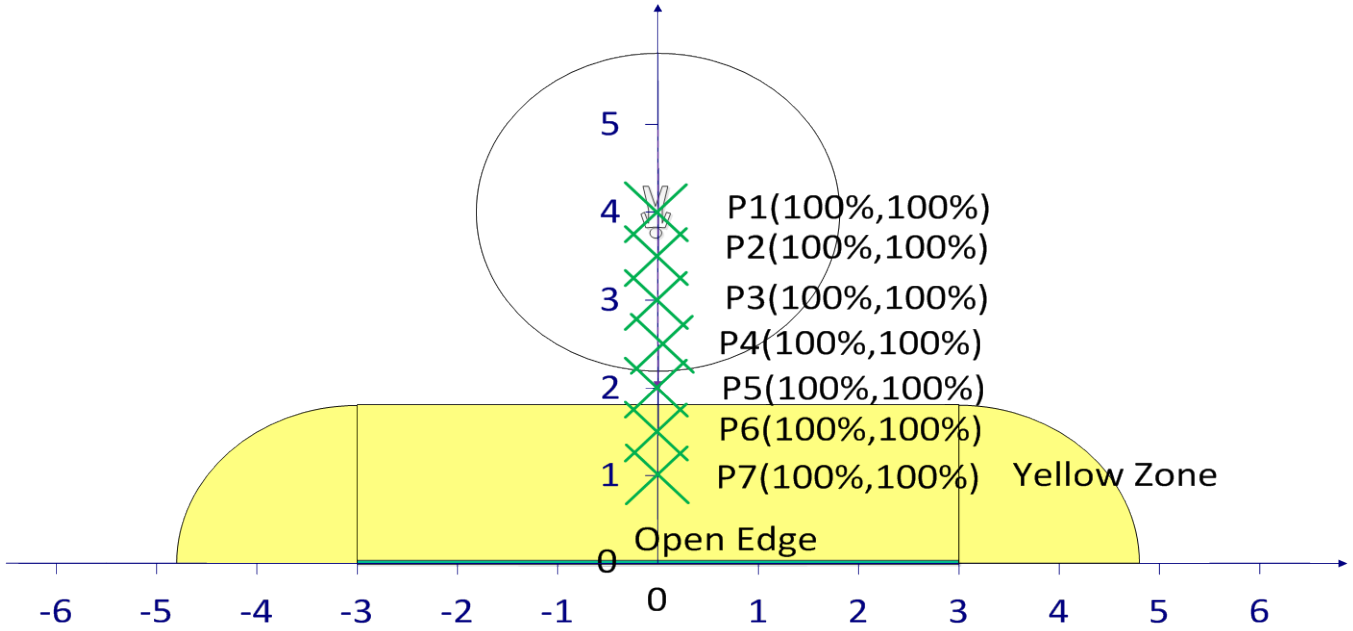
D.9 TEST CASE #9

In test case #5, a worker is backing towards the leading edge without guardrail systems. A forklift is moving away from the open edge to the other side of the floor to transport materials. The initial location of the worker is P1 (0.0,4.0) and the location where the worker finally stops is P7 (0.0,1.0). At each 0.5 meter, the location data is reading from the localization device carried by the worker. The locations of other reading points are: P2 (0,3.5.0), P3 (0.0,3.0), P4 (0.0,2.5), P5 (0.0,2.0), P6 (0.0,1.5). Based on the safety knowledge presented in chapter 3, while using a clearance distance of 6 feet, the worker is in the green zone at point 1, in the yellow zone at P2 to P5, and in the red zone at P6 and P7.



Precision and Recall with testbed data

Point #		1	2	3	4	5	6	7
Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%
Red-Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%



Precision and Recall of Both Systems Along the Worker's Path

The table indicates that the system achieves a perfect performance because the error is relatively small compared with the size of dangerous areas. To better understand the size of error's impacts on system's performance, we use simulation data to evaluate the system's performance with different levels of errors.

Precision and Recall with simulation data

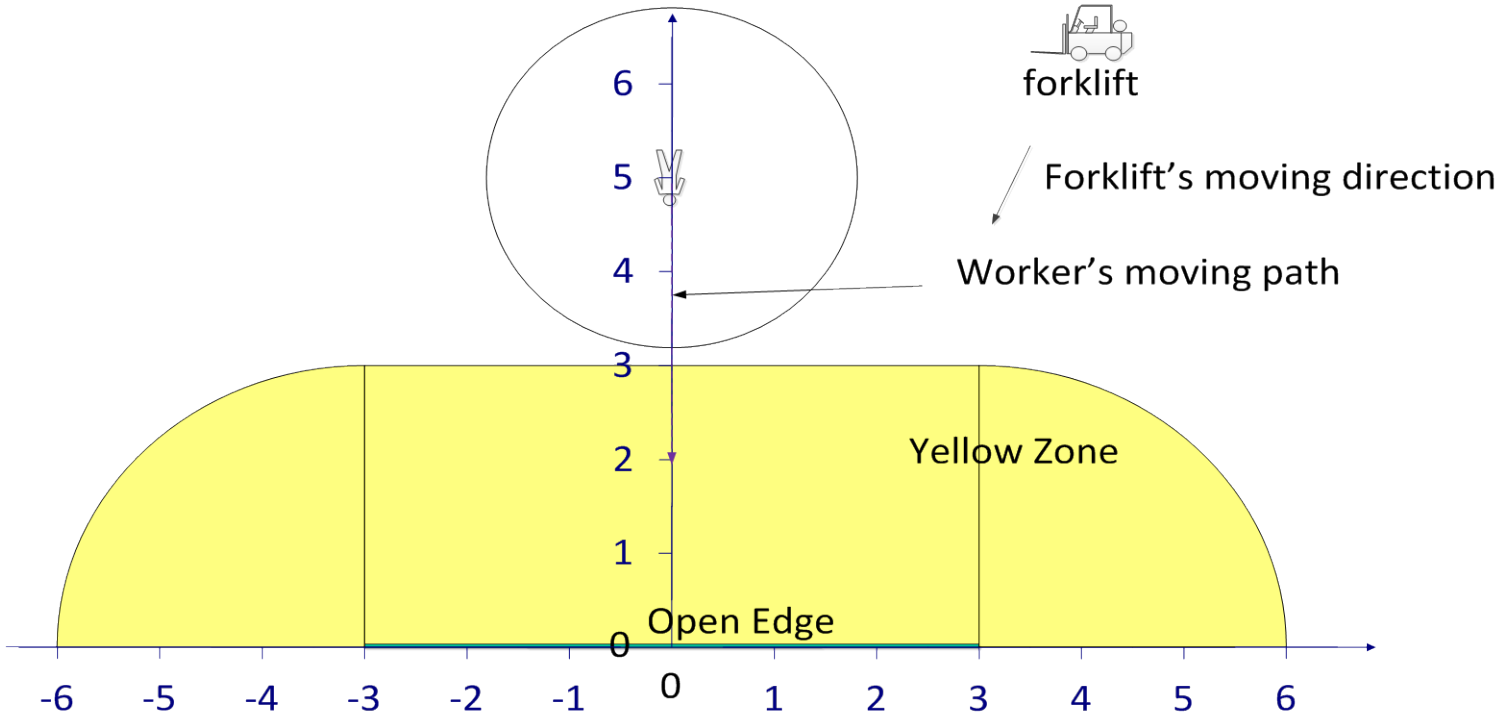
STD/cm \ Point #		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.05	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.1	Recall	100%	85%	100%	100%	100%	100%	100%	100%	85%	100%	100%	100%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.15	Recall	100%	60%	100%	100%	100%	100%	100%	100%	60%	100%	100%	100%	100%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	70%	100%	100%
0.2	Recall	100%	80%	100%	100%	100%	100%	100%	100%	80%	100%	100%	100%	75%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	85%	100%	100%
0.25	Recall	100%	60%	100%	100%	100%	100%	100%	100%	60%	100%	100%	100%	90%	100%
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	85%	100%	100%
0.3	Recall	100%	75%	100%	100%	100%	100%	100%	100%	75%	100%	100%	100%	85%	100%
	Precision	90%	100%	100%	100%	100%	100%	100%	90%	100%	100%	90%	85%	100%	100%
0.35	Recall	100%	65%	90%	100%	100%	100%	100%	100%	65%	90%	100%	100%	75%	100%
	Precision	90%	100%	100%	100%	100%	100%	100%	90%	100%	100%	100%	75%	100%	100%
0.4	Recall	100%	70%	95%	100%	100%	100%	100%	100%	70%	95%	100%	100%	70%	100%
	Precision	80%	100%	100%	100%	100%	100%	100%	80%	100%	100%	100%	80%	100%	100%
0.45	Recall	100%	55%	90%	100%	100%	100%	100%	100%	55%	90%	100%	100%	80%	100%
	Precision	85%	100%	100%	100%	100%	100%	100%	85%	100%	100%	95%	65%	100%	100%
0.5	Recall	100%	35%	95%	100%	100%	100%	100%	100%	35%	95%	100%	100%	65%	90%

The table indicates that:

- When the standard deviation of the error is less than 0.1 meter, the system's precision and recall achieve over 80%.
- As the standard deviation of error increases, the system's performance degrades.

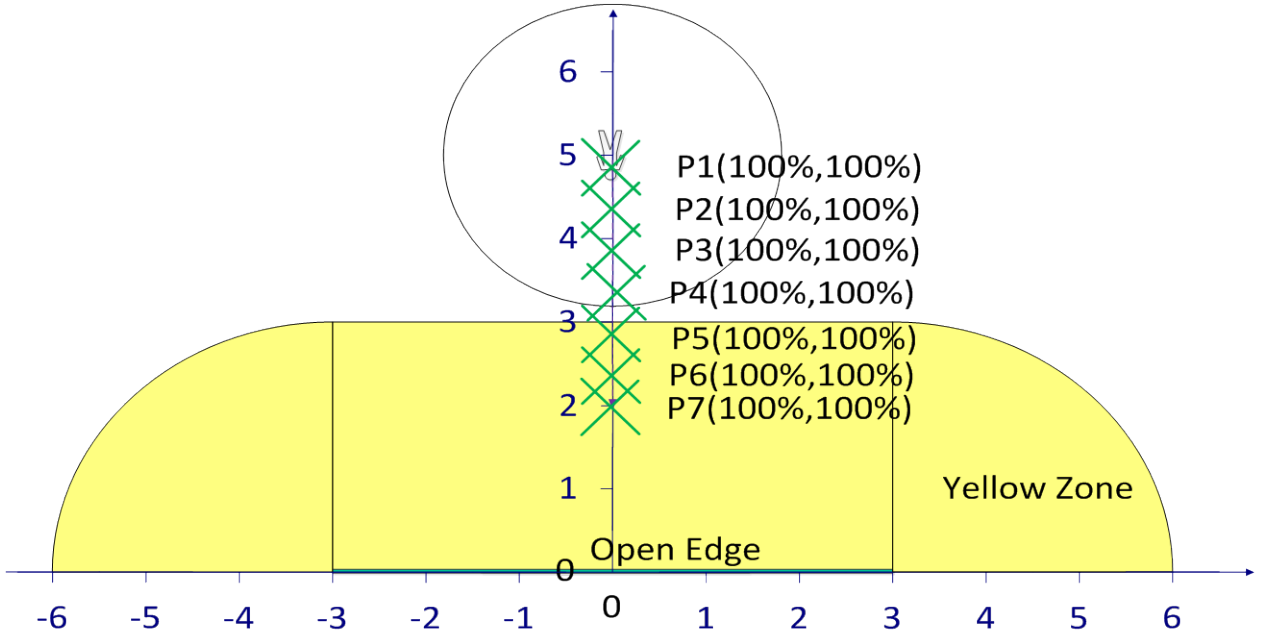
D.10 TEST CASE #10

In test case #6, an unauthorized worker is walking towards the leading edge without guardrail systems. A forklift is moving towards the leading edge to receive the materials transported by the tower crane. The initial location of the worker is P1 (0.0,5.0) and the location where the worker finally stops is P7 (0.0,2.0). At each 0.5 meter, the location data is reading from the localization device carried by the worker. The locations of other reading points are: P2 (0.0,4.5), P3 (0.0,4.0), P4 (0.0,3.5), P5 (0.0,3.0), P6 (0.0,2.5). Based on the safety knowledge presented in chapter 3, while using a clearance distance of 6 feet, the worker is in the green zone at point 1, in the yellow zone at P2 to P4, and in the red zone at P5 to P7.



Precision and Recall with testbed data

Point #		1	2	3	4	5	6	7
Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%
Red-Yellow-Green System	Precision	100%	100%	100%	100%	100%	100%	100%
	Recall	100%	100%	100%	100%	100%	100%	100%



Precision and Recall of Both Systems Along the Worker's Path

Precision and Recall with simulation data

Point # / STD/cm		yellow-green system							Red-Yellow-Green System						
		P1	P2	P3	P4	P5	P6	P7	P1	P2	P3	P4	P5	P6	P7
	Precision	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
0.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	85%	100%	100%
	Precision	95%	100%	100%	100%	100%	100%	100%	95%	100%	100%	100%	100%	100%	100%
1	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	55%	100%	100%
	Precision	85%	100%	100%	100%	100%	100%	100%	85%	100%	100%	100%	100%	100%	100%
1.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	50%	100%	100%
	Precision	75%	100%	100%	100%	100%	100%	100%	75%	100%	100%	100%	100%	100%	100%
2	Recall	100%	95%	100%	100%	100%	100%	100%	100%	95%	100%	100%	60%	100%	100%
	Precision	90%	100%	100%	100%	100%	100%	100%	90%	100%	100%	95%	100%	100%	100%
2.5	Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	55%	95%	100%
	Precision	90%	100%	100%	100%	100%	100%	100%	90%	100%	100%	95%	100%	100%	100%
3	Recall	100%	90%	100%	100%	100%	100%	100%	100%	90%	100%	100%	55%	100%	100%
	Precision	75%	100%	100%	100%	100%	100%	100%	75%	100%	100%	95%	100%	100%	100%
3.5	Recall	100%	80%	100%	100%	100%	100%	100%	100%	80%	100%	100%	50%	90%	100%
	Precision	70%	100%	100%	100%	100%	100%	100%	70%	100%	100%	80%	100%	100%	100%
4	Recall	100%	85%	95%	100%	100%	100%	100%	100%	85%	95%	100%	70%	85%	100%
	Precision	65%	100%	100%	100%	100%	100%	100%	65%	100%	100%	60%	100%	100%	100%
4.5	Recall	100%	80%	100%	100%	100%	100%	100%	100%	80%	100%	100%	60%	85%	100%
	Precision	55%	100%	100%	100%	100%	100%	100%	55%	100%	100%	85%	100%	100%	100%
5	Recall	100%	75%	95%	100%	100%	100%	100%	100%	75%	95%	100%	55%	95%	95%

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