

SUPPORTING CONSTRUCTION PERSONNEL IN THE SAFETY AND PLANNING
OF CONSTRUCTION ACTIVITIES PERFORMED AT HIGH ELEVATIONS
VIA AUGMENTED REALITY TECHNOLOGY

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บทคัดย่อและแฟ้มข้อมูลฉบับเต็มของวิทยานิพนธ์ตั้งแต่ปีการศึกษา 2554 ที่ให้บริการในคลังปัญญาจุฬาฯ (CUIR)

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เพชรรัตน์ ลีสมุขปริยรัตน์ : การสนับสนุนบุคลากรในงานก่อสร้างด้านความปลอดภัยและการวางแผนกิจกรรมก่อสร้างที่ต้องดำเนินการบนระดับความสูงผ่านเทคโนโลยีความจริงเสมือนเสริม. (SUPPORTING CONSTRUCTION PERSONNEL IN THE SAFETY AND PLANNING OF CONSTRUCTION ACTIVITIES PERFORMED AT HIGH ELEVATIONS VIA AUGMENTED REALITY TECHNOLOGY) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รองศาสตราจารย์ ดร.ธนิต ชงทอง, 226 หน้า.

กิจกรรมก่อสร้างเป็นกิจกรรมที่อาจก่อให้เกิดอุบัติเหตุในการทำงาน โดยสาเหตุหลักของการเกิดอุบัติเหตุในงานก่อสร้างมาจากการตกจากที่สูง และการถูกปะทะ หรือพุ่งชนของวัตถุโดยการจัดการอันตรายซึ่งเกิดจากสาเหตุดังกล่าวประกอบด้วย การออกแบบและวางแผน การติดตามและการฝึกอบรม ข้อมูลของโครงการซึ่งแสดงในรูปแบบเอกสารที่แสดงผลแบบสองมิติถูกนำมาใช้ในกระบวนการจัดการความปลอดภัยร่วมกับความรู้และประสบการณ์ของผู้รับผิดชอบ อย่างไรก็ตาม สภาพแวดล้อมจริงในการดำเนินงาน โครงการก่อสร้างมีลักษณะที่เปลี่ยนแปลงตลอดเวลาและมีอันตรายแฝงอยู่ ดังนั้นในการจัดการอันตรายบางครั้งจึงต้องการข้อมูลของสภาพแวดล้อมจริงมาใช้ประกอบการพิจารณาด้วย โดยปกติผู้รับผิดชอบด้านการจัดการความปลอดภัยจะทำการแปล สร้างและประมวลผลข้อมูลสามมิติในจินตนาการร่วมกับสภาพแวดล้อมจริงด้วยตนเอง ซึ่งงานดังกล่าวเป็นงานที่ยาก เป็นภาระและเกิดความผิดพลาดได้ง่าย นอกจากนั้นแล้ว ยังขึ้นอยู่กับประสบการณ์ ความรู้และมุมมองส่วนบุคคลของผู้ปฏิบัติ

ดังนั้น แนวทางด้านนวัตกรรมที่จะช่วยสนับสนุนบุคลากรในการบริหารและจัดการด้านความปลอดภัยที่สะท้อนสภาพการทำงานจริง ณ ปัจจุบัน ผ่านเทคโนโลยีความจริงเสมือนเสริม จึงถูกพัฒนาขึ้น โดยนำเสนอข้อมูลที่เกี่ยวกับความปลอดภัย โดยซ้อนทับกับสภาพแวดล้อมจริง ระบบต้นแบบชื่อ ระบบการจัดการด้านความปลอดภัยที่สามารถมองเห็นได้โดยการใช้เทคโนโลยีความจริงเสมือนเสริม ถูกพัฒนาเพื่อช่วยบุคลากรในงานก่อสร้างในการจัดการงานดังนี้ 1) การออกแบบและวางแผนเพื่อป้องกันอันตรายจากวัตถุหล่น 2) การออกแบบและวางแผนเพื่อจัดเตรียมพื้นที่ทำงานที่ปลอดภัย 3) การติดตามความปลอดภัย และ 4) การฝึกอบรมด้านความปลอดภัย หลักการคำนวณและอัลกอริทึมโดยใช้พื้นฐานทางคอมพิวเตอร์เทคนิคถูกพัฒนาขึ้นเพื่อวิเคราะห์ศักยภาพของอันตรายจากวัตถุตกหล่น ความสามารถของระบบการป้องกันด้านความปลอดภัย และพื้นที่อันตรายเมื่อดำเนินงานเกี่ยวกับเครนและกิจกรรมก่อสร้าง

รูปแบบการทำงาน 3 ส่วนในระบบได้แก่ การนำเสนออันตรายจากการตกของวัตถุ สภาพพื้นที่การทำงานที่ไม่ปลอดภัย และการแสดงผลวัตถุเสมือนที่เกี่ยวกับความปลอดภัยได้ถูกทดสอบในห้องปฏิบัติการและในสภาพแวดล้อมจริง ระบบที่พัฒนาขึ้นได้ถูกนำไปทดลองใช้ในโครงการก่อสร้างอาคารสูง ผลจากการทดลองในหน่วยงานก่อสร้างแสดงให้เห็นว่า ระบบที่พัฒนาขึ้นสามารถนำไปประยุกต์ใช้ในการออกแบบและวางแผนด้านความปลอดภัยเพื่อนำเสนอข้อมูลที่ไม่สามารถมองเห็นและคาดการณ์ล่วงหน้าได้ในสภาพแวดล้อมจริงและเพื่อเสริมมุมมองของบุคลากรในงานก่อสร้างเกี่ยวกับความปลอดภัยก่อนเริ่มดำเนินการก่อสร้าง สำหรับการติดตามและการฝึกอบรม ระบบสามารถช่วยสนับสนุนด้านการสื่อสารระหว่างผู้ที่เกี่ยวข้องในโครงการได้

ภาควิชา.....วิศวกรรมโยธา.....ลายมือชื่อนิสิต.....

สาขาวิชา.....วิศวกรรมโยธา.....ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก.....

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Due to the nature of construction, many of the tasks and activities tend to lead to the occurrence of accidents. The major causations of the accidents in construction industry are fall from height and being struck by falling object. The tasks to execute the safety and prevent the hazards of these causations consist of design and planning, monitoring, and training. The process of each task are carried out based on the project information, which represented by two dimensional and paper format documents accompanied with the construction personnel's knowledge and experiences. However, the actual work conditions at the construction site are dynamic environment and contained the inhered hazards. Thus, the execution of the tasks to prevent the mentioned hazards sometimes requires the information of actual workplace for supporting in the safety considerations. Normally, the in-charge personnel convert, generate and integrate mental three dimensional pictures regarding safety with the actual environment by themselves. However, it is difficult, burdensome, and error prone. Additionally, it depends on the level of experience, knowledge, and individual perspective of undertaker.

Therefore, the innovative and proactive approach for supporting the construction personnel regarding safety management in real time and actual environment via Augmented Reality (AR) technology is developed. The approach provides the virtual safety information and superimposes it on the real world scene. The prototype system, which named Visualized Safety Management using Augmented Reality Technology System (VSMART System), was developed to assist the in-charge personnel in the following tasks: 1) design and planning for preventing the hazards of falling object, 2) design and planning for arrangement of safe work areas, 3) monitoring, and 4) training. The projectile calculation and collision detection algorithms based on the computer vision techniques are developed to analyze the potential hazards of falling objects, the capability of designed falling protection system, and the virtual unsafe zone when operated crane and performed construction activities.

Three functions in the prototype system, which consisted of providing the visualization of possible hazards from falling object, illustrating the unsafe working areas, and presenting the virtual objects regarding safety were tested in both laboratory and real environment. This proposed system was implemented at the real high rise construction project. The experiment results showed that this system is feasibly applied for design and planning task to provide the unseen and unforeseen information in the actual work environment and to envision the construction personnel in safety aspect prior the construction activities begin. For the monitoring and training, this system can support the project participants in communication.

Department : Civil Engineering Student's Signature.....
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Chapter I

Introduction

1.1 Background

1.1.1 Construction safety

Construction is an important economic activity around the world (Van der Molen et al., 2005) and drives economics of every country (Tam, Zeng, and Dang, 2004). Owing to its significance, construction projects are executed and completed with the following targets: being on time, under a defined budget, and of acceptable quality. Besides those described targets, achievement in the safety aspect, such as no accidents at construction sites, is also important. Not only are the human tragedies of the victims and their families consequences of accidents, but losses in construction projects, for example, damage to property, delays in completion, and increasing cost for compensations and reworks are also a consequence. Beyond these primary consequences, other incalculable effects are damages to the company's reputation and losses in market competition. Accident costs have been reported to be in the billions of dollars in economic loss (Yabuki, Limsupreeyarat, and Tongthong, 2010). Additionally, the cost of an accident exceeds its evidence; the indirect costs of accidents might be as much as six times the direct costs or more (Chen, Fisher, and Krishnamurthy, 1995).

Because of the nature of construction, many of the tasks and activities tend to lead to the occurrence of accidents. Workers sometimes have to perform tasks within a limited working area, in an inappropriate posture, and with inadequate and mismatched equipment. They also often operate at a considerable height, outdoors, with complicated on-site plant and equipment operation, coupled with overcrowding of workers (Choudhry and Fang, 2008). Besides the inherent characteristics of construction, continuously-changing workplaces, a peripatetic workforce, and complex project organizational arrangements make this industry a demanding sector in which to undertake research (Van der Molen et al., 2005).

1.1.2 Accident type

There are many root causes of the accidents that occur at construction projects. The Occupational Safety and Health Administration (OSHA) classifies accident causes into five major causes: falls, electric shock, being struck by an object, caught in and/or between equipment or material, and others. However, Hinze, Pedersen, and Fredly (1998) indicated the initial evaluation of accident causation in construction based on the OSHA causes code was insufficient to describe the root causes. They investigated the OSHA accident records in 1994 and 1995 and distributed the

percentage of each initial cause, as shown in Figure 1.1. They then proposed a further accident cause code as described in Table 1.1. Most accidents, according to this scheme, are caused by either unsafe acts or unsafe conditions or both. Unsafe acts include violation of safety procedures and can lead to the occurrence of an accident. On the other hand, an unsafe condition is a hazardous physical condition or circumstance which conduces to accident incidents. Failing to identify the unsafe conditions which exist before an activity begins, or that emerges after, deciding to proceed with a work activity after the existing unsafe conditions are identified, and deciding to act unsafely are the root causes of construction accidents (Abdelhamid and Everett, 2000).

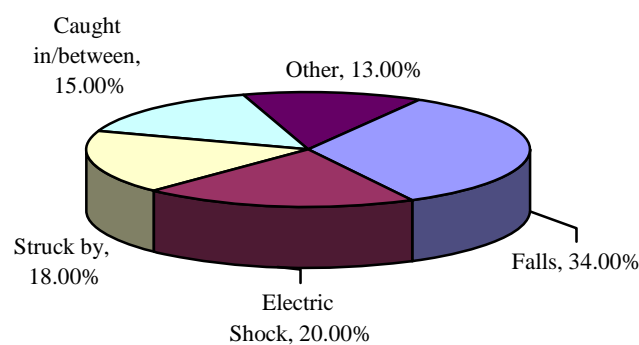


Figure 1.1 Distribution of accident causation (Hinze, Pedersen, and Fredly, 1998)

Although many studies elucidate the root causes of accidents regarding unsafe conditions, the workers in construction are sometimes blamed for being involved in accidents due to their actions, such as carelessness and failure to obey work procedures (Hamid, Majid, and Singh, 2008). In fact, employers must take more actions to prevent unsafe construction-site conditions, such as all entities (owner, architect and engineer, general contractor or subcontractor) having the responsibility for determining safe measures and methods, setting a safe pace for the construction, determining what safety equipment will be used, and monitoring for unsafe conditions and unsafe acts. The in-charge personnel have to understand proper site condition, must be able to observe actual site conditions, and be able to control site conditions.

1.1.3 Safety management in current practice

In order to prevent accidents in the execution of construction, several rules and regulations based on the OSHA provisions have been promulgated by governments in many countries and enforced at construction projects. Additionally, management teams have endeavored to improve construction-site safety in all aspects, including safety policies and standards, safety organization, safety training, inspecting

hazardous conditions, personal protection programs, plant and equipment, safety promotion, and management behavior (Choudhry, Fang, and Ahmed, 2008). Even though various techniques of construction safety management have been applied at construction sites to reduce accidents, the statistics on accidents in the construction industry have not decreased obviously in the past two decades. Construction is still ranked as one of the most hazardous industries. The risk of a fatality in the construction industry is five times more probable than in the manufacturing industry (Sawacha, Naoum, and Fong, 1999). In the United States, one in six workers experience an occupational injury or illness on the average of about once a year (Chen, Fisher, and Krishnanurthy, 1995).

Table 1.1 Revised accident cause code (Hinze, Pedersen, and Fredly ,1998)

Initial cause code	Revised cause code
Falls	Falls from elevation
	Falls from ground level
Electrocution	Electrocution (power lines)
	Electrocution (building power)
	Electrocution (faulty facility wiring)
	Electrocution (faulty construction tool/wiring)
	Electrocution (other)
Struck by	Struck by equipment
	Struck by falling material
	Struck by material (other than falling material)
Caught in/between	Caught in / between equipment
	Caught in / between material
	Cave-in
Other	Explosion
	Fire
	Explosion/fire
	Asphyxiation
	Drowning
	Natural causes
	Other

1.1.4 Improvement of safety management in construction

In this last decade, the processes of construction safety management, such as hazard identification, planning, supervision and monitoring, and training have been improved by many researchers (Hadikusomo and Rowlinson, 2002; Chantawit,

Hadikusomo, and Charoenngam, 2005; Benjaoran and Bhokha, 2009; Sulankivi, Kähkönen, Mäkelä, and Kiviniemi, 2010; Li and Liu, 2012; Li, Chan, and Skitmore, 2012). Information technology, especially visualization techniques, is increasingly utilized at construction sites. The main purpose is to prevent the accidents which may occur at the construction site by providing sufficient information and approach in order to help the in-charge personnel identify the unsafe conditions and to plan for prevention. Furthermore, the communication of safety information among project participants can be improved by using innovative technology.

Beyond the presentation of 2D engineering drawings, the other visualization techniques that have been implemented in construction projects to raise the safety level can be categorized into four types. First, graphical 3D visualization is employed to present the geometry of building components, and the site personnel can consider inherited hazards based on the 3D perspective of the building. However, this technique can assist them in answering only what safety measures should be provided. Then 4D CAD, which is an integration of 3D objects and time (Koo and Fischer, 2000) was implemented. This tool can supply project information and the involved participants can identify and determine what, when, and where the safety measures should be arranged. However, the hazards at construction sites do not reside in building components only, but they also can be found in the construction methods and surrounding project site conditions. Therefore, virtual reality (VR), which offers a natural medium so that the users can visualize the 3D virtual environment and manipulate it in real time (Bouchlaghem et al., 2005) has been applied to simulate the construction processes and the real environment. It allows site personnel to interact with virtual objects and without the dangers found at the real site. Although virtual reality has more benefits than not, it still has some significant drawbacks, such as being time-consuming and expensive for development. In some circumstances it cannot reflect the actual hazards at the construction sites because the environment is simply imitated and is not the actual physical environment. Another technique is Augmented Reality (AR), which is a visualized technique to superimpose virtual objects onto the real world scene (Azuma, 1997). In this way construction personnel can consider the virtual safety information while perceiving the actual conditions at the construction site. Thus, augmented reality can be an effective technology for dealing with construction safety management.

1.2 Problem statements

1.2.1 Need for management action to eliminate unsafe conditions

The unsafe acts of construction worker are often identified as a cause of accidents, such as neglecting to obey work procedures, rules, and regulations. Many

previous studies have suggested approaches to reducing accidents by training the workers to use personal protective equipment or to perform tasks in accordance with safe procedures. However, most construction workers in Thailand are poorly educated and temporarily employed. Thus, they should not be the only party to shoulder safety responsibility at the construction site. On the other hand, it is easier to minimize unsafe conditions rather than unsafe acts. As Holt (2005) has stated, when operating construction activities at high elevations or near machinery, management should pay more attention to providing safe workplaces, measures, and methods for the workers to prevent accidents because the work environment is one of the significant issues that directly involves hazards and accidents. An appropriate and safe workplace will decrease accidents in the construction industry.

1.2.2 Human limitations in the mental generation of 3D pictures and their integration with the actual construction environment

Conversion of 2D information to 3D mental pictures is a difficult and tedious task for construction personnel (Chantawit, Hadikusomo, and Charoenngam, 2005). Moreover, they have to integrate the converted information with the conditions of the real construction site by themselves. Figure 1.2 presents an example of the information integration of site personnel for safety execution. In order to perform these tasks by using the diversity, plenty, and unable to see information, it is tedious, burdensome, and error prone (Chantawit, Hadikusomo, and Rowlinson, 2005; Zhang et al., 2012). In addition, the mental-integration process depends on the level of experience, knowledge, and individual perspective of the construction personnel (Bansal, 2011).

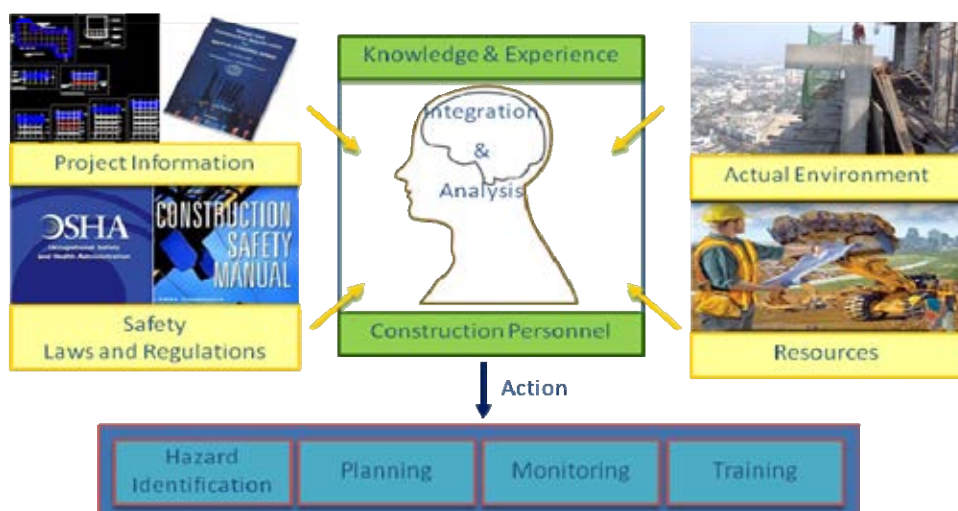


Figure 1.2 the information integration of site personnel for safety execution (modified from Waly and Thabet, 2002)

1.2.3 The real time and actual site conditions that influence construction personnel in the decision-making process regarding safety

Normally, the safety information which is used in construction projects is separated from other project information and is represented in two-dimensional engineering drawings, textual information, and paper format. This presentation is difficult to understand (Hadikusomo and Rowlinson, 2004) and does not reflect the real working conditions. Furthermore, engineers and supervisors may not perceive the actual hazards that occur in the real situation by using such documents—the real situation is very important when considering safety due to the existing hazards in construction operations. Typically, the execution at construction sites is dynamic and updated daily, such as work areas and work paths or the movement of heavy equipment. Therefore, hazard identification and short-term planning carried out based on the real time information of construction execution may reduce the accidents in construction.

1.3 Research objectives

The main objective of this dissertation is to propose the development of an innovative and proactive approach for supporting the in-charge personnel regarding safety management for construction activities performed at high elevations in real time and in the actual environment via a visualization technology called Augmented Reality (AR). The proposed system can assist site personnel when considering the possible hazards of falling objects from the building perimeter and crane operation, preparing safety measures, planning of safe work areas, monitoring, and training. Accordingly, the sub-objectives of this dissertation are:

- 1) To explore and investigate the current practices in preventing falls and falling object accidents in real construction projects for improvement of safety
- 2) To develop a prototype of a visualized safety management system

1.4 Scope of study

This research was carried out on the following predetermined bases:

- 1) Two causes of construction accidents—falls from heights and being struck by falling objects, were mainly focused on.
- 2) The type of construction project was high-rise building projects.
- 3) The visualization technology used for developing a prototype system was augmented reality.

1.5 Research methodology

The research methodology employed in this research is enumerated as follows:

1) A review of the previous literature related to construction safety, accident causation, safety standards, rules and regulations, construction safety management, hazard identification method, and safety planning process

2) A review of previous literature related to visualization technology by focusing on state-of-the-art in construction safety. Suitable visualization technology should transform unseen safety information and produce tangible information for the in-charge personnel associated with the safe and unsafe conditions of construction operations in real time and locations. The selected visualization technology in this study is augmented reality. The advantages and limitations of this technology were identified.

3) High-rise building construction projects are surveyed to investigate the current practices regarding the prevention of falls and falling object accidents. Walkthroughs and direct interviews were applied to collect the data. Additionally, photography and video recording were also implemented. Existing tasks regarding safety, such as design, planning, monitoring, and training, were analyzed to examine the potential improvement.

4) Design the concept of the proposed system from literature review and observed data

5) Develop a prototype system for supporting the construction personnel in safety management. Implement and experiment with the prototype system in both the laboratory and the real environment.

6) Verify and validate the proposed system and identify the system limitations

7) Summarize and discuss the results. Future research is also described in this step.

1.1 Research contributions

The contributions of this research comprise the following:

1) The research outcome will be an innovative and proactive approach to helping in-charge personnel deal with the hazards of falls and falling objects in actual and dynamic work conditions.

2) The result of this research can be used as a prototype for a visualized construction safety management system that is designed to support the following processes: design and planning of the hazards of falling objects from building perimeters and crane operations, selection of safety measures for construction activities performed at high elevations, planning for safe work areas, and safety monitoring and training.

Chapter II

Literature Review

2.5 Introduction

This chapter presents a literature review of related studies. The contents are divided into five sections. First, the causes of accidents in construction are described. In the second section, the improvement of construction safety management is reviewed. The contents in this section are categorized into four groups in accordance with the processes of safety management as follows: 1) hazard identification, 2) safety planning, 3) monitoring, and 4) training. Next, the issues of visualization techniques in construction are described. This section is divided into three subsections as follows: 3D/4D CAD, virtual reality, and augmented reality. Then, the potential applications of augmented reality technology in construction are reviewed. The last section is the discussion and conclusion.

2.6 Causes of accidents in the construction industry

Accidents have been proposed as one factor in a series of domino theories as defined by Heinrich, Peterson, and Roos (1980). The five dominoes represent social environment and inherited behavior, the fault of a person, unsafe acts and conditions, and accidents and injury. However, construction has its own characteristics that are different from the manufacturing industry. Tasks and activities are always performed in an open area and exhibit variation in the physical environment. Moreover, there is a potential for serious accidents in construction sites due to the following causations: many people are close together, many activities are unpredictable, and the tolerance of risk is traditionally quite high, making the frequency and impact of unplanned activities very high (Fewings, 2005). Due to the statistics of accident rates in the construction industry, several studies had been done to investigate the causes of accidents as discussed below.

Abdelhamid and Everett (2000) presented an accident root causes tracing model (ARTCM) to identify the root causes of accidents in the construction industry. This proposed model focused on the causes of unsafe conditions which exist before or emerge after an activity is begun. The following four causes, which are management actions/inaction, unsafe acts of the participants, non-human related events, and unsafe conditions, are a natural part of construction sites.

Toole (2002) demonstrated the following eight root causes of construction accidents which comprise lack of suitable training, inadequate enforcement of safety, improper providing of safety equipment, the provision of safety equipment is not used, unsafe methods or working sequencing, unsafe site conditions, poor attitude

toward safety, and unsafe acts of safety-conscious employees. Working under improper site conditions, such as slippery surfaces, many people working in one area, and hazardous electrical and atmosphere conditions, dramatically increase the opportunities for an accident to occur. Huang and Hinze (2003) also pointed out that the human error factor contributes to fall accidents, for example, in the misjudgment of a hazardous situation. Not only human factors, but also the lack of protection in place, safety devices being inoperative, and equipment in use not being appropriate for operation have been identified as the most frequently causes of accidents (Janicak, 1998).

Many contributing factors from the previous studies can be summarized to be the causes of accidents, such as unsafe construction method statements (Carter and Smith, 2006), the human element (Pipisupaphol, 2003; Haslem et al., 2005), unsafe equipment (Fang et al., 2004; Halperin and McCann, 2004), working conditions and environments (Abdelhamid and Everett, 2000), management (Aksorn and Hadikusumo, 2004; Tam, Zeng, Deng, 2004; Hamid, Majid, and Singh, 2008), and the unique nature of the industry. These factors can be summarized and classified into two groups—unsafe conditions and unsafe acts. In sum, most accidents are caused by either unsafe acts or unsafe conditions or both.

As mentioned above, the construction site is unique, complicated, risky, and usually outdoors due to the construction characteristics. Moreover, many tasks and activities are performed high from the ground conditions. The inherent hazards in construction operations may lead to injuries or the fatalities of workers. According to the cause codes of accidents in the construction industry by OSHA, there are five basic cause codes, consisting of falls, being struck by an object, caught in/between equipment or material, electric shock, and others (Hinze, Pederson, and Fredley, 1998). The statistics on occupational injuries and fatalities then show that falls and being struck by a moving or flying/falling object are the top three accident causations in the construction industry (Haslem et al. 2005; Srinavin, 2007). Wu et al. (2010) investigated the OSHA historical records of injuries and fatalities in USA from 1995 to 2008 and discovered that in 460 cases of accidents which occurred in residential areas, commercial buildings, and manufacturing plants, fall accidents accounted for 49% and the second cause of accidents was being struck by an object, which accounted for 15% of the accidents. The details of the distribution of accident records are presented in Table 2.1. Therefore, the accidents caused by falls and being struck by a falling object in the construction industry have received much attention and publicity, as discussed in the following.

Table 2.1 The distribution of OSHA accident records from 1995 to 2008 (Wu et al., 2010)

Category	Sub-category	Number	Percentage
Falls (49.05%)	1. Fall from/with ladder	293	12.87%
	2. Fall from roof	781	34.31%
	3. Fall from/with scaffold	316	13.88%
	4. Fall from/with bucket (aerial lift/basket)	57	2.50%
	5. Fall from/with structure (other than roof)	363	15.95%
	6. Fall from/with platform catwalk (attached to structure)	53	2.33%
	7. Fall through opening (other than roof)	199	8.74%
	8. Fall from vehicle (vehicle/construction equipment)	36	1.58%
	9. Fall, other	178	7.82%
Struck by (14.94%)	1. Struck by equipment	399	57.58%
	2. Struck by falling object/projectile	294	42.42%
Electric shock (12.18%)	1. Electrocutation by touching exposed wire/source	243	43.01%
	2. Electrocutation by equipment contact wire	188	33.27%
	3. Electrocutation by equipment installation/tool use	70	12.39%
	4. Electric shock, other and unknown cause	64	11.33%
Caught in/between (7.8%)	1. Caught in stationary equipment	29	8.01%
	2. Collapse of structure	203	56.08%
	3. Trench collapse	116	32.04%
	4. Wall (earthen) collapse	14	3.87%
Other (16.03%)	1. Asphyxiation/inhalation of toxic vapour	87	11.69%
	2. Drowning	11	1.48%
	3. Fire/explosion	58	7.80%
	4. Heat/hypothermia	46	6.18%
	5. Other	244	32.80%
	6. Unknown	298	40.05%
Total		4640	

Tam, Zeng, and Deng (2004) explored the perceived probability of serious accidents at construction sites that led to the fatalities of workers in China by using questionnaires. The results indicated that the respondents considered “falling from a height” was most risky. Chang et al. (2009) studied safety at high-rise building construction projects in Taiwan. They stated that the working areas at those projects were among the highest risks in the workplace. Although the Taiwanese government has promulgated and revised various relevant guidelines to ensure adequate protection

in order to prevent accidents, more than 150 workers at high-rise building construction sites are still killed annually. This indicates that the major lethal accident causation in construction is falls and that there are inherent hazards in the workplace at high elevations.

The tasks most often associated with falls are roofing, installation of floor slab formworks, erecting structural steel, and exterior carpentry (Hsiao and Simeonov, 2001; Adam, Pallares, and Calderon, 2009; Huang and Hinze, 2003; and Beaver, Moore, and Schriver, 2009). These operations are normally carried out at elevations or on temporary structures. In addition, Huang and Hinze (2003) investigated the OSHA recorded 7,543 accident data from January 1990 through October 2001 and found that falling accidents accounted for 34.6% of the injuries. The accidents frequently occurred in building construction projects, especially commercial buildings, because most of them were high-rise buildings and comprised multi-stories. Thus, there is the inherent hazard of falling. Not only is this accident a major proportion of injuries in construction, this proportion increases continuously every year. The percentages of fall accidents in commercial and other building construction projects represent more than 50% of the recorded fall accident data from 1997 through 2001, as shown in Figure 2.1. Furthermore, the researchers stated the accidents often occur in new or addition projects more than in alteration or rehabilitation, maintenance or repair, and demolition projects.

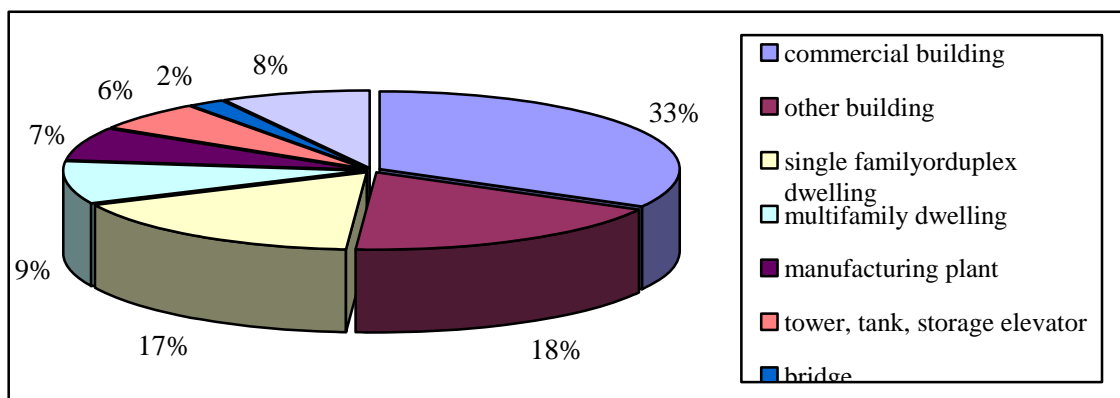


Figure 2.1 Falling accidents in construction projects (Huang and Hinze, 2003)

In order to avoid accidents caused by falls or falling objects, preventive strategies such as identifying the potential hazards, proper selection and use of safety protection system, training in the workplace, and provision of adequate preventive equipment are necessary (Janicak, 1998). According to the preventive strategies, safety programs must be implemented at construction projects. Aksorn and Hadikusomo (2007) have stated that there are sixteen factors in four dimensions,

which are worker involvement, safety prevention and control system, system arrangement, and management commitment, all of which influence the success of safety program implementation. They also confirmed that the most influential factor was management support.

Therefore, these causes of accidents can be eradicated by implementing effective safety managements (Sawacha, Nauom, Fong, 1999), for instance, determining safety working procedures (Helander, 1991), determining safety measures for operations, and creating safe working environments for the worker (Rowlinson, 2003).

2.7 Improvement of construction safety management

In order to prevent accidents and improve the level of safety in construction, various safety management systems are implemented during project-execution phases. According to a study of Benjaoran and Bhokha (2009), safety management is the set of actions or procedures associated with health and safety in the workplace. Three main tasks of safety management consist of hazard identification, safety measure planning, and control. Not only these tasks, but safety education and training are also other essential tasks for achieving a zero accident target. However, in order to support construction personnel and to enhance the efficiency of safety management, potential tools such as information technology are required. Therefore, many previous studies have made an effort to suggest the implementation of information technology in safety management processes, as presented in Table 2.2. The following sections describe the application of information technology in each task of construction safety management.

2.7.1 Hazard identification

The failure of both workers and management to identify hazards and to be able to avoid or prevent them can lead to the occurrence of accidents (Lingard and Rowlinson, 1997). Hazard identification is an important task because it affects the subsequent processes, for example, planning and control (Benjaoran and Bhokha, 2009). Thus, the construction personnel must have sufficient knowledge and capability to recognize and identify inherent hazards. The crucial aspect of this task was studied in the past and the researchers also proposed innovative tools for carrying out the hazard identification as follows.

Hadikusumo and Rowlinson (2004) proposed a method for capturing the knowledge of safety engineers. The experiences of safety hazards at construction sites and accident precaution were collected and they developed a tool named the design-for-safety-process (DFSP). The virtual construction environment, which consists of safety hazards, were displayed and allowed safety engineers to observe and share their

experience in order to identify the inherent hazards. The hazards were thus identified and safety engineers were able to process planning steps.

Carter and Smith (2006) indicated that identifying hazards at the initial stage of construction can improve safety. However, the individual that creates the construction method statement is not usually able to identify every potential hazard in the construction operation. The authors therefore proposed an IT tool, named Total-Safety, to assist safety engineers in developing a method statement. This developed tool can enhance the levels of hazard identification of site personnel in terms of precision and accuracy and the results were influenced to the decision making process of safety engineers in safety planning.

2.7.1 Safety planning

Using planning strategies to improve safety at construction sites can be done by selecting appropriate construction methods and providing preventive measures. However, construction sites are congested and busy areas where the workplace is ever changing. Thus, it is difficult to predict the occurrence of potential hazards before or during construction. Although constraints in work conditions exist, the researcher still endeavored to implement advanced tools in the planning process in order to protect workers from accidents, as discussed below.

Dawood and Benjaoran (2005) proposed a framework for a 4D visualization of temporary safety facilities for construction planning and scheduling processes. A computer-based model was developed to provide for a safe working environment when construction tasks are performed at heights in accordance with H&S rules and regulations.

Bansal (2011) proposed the application of geographic information systems for executing safety planning, named ArcGIS. In this research, not only were 3D models and a schedule of the construction project developed, but also a surrounding topography of the project was created. 4D modeling, geospatial analysis, and topography analysis were linked together within a single environment to assist the safety planners when they considered what, when, where, and why safety measures are required.

Zhang et al. (2012) proposed automated rule checking for safety called the Building Information Models (BIM), which can detect potential hazards of falls and recommend preventive safety measures for the users prior to the beginning of construction. These checking rules, based on the OSHA, were translated into machine-readable rules. This developed system demonstrated that safety planning can be simultaneously carried out with the construction scheduling process for early detection and implementation of a protective safety system.

Table 2.2 Summary of construction safety systems/projects applying digital tools (Zhou et al., 2011)

Tool/Project	Approach	Level	Technology	Citation
H&S competence assessment	Assessment of duty-holders competence	Project	Online databases	Yu (2009)
Construction Safety and Health Monitoring System (CSHM)	Monitor project performance	Project	Online databases	Cheung, Cheung, and Suen (2004)
Design for Safety Process (DFSP)	Simulation and review of construction process for design related safety issues	Process and Product	VR	Hadikusumo and Rowlinson (2002 and 2004)
Virtual Construction Laboratory (VCL)	Simulation and review of innovative processes	Process	VR	Li et al. (2003)
MBA-black building	Safety planning considering environmental conditions	Process	GIS, entity-based 4D CAD	Bansal (2011)
Decision Support System (DSS)	Assist monitoring and control of operations	Process	GIS	Cheng, Ko, and Chang (2002)
Patterns Execution and Critical Analysis of Site Space Organization (PECASO)	Critical space-time analysis	Process	Entity-based 4D CAD	Mallasi (2006)
Rule-based 4D system	Rule-based	Process	Entity-based 4D CAD	Benjaoran and Bhokha (2010)
Mäntylinna building	Visualization	Process	BIM-based 4D CAD	Sulankivi et al. (2010)
Safety Analysis of Building in Construction (SABIC)	Structural analysis	Process	BIM-based 4D CAD	Hu, Zhang, and Deng (2008)

Table 2.2 Summary of construction safety systems/projects applying digital tools (Zhou et al., 2011) (Cont.)

Tool/Project	Approach	Level	Technology	Citation
Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE)	Construction job safety analysis and evaluation of operational risk levels	Operation	Entity-based 4D CAD	Rozenfeld, Sacks and Rosenfeld (2009)
Computer image generation for job simulation (CIGJS)	Simulation of job safety analysis	Operation	VR	Patrucco et al. (2010)
Automated obstacle avoidance support system	Sparse point cloud	Operation	Laser range scanning technology	McLaughlin et al.(2004)
Real-time proximity and alert system	Generate active warning or feedback in real time	Operation	Wireless and RFID communication	Teizer et al. (2010)
WiFi-based indoor positioning system	Indoor positioning	Operation	Wireless and RFID communication	Woo et al. (2011)
Video range imaging system	Detect, model, and track the position of static and moving obstacles	Operation	Video laser range scanning technology	Teizer et al. (2005)
Construction Hazard Assessment with Spatial and Temporal Exposure (CHASTE)	Construction job safety analysis and evaluation of operational risk levels	Operation	Entity-based 4D CAD	Rozenfeld, Sacks and Rosenfeld (2009)

2.7.2 Monitoring

Navon and Kolton (2007) proposed automated monitoring and control algorithms for detection of the guardrails in accordance with safety planning. The fall hazards from the activities and areas in which these activities are performed were focused on. The algorithms of the model were developed in a computer program written in VISUAL BASIC (VB), AUTOCAD, and MS PROJECT. The outputs of this study showed that the model can identify potential fall hazards and dangerous areas in real time and compare them with the planning. Moreover, it can warn the site personnel regarding the existing safety measures that have been missed or removed.

Lee et al. (2009) presented a real-time safety monitoring system which focused on the reduction of fatal accidents caused by falls. This system consisted of a mobile sensing device, transmitter sets and repeaters for sending the detected information to a receiver, and software for interpreting the received information. In the experiment, when the workers entered a defined dangerous area, the system automatically received the data and transmitted the information to the main computer to inform the safety managers regarding hazardous situations.

2.7.3 Training

Not only can the mentioned tasks be effectively carried out to reduce accidents in construction projects, but another effective task is safety education and training. This education and training are used to provide knowledge associated with hazards and accidents in construction operations for enhancing the level of hazard recognition (Helandar, 1991). However, the conventional safety training, which uses a verbal and manual description of OSHA regulations, is insufficient to enable the workers to detect and eliminate fall hazards (Huang and Hinze, 2003). The following studies emphasized the importance of safety training by implementing the advantages of information technology.

Chen, Fisher, and Krishnamurthy (1995) developed a computerized system, which is named "SAFECON," The system emphasizes the analysis of fall accidents and fall protection. This proposed system consists of a database where the user can store and retrieve the information on accidents. Not only a database, but also an expert system which aims to select a climbing and/or fall protection procedure was created. The results showed this system can be used for analyzing accidents, planning fall protection, and identifying areas requiring safety studies and training. This research pointed out that the safety procedures and measures were selected based on the knowledge associated with hazards and accidents.

Irizarry and Abraham (2005) investigated a methodology to improve safety in steel erection by using virtual reality. Their developed applications demonstrated the potential implementation of virtual reality technology and investigated the effects on

construction workers when they performed erection tasks at heights. This method can be used to examine the alleviation strategies for possible hazards and to assess the effectiveness in preventing injuries from working at heights. The researchers developed their applications at the Envision Center for Data Perceptualization at Purdue University which is a 5,000 square foot high performance visualization research facility. Moreover, it included a Virtual Reality (VR) Theatre for immersive applications.

Xie, Tudoreanu, and Shi (2006) proposed a training system named the Virtual Reality Safety Training System. The evaluation of the perceptual and behavioral impacts of the VR environments on a trainee was investigated. This system created 3D virtual images and produced memorable experiences for trainees. The trainees gained experiences and played in a safe and controlled environment, exploring the outcomes after making decisions without risk to him or herself or the equipment. The researchers stated that the virtual reality simulation for safety training can help the users understand and easily learn safety rules, standards, and regulations.

Li, Chan, and Skitmore (2012) proposed a new assessment method, which was named the 4D interactive safety assessment. This method was developed to assess the workers regarding construction safety knowledge and safety attitudes by integrating game technology. They aimed to improve the ability to identify hazards of individual workers via a safety training system. The users were allowed to visualize the simulated scenarios of unsafe site conditions, unsafe working behavior, and unsafe construction methods and sequencing. Then they were asked to answer the questions in accordance with the unsafe scenario that they encountered. Their answers were stored in the database and validated to evaluate the performance of the user. This developed method could indicate the weakness of the users that could pass the traditional assessment process.

As mentioned above, the management of hazardous events is a vital key to construction safety (Carter and Smith, 2006). However, the tasks of safety management, such as hazard identification, planning, and monitoring, have been conventionally carried out by using 2D construction drawings in which the information from architects, structural engineers, mechanical, and electrical engineers is put together. Hence, such tasks cannot be effectively executed because these drawing only represent the physical aspects of project information and the inherited hazards cannot be presented (Hadikusomo and Rowlinson, 2002). Moreover, in order to improve the situation awareness of construction personnel, as defined by Endsley (2000) as “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future,” the construction industry needs to improve the inefficiencies of

conventional tools and processes, such as paper-based document and manual safety execution. The conceptual model of the situation awareness approach can support construction safety management and improve the safety manager's decision-making processes (Gheisari, Irizarry, and Horn, 2010). Hadikusomo and Rowlinson (2002) indicated that the 3D or 4D visualization or/and virtual reality are more effectively used for hazard recognition than the conventional 2D design drawings. Therefore, innovative and effective technology, such as visualization, is required to improve the comprehension of construction personnel to effectively execute safety and also communicate among involved parties. Thus, the studies which focus on the implementation of information technology in terms of visualization techniques are described in the next section.

2.8 Visualization techniques in construction

Visualization technology is an effective tool for safety management. Its advantages are as follows: very powerful and flexible for cognition, facilitates the communication of knowledge, extends the capacity for humans to memorize information and increase the duration of their memory, and is useful for problem-solving as well as for education (Han et al., 2009). For this reason, the following techniques in visualization are implemented in construction.

2.8.1 3D/4D CAD

Reinschmidt, Griffis, and Bronner (1990) investigated the use of 3D computer models for improving construction productivity at construction sites. One of their hypotheses was to prove that 3D computer models can be effectively utilized in planning and simulation at construction sites. They found differences in productivity between control and test crews. The first crew used conventional two-dimensional drawings. On the other hand, the latter used three-dimensional computer models to plan their procedures.

Jarko and Kalle (1999) proposed a system called CoVe (Construction Value engineering and management), which provided building product modeling, resulting in a solution of various information needs of construction management. They also studied the application of 4D (3D plus time) to construction project planning. The results of the implementation of the 4D model in the case study were less reworking, safer, and cost saving.

Kang, Anderson, and Clayton (2007) presented a combination of 4D visualization with Web-based information management to assist construction personnel and enhance the collaborative decisions in planning and scheduling. The results of their experiments showed that the sample team which used the 4D models

could detect logical errors more frequently, faster, and with fewer mistakes than the team which used the 2D drawings and bar charts.

Benjaoran and Bhokha (2009) stated that the visualization of construction scenes and sequences can be provided by implementing a 4D CAD model. The integrated system based on the 4D CAD model and rule-base algorithms can support and assist safety engineers in traditional hazard identification. This visualization technique can clearly present the requirements for safety measures at the work area and enhance the awareness of all relevant parties. In order to formulate the 4D CAD models, an integrated system was combined with design information on the building components and scheduling about construction activities. The rule-based system was implemented to detect and analyze the hazards when activities at high elevations were performed, and to indicate required safety measures. The results showed that the developed system could support the project participants in the aspect of collaboration.

2.8.2 Virtual Reality

Immersive virtual reality can be defined as technology that provides the psychophysical experience of being surrounded by a virtual, computer-generated environment for the user. This experience was stimulated by using a combination of hardware, software, and interaction devices. A stereo 3D visual display can generate better immersion rather than a computer-determined point of view. Two typical forms of immersive virtual reality are head-mounted display (HMDs), which contains a small display screen in front of the user's eyes, and the Cave Automatic Virtual Environment (CAVE) (Dam et al, 2000). The applications of VR are described as follows.

Assfalg, Bimbo, and Vicario (2002) developed a virtual training environment called VECWIT (Virtual Environment for Construction Workers' Instruction and Training) to test the suitability of a virtual environment as a complementary tool supporting education and training for construction workers' safety. This approach was evaluated in the following two aspects: user's satisfaction and effectiveness. After implementing this system, the results showed that the users could convey more of the course's information components.

Savioja et al. (2003) presented some basics of VR and the requirements of software and hardware components from the viewpoint of a construction project. A new lecture hall at the Helsinki University of Technology was selected to be a case study. Additionally, they pointed out that the virtual reality techniques were useful for the designer to communicate among involved parties as well as among decision makers and with the end users. Construction projects can retrieve major benefits from the application of virtual environments.

Messner, Riley and Horman (2005) attempted to implement interactive construction learning modules in an immersive virtual reality environment for improving engineering education in building and infrastructure design. They developed a Virtual Construction Simulator (VCS) and allowed the engineering students to perform a detailed analysis of the design and create a construction plan where they immersed themselves in the 3D construction project. They also identified that students had a high level of interest and had a perception of improved learning after implementation of the immersive virtual reality facilities.

2.8.3 Augmented Reality

The definition of Augmented Reality is a technology or an environment where the virtual information created by a computer is superimposed onto the user's view of a real world scene. The user can work in a real environment while he or she can visualize and retrieve additional computer-generated or modeled information to support the task at hand (Wang, 2005). AR is a subset of the Mixed Reality range of the Reality-Virtuality (RV) continuum. Mix Reality has been formally defined by Milgram and Colquhoun (1999) as a special class of Virtual Reality- (VR) related technologies for creating environments wherein real world and virtual world objects are presented together in a single display. The Reality-Virtuality continuum is shown in Figure 2.2.

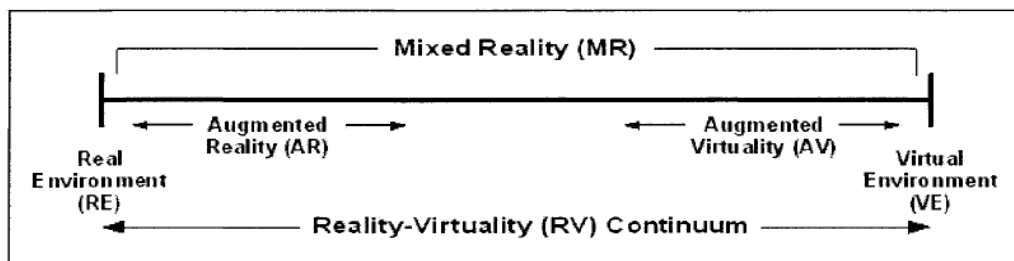


Figure 2.2 Reality-Virtuality Continuum (Milgram and Colquhoun,1999)

Rather than pushing the user into a completely computer-generated virtual world, AR provides virtual information for the user's real world view. Moreover, the display of augmented reality technology can enhance the user's perception of the actual environment in real time. AR technology is properly applied for information-intensive tasks which deal with information access and communication (Wang and Dunston, 2006).

Azuma (1997) classified the two ways of accomplishing augmentation in accordance with the type of output device: optical or video technologies. For the optical see-through HMDs, the optical combiners are placed in front of the user's eyes. The user can see virtual images bounced from the combiners from the head-

mounted monitors. The users can look through the combiners, which are partially transmissible. Figure 2.3 presents a conceptual diagram of an optical see-through HMD.

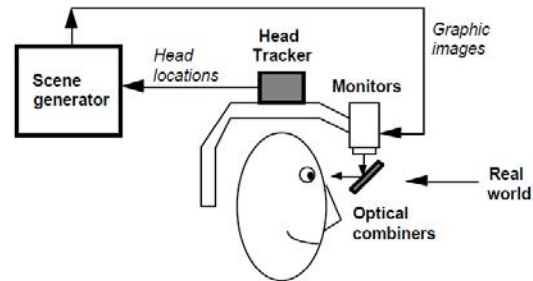


Figure 2.3 Optical see-through HMD conceptual diagram (Azuma, 1997)

On the other hand, video see-through HMDs are performed by combining a closed view HMD with one or two head-mounted video cameras. This device combines the video from these video cameras with the graphic images created by the scene generator. These graphics blend the real and virtual. Then, the scene generator sends the results to the monitor in front of the user's eyes in the closed-view HMD. Figure 2.3 presents a conceptual diagram of a video see-through HMD.

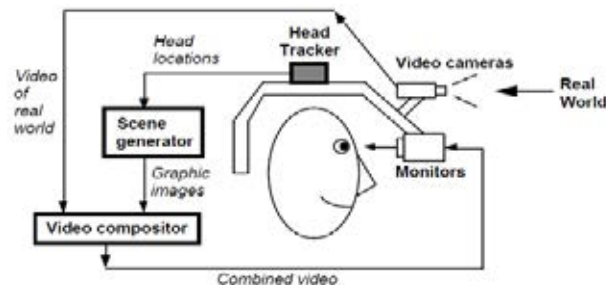


Figure 2.4 Video see-through HMD conceptual diagram (Azuma, 1997)

Tracking and orientation are other important processes in augmented reality technology. Currently, there are the following two methods: the sensor-based method using Global Positioning System (GPS), gyro sensors or electro-magnetic sensor, and an image-based method using a video camera (Ota, Yabuki, and Fukuda, 2010). The advantages of the second method are that it is cheaper and easier to install. Furthermore, some researchers in AR have provided a set of open source libraries for AR for the developers in the academic domain. In addition, AR can be classified into the following two categories: indoor and outdoor. For the indoor AR, the users are allowed to move in a finite space, but the advantage is in the preparation and accessibility of the environment. However, this benefit is not suitable for construction

because most construction activities are performed in outdoor and unprepared environments (Behzaden, 2006).

2.9 The potential application of augmented reality technology in construction

Augmented Reality has been applied to scientific visualization and gaming entertainment in the past. Azuma (1997) for example surveyed the potential applications of AR and categorized them into the following six classes: medical, military aircraft navigation and targeting, maintenance and repair, robot path planning, entertainment, and annotation. In the medical area, the doctors can use AR as a visualization and training medium for surgery. For military aircraft navigation and targeting, AR is implemented to merge the vector graphics upon the pilot's view of the real world scene. In the maintenance and repair of complicated machinery, the instructions are provided to the practitioners by showing the tasks step by step. In the robot path planning vision, the user can plan and define the robot's actions by manipulating the local virtual version in real time and the results are shown in the real world. AR is also applied to entertainment where virtual objects are merged in the real world scene to create digital actors. An example of an AR application in annotation is a hand-held display which can provide information about the contents of library shelves as the user walks around the library. Wang and Dunston (2006) have stated that the implementation of AR is widely used in the AEC industry as follows. Information concerning the implementation of AR and previous studies in the AEC industry is presented in Table 2.3 and the details are described as follows.

Webster et al. (1996) developed two preliminary Augmented Reality systems. The first system, called Architectural Anatomy, presented the hidden information of a building component behind architectural or structural finishes. This demonstration system was an "x-ray vision." The users were provided the augmented graphics by using a see-through head-mounted display with monocular and they tracked the position and orientation of their head with an ultrasonic tracking system. The presented graphic images did not to a great extent reflect their reality. The second system was the spaceframe construction. This system was developed for instructing practitioners in assembly. Besides providing 3D graphics models, a digitized set of audio files which contained the instruction was also included. Both presented systems aimed to improve architectural construction, inspection, and renovation.

Wang (2005) investigated the suitability and usability issues concerning the application potentials of Mixed Reality technology. The researcher also developed a concept named Mixed Reality based collaborative virtual environments (MRCVE) to enhance design comprehension and support collaborations.

Table 2.3 Implementation of Augmented Reality and previous studies in the architecture, engineering and construction industry (modified from Wang and Dunston, 2006)

Aspects	Description	Previous Studies
Design	AR can enhance design comprehension and support collaboration among project participants.	Wang (2005)
Construction and assembly	To guide and help construction personnel in integrating and interpreting planning information with the actual construction site	Wang (2007) Behzadan (2008) Park et al (2011) Yabuki, Miyashita, and Fukuda (2011)
Maintenance and renovation	Maintenance workers can visualize hidden features such as buried infrastructure, electrical wiring, and structural elements. AR can reduce accident damage and speed up maintenance and renovation operations.	Webster et al. (1996) Schall et al. (2008) Lee and Akin (2011)
Inspection	In this aspect, inspectors can work without reference to conventional construction drawing. Moreover, they can ensure that every needed item will be checked.	Yabuki and Li (2007)
Safety	This technology can improve the safety management by visualizing safety measures and procedures in construction activities. It can produce better understanding and cognition of workers.	Behzadan and Kamat (2009) Han et al. (2009)
Training	AR has the capability to speed the user's transition from novice to expert by reducing potential errors via efficient information access. This technology can supplement human associative information processing and memory.	Wang and Dunston (2007)

Yabuki and Li (2007) proposed a cooperative reinforcing bar arrangement support system using AR. At the construction site, reinforcing a bar arrangement requires experienced workmen to carry it out. Their knowledge will be transferred to the novice workers. In their experiments, the multiple users that were assumed to be the workmen, wore a head-mounted display installed with a video camera and moved special markers to discuss the reinforcing bar arrangement. Showing the markers linked with the designed objects to the video camera, the system displayed the object images on the markers on the video screen. The results of this experiment demonstrated that this system was more efficient and effective than the conventional pencil-and-eraser method. Furthermore, the researchers developed a cooperative

reinforcing bar checking support system to reduce errors and the time in this process. This system was tested at real construction site by placing the markers linked to computer graphics images. After implementation, the problems were identified as follows: difficulty in overlapping the real and virtual image completely, delays in rendering large amounts of information, quality in viewing combination of virtual and real objects, and limitations in the user's view based on one marker. Moreover, they attempted to solve the remote work problems by developing a remote cooperative reinforcing bar checking system in their future work.

Wang (2007) proposed the Augmented Reality system called the AR planner to assist site personnel in planning construction site layouts. The planners could locate materials and machines/equipment, handling devices, and the corresponding routing lines at the planned worksite. This system was developed in the laboratory where multiple users wore head-mounted displays with a video camera to get a tangible interface while discussing. The employed tracking system, called ARtag, consisted of 2D fiducial markers and a computer vision system for AR. In this study, they used a paddle as input device and they found that the exact touching of the virtual element with this paddle was difficult. This study was at the preliminary stage and was lab-based, and may not have reflected a real construction site.

Wang and Dunston (2007) presented a system called the AR-based real world Training System (ARTS), which focused on training inexperienced operators in a real construction environment populated with virtual materials and instructions. The researcher believed that people that were trained in virtual environment may perform well with his or her competency regarding safety in real-world operations.

Behzadan (2008) proposed an alternate approach for animating and demonstrating construction operations using Discrete Event Simulation (DES) in an outdoor environment. In this research, the users were allowed to navigate their virtual views superimposed into a real world scene freely in unprepared and unrestricted locations. The outputs were ARVISCOPE, a general purpose AR animation authoring language, and UM-AR-GPRS-ROVER, a mobile computing hardware framework. The first output enabled the modelers to automatically create and display AR animations of the construction operation that resulted from the DES simulations. They developed a second output to respond to the construction requirements which were needed to enable the personnel to investigate the simulated operation in actual situations. Thus, the required hardware and software for tracking the user's position and orientation were created. Figure 2.5 presents a hardware setup diagram for mobile outdoor Augmented Reality. The additional and different device from the indoor augmented reality device sets was the Global Positioning System (GPS) receiver. This device was employed to provide the AR platform with real-time position data in the

global space. This research provided better methods for verifying, validating, and communicating the results of simulated operations by providing effective and immersive visualization.

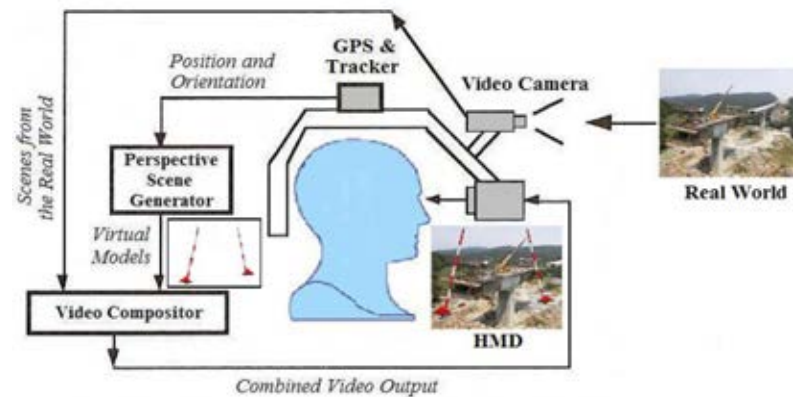


Figure 2.5 Hardware setup diagram for mobile outdoor AR (Behzadan, 2008)

Schall, Mendez, and Schmalstieg (2008) presented the capability of a mobile Augmented Reality System to support underground infrastructure inspection. Conventionally, the utility inspectors locate particular data such as schedules for maintenance on printed paper maps or 2D geographic information system on a laptop computer. They have to take these to the field. In this system, the graphic information was transmitted to the inspector's handheld computer, which received the signal to identify the practitioner's position by using Global Positioning System (GPS). The inspectors are allowed for the specification of the particular data and stored it in a central database. The result of implementation this system to the real practices was satisfied.

Behzadan and Kamat (2009) proposed safety improvement in urban construction projects by applying advanced visualization and tracking technologies. This presented system used AR and GPS to create real time views which inserted the virtual utility objects into the live video streams of the jobsite for excavation or drilling. A video camera was mounted on the equipment and captured the real time views. In order to produce the final augmented views of the excavation site for the operator, two important sources of information were required: data on the local utility company and input data from the tracking and video. The data flow of the designed system is shown in Figure 2.5. The results of the integration were displayed inside the operator cabin or in the head-mounted display or other display device of the site personnel. In this experiment, the operators were warned visually and audibly if they performed tasks closer than the specific distance in the regulation. The experiments proved that the risk of damaging hidden utilities was reduced by enhancing the operators' perception of the environment in which the actual operation took place.

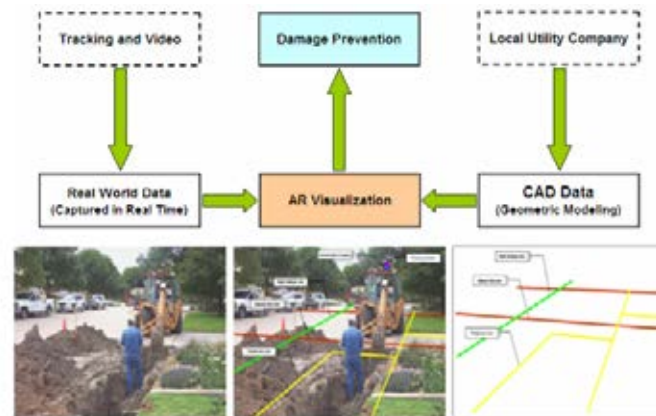


Figure 2.5 AR visualization in excavation (Behzadan and Kamat, 2009)

Han et al. (2009) presented the application of the D⁴AR model (4-dimensional augmented reality model). This model can superimpose a four dimensional virtual object according to the construction schedule onto the site photograph. This study improved the level of communication between managers and workers. One expectation regarding the use of the visual information was that safety managers or project managers could understand the location of unsafe activities and practices faster. Furthermore, they should be able to inform workers regarding safety guidelines more effectively.

2.10 Conclusion

Accidents occur at construction sites when work conditions are unsafe or when people act in an unsafe manner or both. In order to prevent accidents, especially falls and being struck by falling object, and to improve construction safety, effective measures for safety management such as hazard identification, safety planning and control, and safety education and training should be implemented. For planning and control, inherent hazards must be identified before they lead to accident occurrence. These tasks require the absolute comprehension all possible accident causes. Thus, safety education and training, which can provide knowledge for construction personnel, must be supplied. The trained construction personnel must be able to recognize hazards in operations and have the capability to provide safety equipment and methods for construction workers. Therefore, these measures require effective tools for access to and communication of information among the involved participants. Additionally, in order to safely operate the construction tasks, monitoring and control process is also required the effective approach.

Previously, information technology was implemented to improve the safety management system in various aspects. In addition, visualization technology was indicated to be an effective technique. 3D/4D CAD, virtual reality, virtual

environment, and Augmented Reality were implemented in many previous studies. However, each technique has its own limitations. 3D CAD models were developed for representing real geometric objects at construction sites. They cannot convey, however, an understanding of complexity. To provide visual construction sequences, 4D CAD, which illustrates virtual 3D objects plus time, was created. Using 4D CAD, the simulations, for example construction processes, can be demonstrated to communicate information among project participants. This technique is useful for design and planning. Although some studies have indicated that the 4D CAD model can assist with the hazard identification process, the planner still cannot obtain actual information of the construction site.

For enhancing the situational awareness of construction personnel, a more effective and advance visualization technique is required. Thus, virtual reality is implemented to allow users to interact with the virtual objects generated by a computer. The immersive virtual reality emphasizes providing the feeling of “being there.” In safety education and training, the users can experience the inherent dangers of their work environment without being in real jeopardy. Furthermore, this technique can improve their understanding regarding hazards. However, creating virtual objects is time-consuming and expensive. Moreover, virtual reality cannot provide a high degree of realism. Even if it is developed in an immerse system that surrounds the user, it is not as precise as the real world.

A newer visualization technique is Augmented Reality, which has the main feature of inserting the virtual objects into the real world and displaying them for the user’s view. The users thus are able to interact with both real and virtual objects. This technology is suitable for the nature of the construction industry because the construction process involves various types of tasks that deal with the creation of physical structures and elements, and most often require visual information so that workers can understand and communicate their complexity and relation to existing structures or elements.

To reduce the number of accidents in the construction industry, unsafe conditions must be eliminated from the workplace by implementing effective safety management systems. In-charge personnel have to perceive and identify hazards before making decisions in the planning process. Dealing with large amounts of information on construction activities, such as drawings and specification, tools and equipment, construction method, and resources, is difficult to undertake. The in-charge personnel have to consider building information and integrate this with the actual construction conditions. They identify inherent hazards and accidents by using their knowledge and past experience.

According to the literature review, a visualization system which can assist the construction personnel in planning the processes at actual construction sites and that can also educate them with knowledge related to the hazards in the construction operations performed at high elevations have not been revealed. Therefore, this research will develop an innovative visualization system by using augmented reality and investigating the development of construction personnel after implementing this system.

Chapter III

Introduction

3.1 Introduction

This research consists of six steps of methodology as follows: (1) literature review, (2) construction site observation, (3) system design and development, (4) testing and verification, (5) validation, and (6) research summarization and discussion.

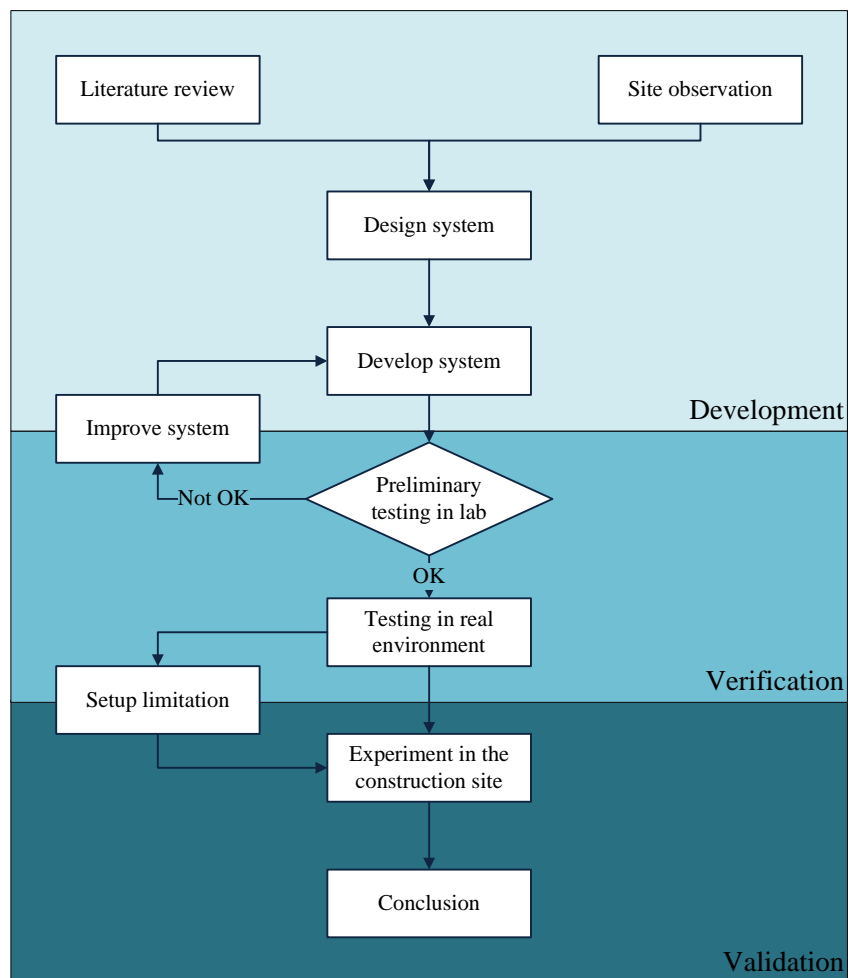


Figure 3.1 Research methodology

3.2 Research methodology

3.2.1 Literature review

Journal articles, textbooks, conference proceedings, theses, dissertations, and other documents related to this research are reviewed to explore the approach which can assist construction personnel in the processes of safety management, such as hazard identification, safety planning, monitoring and control, and training. Therefore,

the literature classification in this research is described as follows: (1) an overview of construction safety, (2) factors and causations in construction accidents, (3) safety standards, rules, and regulations which are implemented in construction projects by focusing on hazards from falls and falling objects, (4) the safety management process regarding hazard identification, safety planning, safety monitoring, and training in construction projects, and (5) the definitions, basic concepts, benefits, and implementation of visualization techniques for construction safety.

3.2.2 Construction site observation

According to accident statistics for the construction industry, the causes of accidents, which are falls and being struck by falling objects, were selected as the case study in this research. The selected activities regarding fall hazards were the construction activities performed at the perimeter of high-rise buildings. In addition to that cause, the hazard of falling objects is also discussed. Therefore, construction-site surveys were implemented to investigate the current practices of selected construction activities and to identify the problems and requirements related to hazard identification, safety facility planning, preparation, monitoring and inspection, and training. The methods for collecting the data and information were direct interviews, document reviews, photography, and video recording.

The interview method was employed to gain detailed data and information from project staff that have responsibility for hazard identification, safety planning, safety measure arrangements, monitoring and inspection, and training. Construction site staff were asked to describe the safety measures, equipment and tools, construction procedures and concerned factors when they identified hazards, planned and arranged the workplace, monitored safety, and prepared training for executing construction activities. Moreover, documents concerning the safety standards, rules, and regulations applied in the processes of safety planning will be reviewed.

Photography and video recording was employed to record the safety equipment, temporary facilities, construction sequences and operation methods, number of workers, and workers' posture and position when they operate selected activities in real site conditions, and also the actual surrounding environments.

3.2.3 System design and development

The concept of the proposed system was chosen from the literature review and construction site survey. The problems of current practices in safety management process are analyzed, while the advantages and limitations of visualization techniques are examined to solve those problems. A suitable technique should contain the ability to provide and integrate appropriate safety information with the actual surrounding environment for supporting the site participants. They will not be required to convert,

interpret, or combine any of the mentioned information by themselves and they can consider and make decisions about safety while perceiving the real and existing hazards.

According to the literature review, the selected visualization technique in this study is augmented reality (AR), which can supply an amount of information through computer graphics and merge virtual objects into a real-world scene. The advantage is that it provides 3D virtual objects just as they are in the real world while the user perceives the real surrounding environment. This enables the user to perceive, understand, and memorize information more easily. Additionally, it can support construction project participants in their visualization and understanding of the project details presented by computer graphics in actual construction surrounding environments. Thus, AR was appropriate for testing this research hypothesis.

A prototype system was designed and developed for this study in four parts due to the tasks collected from site observation, which are design and planning for preventing the hazards of falling object, design and planning for arrangement of safe work areas, monitoring, and training. The considered accident causes for prototype system development are falls and being struck by falling objects. In the first part, the approach to design and planning for preventing the hazards of falling objects is developed to provide the falling object situations and to allow site personnel to perceive and indicate potential hazards. The falling object hazards are considered and the case studies consist of falling objects from the perimeter of high-elevation buildings and falling objects from crane operation. The possible projectile path and area of the falling object are presented in order to inform the site personnel about the potential hazards of falling objects and unsafe working areas. A virtual unsafe working area is generated and can be visualized via computer graphics. A collision detection algorithm was applied for warning the construction personnel about unsafe conditions from both of the potential hazards mentioned above in real time. In this way, they can consider prevention methods for protecting people and property.

The second part focuses on safety design and planning based on the hazards of falling. Fall hazards can be reduced by providing proper and adequate safety measures and by specifying safe working areas when constructing building components located near the building perimeter. Thus, the creation of virtual construction object models, the data and information from site observations, literature, safety standards, and rules and regulations will be used. The models of safety measures for preventing fall hazard such as working platforms, guardrails, and safety nets, and temporary facilities such as scaffolding, will be created. Furthermore, computer applications are developed in order to demonstrate the implementation of virtual safety measures and virtual safe working areas for each building component.

Next, safety monitoring is also developed in the prototype system to assist the construction personnel in the control and inspection of safety measures, signs, and personal protection equipment at the construction project. 3D modeling is implemented to develop safety measures which are assigned to the location of working areas according to safety planning. Not only 3D models, but also 2D images are developed to represent the essential caution signs at the construction site. These virtual construction signs are arranged for the workplace, and the site personnel can use the prototype system to inspect and compare them with real practices. A database for collecting worker information was also created and used in the application for monitoring the personal protection equipment of workers.

Last is training, which was developed to provide appropriate safety information for helping superintendents and workers to perform construction activities. The presentation methods for training are divided into two types: video media and 3D animations and models. The first method was created to present the safe procedures of construction activities in the video recording format. In the second method, 3D animations and models were developed and divided into three presentation patterns, which are step-by-step safe assembly, all-in-one process safe assembly, and solid and transparent safe assembly. Each method provides an appropriate presentation for construction tasks in order to improve the understanding of in-charge personnel when carrying out these tasks.

3.2.4 Proposed system verification

During the development step, the proposed system was always tested to check for accuracy in the laboratory. The factors which may have affected system accuracy were collected and used for determining the limitations of the prototype system. After testing in the laboratory for ensuring the reliability of the proposed system, implementation and experiment in actual conditions were performed. In the actual construction situation, the system was tested and its implementation and accuracy were observed. The outputs of the proposed system were then collected and analyzed for further study.

3.2.5 Validation

After the verification step, the proposed system was implemented in real-world conditions to experiment with and investigate the feasibility of the implementation in real construction project. A high-rise building construction project was selected to be the sample project and the construction personnel, who were engineers and foremen, were chosen to be the samples. In this step, a questionnaire was used as the method for collecting data. The four work scenarios were defined and the construction personnel were asked about their comprehension and execution of

each scenario in order to investigate their considerations. After that, the outputs of the proposed system for each scenario were provided so that the proposed system could be evaluated.

3.2.6 Discussion and conclusion

The results from this research are summarized and discussed in this step. The recommendations and limitations are also presented. Furthermore, the contributions of this research and the possibilities for future research are also discussed.

Chapter IV

Construction Site Survey and Conceptual System Development

4.1 Introduction

This chapter presents the construction site survey and the concept of the proposed system. First, the high-rise construction projects are observed to explore the current practices of safety management for construction execution. This study mainly focuses on the hazards of falls and falling objects. The tasks, which were carried out to prevent the underlying hazards were investigated in terms of existing processes, implemented tools and documents, and problems. Finally, the conceptual proposed system, which was developed from observed data and reviewed literature is presented.

4.2 Overview of construction site survey

This research focuses on two types of accident causes, falls from high elevations and being struck by falling objects, based on the literature review in the previous chapter. The field observation processes were carried out at high-rise building construction projects due to the existing potential hazards there. The details of the surveyed construction projects are listed in Table 4.1. Most of the observed construction projects are residential buildings and are classified as high-rise buildings in accordance with the definition of Thailand's safety laws and regulations. The minimum number of stories is eight and the maximum number is thirty-seven. Thus, safety laws and regulations are enforced when construction activities are executed.

Table 4.1 Details of construction project observation

Project number.	Type of building	Number of stories	Estimated construction cost (MB)
1	Residential	29	200
2	Residential	37	876
3	Residential	19 (2 buildings)	500
4	Residential	8	130
5	Residential	8	89
6	Residential	8	144
7	Residential	8	43
8	Residential	8	110

Walk-in construction site surveys, which aimed to capture an overview of current practices of safety management, were performed. Photography and video recording were implemented to record when construction tasks were executed. Both collecting data on construction activities and direct interviews with the project

participants were also carried out. During the surveys, the potential hazards of falls and falling object were found in every sample project, as shown in Figure 4.1 to Figure 4.3.



Figure 4.1 Existing fall hazards from sample project number 2 and project number 3



Figure 4.2 Existing fall hazards from sample project number 4 and project number 5



Figure 4.3 Existing falling object hazards from sample project number 1 and project number 3

Even though safety laws and regulations indicate that the safety officers are required to identify hazards, and monitor and inspect safety when construction activities are performed at high-rise buildings, half of the sample projects lacked full-time safety officers and most of them did not methodically apply the safety management system. The foremen and superintendents of the main contractors that controlled the construction tasks also took responsibility associated with safety. They had to identify the hazards which may occur in the actual working conditions by themselves. However, they were pressured by the project progress and paid less attention to safety. Not only were activities rushed, which led to the creation of dangerous situations, but novice site personnel sometimes neglected to mention potential hazards due to their knowledge and experience. In the case that foremen and superintendents could not amend the hazard problems, they informed the project managers so that they could brainstorm and make a decision.

4.3 Current practices to prevent hazards of falls and falling objects

In accordance with the field observation and direct interviews, the tasks, which were carried out to prevent the hazards of falls and falling objects were classified into the following three groups: design and planning, monitoring, and training. These tasks had their own processes and employed the different documents and information to carry out the safety as described below.

4.3.1 Design and planning

According to the field observations, none of the main contractors in the construction projects implemented long-term planning for safety management. Some of them used a few safety documents and weekly meetings to design and plan according to the minimum requirements of safety laws and regulations. After the site personnel raised problems regarding hazards, the project teams arrived at conclusions for solving the hazard problems. Then they produced some documents, such as 2D shop drawings, memorandums, and safety inspection forms, and used those documents to carry out solutions to these safety problems. The observed data regarding the task of design and planning was categorized into two types: design and planning for preventing the hazards of falling objects and design and planning for arrangement of safe work areas.

4.3.1.1 Design and planning for preventing the hazards of falling objects

There are the risks from falling objects when the overhead works are carried out or the construction personnel work beneath cranes. In order to prevent against the falling objects from the overhead works located near the building perimeter, safety nets were installed according to the decision of the engineer as

shown in Figure 4.4. Most of the sample projects did not completely prepare the protection system. Thus, they could not totally prevent against falling object hazards.



Figure 4.4 Prevention against falling objects from building perimeter

From the direct interviews, the processes for design and planning the safety measures for preventing the hazards of falling objects from the building perimeter and the employed information type were presented in Figure 4.5. The engineers investigated the actual site conditions accompanied with 2D construction drawings as demonstrated in Figure 4.6. They also considered the safety laws and regulations. After that they used their knowledge and experience to design the safety protection system. However, the theories for calculation of the trajectory of falling objects were not applied. The 2D shop drawings of safety measures were produced and used in the prefabrication and installation process. Finally, the engineers evaluated the appropriateness of designed safety measures when the safety measures were installed at the actual location.

The problems discovered from the current practices consisted of the 2D drawings could not reflect the actual environment and the effect of falling objects on the surrounding buildings cannot be seen. Therefore, the designed safety measures were not evaluated until they completely were installed. According to the site survey, documents of other safety measure preparation, such as safety nets, were not produced in some sample projects. The engineers always paid attention to the safety measures which were used for performing construction tasks.

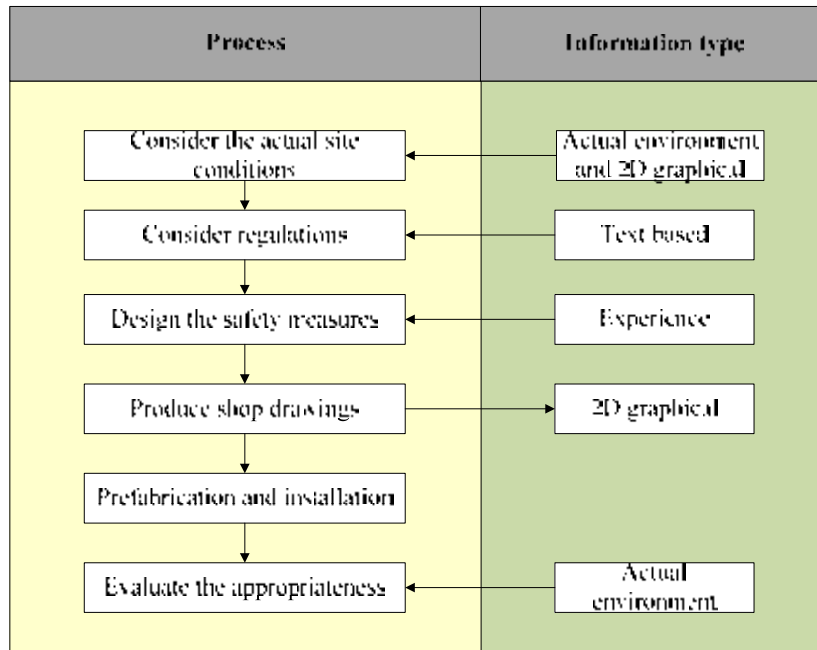


Figure 4.5 Processes and information type for design and planning for preventing the hazards of falling objects from building perimeter

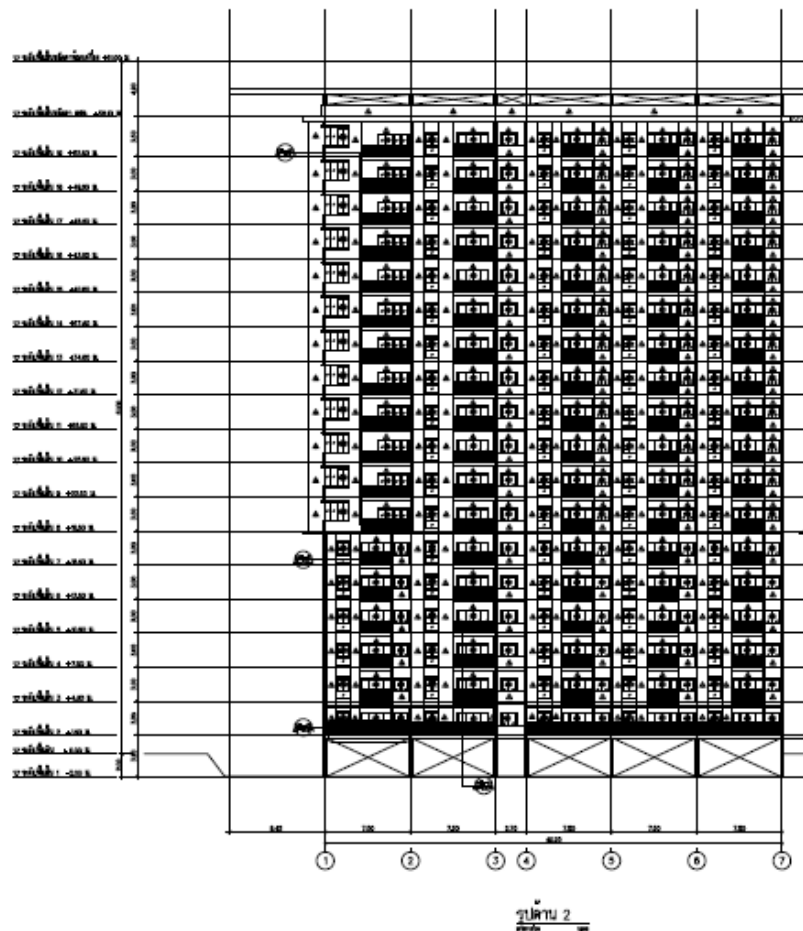


Figure 4.6 Example of 2D construction drawing represented the side view of building

From the site surveys and direct interviews, the defined path of equipment, such as cranes from which objects could drop down onto the working area, was not specified. The working areas beneath the crane’s moving path were crowded, as shown in Figure 4.7. For the crane operation, only documents such as crane specifications, which were provided by the supplier, were implemented, as shown in Figure 4.8. The supervisor and crane operator only considered the lifting capacity of cranes and hoists, but they did not consider the potential hazards of falling objects. According to OSHA recommendations, the working beneath loads being moved should not be allowed. Moreover, the unauthorized person should avoid to work and walk under the moving path of crane operation.



Figure 4.7 Prevention against falling objects from crane operation

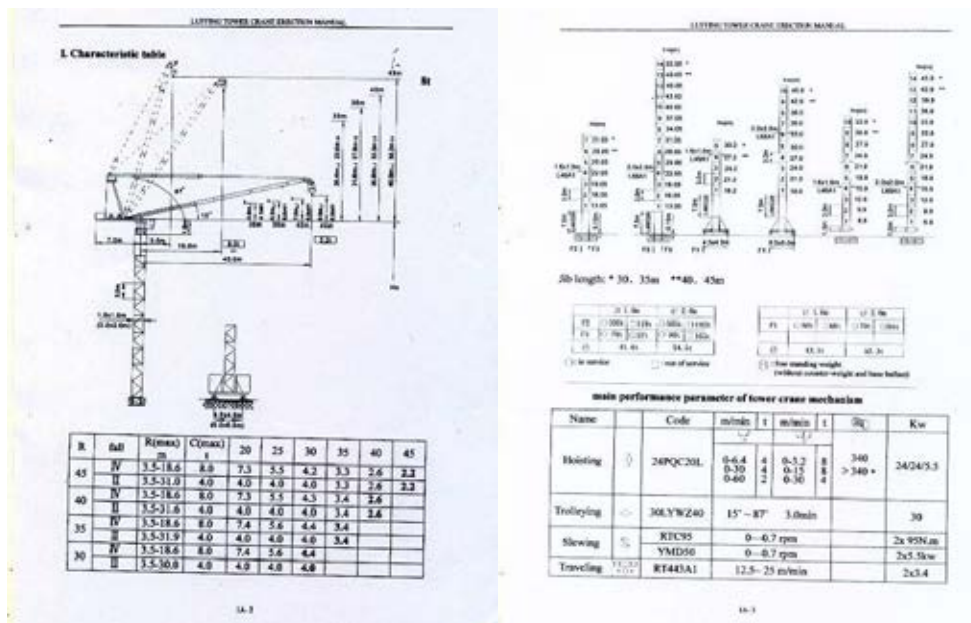


Figure 4.8 example of crane specification

For safe operation, the in-charge personnel should attend to this situation because the crane operator may not see the current condition due to blind spots. However, only experienced construction personnel could indicate the unsafe zone of the hazards of falling objects from crane operation. In addition, it is difficult to identify the cover range of the falling object hazards while operating crane.

4.3.1.2 Design and planning for arrangement of safe work areas

For fall hazard prevention, safety measures were designed according to the understanding of the engineers. The safety measures, such as working platforms for performing construction activities at great heights, were inadequately and improperly provided. In Figure 4.9(a), it can be seen that the platform that was installed at the building perimeter lacked a guardrail around the platform boundaries to protect the workers. In the case that the platform was not installed, as shown in Figure 4.9(b), the workers used their own personal protection equipment, such as safety belts, and hooked them to the formworks of the building components and performed their tasks. Thus, the safety of workers relied on temporary facilities, which were dangerous.



Figure 4.9(a) and (b) Working platform preparation

As mentioned above, safety management systems are not fully implemented in traditional construction projects and are excluded from construction execution planning. The management team provides safety measures and safe working areas according to minimum requirements of Thailand's laws and regulations. When the construction personnel that are responsible for safety arrangements have to prepare specific safety measures, they will consider 2D construction drawings and sketch drawings of safety measures as presented in Figure 4.11. This figure shows hand sketch drawings of working platforms which have been prepared for column construction. This platform was temporarily installed in the stairway area. Due to the construction sequences, the stairs were constructed after

other building components on the current construction floor. Thus, the stairway was a void space and fall hazards were observed. Then, the foreman informed the engineer to plan for and prevent the hazard. A working platform was designed and a decision was made by the engineer, and later he produced a 2D sketched shop drawing which presented a plan and side view of the platform. The platform width and length were consequently 1.0 meter and 4.2 meters. The engineer also provided a guardrail with a top handrail whose height was 0.9 meter. However, they ignored providing a medium handrail even though it was required by laws and regulations. Later, a platform was fabricated, installed, and used in the working area, as shown in Figure 4.12.

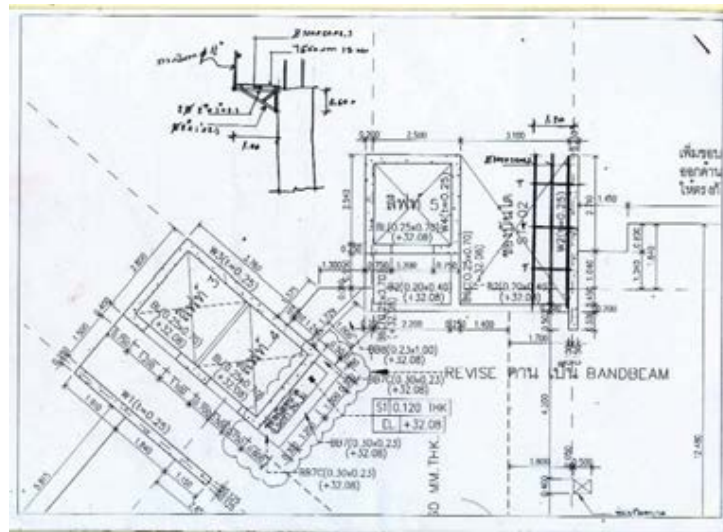


Figure 4.10 Example of sketched drawing for safety measures



Figure 4.11 Platform installation

Similar to the processes of design and planning for prevention of the hazards of falling objects, the safety measures were evaluated the appropriateness in terms of type, shape, and quantity after they were installed at the actual work condition. Only the conventional documents, such as 2D shop drawing and text based regulations, were employed for carrying out this task.

In the sample construction projects, the safe working areas were also not confined and the project participants were not informed, as seen in Figure 4.12. The supervisors were daily assigned the construction tasks regarding building component. Then, they considered the actual location at the construction site and defined the work space for performing the assigned tasks. The supervisors used the 2D drawings and their experiences in the execution. In case that the supervisors did not have sufficient experience, conflicts regarding adjoining working areas that tended to lead to unsafe situations were not considered.



Figure 4.12 Unsafe work areas

4.3.2 Monitoring

For safety monitoring, the superintendents normally inspected the actual condition to identify the hazards based on their knowledge and experience. Shop drawings and safety checklists sometimes were applied. However, the in-charge personnel frequently relied on the personnel protective equipment of workers and neglected the hazards. Most of the construction projects utilized their own checklist forms, such as those for personnel protection equipment, safety system evaluation, etc., as presented in Appendix A. However, these forms contained rough details only and were ineffective for monitoring safety at the construction site. Moreover, the site personnel used the safety check list for monitoring only once a week. Not only were the checklists applied, the project team also used the presentations, which were created by Microsoft PowerPoint, for weekly meetings to discuss, plan, and monitor the safety measures at their construction sites. Nevertheless, this technique was not effective and did not provide enough information for carrying out and communication.

4.3.3 Training

In order to perform the construction activities, the engineers used the 2D construction drawings to produce the method statements, which were presented in text based or 2D graphical documents. The communication method, which was implemented, normally was verbal description. In the sample construction projects, most of the laborers were foreigners which came from neighboring countries of Thailand. Hence, there were some barriers such as language for communicating between project participants, and these barriers influenced the safety training.

4.4 Proposed conceptual system

In order to enhance the level of construction safety management and reduce accidents, the site personnel should understand the risks and be able to control the risks that can occur in construction activity execution. They should be able to identify and assess potential hazards, plan for prevention and protection, monitor and control unsafe conditions, and provide appropriate knowledge and training for the workers. To perform these mentioned tasks, various and numerous information is required. When the in-charge personnel identify hazards and plan for safety, they should not consider only project information and safety requirement. They should also consider other factors which influence worker safety, such as means, methods, and resources. However, the majority of information is presented in two dimensional, text-based, paper format. After the construction personnel obtain all of the information, they convert, interpret, and integrate that which they consider to be of concern to them. The capability to perform these tasks depends upon the level of experience, knowledge and individual perspective of the engineers and the supervisors. They mentally transform and generate combined pictures. Then they make decisions and produce the results of design and planning, monitoring, and training.

In fact, another important piece of information which is significant and should be included when considering safety management is the actual construction conditions. Utilization of 2D and textual information is not enough to identify and comprehend hazards. Figure 4.13 presents some of the problems in performing construction safety management which are concluded from current practice. These problems affect the capabilities of construction personnel and lead them to produce deficient hazard identification, ineffective safety planning, impractical monitoring, and inadequate training. Finally, the overall outputs of these processes tend to lead to poor safety management at construction projects. The problems consist of the following:

1. There are large amounts of information
2. Information is difficult and too complicated to convert and understand
3. The construction personnel misinterpret the gained information

4. Some information cannot be seen and the leads to unforeseen problems
5. The actual hazards in the real environment are excluded
6. Experienced persons are required
7. Mistaken communication is occurred

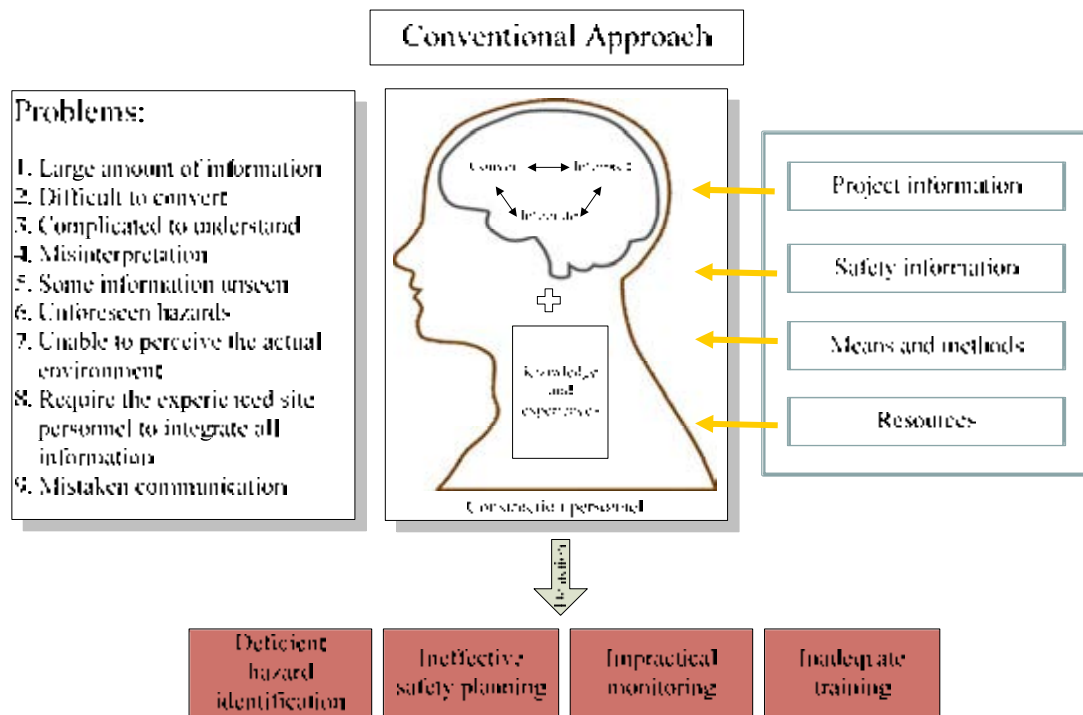


Figure 4.13 Problems regarding the poor conventional approach to safety management

As mentioned above, there are many factors which construction personnel need to consider regarding safety management. According to the literature review in Chapter 2 on the tasks employed in executing safety at construction sites by converting, interpreting, and integrating all of the information, it can be confirmed that the implementation of safety is complicated, time-consuming, and burdensome. Many studies attempt to improve the safety management processes, such hazard identification, design and planning, monitoring, and training, by using the advantages of modern technology. This previous research implemented visualization technology for providing information on construction projects, such as 3D models of building components and the surrounding environment, 4D CAD and geospatial analysis, and the virtual reality of construction sequences on a single platform in order to help construction personnel develop effective safety management. The physical building components, the surrounding environment, and scheduling were provided, simulated, and presented to the site personnel. In this way they can visualize the integrated information and not reiteratively interpret it in their minds. The real and present

construction site conditions were also very important and influenced the safety considerations of the in-charge personnel. Nevertheless, the working conditions and actual surrounding environment were not included in the traditional method.

In order to execute safety at the construction site, developing virtual information for the entire construction project is expensive and would not reflect the real conditions. Therefore, this research gains ideas from the mentioned problems to support the construction personnel in the safety management process for preventing falls and the hazards of falling objects. The proposed system makes clear unseen safety information and converts it along with information about the current environment by using augmented reality technology, as shown in Figure 4.14. All essential information is transformed, integrated, and generated in this proposed system by implementing the augmented reality technology. The advantages of augmented reality are that visualization of the virtual objects is merged with the actual environment in real time and at the location.

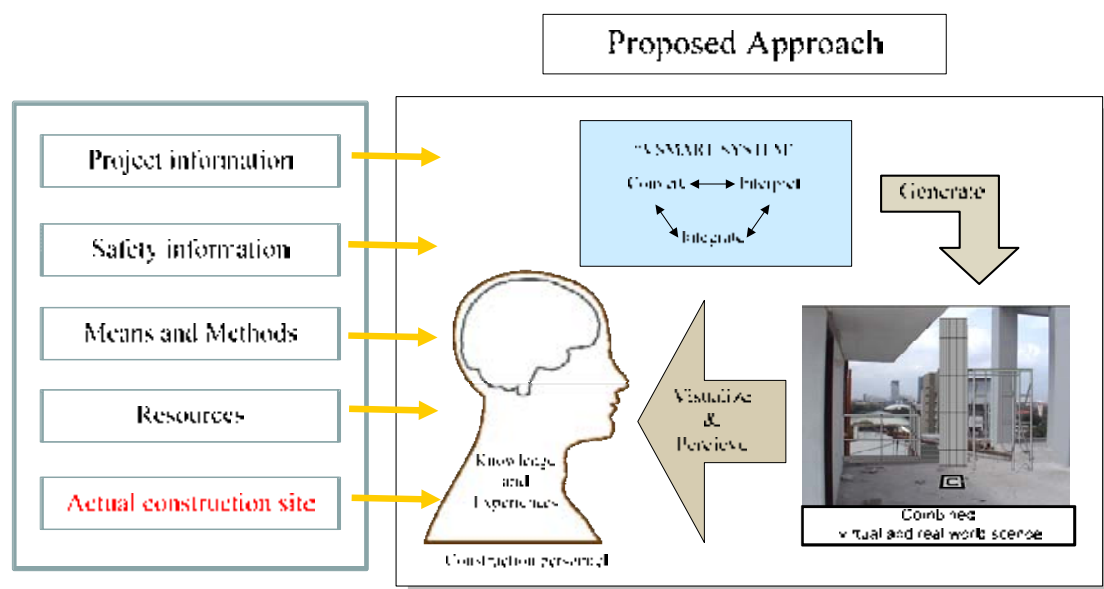


Figure 4.14 Concept of the proposed system

The mentioned tasks, which are design and planning, monitoring, and training were examined to identify the problems and to improve the existing processes. The proposed system was developed to help the construction personnel for carrying out these tasks as described below.

4.4.1.1 Ideas for improvement of the design and planning for preventing the hazards of falling objects

Conventionally, the evaluation of the appropriateness of designed safety measures for prevention against the falling objects usually was done after installation

at the real location. The ideas for improving this task consisted of: 1) creating the simulation of trajectory of a falling object, which was calculated in accordance with projectile formulas, 2) illustrating the effect of the falling objects to the neighboring buildings and areas, 3) providing the virtual safety measures, and 4) evaluation the appropriateness of designed safety measures in terms of size, position, and capability. In Figure 4.15, the proposed processes and information type for design and planning of safety measures to prevent the hazards of falling objects from the building perimeter are presented. This aims to help the construction personnel in the decision making process before the safety measures are prefabricated and installed.

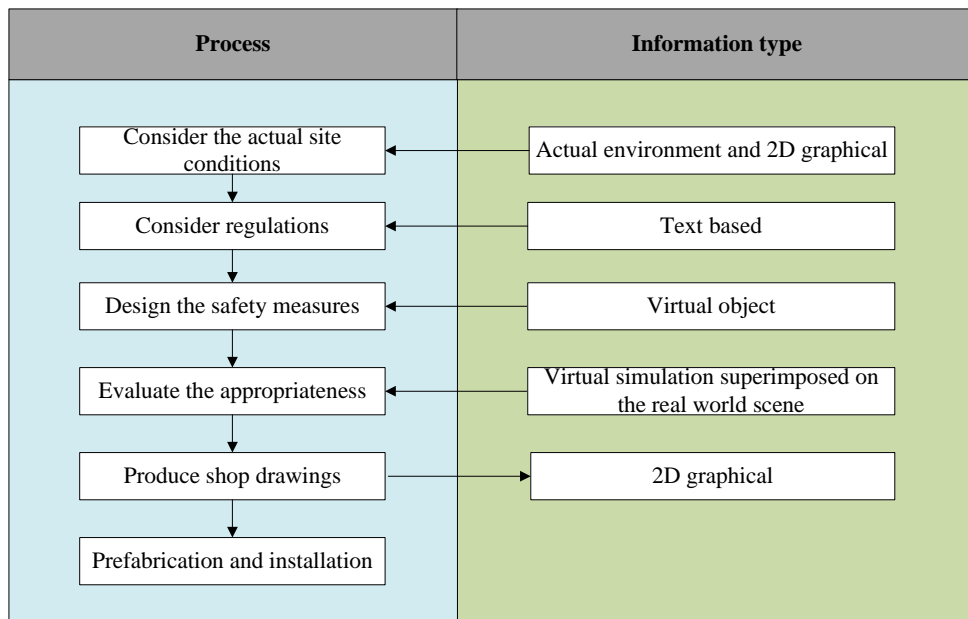


Figure 4.15 Proposed processes and information type for design and planning of safety measures to prevent the hazard of falling object

Not only the hazards of falling objects from building perimeter, the idea to assist the construction personnel to perceive the hazards of falling objects from crane operation was initiated. As described, the cover range of the hazard of falling object according to the projectile calculation depends on the height of falling objects and initial velocity. When crane lifts and moves a load, the height and velocity frequently are changed and the potential range of hazard also is updated. From this reason, it is difficult to identify the hazard range in the real environment. The proposed system was developed to provide the visualization of the hazards of falling objects from crane operation and the effect of the hazards to the work areas and unauthorized person who enter in the unsafe zone.

4.4.1.2 Ideas for improvement of the design and planning for arrangement of the safe work areas

In order to provide the safe work areas, the safety measures, which are suitable for construction method statements should be supplied. As described above, the appropriateness of safety measures was evaluated after they were installed. The proposed system contained the idea to facilitate the construction personnel in the decision making process for arrangement of the safety protection system. The virtual safety measures are created and present to the in-charge personnel as they are installed at the real location. Hence, the construction can visualize the assigned safety measures and evaluate them prior the construction tasks begin.

In addition, the work space is another factor which the in-charge personnel have to concern when preparing the safe work area. The safety boundaries around the building component which is constructed should be adequate and the other works should not be performed at the same location. Thus, the developed system proposed the tool to help the construction personnel to define the required safe work area in the real environment.

4.4.1.3 Ideas for improvement of safety monitoring

The ideas to improve the monitoring process came from the existing tools and documents which were text based and rough description. To perform this task, it required the knowledge and experience of the in-charge personnel to identify and track the safety protection system or personnel protective equipment of the workers. The proposed system contained the purpose to assist the construction personnel when they inspect the safety measures, signs, and workers at the construction sites. The virtual safety information is produced, stored in a database which can be retrieved and presented in the real world scene.

4.4.1.4 Ideas for improvement of safety training

According to the field observation, there were some barriers to implement the tools for safety training which consisted of language and education level. Thus, this system aims to provide the intelligible information, such as 3d models, animations, to present the safe work procedures in the actual work condition, and to support the communication among the project participants.

4.5 System and expected benefits

With this knowledge, the in-charge personnel can visualize and perceive the safety information as they are in the actual conditions; they are not required to mentally interpret the information by themselves. Moreover, the in-charge personnel will not spend time and money to create the virtual objects of the overall project

information. After they obtain the visualized information, they can make correct decisions, will be able to identify potential hazards, produce design and planning, monitoring, and control of safe construction operations, and provide adequate training to prevent falls and falling object accidents at their construction site. Moreover, the in-charge personnel can communicate the output of each safety management process among the project participants.

4.6 Conclusion

In this chapter, the current practices of safety management, such as hazard identification, design and planning, monitoring and control, and training, were explored in the construction site survey. The walk-in method, direct interviews, photography, and video recording were applied in this step. The findings of site observation indicated that most of sample construction projects did not fully implement safety management to prevent accidents, and project teams did not completely identify hazards before construction activity execution. The safety measures at the sample sites were insufficiently provided according to the minimum requirements of Thailand's laws and regulations. Moreover, most of the construction projects still used only 2D drawings of physical building components when considering existing hazards. None of them utilized advanced information technology such as BIM or 4D CAD in their projects.

The problems of conventional safety management consist of the following: a large amount of complicated information to convert and understand, unseen and unforeseen hazards, the need for experienced persons to interpret, integrate, make decisions, and communicate the safety information. Additionally, the actual environment was not included in the safety considerations. Thus, an innovative and proactive system is proposed in the present study to support the safety management processes, such as design and planning, monitoring, and training in order to prevent the hazards of falls and falling objects. This system can provide the visualized safety information interpreted by and integrated with the in-charge personnel while they perceive the actual site conditions. In this way they can identify all of the potential hazards, produce design and safety planning, monitor safety, and provide sufficient training to reduce the accidents caused by falls and falling objects at the construction projects.

Chapter V

System Design and Algorithm Development

5.1 Introduction

This chapter presents the design and development of an innovative and proactive proposed system according to the conceptual idea in Chapter 4. This system is designed to support the processes of safety management in accordance with the current practices, such as safety design and planning, monitoring and control, and safety training for preventing the accidents caused by falls and falling object hazards. The visualization technique, which is augmented reality, is implemented in the system development process. The software library for building the augmented reality application is ARToolKit. Additionally, the proposed calculation and algorithms based on computer vision theory, which are the trajectory of falling object and collision detection, were developed to provide information about potential hazards and safe working areas. The preparation procedures for developing the prototype system are also described.

5.2 System design

In this section, the proposed system for supporting the processes of safety management, such as design and planning, monitoring, and training, is presented. It mainly focuses on the prevention of falls and falling object hazards. The proposed system architecture is configured and shown in Figure V.1. The hardware components for developing this system consist of a laptop computer and a video camera. The black square patterns, which are called markers, were prepared for tracking the process according to computer vision algorithms. The proposed system, which is named the Visualized Safety Management using Augmented Reality Technology System (VSMART System), was developed in the laptop computer.

In order to assist the construction personnel in the tasks regarding safety, which were observed from the current practices at the construction sites, this system comprises the following five modules: 1) the module for design and planning for preventing the hazards of falling objects, 2) the module for design and planning for arrangement of safe work areas, 3) the module for monitoring and inspection, 4) the module for safety training, and 5) the module of augmented reality. Further, 3D models for safety measures and a worker database were also produced to support this proposed system. Moreover, each module contains sub-modules. First, the sub-modules for design and planning for preventing the hazards of falling objects consist of falling objects from building, falling objects from the crane to the work area, and falling objects from the crane to the workers' space. Secondly, the sub-modules for

design and planning for arrangement of safe work area comprise safety measure selection and safe work area preparation. Third, the sub-modules for monitoring consist of safe work area monitoring and personal protection equipment monitoring. Fourth, the sub-modules for training comprise safe assembly training and construction task media training. In the module of augmented reality, the processes that provide a combined virtual object and real world scene were developed according to the processes of the ARToolKit. There were five main processes involved: capturing the video input frame, detecting and identifying markers, calculating camera transformation, calculating the distance of markers, and rendering and drawing the combined scenes of the virtual objects and actual environment.

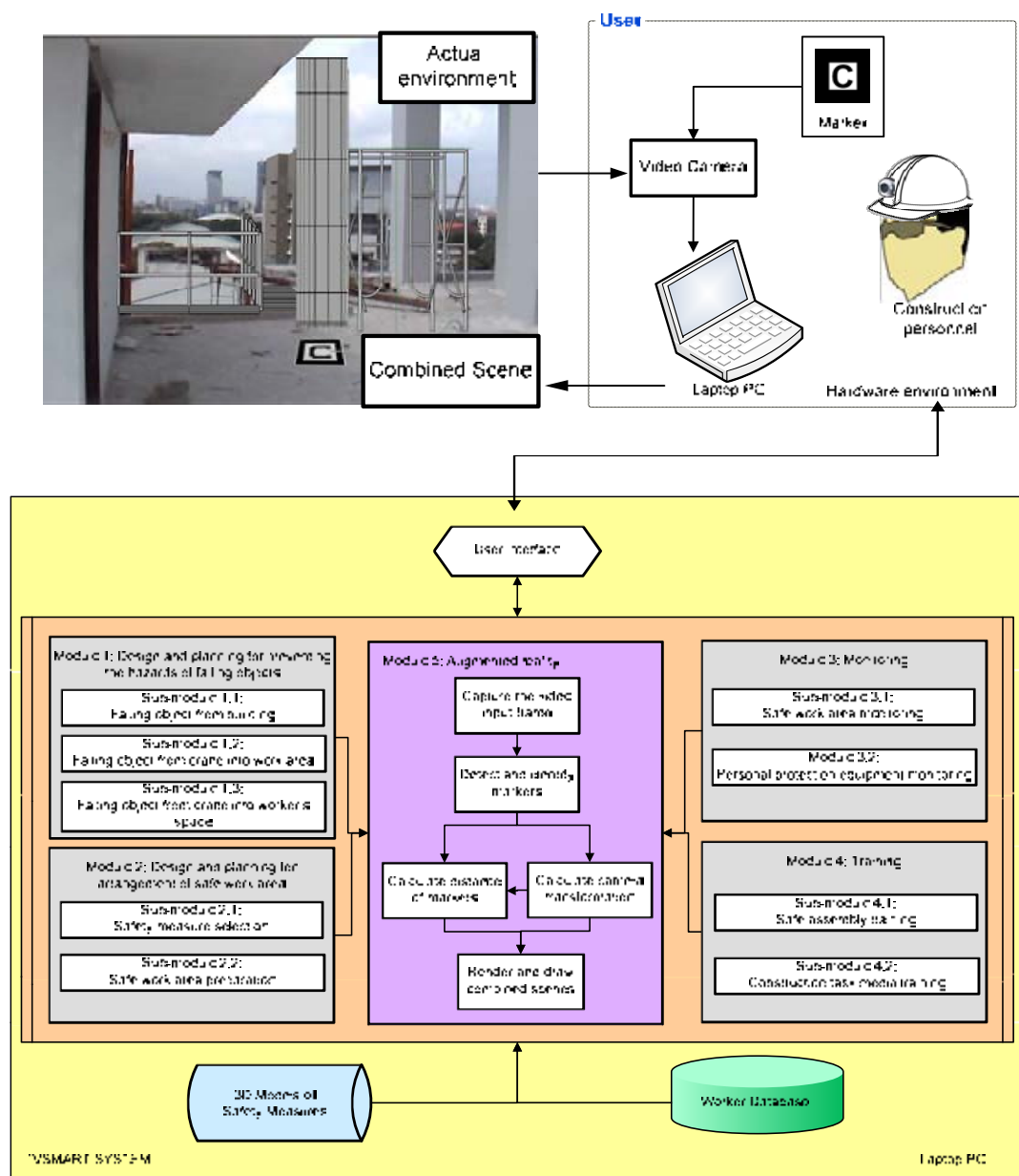


Figure 5.1 Proposed system architecture

The user interfaces were created for communication between the user and the proposed system. In order to develop and implement the VSMART System, it required both hardware and software preparation. Moreover, the calculation algorithms were created for detecting the safe and unsafe conditions in each scenario. These mentioned contents are described in the next section.

5.3 System preparation

5.3.1 Hardware preparation

In this research, the hardware components for developing the proposed system consist of a laptop computer, a web camera, and markers. The functionalities of each hardware component are described in Table 5.1. The web camera which was selected to be used in this study was a Logitech B905 due to its specifications. The dominant performances of this web camera are high definition video capturing and a video frame rate up to 30 frames per second. The vertical and horizontal field of view angle is 75 degrees. Moreover, its weight is light and it is easily portable, as shown in Figure 5.2.

Table 5.1 Hardware components

Functionality	Hardware component	Specifications
Video capturing	Web camera	Logitech B905
Application processing	Laptop	Lenovo IdeaPad Y430
Video output	Laptop screen	Processor: Intel Core 2 Duo T5800/2.0 GHz Memory: 3.0 GB/4.0 GB(max) Display type: 14.1 inch TFT active matrix Graphic processor: Intel GMA 4500MHD Dynamic Video Memory Technology 5.0 Audio: sound card
Sound output	Laptop speaker	
User input	Laptop keyboard and touchpad (mouse is optional)	



Figure 5.2 Logitech web camera

5.3.2 Software preparation

In this section, the development environments which were prepared for developing the proposed system are described in two parts. The first part presents the environment for developing the augmented reality application and the second part presents the other environment for supporting the development of the proposed system.

5.3.2.1 Development environment of augmented reality application

In order to develop the augmented reality application for the proposed system, the following environments, as shown in Table 5.2, were required and used. All of the mention prerequisites were free and could be downloaded from the Internet. The software structure is presented in Figure 5.3

Table 5.2 Development environment of augmented reality application

Prerequisite	Version
Microsoft Visual Studio (C/C++ language)	Microsoft Visual Studio 2008
ARToolkit libraries	ARToolKit-2.72.1
DSVideo libraries	DSVL-0.0.8b
GLUT library	Glut-3.7.6
OpenVRML library	OpenVRML-0.14.3-win32
OpenCV library	OpenCV-2.2
IrrKlang library	IrrKlang-1.3.0b
Freetype library	Freetype-2.4.5
Directx	Directx 9.0c or later Software Development Kit(SDK)

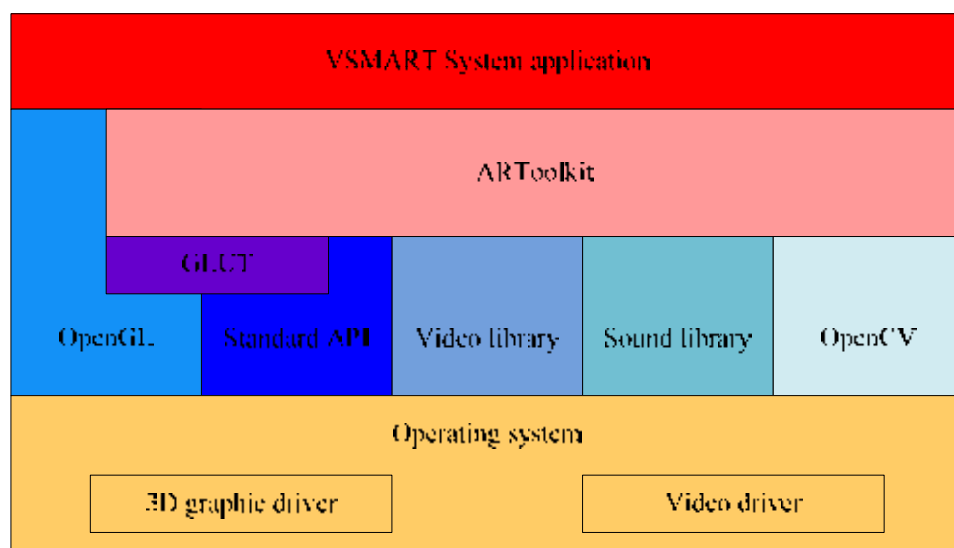


Figure 5.3 Software structure of the proposed system (modified from HIT Lab, 2009)

ARToolKit

In this research, ARToolKit, which is a free and open source library, was selected for developing the augmented reality application. The selection reasons were that this toolkit is free for non-commercial purposes, is widely used in academic areas, and is low cost so that users can prepare a simple web camera and printed black square patterns. Moreover, this toolkit overcomes the registering and tracking problems with a simple pattern recognition mechanism according to computer vision algorithms (Bozlu, 2005).

ARToolKit is a C and C++ language software library which allows programmers to easily develop augmented reality applications. The ARToolKit uses techniques of computer vision for calculating the real camera position and orientation relative to marked cards, allowing the programmers to overlay virtual objects onto these marked cards (HIT Lab, 2009). For development of the proposed system, a video see-through augmented reality, which overlay the virtual images on a live video of the real world, was applied.

One of the significant tasks for processing the augmented reality application is the tracking process. As mentioned above, this toolkit uses black squares as tracking markers. The work flow can be presented as shown in Figure 5.4. The web camera, connected with the laptop computer, starts to capture videos of the real world. Then, the AR application searches through each video frame for any black square shapes. In this process, the image is converted to a binary image and the black square marker is identified. After detection, the AR application uses the mathematics to calculate the position of the camera relative to the marker. The image pattern inside the marker is identified and matched with the templates in memory for use in the next process. Finally, the virtual objects are aligned and rendered on the markers based on the calculation of position and orientation.

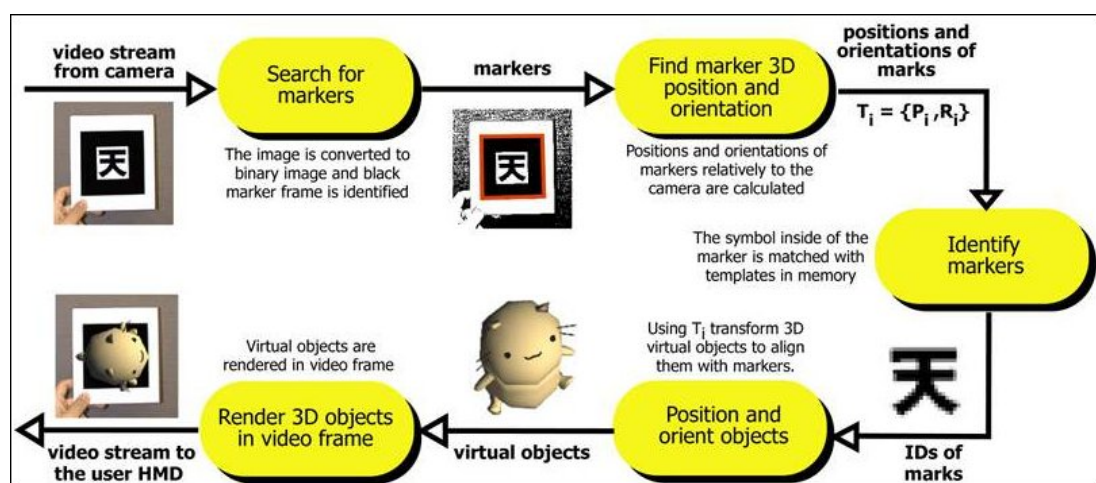


Figure 5.4 ARToolKit working method (HIT lab, 2009)

There is a main loop in the whole process that continuously runs the AR application until the user closes the application. The main loop contains six steps, as presented in Table 5.3. The function from step 2 through step 5 repeatedly runs in the main loop until the application quits, while step 1 and step 6 are consequently performed on the initialization and closing of the augmented reality application.

Table 5.3 Steps of ARToolKit working method (HIT Lab, 2009)

Initialization	1. Initialize the video capture and read in the marker pattern files and camera parameters
Main loop	2. Grab a video input frame
	3. Detect the markers and recognized patterns in the video input frame
	4. Calculate the camera transformation relative to the detected pattern
	5. Draw the virtual object on the detected patterns
Shutdown	6. Close the video capture

Camera calibration

Before starting to develop the augmented reality application, the web camera must be calibrated in order to remove camera distortion. The ARToolKit also provides two methods for calibrating the camera, which consist of the one-step calibration approach and two-step calibration approach. Even though the latter approach is difficult to use, it was selected and applied in this research in order to obtain more accurate results. The two-pattern files sourced from the ARToolKit package were printed out. The first pattern contained a 6 x 4 dot pattern and the second pattern was a grid of lines, as shown in Figure 5.5(a) and (b) respectively. The ARToolKit also provided the program is used to measure the image center point and lens distortion and produced the other camera properties, such as camera focal length.

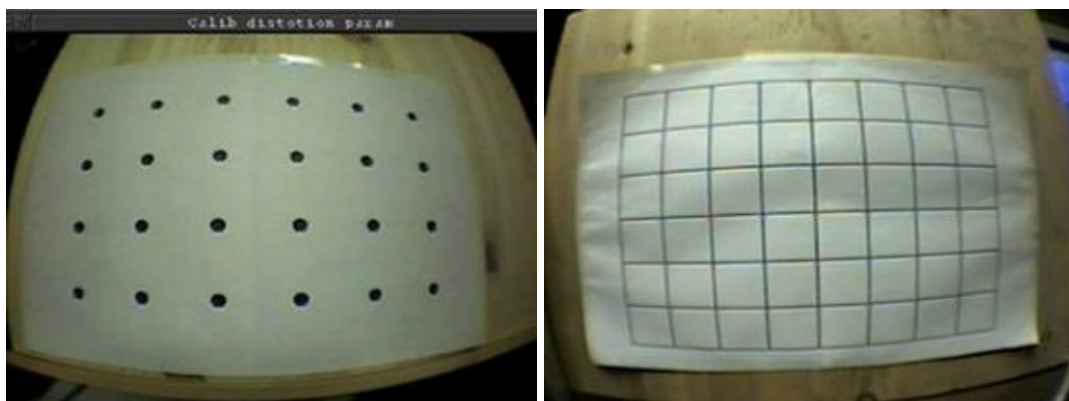


Figure 5.5(a) and (b) Calibration patterns (HIT Lab, 2009)

The dot pattern was used to calibrate the camera by measuring the spacing between the dots, and this information was used to calculate the lens distortion, as shown in Figure 5.6. The marking dots process was repeatedly done for 5 to 10 images from various angles and positions. Then, the program calculated the parameters, such as the distortion factor. The second step for calibration used the pattern of the grid of lines in order to find the camera focal length and other parameters, as presented in Figure 5.7. Similarly, this process was done repeatedly five times by moving the calibrated pattern 100 millimeters away from the camera. After finishing the two steps, the calibration program produced the camera data file which was used in the development of the AR applications.

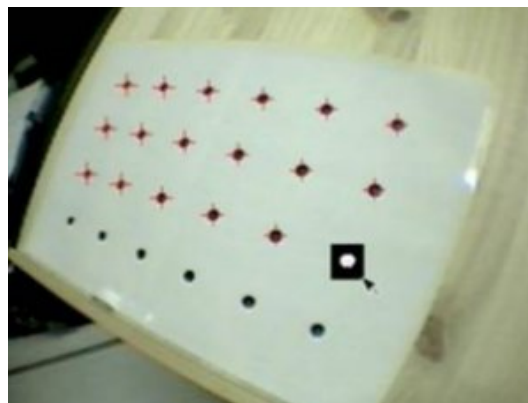


Figure 5.6 Calibration dots were marked by user

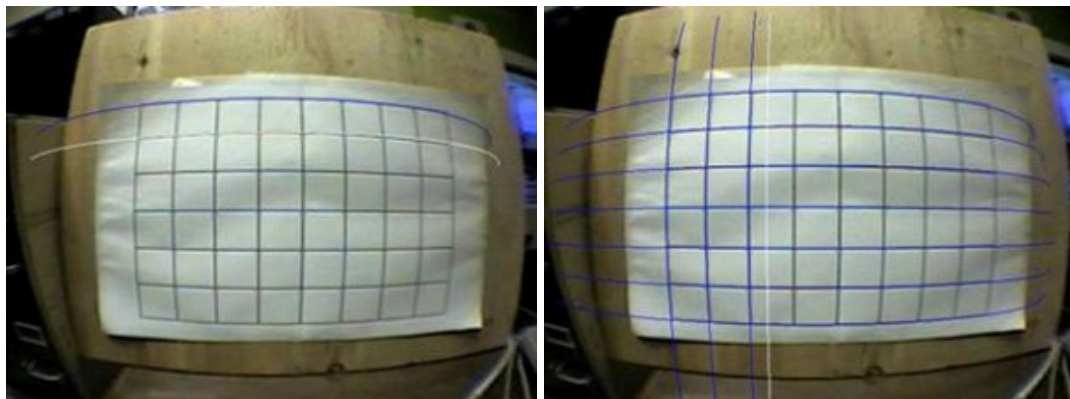


Figure 5.7 Grid line placement for camera calibration

Marker creation and training

In order to develop the augmented reality application by using the ARToolKit, the black squares containing the pattern inside, called the marker, were arranged. The markers can be created by using any image editing program and printed out. The ARToolKit recognizes and tracks the marker in a video stream. The

constraints of the markers comprise the following: they must be square, have a continuous border with either full black or pure white, the design must be unique to avoid confusion, it should be installed on a background of contrasting color, and the area inside the border, which is referred to as the marker image, must not be rotationally symmetric (ARToolworks, 2009). In order to represent the virtual objects, the sets of markers, which were of various patterns and sizes, were created, as presented in Appendix B. The example size and pattern of the marker are presented in Figure 5.8. After creating the new marker, the training process by using the `mk_patt` program was required to allow the ARToolKit to recognize the marker's appearance, as shown in Figure 5.9. The output of this training process was a pattern file (.patt file), which was used in the prototype applications.



Figure 5.8 Example marker size and pattern



Figure 5.9 Marker training

Coordinate system of ARToolKit

The coordinate system which was used in the ARToolKit was based on computer vision algorithms. Kato and Billinghurst (1999) summarized the main

coordinate system of the ARToolKit as shown in Figure 5.10. When using the ARToolKit with the OpenGL, the Z axis comes to the user in case the camera is facing in the direction of Z axis for the reason that the OpenGL is a right-handed coordinate system.

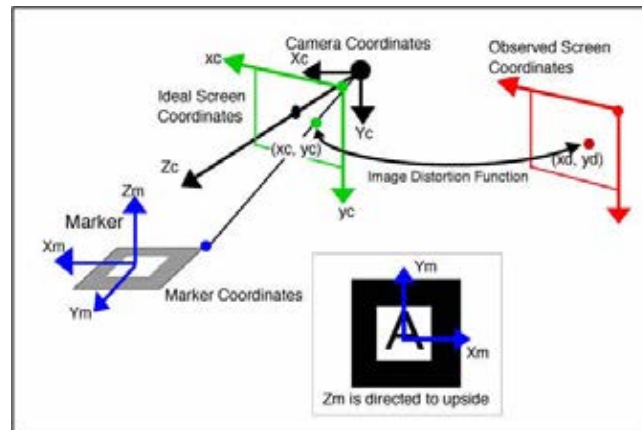


Figure 5.10 Coordinate system of the ARToolKit (Kato and Billinghurst, 1999)

OpenGL/GLUT

For drawing the 2D and 3D scenes in this proposed system, the ARToolKit requires a library, such as the OpenGL and GLUT, to perform this work. The OpenGL is a library for writing applications and simulating the physics that produce 2D and 3D computer graphics. This library performs the rendering part in the AR application. Additionally, the GLUT is an abbreviation of the OpenGL Utility Toolkit, which is a window system independent toolkit for writing OpenGL programs. The GLUT is used both for rendering and handling the windows/event. Figure 5.11 shows an example of the rendering of a 3D graphic in the AR application using the OpenGL.

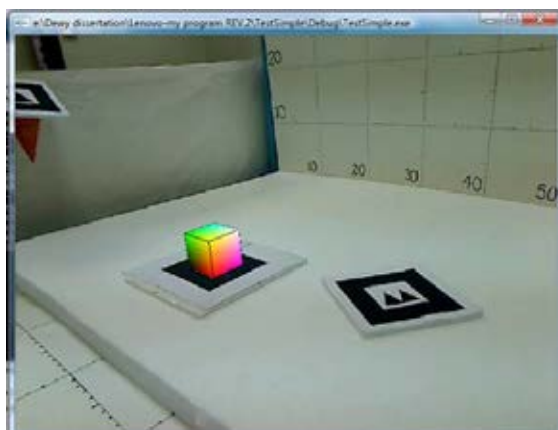


Figure 5.11 Example of rendering scene using OpenGL

OpenCV

OpenCV is an abbreviation of Open Source Computer Vision Library, which is a library for programming functions mainly aimed at real time computer vision (Sourceforge, 2010). Due to the limitation of the ARToolKit regarding lighting, the OpenCV was implemented in this research to reduce the mentioned limitation. To completely run the augmented reality applications in this research, the images of video input were binarized into two colors (black and white) and the markers had to be detected at the beginning at the initial threshold. In case that the lighting condition was too bright or too dark, the threshold value of binary image processing had to be adjusted (Ota, Yabuki, and Fukuda, 2010). Then, the ARToolKit can easily detect the boundaries of the markers and proceed to the next step. Thus, the OpenCV can overcome the problems regarding lighting, as presented in Figure 5.12.

Other supporting libraries

Not only were the previous libraries discussed used to develop the proposed system, but the other libraries were also applied, such as the following:

- OpenVRML is a library for adding VRML support to the developed application. The ARToolKit can render the 3D virtual models which are created in the VRML format.
- irrKlang is a high-level 2D and 3D cross platform sound engine and audio library. This library is implemented to present the sound media and explanations.
- Freetype is a software library that implements a font rasterization engine. This library can render text and provide support for other font-related operations (Sourceforge, 2011).

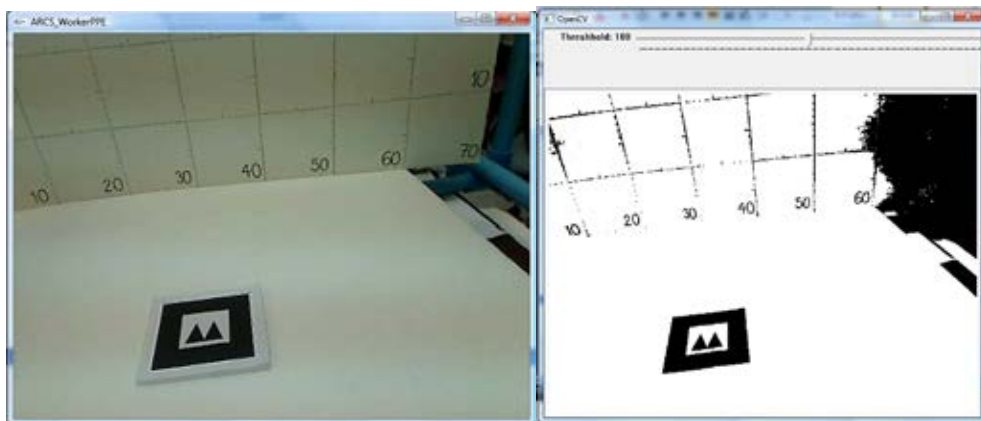


Figure 5.12 Binarization of images from video input

5.4 3D modeling and supported file preparation

To improve the construction personnel's understanding regarding safety, the better approach for achieving this target is by providing more realistic information to them as much as possible. The AR proposed system can generate 2D and 3D computer graphics and superimpose these onto the real world scene. However, the 3D modeling for virtual safety information and the other supported files must be prepared and used as input data. This section describes the process for creating the 3D virtual models and supported files.

5.4.1 3D modeling

Not only were computer graphics generated by using the OpenGL used in this proposed system, but the 3D modeling created by other software was also applied. According to the construction site survey, the in-charge personnel produced the shop drawings of safety measures by hand sketching, as shown in Figure 5.13. These drawings only present the top and side views of safety measures. In fact, the safety measure components comprise steel frames, platforms, and top guardrails. The details of safety measures such as material and size should also be presented.

First, the 3D models of safety measures were generated by using CAD software called "Autodesk Revit Architecture" according to the shop drawings, as presented in Figure 5.13. Currently, this software is one of the famous software for creating building information modeling (BIM) and a fully-parametric solid modeler. It can produce complex shapes. Figure 5.14 shows an example of the 3D safety measures which were created by using the Autodesk Revit Architecture. The user can visualize the 3D models from many viewpoints. After creating the 3D models, they were exported from the revit format (.rfa file) to the CAD format (.dwg file).

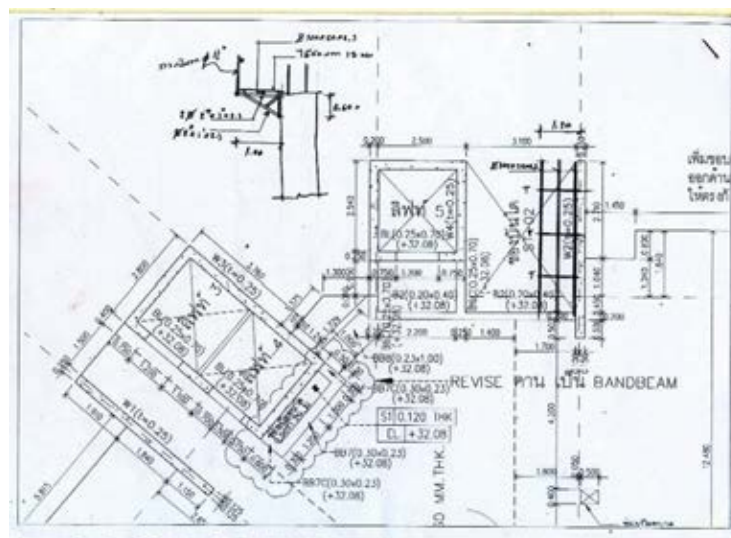


Figure 5.13 Example of shop drawing of safety measures

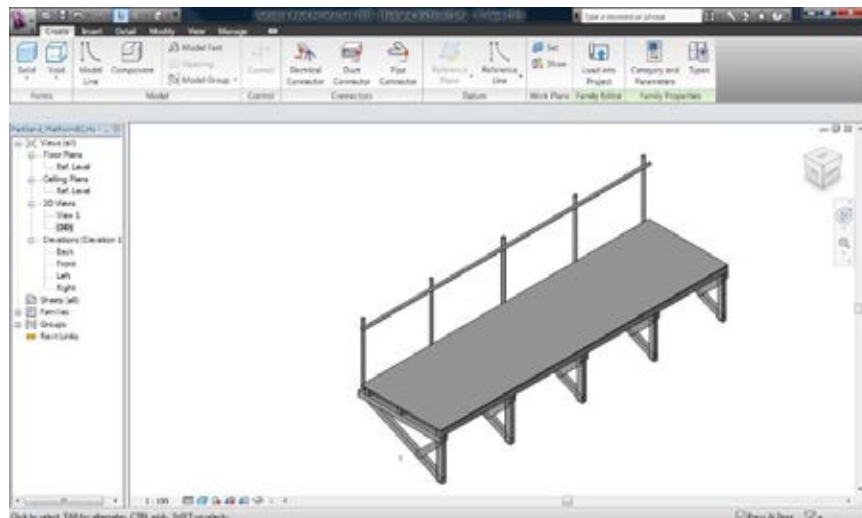


Figure 5.14 Example of a 3D model of a safety measure generated with CAD software

Next, the exported 3D models were imported into the 3D software, called “Autodesk 3D Max.” This importing process was done in order to modify and add more information, such as the color of the models, a description of the safety measures, and transparentness in some parts of models, as shown in Figure 5.15 to Figure 5.17. Animations of the construction work procedures were also created in this process. Figure 5.16 presents an example of the 3D safety measures of a housing project, which was a sample of real experiment testing. The 3D safety measures were created based on the minimum requirements of Thailand’s laws and regulations. The height of the top handrail and length of the guardrail were 0.95 m. and 3.40 m. respectively. Moreover, a middle guardrail and toe board were also created.

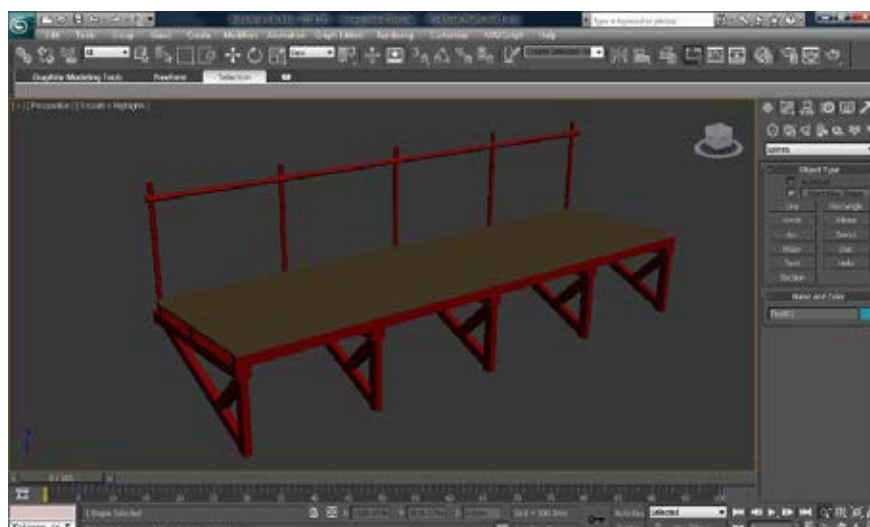


Figure 5.15 Example of 3D model imported into Autodesk 3D Max

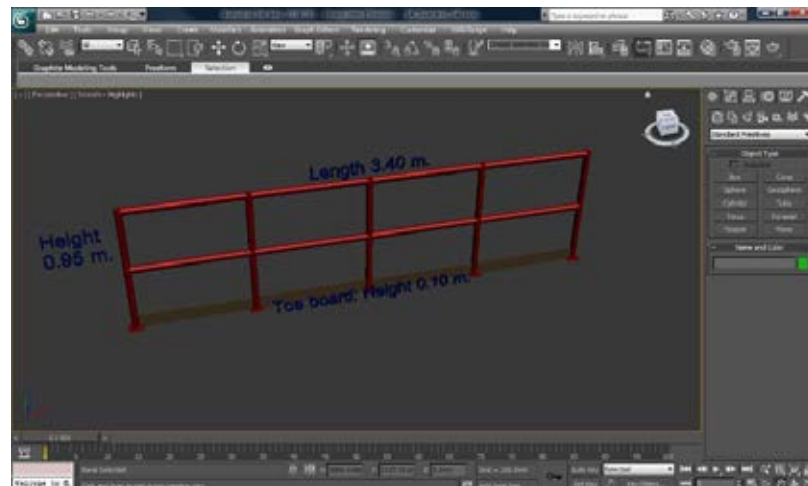


Figure 5.16 Example of 3D model with description

The 3D transparent models were produced to provide the hidden information, which the construction personnel could not see in the solid objects such as sanitary pipes, as shown in Figure 5.17.

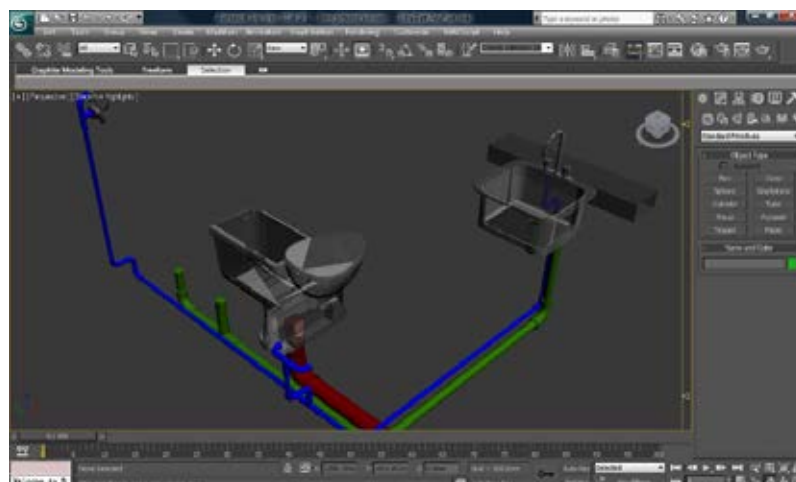


Figure 5.17 Example of 3D transparent model

At this time, the 3D models and animations were saved in 3D Max format (.max file). In order to use these 3D models and animations in the AR application, they required to be converted into the Virtual Reality Modeling Language (VRML) format (.wrl file). VRML is a text file format where vertices and edges for a 3D polygon can be specified, along with the surface color, shininess, transparency, and so on, as presented in Figure 5.18. However, the VRML format can be viewed by using a web browser such as Internet Explorer, as shown in Figure 5.19.

```

# Produced by 3D Studio MAX VRML 97 exporter, Version 12, Revision 1.06
# MAX File: Platform_Platform01.max, Date: Thu Jun 28 14:14:25 2012

DEF Generic_Models_Transformers {
  translation -707.5 -37.5 0
  children [
    DEF Generic_Models_0_Transformers {
      translation 0 0 0
      children [
        Shape {
          appearance Appearance {
            material Material {
              diffuseColor 0.51515 0.67153 0.67153
            }
          }
        }
      ]
    }
    geometry DEF Generic_Models_0-FACES IndexedFaceSet {
      cow TRUE
      solid TRUE
      coord DEF Generic_Models_0-COORD Coordinate { point [
        25 37.5 -600, -25 37.5 -600, -25 -37.5 -600, 25 -37.5 -600,
        25 37.5 -600, 25 -37.5 -600, -25 -37.5 -600, -25 37.5 -600,
        -25 37.5 -600, 25 37.5 -600, 25 37.5 -600, -25 37.5 -600,
        -25 -37.5 -600, -25 37.5 -600, -25 37.5 -600, -25 -37.5 -600,
        25 -37.5 -600, -25 -37.5 -600, -25 -37.5 -600, 25 -37.5 -600,
        25 37.5 -600, 25 -37.5 -600, 25 -37.5 -600, 25 37.5 -600]
      }
      coordIndex [
        3, 0, 2, -1, 0, 1, 2, -1, 6, 7, 5, -1, 7, 8, 3, -1,
        11, 8, 10, -1, 8, 9, 10, -1, 15, 12, 14, -1, 12, 13, 14, -1,
        19, 16, 18, -1, 16, 17, 18, -1, 23, 20, 22, -1,
      ]
    }
  ]
}

```

Figure 5.18 Example of VRML file format of 3D safety measures

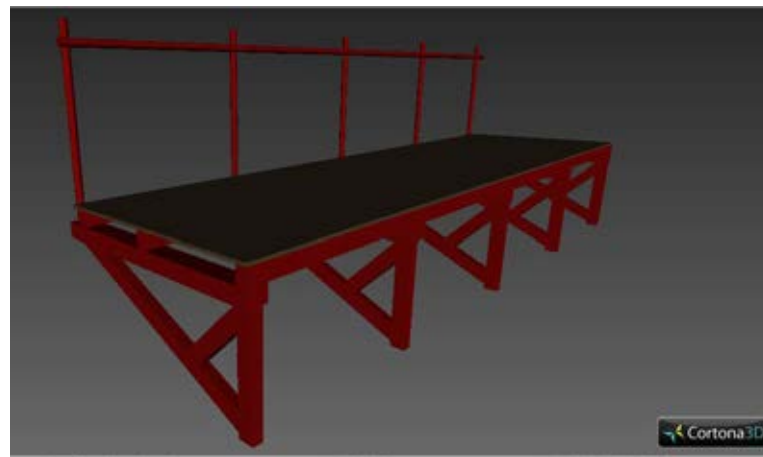


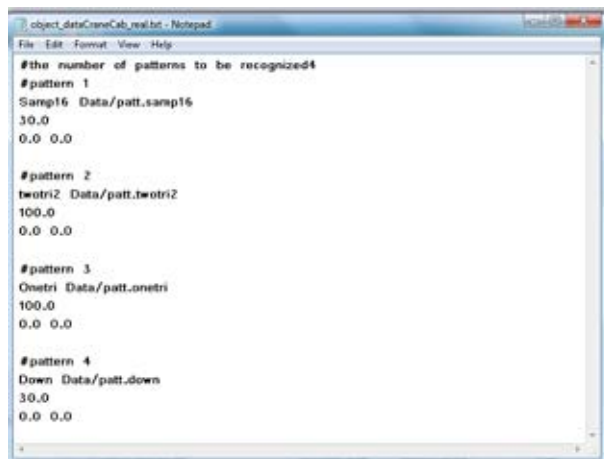
Figure 5.19 Example of 3D model converted into VRML format

5.4.2 Other supported files

In order to develop the AR application, the other supported file formats, which contain the essential information such as text, image files, and database file, were created. For the text files (.txt file), they were created to list data on the markers, 3D models, 2D images, video and sound media, or combined information. Therefore, there were many patterns of text files used in the proposed system, as described in Table 5.4. These text file patterns were differently used in accordance with the functions of the AR prototype applications. Another type of text file was the DAT file, which was created to contain the data of the 3D VRML files. The AR applications retrieved this file type when rendering the 3D VRML models. Figure 5.26 presents an example of a DAT file.

Table 5.4 Summary of patterns of text file

Pattern of text file	Shown in figure
Marker data	Figure 5.20
3D VRML data	Figure 5.21
2D images data	Figure 5.22
Combined marker and 3D VRML data	Figure 5.23
Combined marker and 2D image data	Figure 5.24
Combined marker data and video and sound media	Figure 5.25



```

object_dataCraneCab_real.txt - Notepad
File Edit Format View Help
#the number of patterns to be recognized4
#pattern 1
Samp16 Data/patt.samp16
30.0
0.0 0.0

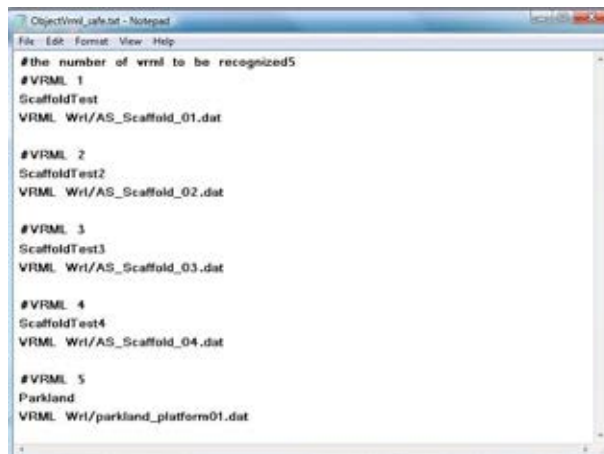
#pattern 2
twotri2 Data/patt.twotri2
100.0
0.0 0.0

#pattern 3
Onetri Data/patt.onetri
100.0
0.0 0.0

#pattern 4
Down Data/patt.down
30.0
0.0 0.0

```

Figure 5.20 Example of text file for listing marker data



```

ObjectVrml_cafe.txt - Notepad
File Edit Format View Help
#the number of vrml to be recognized5
#VRML 1
ScaffoldTest
VRML Wri/AS_Scaffold_01.dat

#VRML 2
ScaffoldTest2
VRML Wri/AS_Scaffold_02.dat

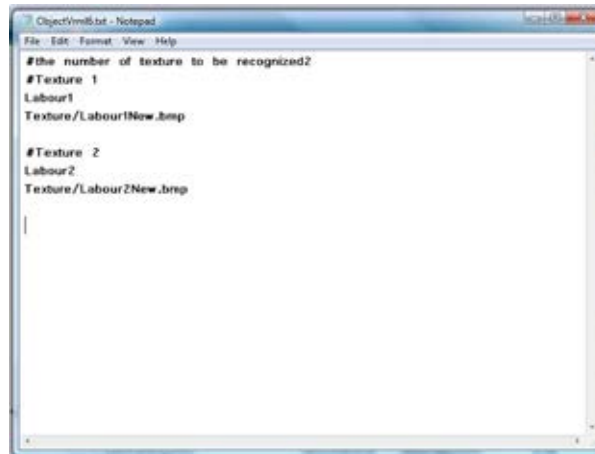
#VRML 3
ScaffoldTest3
VRML Wri/AS_Scaffold_03.dat

#VRML 4
ScaffoldTest4
VRML Wri/AS_Scaffold_04.dat

#VRML 5
Parkland
VRML Wri/parkland_platform01.dat

```

Figure 5.21 Example of text file for listing 3D VRML model data



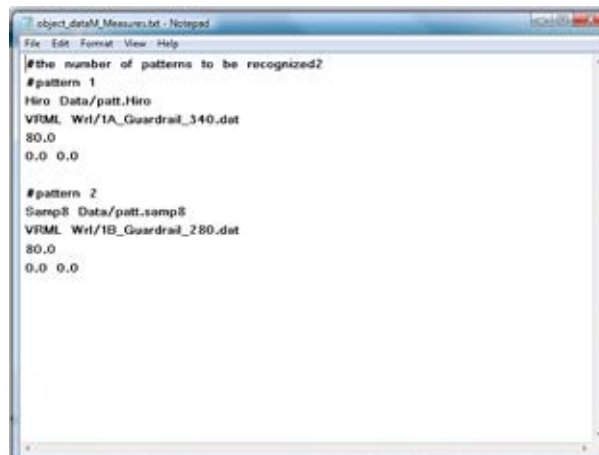
```

Object\mib.txt - Notepad
File Edit Format View Help
#the number of texture to be recognized?
#Texture 1
Labour1
Texture/Labour1New.bmp

#Texture 2
Labour2
Texture/Labour2New.bmp

```

Figure 5.22 Example of text file for listing 2D image data



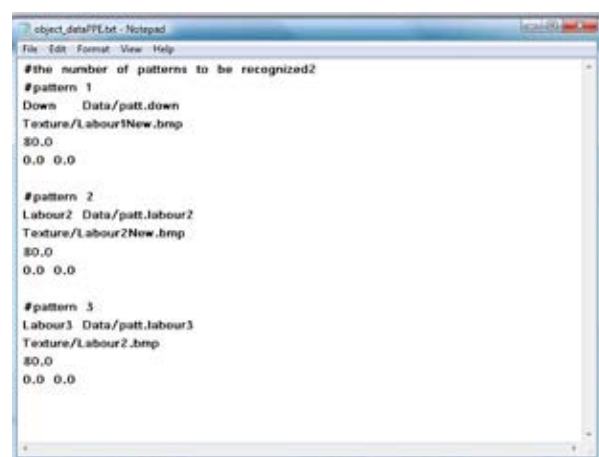
```

object_data\Measure.txt - Notepad
File Edit Format View Help
#the number of patterns to be recognized?
#pattern 1
Hiro Data/patt.Hiro
VRML Wrl/1A_Guardrail_340.dat
80.0
0.0 0.0

#pattern 2
Samp8 Data/patt.samp8
VRML Wrl/1B_Guardrail_280.dat
80.0
0.0 0.0

```

Figure 5.23 Example of text file for listing the combined marker and 3D VRML data



```

object_data\PE.txt - Notepad
File Edit Format View Help
#the number of patterns to be recognized?
#pattern 1
Down Data/patt.down
Texture/Labour1New.bmp
80.0
0.0 0.0

#pattern 2
Labour2 Data/patt.labour2
Texture/Labour2New.bmp
80.0
0.0 0.0

#pattern 3
Labour3 Data/patt.labour3
Texture/Labour2.bmp
80.0
0.0 0.0

```

Figure 5.24 Example of text file for listing the combined marker and 2D image data

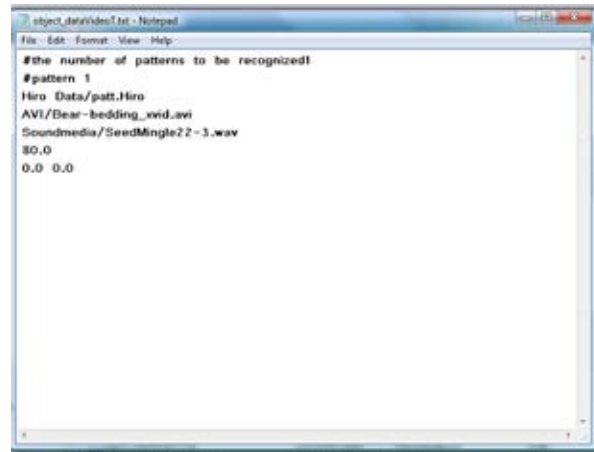


Figure 5.25 Example of text file for listing the combined marker and media data

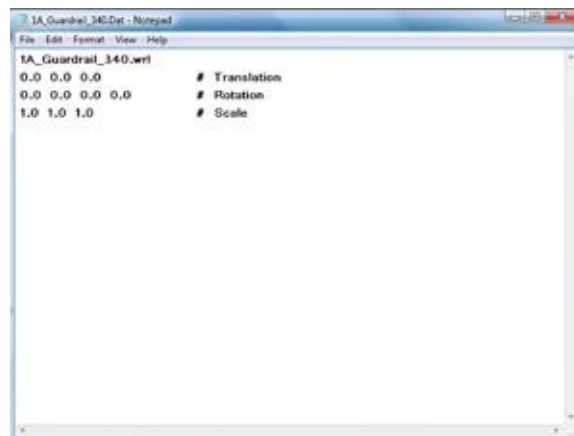


Figure 5.26 Example of DAT file containing the 3D VRML data

Additionally, the file format for supporting the AR application to render the 2D images was the .bmp file. For the video and sound media, the file formats which were used in the program based on the OpenCV library were .avi and .wmv files. Furthermore, a database file was created to store the worker information by using MySQL.

5.5 Calculation and algorithms of the proposed system development

5.5.1 Projectile calculation

In this proposed system, the falling object hazard was one of the hazards which should be prevented to reduce accidents at construction projects. The injury situations caused by falling objects may occur from the worker throwing or kicking tools, materials, or debris above the ground level of the building. To prevent objects from falling from high elevations, the in-charge personnel should know the trajectory of the falling object. Thus, the calculation of the falling object trajectory in physics

was applied. The trajectory of a projectile is presented in Figure 5.27. The horizontal distance from the initial position of the falling object was calculated by using physics formulas as follows.

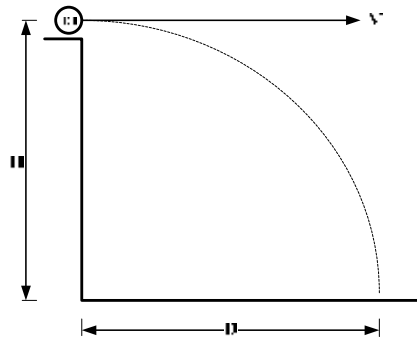


Figure 5.27 Trajectory of a projectile

$$t = \sqrt{\frac{2H}{g}} \quad (5.1)$$

$$D = V_0 t \quad (5.2)$$

where

t	=	time of flight (seconds)
H	=	height of launch (m.)
g	=	downward acceleration of gravity of 9.8 m./s ²
D	=	horizontal distance (m.)
V ₀	=	launch velocity (m/s)

The falling object was assumed to fall from a high elevation without a throwing angle or air resistance in this study. The results of the trajectory are demonstrated in the system in order to help construction personnel perceive the unsafe conditions of falling object hazards. The algorithm for presenting the visualized trajectory of the projectile based on the computer vision technique is shown in Figure 5.28. The system begins by detecting two markers and calculating the distance between them, as demonstrated in Figure 5.29. Each marker contains its own coordinated data in an XYZ axis. Then, the values were stored as the height distance between the two markers and used in the next step.

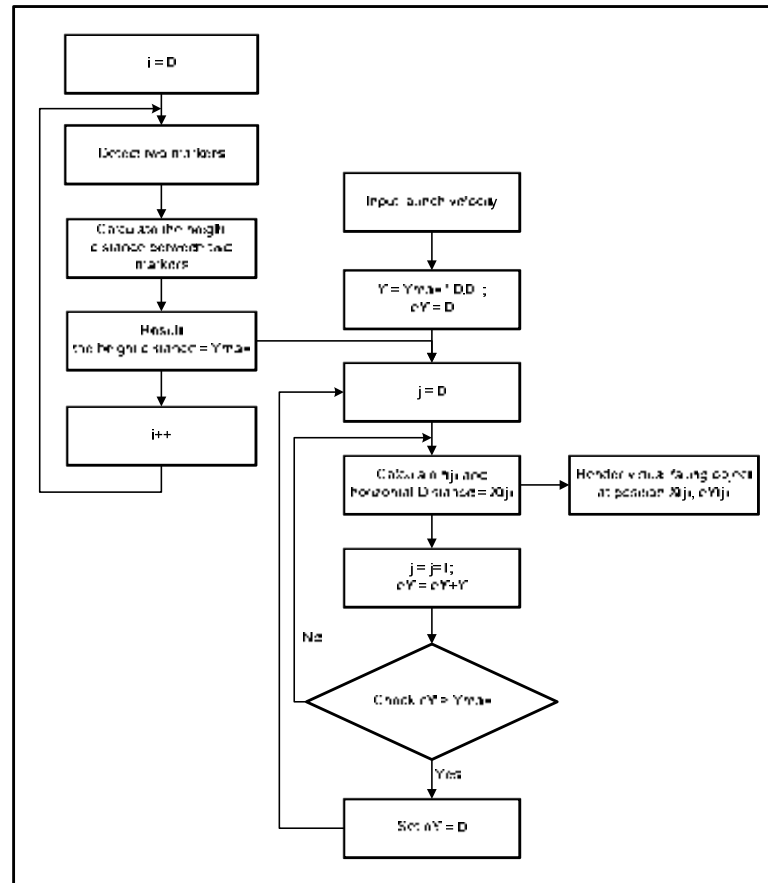


Figure 5.28 Algorithm for presenting the visualized trajectory of a projectile

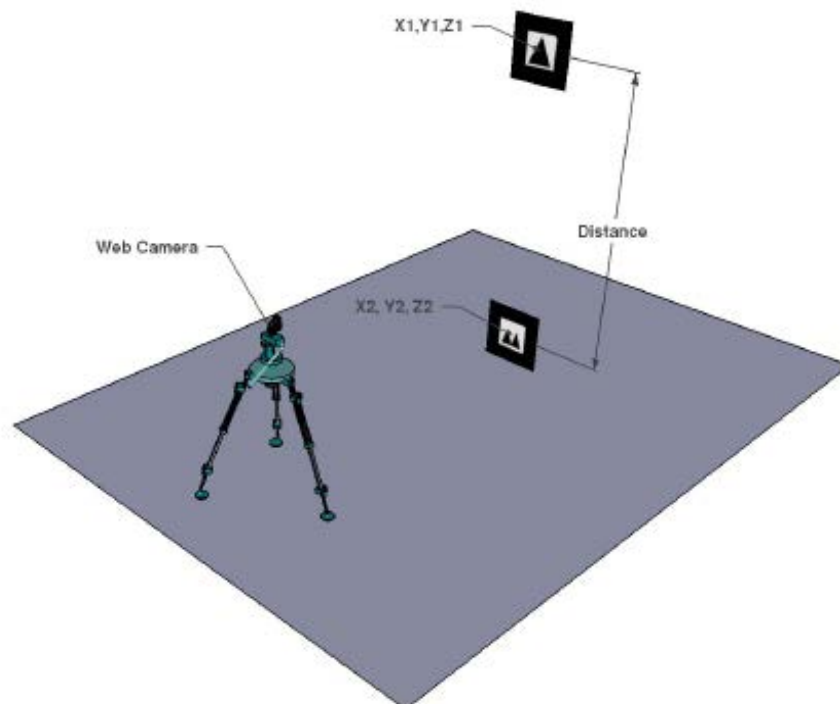


Figure 5.29 The distance between markers

The codes for calculation of the distance between the two markers are shown as follows.

```

if (object[0].visible > 0 && object[1].visible > 0)
{
    arUtilMatInv(object[0].trans, wmat1);
    arUtilMatMul(wmat1, object[1].trans, wmat2);
    draw(object, objectnum, wmat2[0][3],
        wmat2[1][3], object[0].trans);
}

```

In order to present the moving object falling from a high elevation, the value of the total height distance was divided into small values, as described in Figure 5.30. Each divided height distance was used to calculate its horizontal distance by using equations 5.1 and 5.2. The horizontal distance was measured from the center of the top marker. The positions of the moving object in the system came from the coordinate points of the calculated horizontal distance (X axis) and divided height distance (Y axis). The system continuously and reiteratively renders the moving object from the launch height to the based area until the user quits the running application.

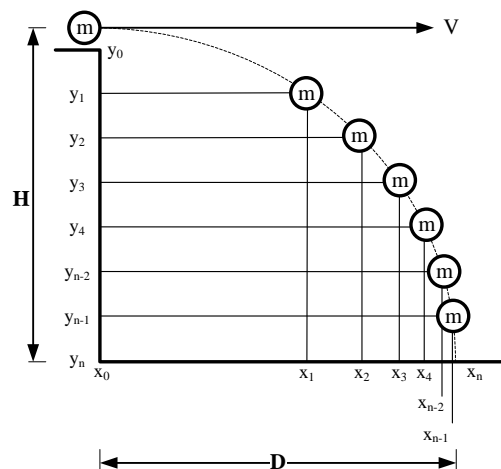


Figure 5.30 Total height distance divided into small values

The codes for calculation of the horizontal distance of the falling object are shown as follows.

```

ymax = ymax - ((object[1].marker_width/2));
y = (ymax*-1)*0.01;
exTy = exTy - y;
if (ymax < 0)
{

```

```

        Time_Calc = sqrt(((2*exTy)/(9.8*100))* -1);
        ytemp = ymax*-1;
    }
    else
    {
        Time_Calc = sqrt((2*exTy)/(9.8*100));
        ytemp = ymax;
    }

    X_Dist = (Initial_Vel * 100)* Time_Calc;

    if ((exTy*-1) > ytemp)
    {
        exTy = (exTy*-1) - ytemp;
    }

```

There were two scenarios for the falling objects in this research, which were falling objects from buildings and falling objects from crane operation. For the first scenario, the launch velocity of the falling object, whose unit was meters per second, came from the user input. However, there were some differences in the second scenario, where the rotation specification of the crane was measured in terms of the frequency of a rotation. The unit of the frequency of a rotation was revolution per minute (abbreviated rpm or r/min). The unit conversion was applied to calculate the angular velocity. Then, the angular velocity was converted to linear velocity by using formulas as follows.

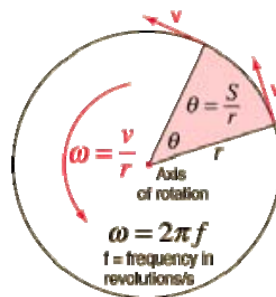


Figure 5.31 Conversion of angular velocity to linear velocity

$$\omega = \frac{2\pi f}{60} \quad (5.3)$$

$$V = \omega r \quad (5.4)$$

where

f	=	frequency of rotation (rpm)
ω	=	angular velocity (rad./s)
r	=	radius (m.)
V	=	linear velocity (m./s)

5.5.2 Collision detection algorithm

The collision detection algorithms in this study were classified into two types based on the safety scenario. The first algorithm was developed for application to the scenario, in which the construction personnel attempted to arrange the safety measures for protection against the hazard of falling objects. The second algorithm was developed for implementation with the scenario in which the construction personnel prepared a safe work area. This algorithm can be applied for defining the work area for building component construction and for considering the hazards of falling objects from crane operation, which may lead to worker accidents. All of the collision detection algorithms are thoroughly described in the next section.

5.5.2.1 Collision detection algorithm for preparation of a falling object protection system

In order to create a falling object protection system at a construction site, the in-charge personnel must comprehend the characteristics of accident occurrence. The safety protection system must be able to protect one from falling objects. The installation of this protection system must be carefully considered. However, it is a difficult and complicated task to imagine events and it is too dangerous to experiment in the real situation. Thus, a simulation situation which allowed the site personnel to perceive the experience of a real falling object dropping from a high level while providing virtual safety measures to protect them from this object was developed.

An algorithm for detecting the collision of falling object and prepared safety measures was developed; a flowchart of this algorithm is described in Figure 5.32. At the beginning, the system detected the markers and rendered the projectile path of the falling object. Then, the system calculated and drew the safety measures based on user input. In Figure 5.33, the length of the falling object protection system is represented by A , the installation height (h) of safety measure is the distance from ground to base position of the safety measure, and the angle (θ) was measured from horizontal to the inclined position of the safety measure. Finally, the system proceeded and checked the collision detection. In the case where the defined safety measures can protect against the falling object, the system will display the output on the screen, as this protection system can protect or not protect one from the falling object.

Figure 5.33 and Figure 5.34 present example situations which the safety measure was arranged while the falling object was dropped from the upper level. In the first figure, the length of the safety measure was sufficient and the installed position was appropriate. Thus, this safety measure could protect from the falling object. On the other hand, a safety measure was installed at the inappropriate position in the later figure. The angle of installation was less than the previous one. Even

though the safety measure was the same length, this safety measure could not prevent the hazard of the falling object.

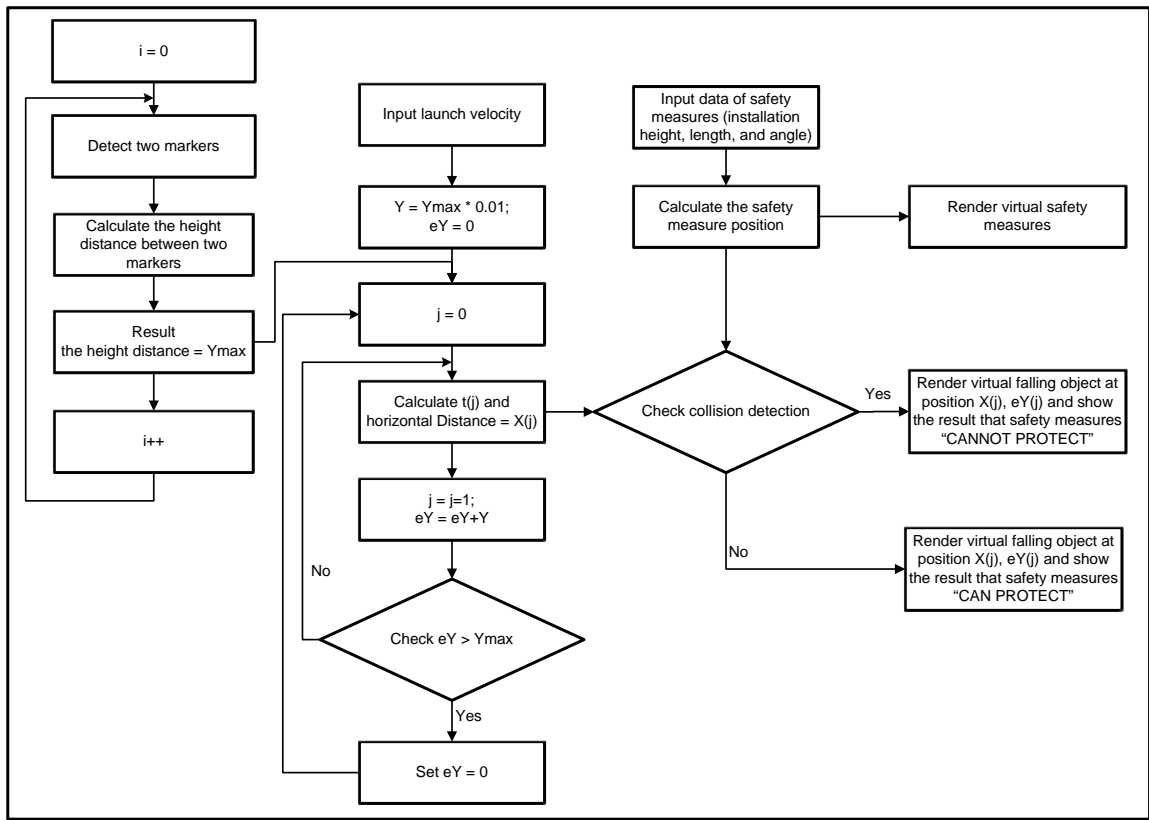


Figure 5.32 Flowchart of collision detection algorithm for falling object protection system

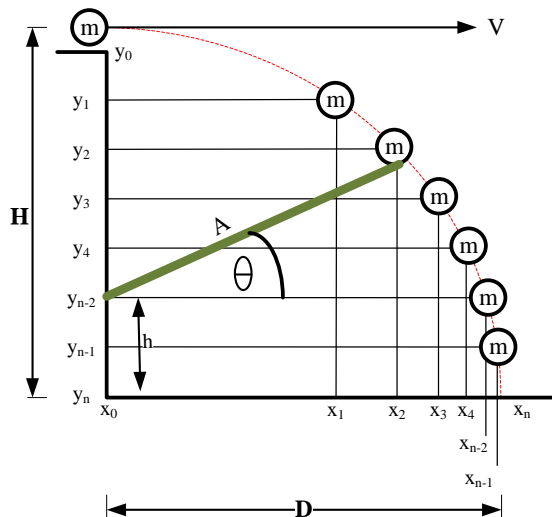


Figure 5.33 Case 1: protection system can protect the falling object

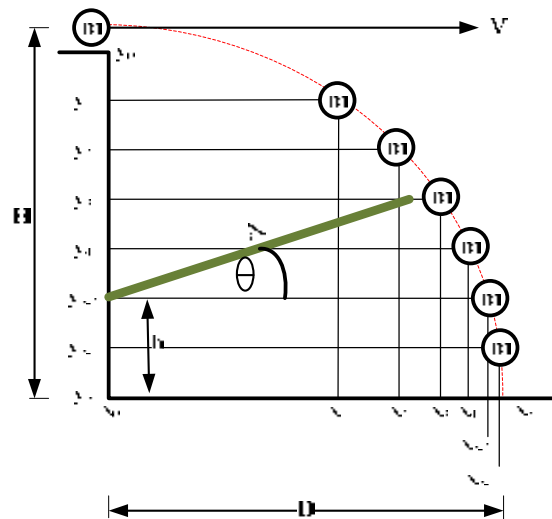


Figure 5.34 Case 2: protection system cannot protect against falling object

The codes for detecting the collision of the falling object with the safety measure are presented as follows.

```
//===== calculate the position of safety measures

TempAngle = (3.14159/180)*Safe_Install_Angle;
TempX = (Safe_Equip_Length*100) * cos(TempAngle);
TempY = (Safe_Equip_Length*100) * sin(TempAngle);
Install_Height = Total_Height - (Safe_Install_Height*100);
X_SE_comp = TempX;
Y_SE_comp = (Install_Height-TempY);

//===== check collision detection
void Check_Safety_Equipment()
{
    double Time_temp;
    double X_obj_comp;
    double X_SE_comp_Abs;

    if (Y_SE_comp <=0)
    {
        safe_check = 1;
    }
    else
    {
        Time_temp = sqrt(((2*Y_SE_comp)/(9.8*100)));
        X_obj_comp = (Initial_Vel * 100)* Time_temp;

        if (X_SE_comp >= X_obj_comp)
        {
            safe_check = 1;
        }
        else
        {
            safe_check = 0;
        }
    }
}

//===== render results
```

```

if (safe_check == 0)
{
    glColor3f(0.19,0.19,0.8);
    Menu_Text(30, ysize - 360, "Safety protection");
    Menu_Text(30, ysize - 420, "the falling object");
    glColor3f(1.0,0,0);
    Menu_Text(15, ysize - 390, "CAN NOT PROTECT");
}
if (safe_check == 1)
{
    glColor3f(0.19,0.19,0.8);
    Menu_Text(30, ysize - 360, "Safety protection");
    Menu_Text(30, ysize - 420, "the falling object");
    glColor3f(0.13,0.56,0.44);
    Menu_Text(40, ysize - 390, "CAN PROTECT");
}

```

5.5.2.2 Collision detection algorithm for safe working area

The second collision detection algorithm which was applied in this research was developed for safe working-area arrangement. This system provided the following two modules for design and planning regards to safe area. In the first module, the scenarios which were used as the case study were the falling object dropping from a crane operation to the work area and to the worker's work space.

For both scenarios, the system began with detecting the crane marker and reference marker. Then, the distance between these two markers and stores was calculated as the height distance. After that the height distance was used for calculating the horizontal distance of the projectile according to the initial velocity, which is input by the user. The horizontal distance was the radius of the area in which the falling object may drop. Meanwhile, the system detected the markers of the work area and required the user to input the size of the work area. The calculated horizontal distance of the falling object and size of the work area were then used for calculating the required distance, which was used to compare the distance between markers measured by the system.

In case the maximum distance between the two markers measured by the system was less than the required distance, the system detected the collision of the virtual objects, and changed and rendered the color of the virtual objects from green to red to indicate the unsafe condition. Figure 5.35 presents the scenario of a falling object from a crane operation to the work area for which the collision detection algorithm was applied to check the unsafe situation. A flowchart of the collision detection algorithm for the falling object dropping from the crane to the work area is shown in Figure 5.36.

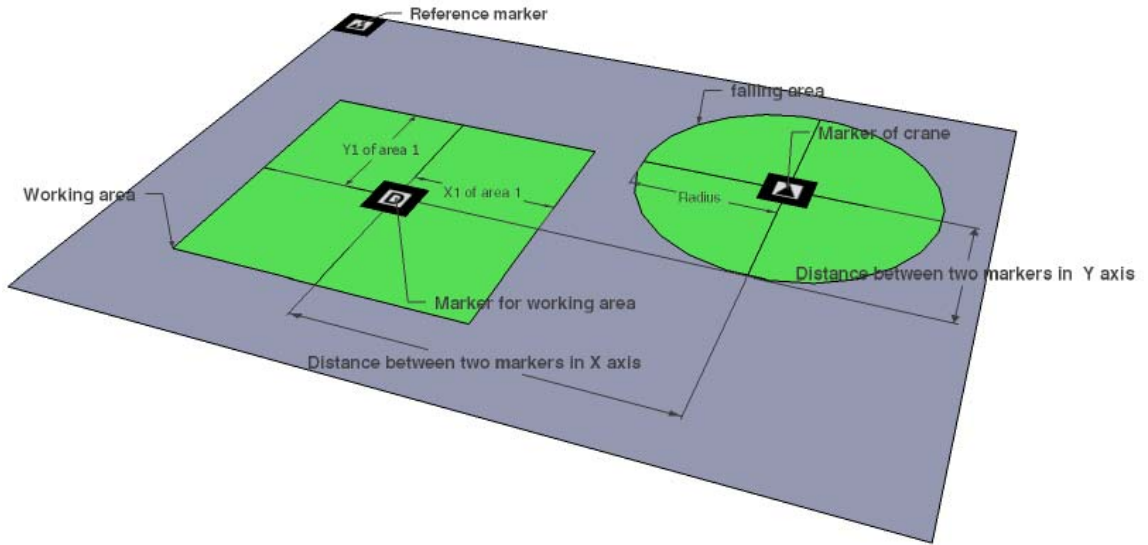


Figure 5.35 Applying the collision detection algorithm to the scenario of a falling object from a crane to the work area

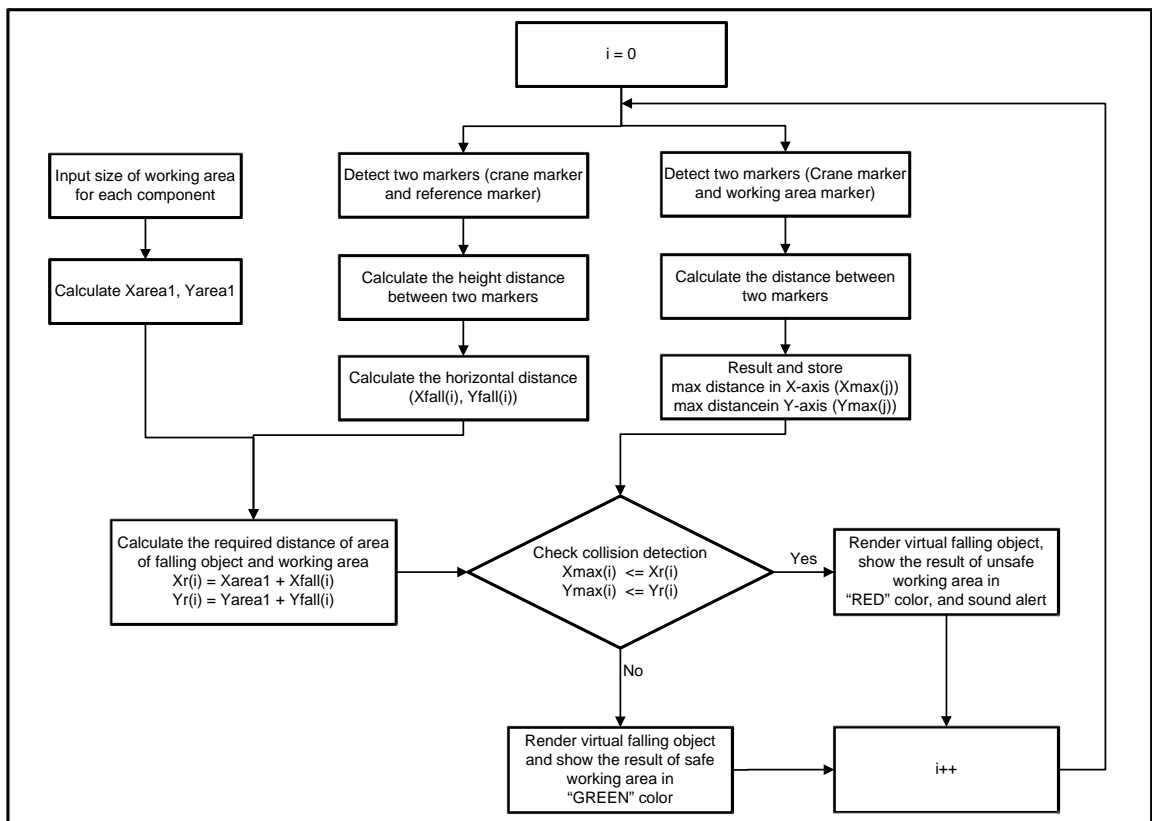


Figure 5.36 Flowchart of collision detection algorithm for scenario of falling object from crane to work area

The codes for detecting the collision of falling object from crane operation to work area are presented as follows.

```
//===== calculate the distance between crane marker and reference marker
if (object[0].visible > 0 && object[1].visible > 0)
{
    arUtilMatInv(object[0].trans, wmat[1]);
    arUtilMatMul(wmat[1], object[1].trans, wmat[2]);
    Color_Change();
    draw(object, objectnum, wmat[2][0][3], wmat[2][2][3],
    object[0].trans);
}
//===== calculate about projectile
Total_Height = wmat[2][2][3]*-1;
Time_max = sqrt ((2*(Total_Height))/(10*100));
Horizontal_Dist_Max = (Initial_Vel * 100)* Time_max;
//==calculate the distance between crane marker and marker of working area==
if (i > 1)
{
    if (object[0].visible > 0 && object[i].visible > 0)
    {
        arUtilMatInv(object[0].trans, wmat[m]);
        arUtilMatMul(wmat[m], object[i].trans, wmat[m+1]);
        Conflict_X[i-2] = wmat[m+1][0][3]; Conflict_Y[i-2] =
        wmat[m+1][1][3];
    }
}
//===== detect collision=====
if((strcmp (fall_direction, "both" ) == 0))
{
    if(Conflict_Y[i-2] > 0) // marker อยู่หน้าคอน
    {
        if (abs(Conflict_X[i-2]) < Horizontal_Dist_Max +
        ((Component_width[i-2]*100)/2) && (abs(Conflict_Y[i-2])
        < Horizontal_Dist_Max + ((Component_length[i-2]*100)/2)))
        {
            Check_Area_Conflict =1;
            Color_work1[i-2]= 1.0;
            Color_work2[i-2] = 0.0 ;
            Color_work3[i-2] = 0.0;
            Color_work4[i-2] = 0.1;
            test_irrKlang();
        }else
        {
            Check_Area_Conflict =0;
        }
    }

    if(Conflict_Y[i-2] < 0)
    {
        if (abs(Conflict_X[i-2]) < Horizontal_Dist_Max +
        ((Component_width[i-2]*100)/2) && (abs(Conflict_Y[i-2])
        < Horizontal_Dist_Max+ ((Component_length[i-2]*100)/2)))
        {
            Check_Area_Conflict =1;
            Color_work1[i-2]= 1.0;
            Color_work2[i-2] = 0.0 ;
            Color_work3[i-2] = 0.0;
            Color_work4[i-2] = 0.1;
            test_irrKlang();
        }else
        {
            Check_Area_Conflict =0;
        }
    }
}
}
```

Another scenario is the falling object dropping from the crane operation to the worker's work space. In this system, the worker's space at the construction site was defined to be of a cylinder shape whose radius was 1.00 m. according to human ergonomics (Intranont, 2005). The system proceeded to check the collision similar to that in the previous situation. The difference was that the required distance between worker's space and the area of the falling object was calculated from the radius of the worker's space plus the radius of the area of the falling object. This value was used to compare the maximum distance between the crane marker and the worker marker. The scenario of the falling object from crane to worker's space where the collision detection algorithm was applied to check the unsafe situation is demonstrated in Figure 5.37. In Figure 5.38, a flowchart of the collision detection algorithm for falling object dropped from a crane to the worker's space is denoted.

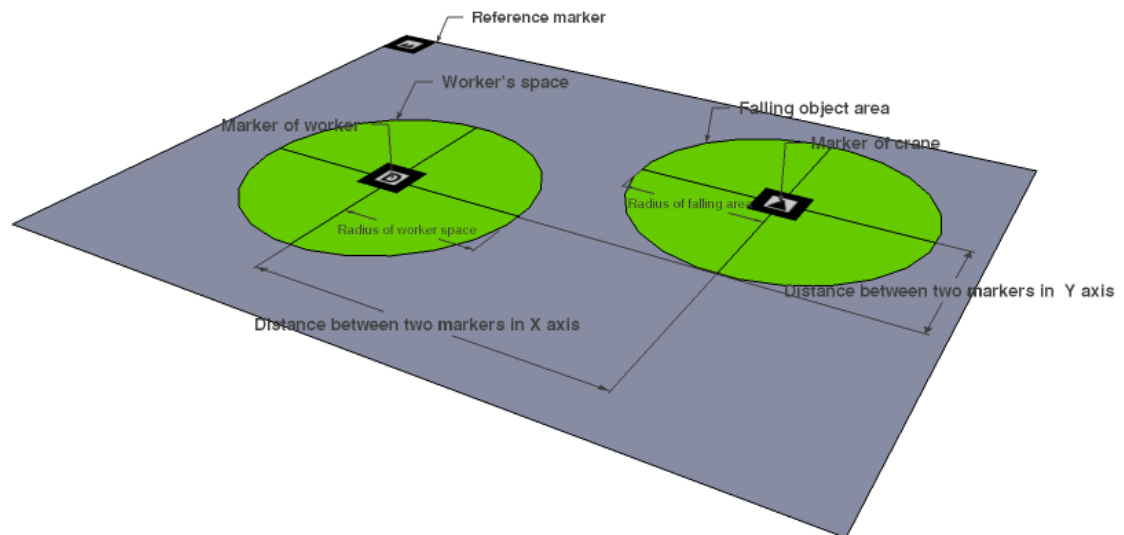


Figure 5.37 Applying the collision detection algorithm to the scenario of a falling object from the crane operation to the worker's work space

The codes for detecting the collision of falling object from crane operation to worker's space are presented as follows.

```

//===== detect collision=====
if((strcmp (fall_direction, "both" ) == 0))
{
    if(Conflict_Y[i-2] > 0)
    {
        if ((abs(Conflict_X[i-2]) < (Horizontal_Dist_Max + R_CY)) &&
(abs(Conflict_Y[i-2]) < Horizontal_Dist_Max+R_CY))
        {
            Check_Area_Conflict =1;
            Color_work1[i-2]= 1.0;
            Color_work2[i-2] = 0.0 ;
            Color_work3[i-2] = 0.0;
            Color_work4[i-2] = 0.1;
            test_irrKlang();
        }
    }
}
else
{

```

```

        Check_Area_Conflict = 0;
    }
}
if(Conflict_Y[i-2] < 0)
{
    if ((abs(Conflict_X[i-2]) < Horizontal_Dist_Max + R_CY)&&
(abs(Conflict_Y[i-2]) < Horizontal_Dist_Max+ R_CY))
    {
        Check_Area_Conflict = 1;
        Color_work1[i-2]= 1.0;
        Color_work2[i-2] = 0.0 ;
        Color_work3[i-2] = 0.0;
        Color_work4[i-2] = 0.1;
        test_irrKlang();
    }else
    {
        Check_Area_Conflict = 0;
    }
}
}
}

```

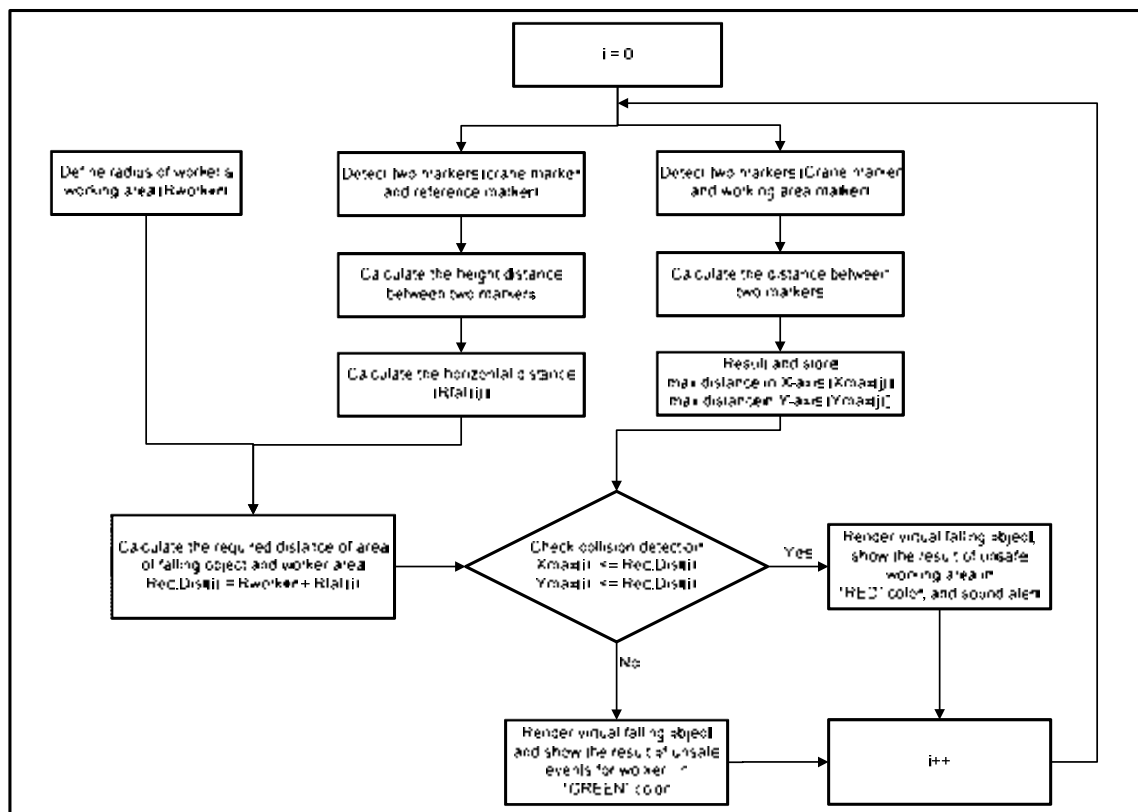


Figure 5.38 Flowchart of collision detection algorithm for scenario of falling object from crane to worker's space

For another design and planning module, the in-charge personnel have to plan for a safe working area for constructing the building components. If so, the system can provide an algorithm for detecting the unsafe condition in the prepared work area. The required work area was calculated from type and size of building component, including the space for constructing the building component, which was

input by user. In order to check for an overlap of the work areas, the system required the user to input the radius of the other work area. Then, the system calculated the required distance by adding the size of the work area with the radius of the other area. Later, the system detected the collision of both work areas by comparing the required distance and maximum distance of both markers. If the maximum distance was less than the required distance, the system made a sound alert in order to let the user know about the unsafe work condition. The collision detection algorithm for preparation of the work area for a building component is denoted in Figure 5.39. The flowchart of this algorithm is presented in Figure 5.40.

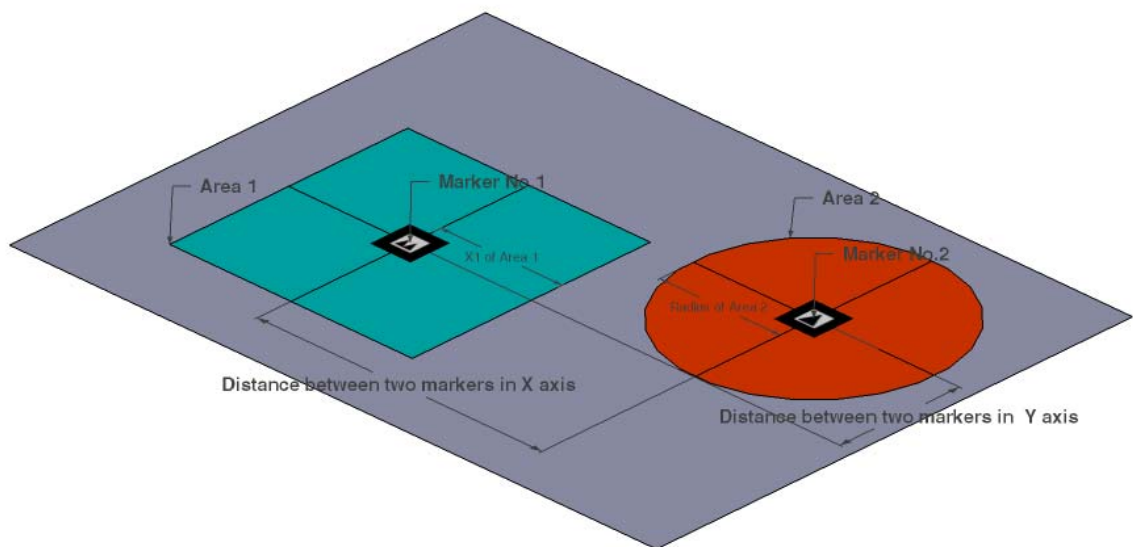


Figure 5.39 Collision detection algorithm for creating a safe work area for the building component

The codes for the collision detection algorithm for creating a safe work area for the building component are presented as follows.

```
//==== calculate distance between two markers
if (object[0].visible == 1 && object[i].visible == 1)
{
    arUtilMatInv(object[0].trans, wmat1);
    arUtilMatMul(wmat1, object[i].trans, wmat2);
}

//==== check collision detection
if(strcmp (Component_type, "column" ) == 0)
{
    set_disX = (object[i].marker_width/2+((Component_length*100)/2-
    (object[i].marker_width/2))+(ex_length*100)+(OtherWork_Dia*100));

    set_disY_back = -object[i].marker_width/2-(Component_width*100)-
    (ex_width*100)-(OtherWork_Dia*100);

    set_disY_front = -(object[i].marker_width/2)+
    (ex_width*100)+(OtherWork_Dia*100);
}
```

```
if ( Temp_otherX < set_disX && set_disY_back < wmat2[1][3] && wmat2[1][3]<
set_disY_front)
{
    Check_Area_Conflict =1;
    test_irrKlang();
}else
{
    Check_Area_Conflict =0;
}

if(strcmp (Component_type, "beam" ) == 0)
{
set_disX = (object[i].marker_width/2+((Component_length*100)/2-
(object[i].marker_width/2)))+(ex_length*100)+(OtherWork_Dia*100));

set_disY = (object[i].marker_width/2+((Component_width*100)/2-
(object[i].marker_width/2)))+(ex_width*100)+(OtherWork_Dia*100));

if (Temp_otherX < set_disX && Temp_otherY < set_disY)
{
Check_Area_Conflict =1;
test_irrKlang();
}else
{
Check_Area_Conflict =0;
}
}

if(strcmp (Component_type, "slab" ) == 0)
{
set_disX = (object[i].marker_width/2+((Component_length*100)/2-
(object[i].marker_width/2)))+(ex_length*100)+(OtherWork_Dia*100));

set_disY = (object[i].marker_width/2+((Component_width*100)/2-
(object[i].marker_width/2)))+(ex_width*100)+(OtherWork_Dia*100));

if (Temp_otherX < set_disX && Temp_otherY < set_disY)
{

Check_Area_Conflict =1;
test_irrKlang();
}else
{
Check_Area_Conflict =0;
}
}
```

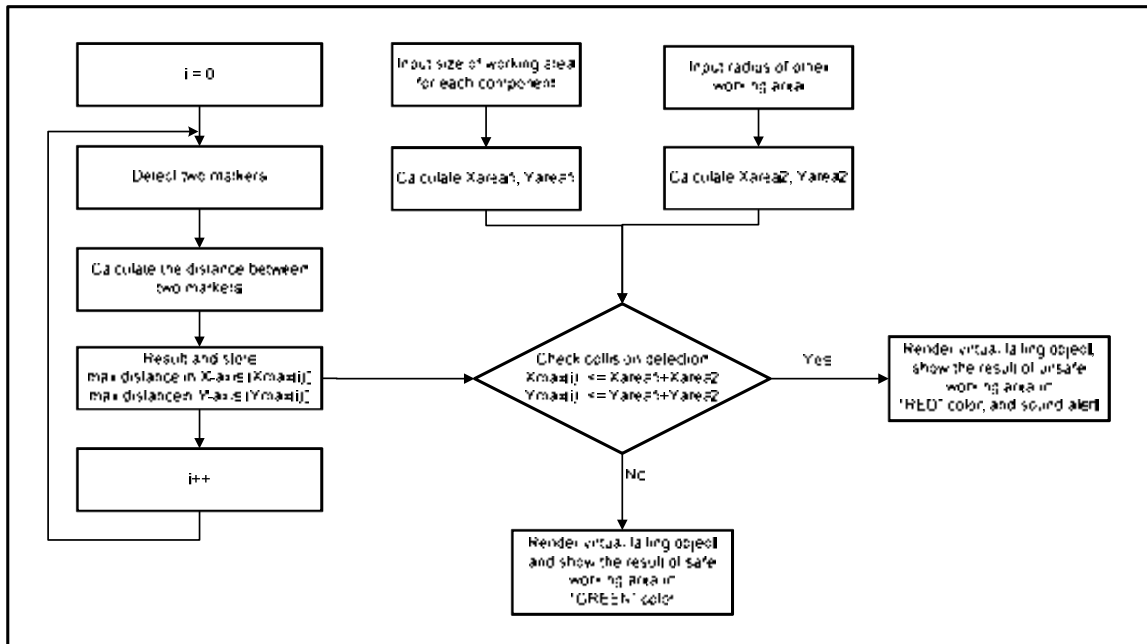



Figure 5.40 Flowchart of collision detection algorithm for creating a safe work area for the building component

5.6 Conclusion

In this chapter, an innovative and proactive system for safety management was designed according to the problems of current practices collecting from site observation. The proposed system was initiated to assist the in-charge personnel in safety management processes, such as hazard identification, safety planning, monitoring, and training. In order to develop this system, the ARToolKit, which is free, open source, and widely used in academic research, was implemented. Further, other open source libraries for providing visualized and audio information were also prepared and applied. The 2D images, 3D models, video media, and sound media were arranged to support this system. Moreover, projectile calculation and collision detection algorithms were proposed. The trajectory of projectile was used in order to demonstrate the possible horizontal distance and area of the falling object.

Furthermore, there were two main algorithms of collision detection which consisted of: 1) a collision detection algorithm for preparation of a falling object protection system, and 2) collision detection algorithm for the creation of a safe work area. The first algorithm resulted from the collision of the falling object from a high elevation and the safety protection system. The visualized results can be presented to construction personnel and can be used as a simulation for preparation of a falling object protection system. The second algorithm was divided into three scenarios: collision detection of a falling object from a crane with the work area, collision detection of a falling object from a crane with the worker's space, and collision detection considering the work area and other work areas. All collision detections

mainly focused on identifying the unsafe working conditions that would tend to lead to accidents in construction projects.

Chapter VI

Prototype System Development

6.1 Introduction

This chapter presents with the development of a prototype system according to the conceptual system design in the previous chapter. The prototype system consists of four main modules for supporting the safety management and augmented reality module. In each module regarding safety management, the contents of preparation, input, process, and output are different. These modules produce divergent results for serving the essential visualized information for the in-charge personnel that undertake safety and carry out the construction activities. The next section describes the development of each module. Further, the output results and testing of the prototype system are illustrated in the last section.

6.2 Development of the applications in the prototype system

The VSMART System (acronym for Visualized Safety Management using Augmented Reality Technology) was developed as a dialog-based MFC application using Microsoft Visual Studio 2008, as presented in Figure VI.1, in cooperation with the specific libraries as denoted in the previous chapter. To supply the visualized results of each module, the exiting safety information, which was both graphic and non-graphic, was prepared and input into the proposed system. Then, each module performed its function and the visualized results were presented. The outputs of each safety module were displayed by using the module of augmented reality.

Normally, the ARToolKit provides a video dialog for the initial setup, which allows the user to select the option of the video output. The color space/compression, the display resolution of output size, and frame rate can be selected by the user, as shown in Figure VI.2. The alternatives of these options depend on the camera device which is connected to laptop computer. However, this proposed system requires users to specify the display resolution of the output size 800 x 600 pixels and a frame rate of 30 frames per second (fps).

As mentioned above, the four safety modules and the module of augmented reality were developed in this prototype system to manage safety at the construction site. All developed modules had their own applications in assisting the construction personnel in performing their tasks. The applications to support the tasks regarding safety contained in each safety module are presented in *ผิดพลาด! ไม่พบแหล่งอ้างอิง* and the main user interface for selecting the applications is shown in Figure VI.4.

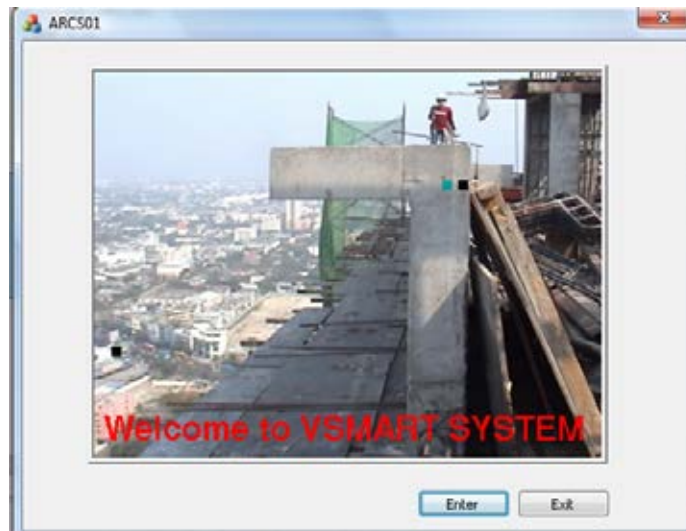


Figure 6.1 User interface when starting the VSMART system

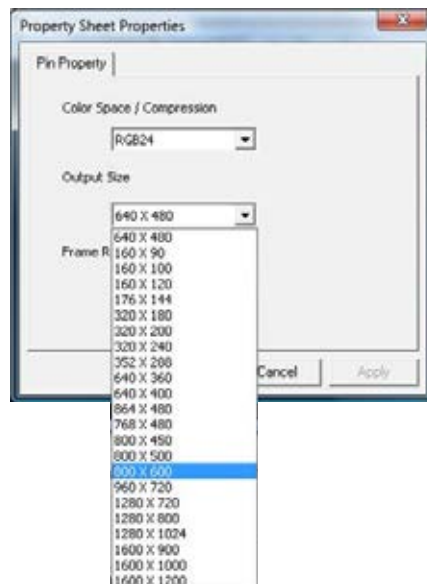


Figure 6.2 Initial setup of video dialog

The first module was design and planning for preventing the hazards of falling objects, which comprised the falling object hazard from buildings, falling object hazard from crane to work areas, and falling object hazard from crane operation to workers' space. Secondly, the module of design and planning for arrangement of safe work area consisted of the following two applications, which were safety measure selection and safety work area preparation. The third was the monitoring module, which was comprised of safety work area monitoring and personal protection equipment monitoring. In addition, the last module comprised safe assembly training and construction task media training. The calculations and algorithms which were formerly mentioned were applied in the development process.

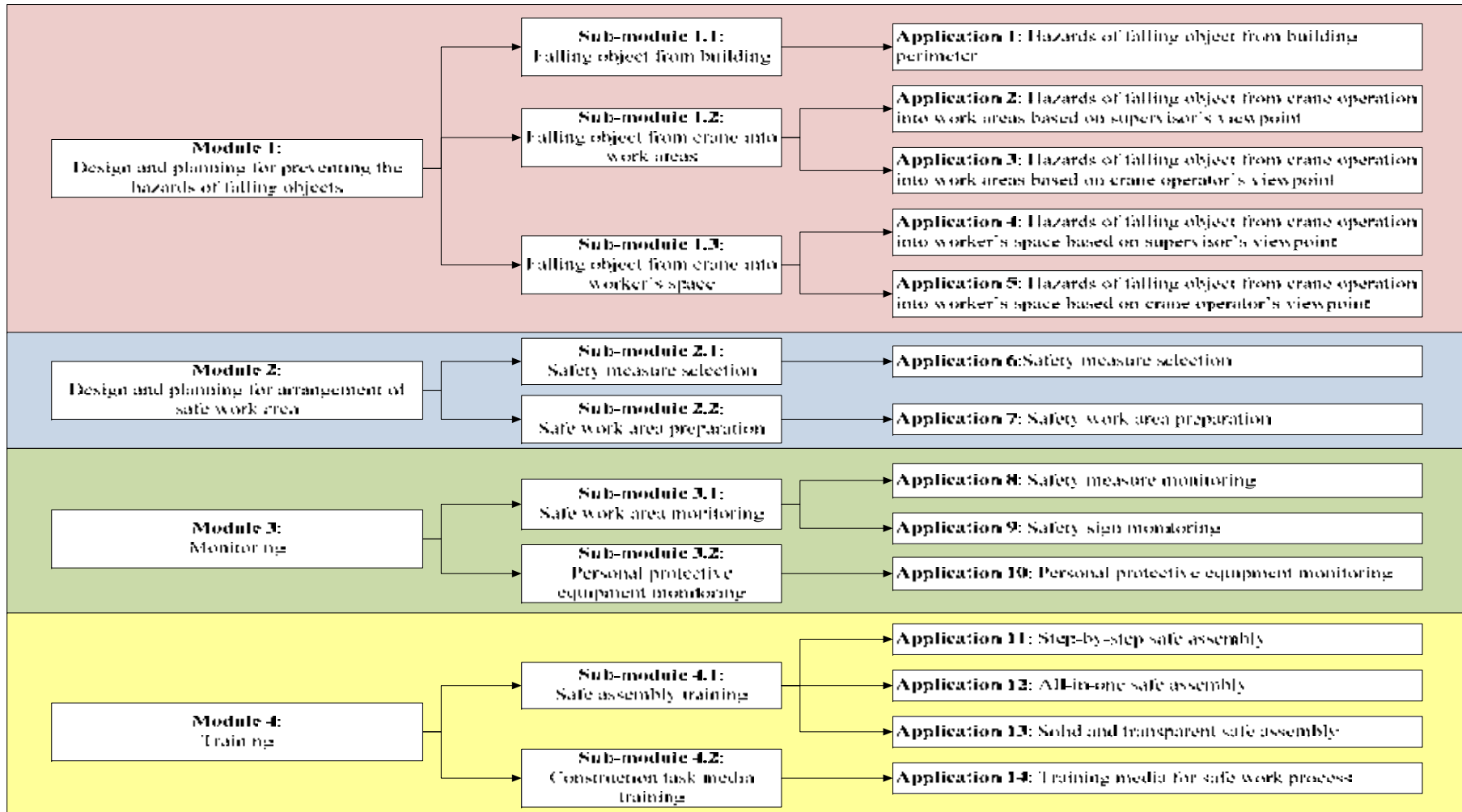


Figure 6.3 The applications contained in the four safety modules

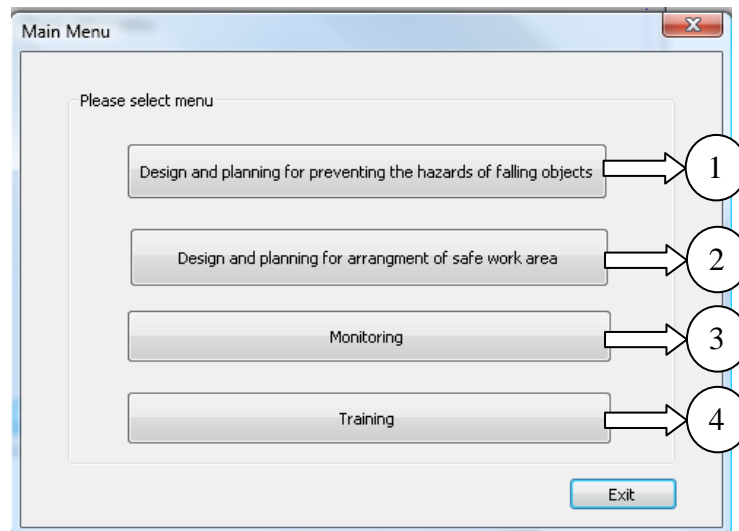


Figure 6.4 Window of user interface for the main menu

In the next section, the development of the four safety modules is thoroughly described. The user interfaces of input and output are also demonstrated.

6.2.1 The module of design and planning for preventing the hazards of falling objects

The module of design and planning for preventing the hazards of falling objects is the first module in the VSMART System. The purpose for developing this module was to provide an effective tool for preventing the hazards of falling objects. The following three sub-modules consist of the hazard of falling objects from buildings, the hazard of falling objects from cranes into the work area, and the hazard of falling objects into the worker's space, as shown in Figure 6.5. The user can select the considered hazard by pressing a button.

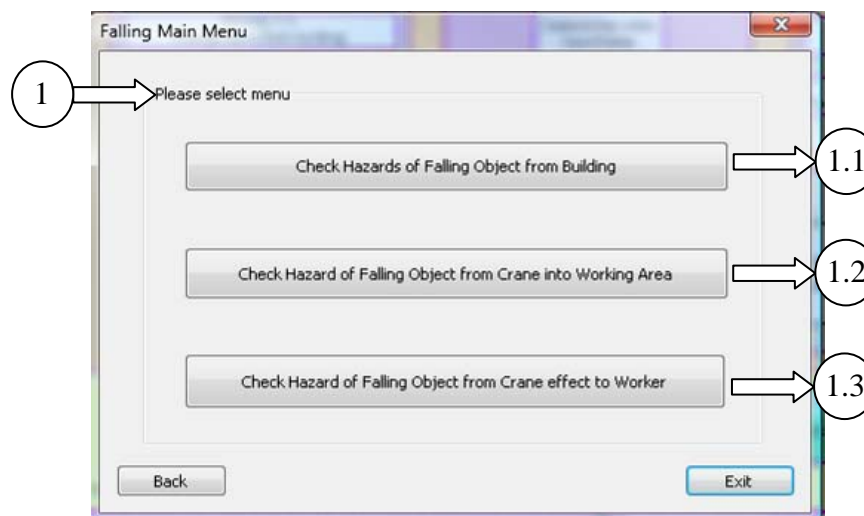


Figure 6.5 Main user interface of hazard identification module

6.2.1.1 Hazard of falling objects from high elevation of building perimeter

This sub-module was developed to assist the site personnel when they arrange the safety protection system for preventing object from falling. The falling objects, such as tools, materials, or debris, may be dropped from a high level. Normally, a falling object protection system is prepared and installed at the building perimeter. The length and position of the protection system is designed by engineers. Conventionally, Thailand's laws and regulations state that a falling object protection system is required in the construction projects located near public buildings and of heights of buildings of more than 10 m. and a distance between building and site boundaries less than half the building height. Figure 6.6 demonstrates the requirements of the laws and regulations concerning the falling object protection system.

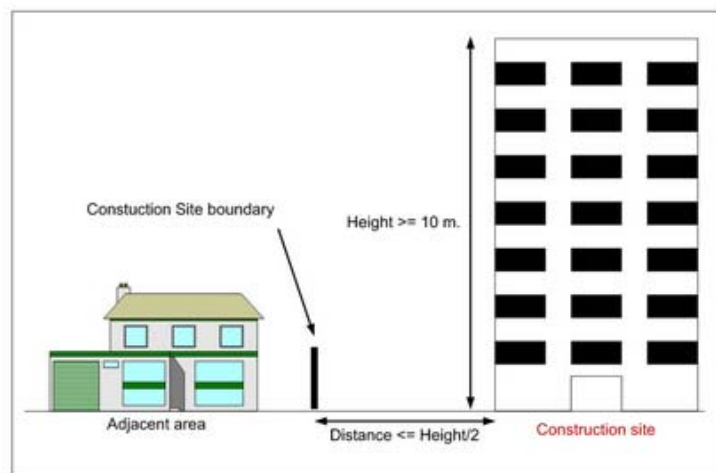


Figure 6.6 Illustration for construction projects which require a falling object protection system

As described in the previous chapter, a falling object from a high elevation with the velocity produces the projectile path, as presented in Figure 6.7. In order to arrange safety measures to protect against the falling object, the engineer must calculate the maximum horizontal distance from the falling point and comprehend the unseen projectile path. The length of the safety measures, and the height and angle position for the installation, must be approximately generated and simulated. Nevertheless, the traditional preparation process cannot reflect the actual condition, such as the effect of falling objects on the neighboring building. Therefore, the application in this sub-module will assist the users in simulating the falling object events while they perceive and consider the actual surrounding environment.

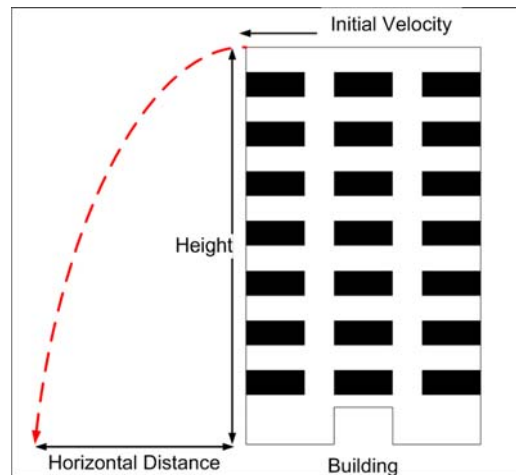


Figure 6.7 Projectile path of falling object from a high elevation

The following four steps are employed in the performance of the application: preparation, input, process, and output, as shown in Figure 6.8. In the first step, two markers, as shown in Figure 6.9, were prepared and printed out as described. For testing in the laboratory, the marker size was 8 cm, but it was changed to 100 cm when testing in the real environment. In addition, the markers were installed in the position as presented in Figure 6.9. Marker no.1 was installed at a higher level, which was the falling point, and marker no.2 was installed at the base level.

Then, the system requires the user to input the data, such as falling object direction (left or right), initial velocity, length of protection system, installed height position, and installed angle measured from the horizontal. The user interface for the input data is presented in Figure 6.10. After inputting the required data, the system was processed according to the ARToolKit algorithm, beginning with capturing the video input frame, detecting the markers, calculating the camera transformation, and calculating the distance between two markers. Later, the system calculated the horizontal distance of the projectile and cover range of the safety measure based on the proposed algorithm in the previous chapter. Moreover, this application applied the collision detection algorithm for the preparation of the falling object protection system. The possible results of the collision detection are presented in Figure 6.11 and Figure 6.12. The falling object may drop from the left or right side of building, where the safety measures are installed in the same direction. In case that the length of the safety measure is sufficient and the installation height and angle of the safety measure are appropriate, the result is displayed as the protection system can protect against the falling object. On the other hand, if the length of the safety measure is insufficient or the installation height and angle are improper, the result is displayed as the protection system not being able to protect against the falling object.

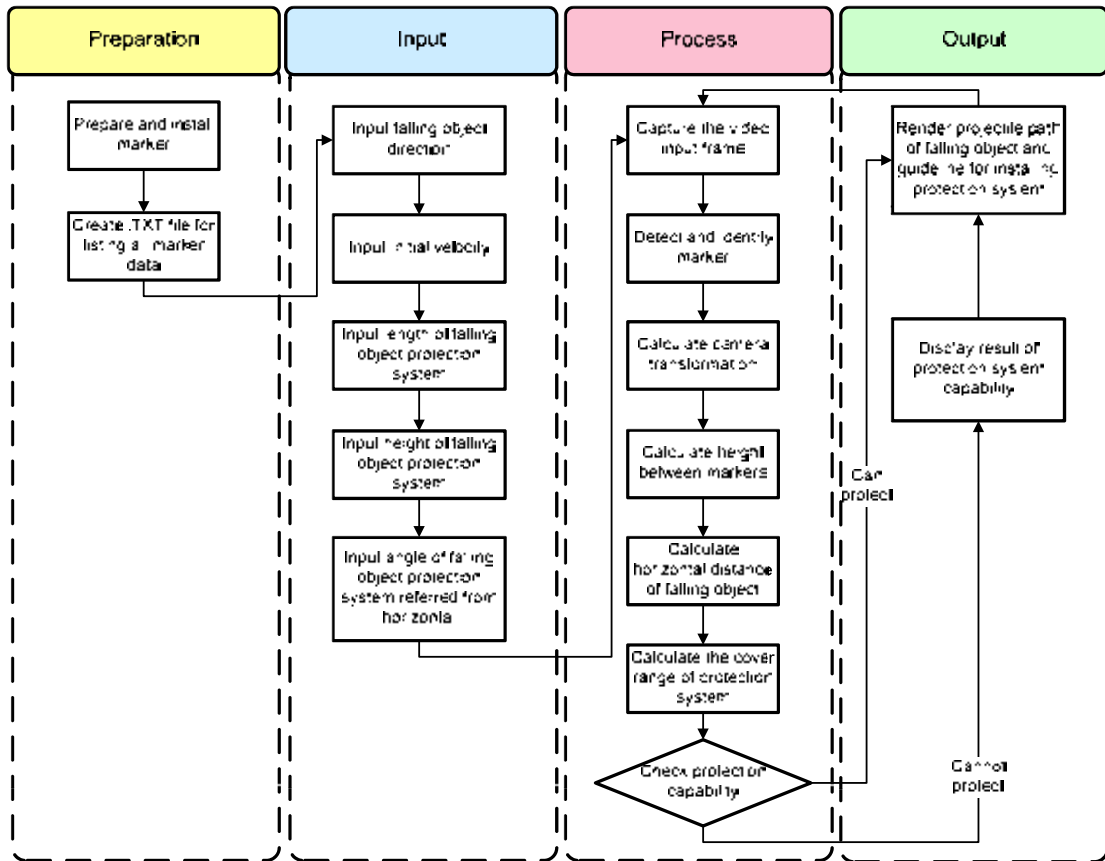


Figure 6.8 Flowchart of application for falling object hazard from building

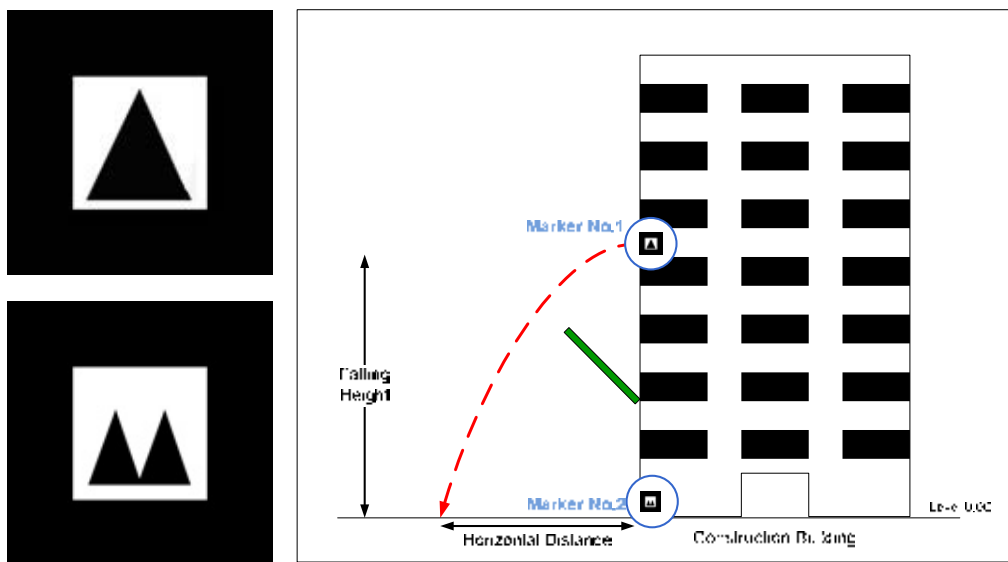


Figure 6.9 Marker preparation and installation

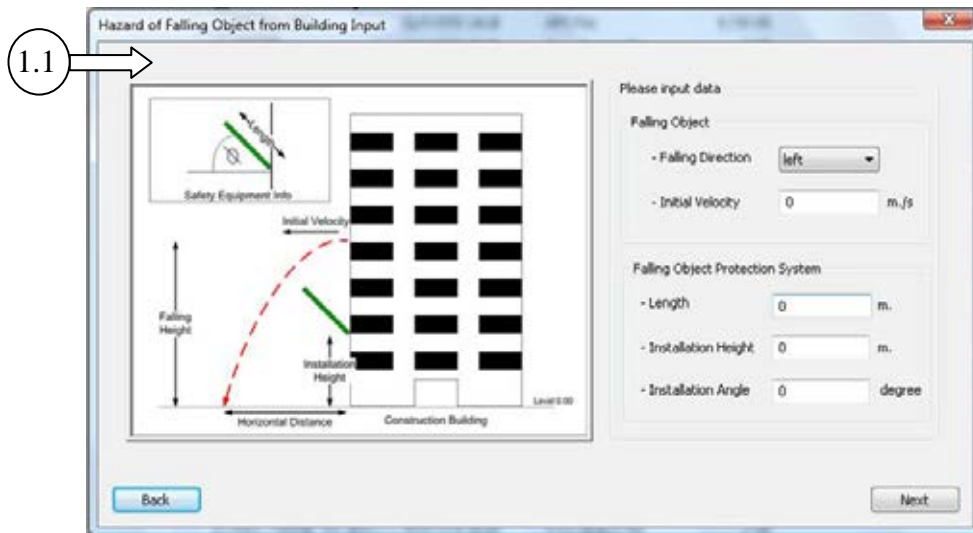


Figure 6.10 User interface for input data of falling object hazard from building

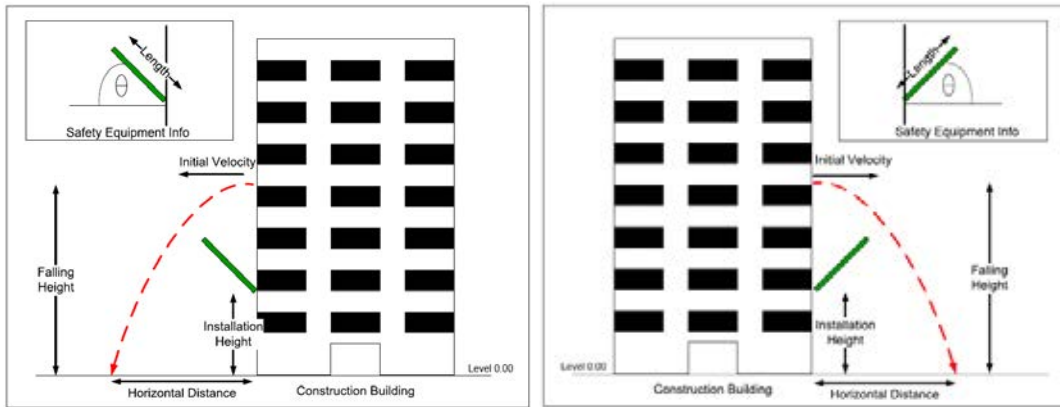


Figure 6.11 Example results where the protection system cannot prevent against the falling object

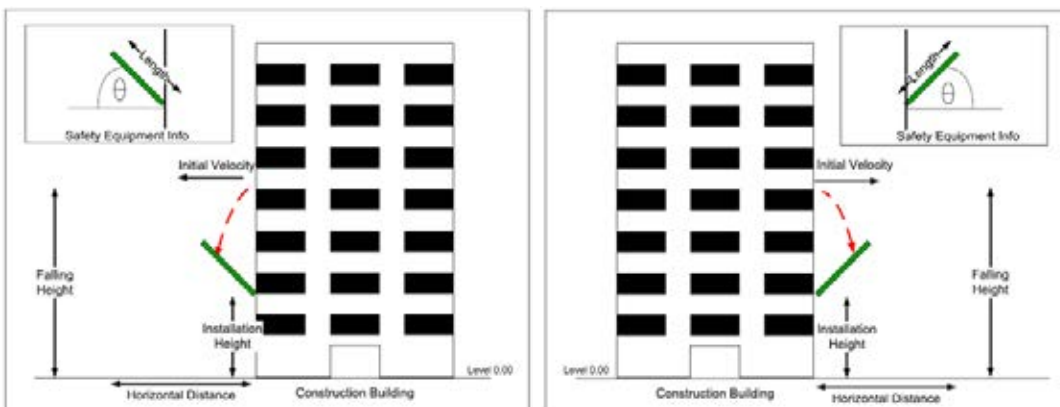


Figure 6.12 Example results which the protection system can prevent the falling object

An example of the AR result of a falling object hazard from a high elevation of building is shown in Figure 6.13. This testing was done in the laboratory. The falling direction was toward the right and the initial velocity was 0.3 m/s. For the safety protection system, the length of the safety measure was input as 0.2 m. Moreover, the installation height and angle were 0.2 m. and 45 degree respectively. The red sphere represented the falling object, which fell from the center of the higher marker to the base level. The green line represented the protection system which was installed according to the input data. The system presented the results that the falling height measured by the program was 0.395 m. compared with the real distance (0.40 m.). If the safety protection system was not installed, the falling object would fall far from the center of the higher marker equal to 0.0851 m. However, the length of the virtual protection system was sufficient; thus it could protect against the falling object, as displayed in the results.

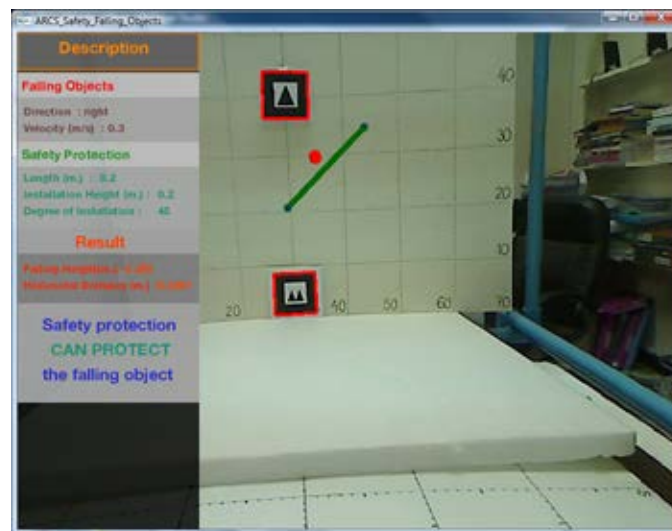


Figure 6.13 Example of AR results of falling object hazards

6.2.1.2 Hazard of falling object from crane operation into the work areas

This second sub-module of the module of design and planning for preventing the hazards of falling object was the hazard of a falling object from a crane operation into the work areas. This scenario was selected to be the case study in this research due to the accident statistics at construction sites. Heavy equipment such as cranes can cause serious accidents, such as collision accidents, missed moving, and hitting people (Park et al., 2011). This prototype application aims to prevent these accidents by providing the visualized unsafe zone when the crane operates, as shown in Figure 6.14. Not only was an unsafe zone for the falling object illustrated, but also an overlap of the unsafe zone with the other work areas were provided.

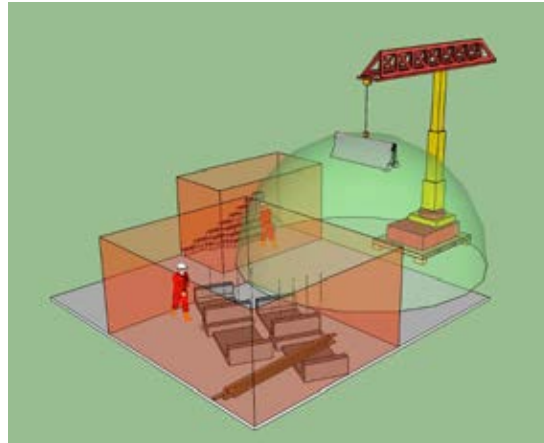


Figure 6.14 Hazard of falling object from crane operation into work area

This sub-module was divided into two applications based on the web camera position, as shown in Figure 6.15. In the first application, the web camera was installed on crane cabin to represent the crane operator's viewpoint. Therefore, the output results were displayed to the user from the top view. The results of this application can assist crane operators when they manipulate this equipment. The second application was a web camera installed on the work area level. The result of this application can aid the superintendents that control the construction activities to avoid the hazards of falling object into the work space.

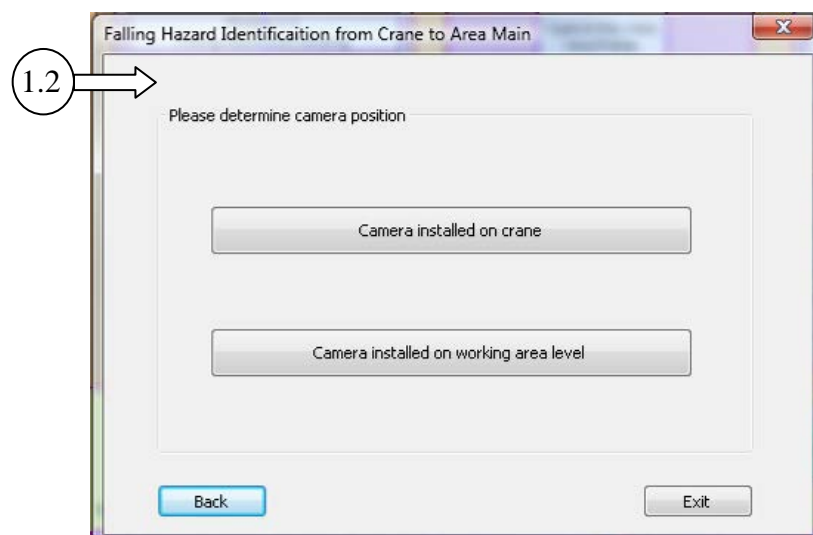


Figure 6.15 Two options of module of falling object hazard from crane to work area

Similarly, there are four steps for processing the applications, as presented in Figure 6.16. The first step is preparation, in which the following five markers are arranged and printed out, as shown in Figure 6.17 and Figure 6.18. Marker no. 1 was installed at the hoist of the crane and markers no. 2, 3, 4, and 5 were installed at the

base level. All markers were installed perpendicular to the web camera in both options. A text file for listing the markers was also prepared.

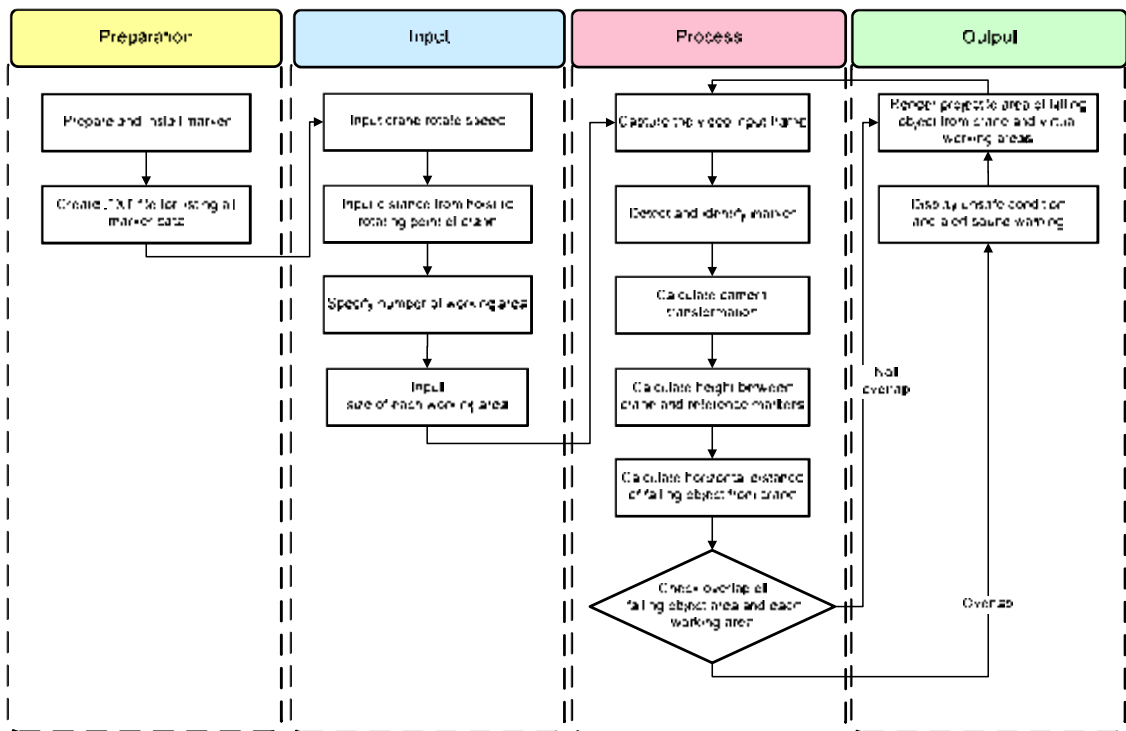


Figure 6.16 Flowchart of the applications of falling object hazard from crane operation to work area

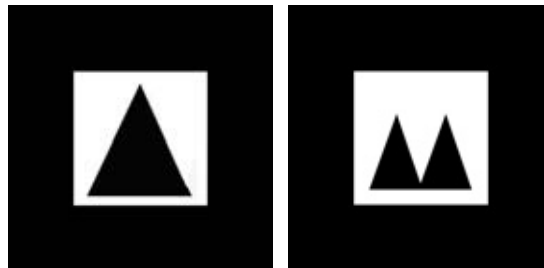


Figure 6.17 Markers no. 1 and no. 2 for falling object



Figure 6.18 Marker no. 3, 4, and 5 for work areas

In the input step, the prototype application requires the user to input data regarding crane rotating speed, the distance from hoist position to rotation point, number of considered areas, and the size of considered area as shown in Figure 6.19. Consequently, the system processes are similar to those of the previous sub-module. Furthermore, this sub-module applies another algorithm, which is the collision detection algorithm, for a safe work area, as described in the previous chapter. Thus, the system detects the unsafe condition where the area of the falling object overlaps into the work area.

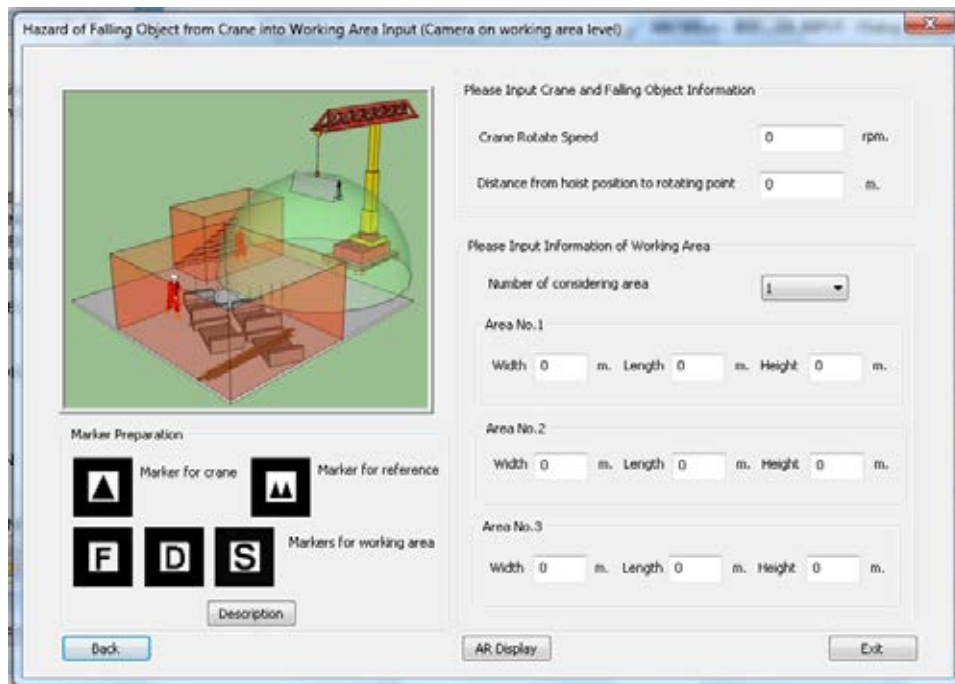


Figure 6.19 User interface for input data of falling object hazard from crane operation into work area

Examples of the AR results of the falling object hazard from the crane into the work area are presented in Figure 6.20 and Figure 6.21. The linear velocity was calculated from the angular velocity and distance from hoist to rotating point input by the user. The falling height and horizontal distance were consecutively measured and calculated by the program. The virtual objects, which were projectile range and work areas, were rendered by using the OpenGL in the output windows. Figure 6.20 presents the output window from the top view, as the web camera was installed on the crane's cabin. Marker no. 1 was installed at the hoist of crane, and the height of the falling object was measured by the program at 0.12 m. Then, the program calculated the horizontal distance, which was 0.073 m., and rendered the green covering according to the projectile path. The tip of 3D virtual projectile covering was at the center of marker no. 1. The size of the virtual work area was 0.1 x

0.1 x 0.1 m. and was rendered as a cube on marker no. 2. Both virtual objects were displayed in green color because they did not overlap on another. On the other hand, the color of the virtual objects in Figure 6.21 was red due to the overlapping of the projectile range and work area. The result meant that an unsafe condition was arrived at. Not only changing the color to indicate the unsafe condition, but a sound warning was also alerted to the user.



Figure 6.20 Example of output window for hazard of falling object from crane into work area (camera installed above base level)

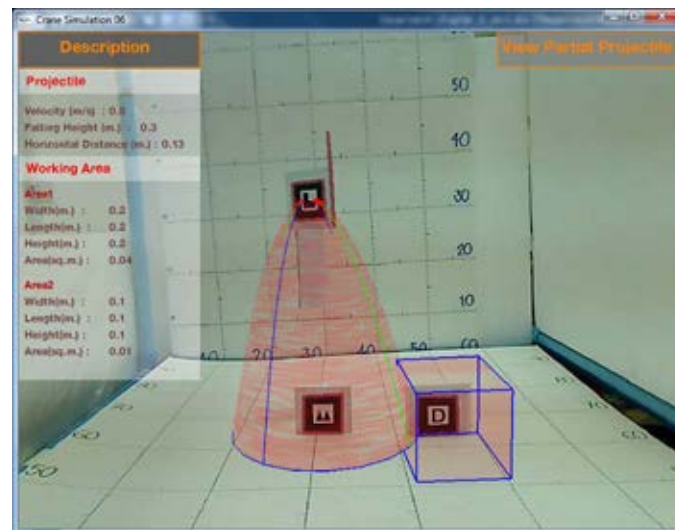


Figure 6.21 Example of output window for hazard of falling object from crane into work area (camera installed on the base level)

6.2.1.3 Hazard of falling object from crane operation into the worker's space

This third sub-module was the hazard of a falling object from the crane into the worker's space. As mentioned above, the people that work at construction sites frequently encounter accidents caused by falling objects. Due to the crane operators' field of view, there are some blind spots that the operator cannot see. Thus, this application aims to assist the crane operators and superintendents by providing visualized information regarding falling object hazards. The virtual projectile range when the crane lifted and moved the objects is presented together with the virtual workers' space in Figure 6.22.

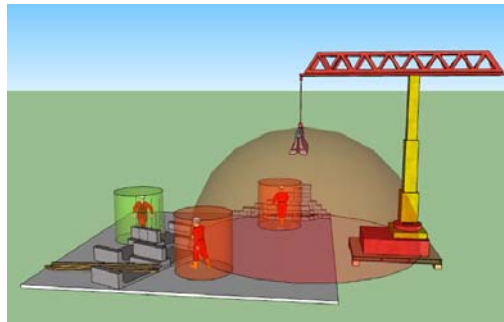


Figure 6.22 Projectile range of falling object from crane and workers' working spaces

This sub-module also contains two applications based on the web camera, position as shown in Figure 6.23. The two applications consist of a camera installed on the crane cabin level and a camera installed at the base level. The first application presents the output from the top view perspective as the crane operator's viewpoint, and the second application presents the output as the superintendents' viewpoint from the work area level.



Figure 6.23 Two applications for the sub-module of falling object hazard from the crane to the workers' space

The steps of the applications for identifying the falling object hazard from the crane operation into the worker's work space were like the steps in the previous application, as shown in Figure 6.26. The set of markers was prepared, as shown in Figure 6.24 and Figure 6.25. Marker no. 1 was installed at the hoist of the crane and markers no. 2, 3, 4, and 5 were installed at the base level. Markers no. 3, 4, and 5 represent the individual workers. The workers that perform construction tasks have their own work space according to ergonomics. The proportion of the length of the human body is presented in Appendix C. All markers were installed perpendicular with the web camera in both options. A text file for listing the markers was also prepared.

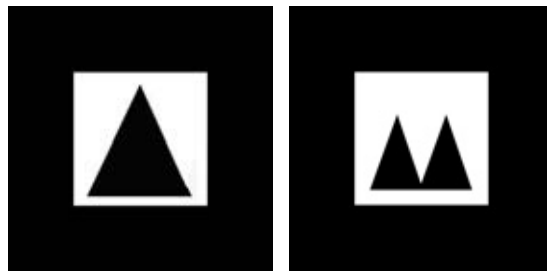


Figure 6.24 Markers no. 1 and no. 2 for falling object



Figure 6.25 Marker no. 3, 4, and 5 for workers' space and information

In the input step of this prototype application, the information on the crane was required similar to the previous one. In addition, the marker and worker data which were contained in the text files were edited and updated. Workers' information was prepared as pictures in .bmp format. The user interface for the input data is presented in Figure 6.27. After pressing the AR display button, the system begins to capture the video input and detects all of the markers in the web camera's field of view. If marker no. 1 and no. 2 are detected, the system measures the distance between two markers and calculates the projectile range of the falling object. If the markers of worker are also detected, the system uses the collision detection algorithm for the falling object hazard from the crane into the worker's work space to check for the collision. Thus, the system can detect the unsafe condition where the workers are in the area of the falling object.

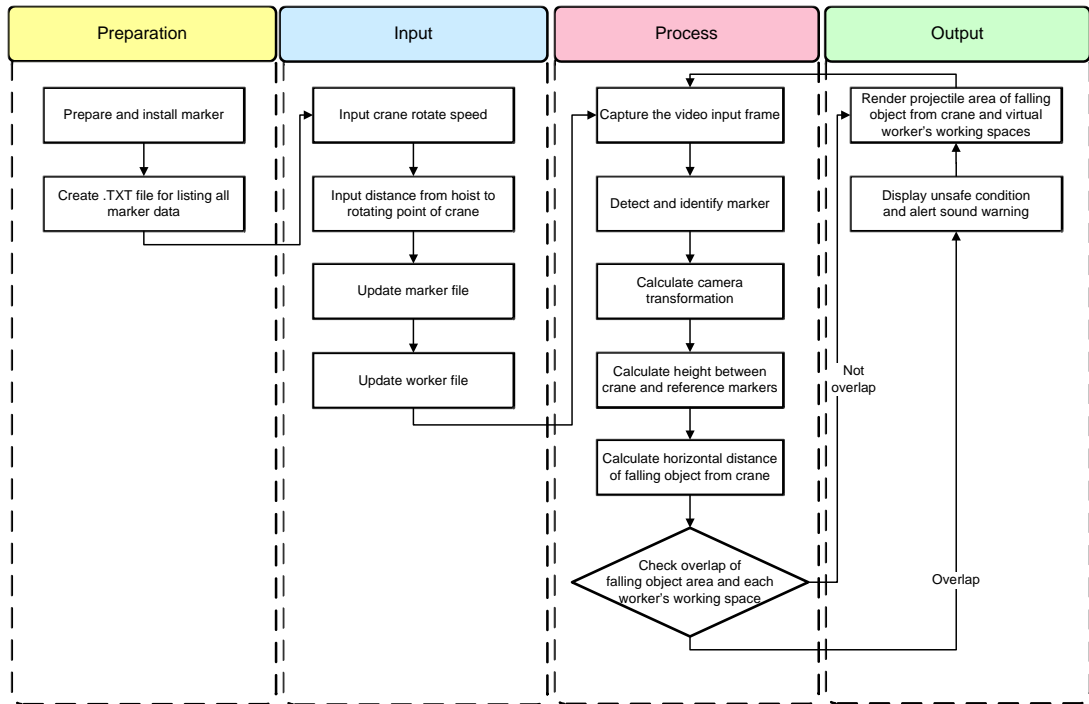


Figure 6.26 Flowchart of application for falling object hazard from crane to workers' space

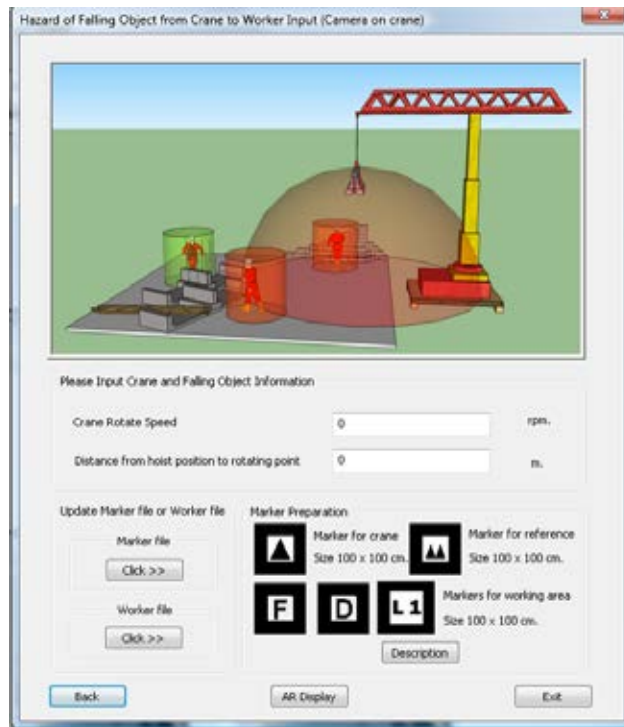


Figure 6.27 User interface for input data of falling object hazard from crane into workers' space

The output windows, as shown in Figure 6.28 and Figure 6.29, demonstrate the AR results for the hazard of falling objects from crane operation to

worker's work space. In the first figure, the top view perspective was displayed and the user could visualize the virtual projectile range and the worker's work space. A cylinder shape was used to represent each worker's space. For testing the prototype application in the laboratory, the radius of the worker's space was specified at 5 cm. Both output windows present the safe situation, in which the projectile range of the falling object did not overlap into the worker's work space. On the contrary, if the crane or workers moved and the system could detect a collision of the virtual objects, the color of the virtual objects was changed from green to red. Furthermore, the system can alert a sound warning every time that a collision occurred. Thus, the crane operators and supervisors can realize that an unsafe condition exists.

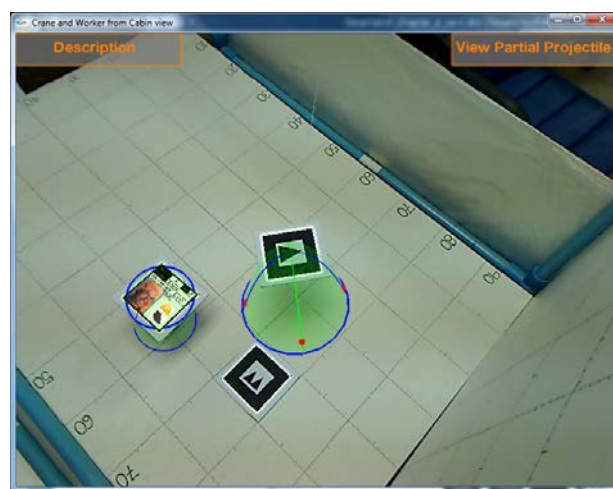


Figure 6.28 Example of output window for hazard of falling object from crane into worker's space (camera installed above base level)

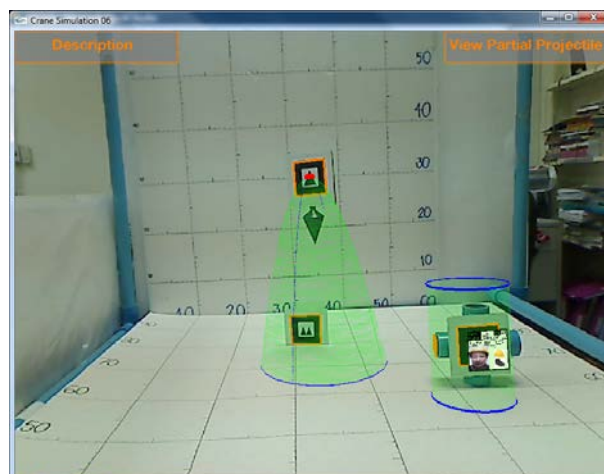


Figure 6.29 Example of output window for hazard of falling object from crane into worker's space (camera installed on base level)

6.2.2 The module of design and planning for arrangement of safe work areas

The second module, which was developed in the VSMART System, was the safety planning module. The following two prototype applications consist of 1) safety equipment selection and 2) safe work area preparation. Both applications were developed to assist the in-charge personnel that plan and arrange the safety measures and work areas for the worker.

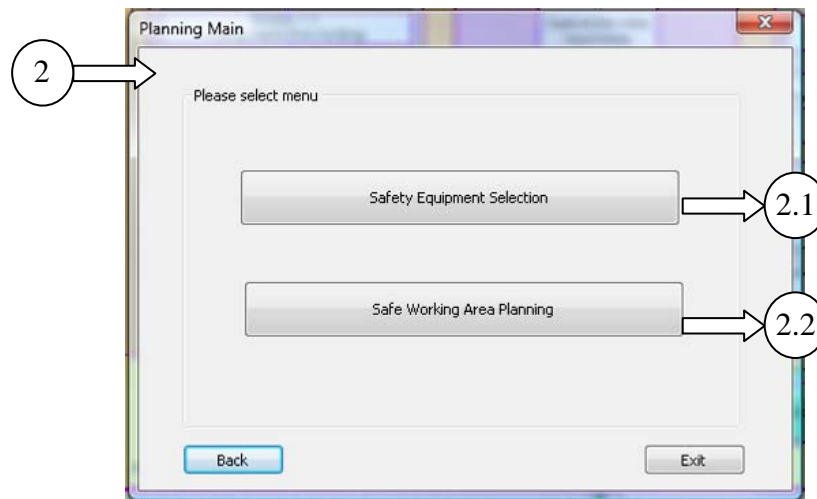


Figure 6.30 User interface for safety planning module

6.2.2.1 Safety equipment selection sub-module

The idea to develop this sub-module came from the current practices collected in construction site observation, where engineers arrange the safety measures by using 2D construction drawings. They mentally combine the design of safety measures with the memorized construction environment. They are aware of and realize the hazards in their minds when they consider the safety information. Then the designed safety measures are fabricated and installed at the work location. Later, supervisors and engineers evaluate these safety measures. The safety measures should be evaluated before they are implemented in the real situation.

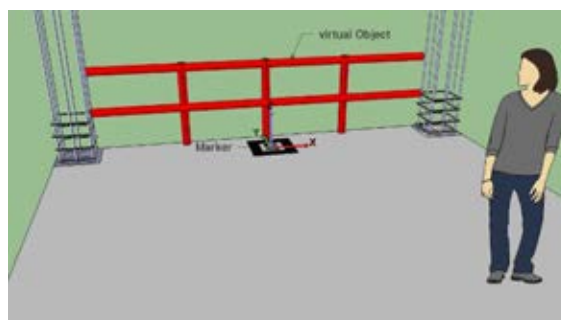


Figure 6.31 Idea for developing safety equipment selection sub-module

Therefore, a prototype application was developed for facilitating the in-charge personnel when they consider, design, and arrange the specific safety measures for special construction tasks. The four steps in performing this application are presented in Figure 6.32. The 3D models of safety measures were created as described in the previous chapter. Two types of text files were also arranged for listing the data on the 3D models. Similarly, the marker and its file were prepared as shown in Figure 6.33.

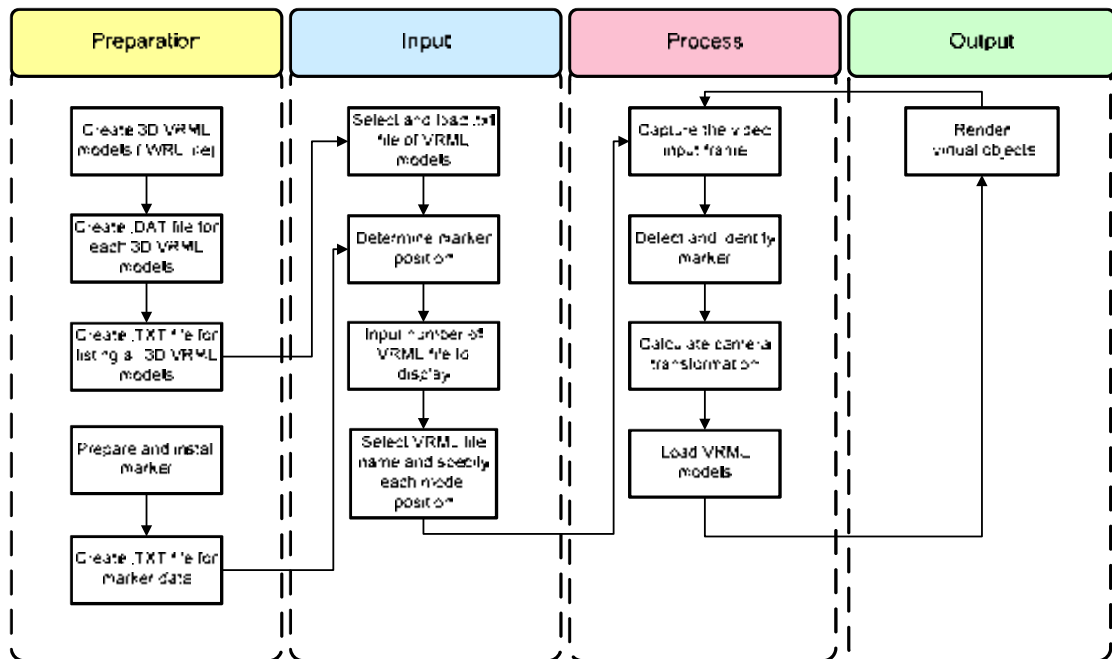


Figure 6.32 Flowchart of application for safety measure selection



Figure 6.33 Marker for application of safety measure selection

This application requires input data for processing as follows. The marker position was used for the 3D model orientation. The number of models displayed is essential data when preparing safety measures. Only if the platform is not large enough for performing the construction tasks, a safety net and other protection systems sometimes are required. The prototype application allows users to load any text files which contain the list of VRML files. After loading the text file, the

application retrieves the names of the VRML files and puts them into the combo box. The user has to define the position of the loaded 3D models by using the distance in the XYZ axis measured from the center of the marker. An example of an output window which rendered the virtual 3D safety measures is shown in Figure 6.35.

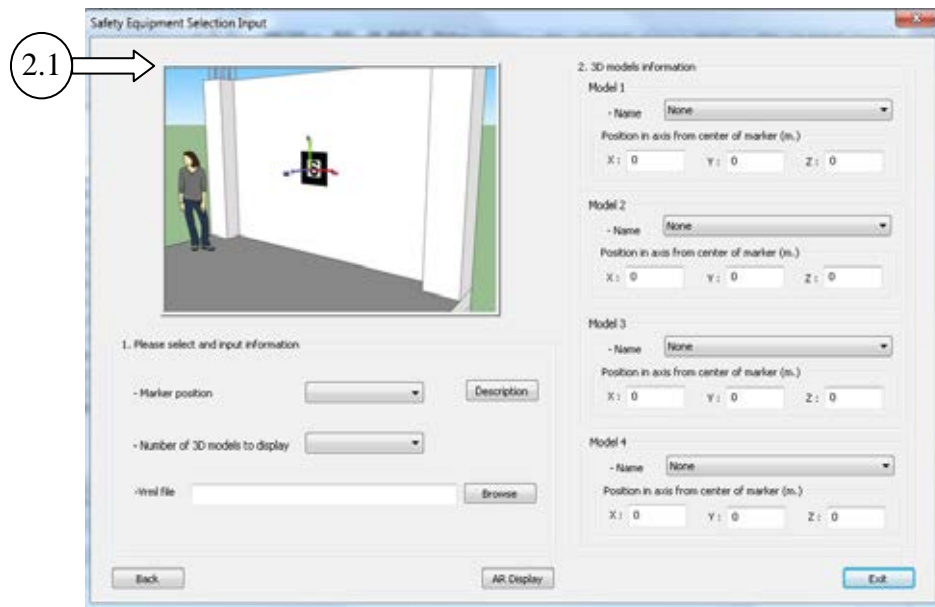


Figure 6.34 User interface for safety equipment selection

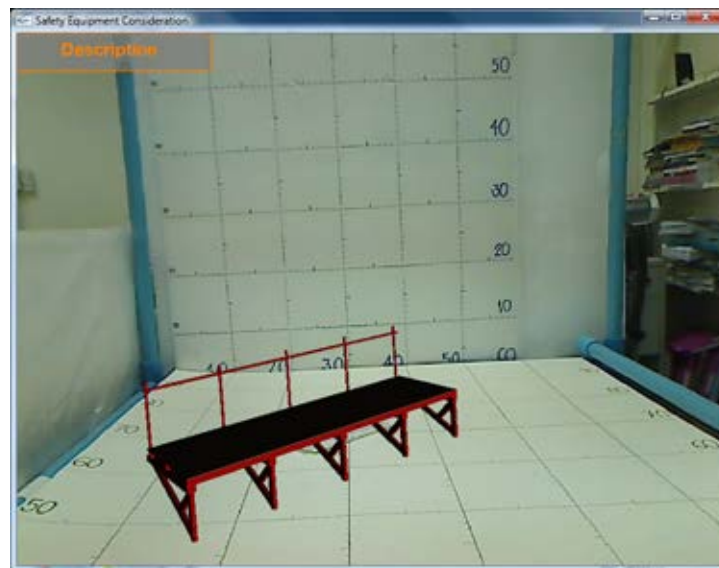


Figure 6.35 Example of output window for safety equipment selection

6.2.2.2 Safe work area preparation sub-module

When performing construction activities at a height or near the building perimeter, clear work spaces for in-progress activities are required. In order to assist the site personnel in planning a safe work area, this AR application was developed.

The boundaries depend on the building component type. Each type of building component requires different surrounding safety boundaries and work space size. The offset distance is set for the temporary supporting structures and hazardous space around the building component during their construction. In this sub-module, the site personnel can simulate the virtual building component and required working space before the real activities are performed. They can examine the arranged work space as to whether it is sufficient for carrying out the construction activities. The geometric properties of the building component are presented in Figure 6.36. The safe work areas are classified in accordance with the component type, such as column and wall, beam, and slab, as shown in Figure 6.37 to Figure 6.41. Moreover, the site personnel position when considering the work area is important for specifying the height of safe boundaries.

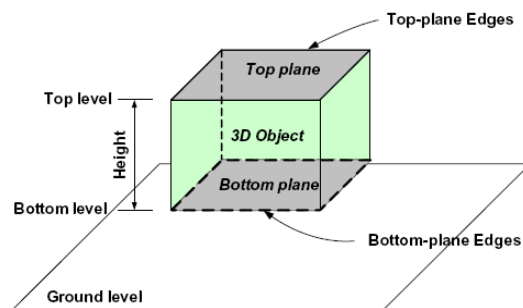


Figure 6.36 Geometric properties of a 3D CAD object (Benjaoran and Bhokha, 2009)

The height of the boundaries of the columns and walls is the same as the height of the building components, and the position of the site personnel when considering the work area normally is on the same level with the building component. Thus, the safe height is measured from the bottom plane upward by the column or wall height. In case of the existence of beams and slabs, the height of the safe work area depends on the site personnel position. If the in-charge personnel stand on the same level with the building component, the height of safe boundaries is measured downward from the top plane of the component. On the other hand, if the site personnel stand on the below level, the height is measured upward from the below level to the top plane of the building component.

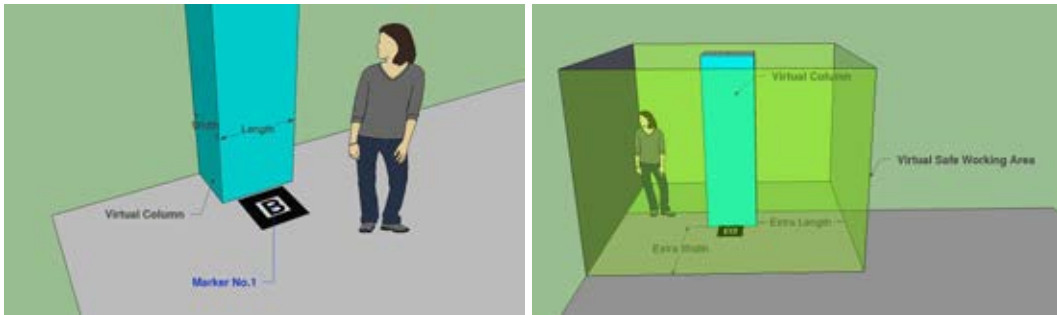


Figure 6.37 Geometric properties of column and required work space

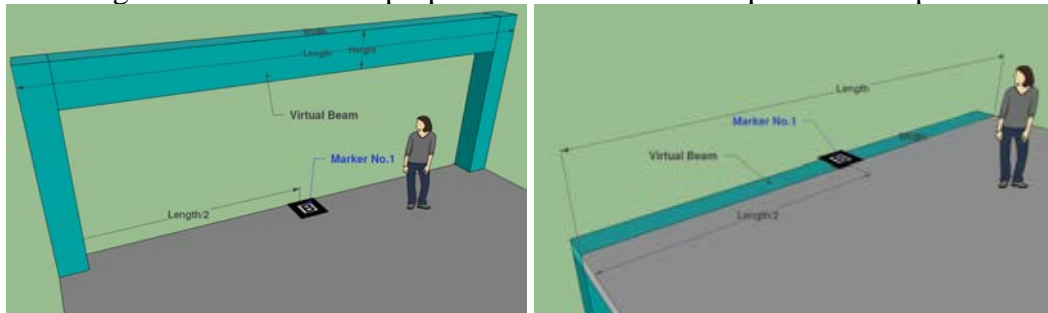


Figure 6.38 Geometric properties of beam

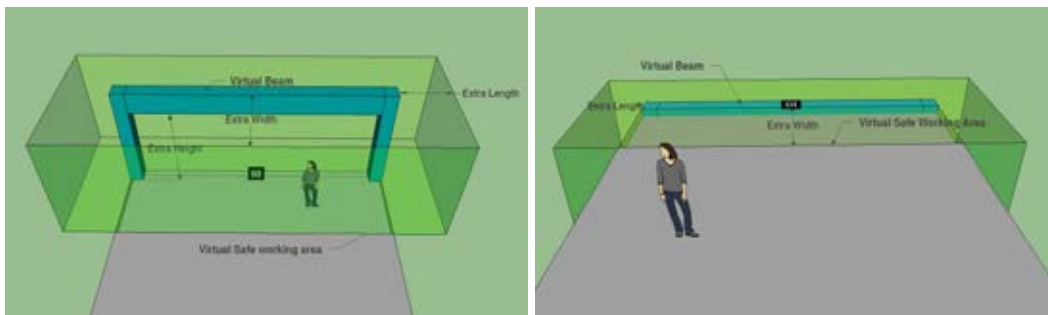


Figure 6.39 Required work space for beam

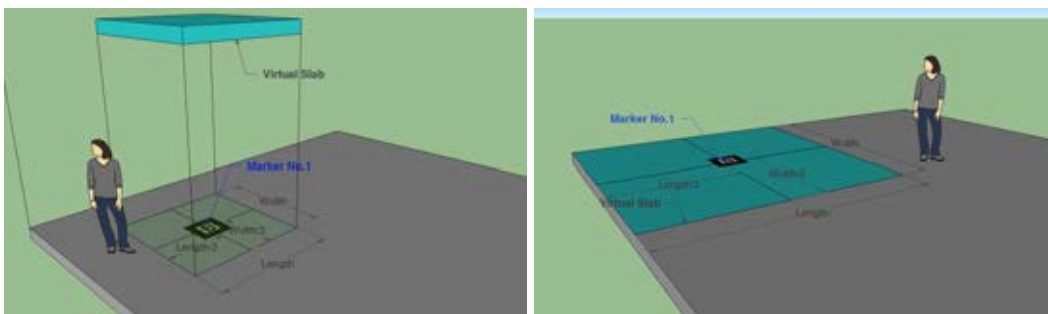


Figure 6.40 Geometric properties of slab

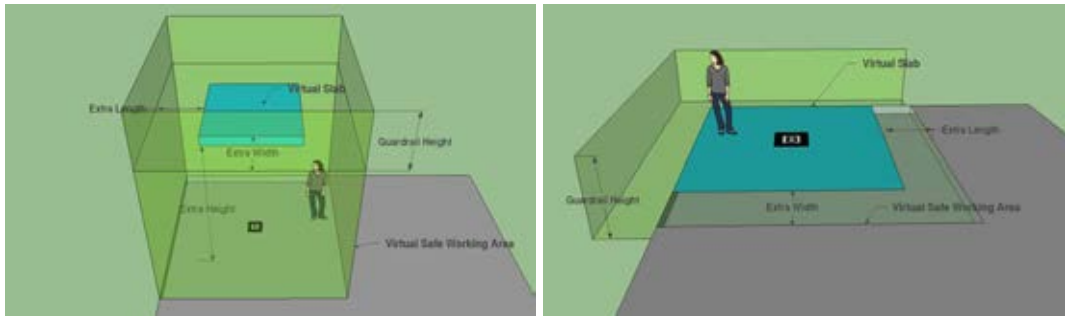


Figure 6.41 Required work space for slab

Figure 6.42 presents a flowchart of the prototype application of the safe work area module. The first step is marker preparation as with the other applications. Then, the user has to input the type and size of the building component and determine the marker position. In addition, the required size of the work area during the construction of the building is provided. If the user wants to check the overlap of the considered work area with another adjoining area, the user can input the radius of the adjacent area. After that, the application proceeded by capturing the video input frame, detecting and identifying markers. The application also calculates the distance between the two markers and checks overlapping by using the collision detection algorithm for arranging a safe work area for the building component.

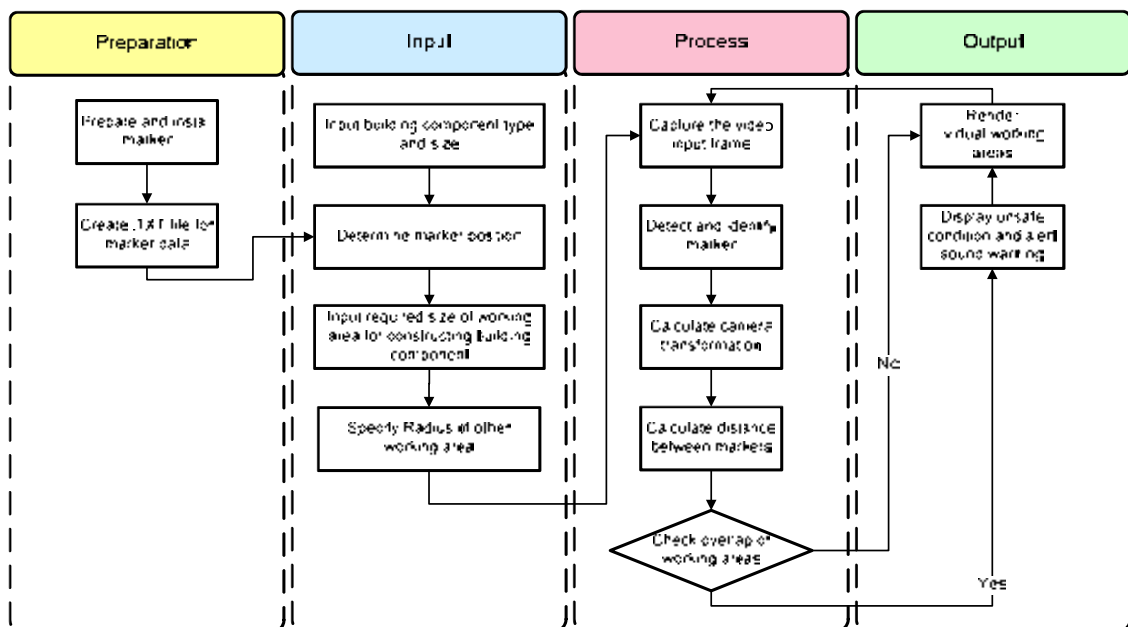


Figure 6.42 Flowchart of application for safe work area preparation

An example of a user interface for the input of the information of this submodule is shown in Figure 6.43. After inputting the data, the user has to press the next

button to view and check all of the input data. In the next user interface, there is an AR Result button which is provided to display the output window. The output windows of this module are demonstrated in Figure 6.44 to Figure 6.46.

The first example of output windows demonstrates the safe work area for the column. The building component is displayed as the sky blue box with red a perimeter and the required work area is displayed as a transparent orange box with a green perimeter. The left picture represents the required work area and adjoining area, neither of which overlap with each other, whereas overlapping occurs in the right picture.

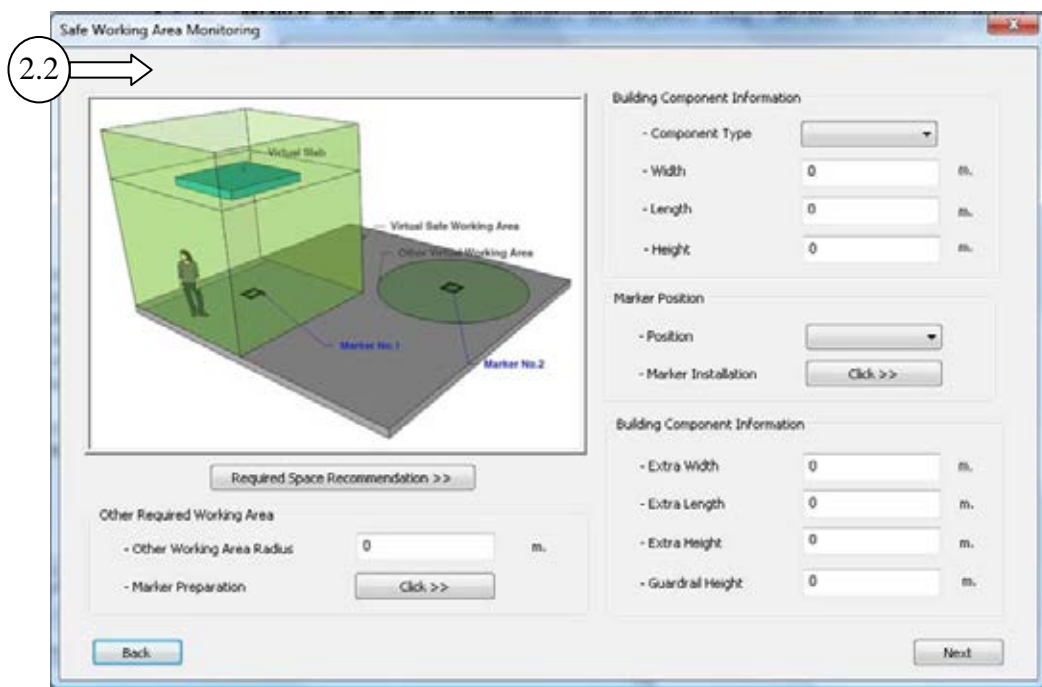


Figure 6.43 Example of user interface for safe work area preparation module

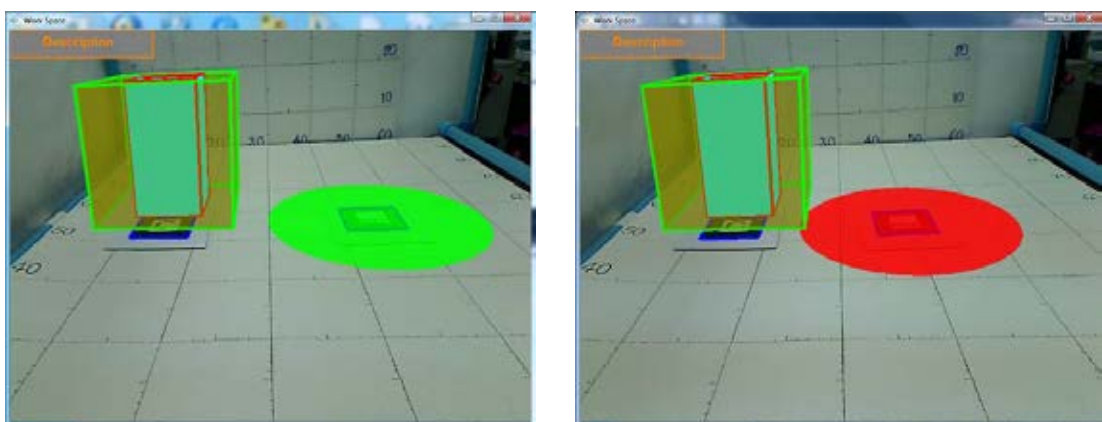


Figure 6.44 Example of output windows for checking for safe work area of column

The figure below demonstrates the output window for a safe work area for the beam. Not only are the virtual 3D graphics are presented, but other information such as component type, size of component, required work area, adjacent area, and checking results is also provided. Similarly, information on the safe work area for the slab is presented in Figure 6.46. Moreover, the height of the safety measure, i.e. guardrail, is provided.

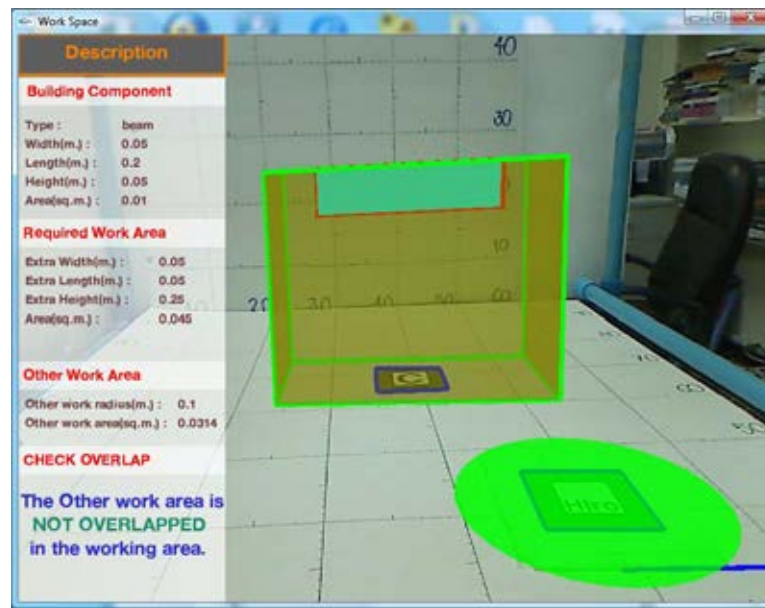


Figure 6.45 Example of output window for checking the safe work area of the beam

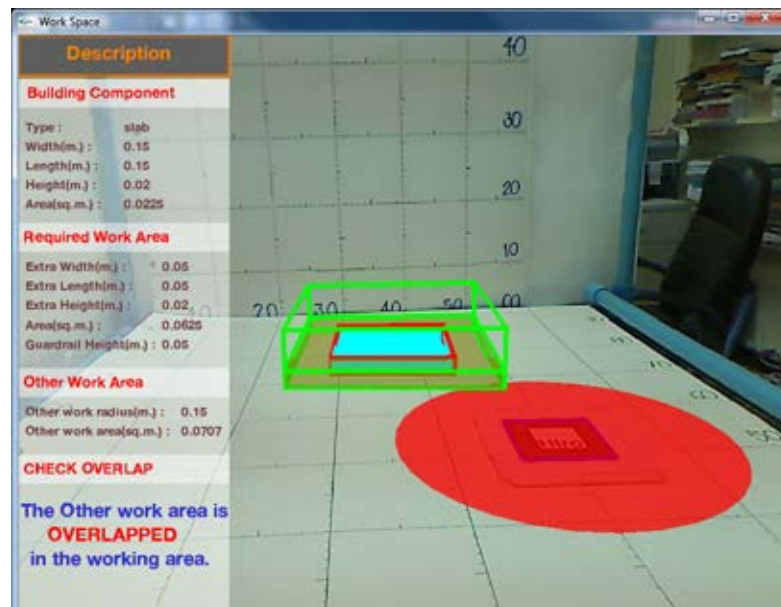


Figure 6.46 Example of output window for checking the safe work area of the slab

6.2.3 Monitoring Module

As mentioned above, monitoring and control are among the main tasks of safety management. Therefore, this system provides a monitoring module for helping the construction personnel to effectively perform this task. The monitoring module was divided into the following sub-modules: safe work area monitoring and personal protection equipment monitoring, as shown in Figure 6.47. The details of each sub-module are described as follows.

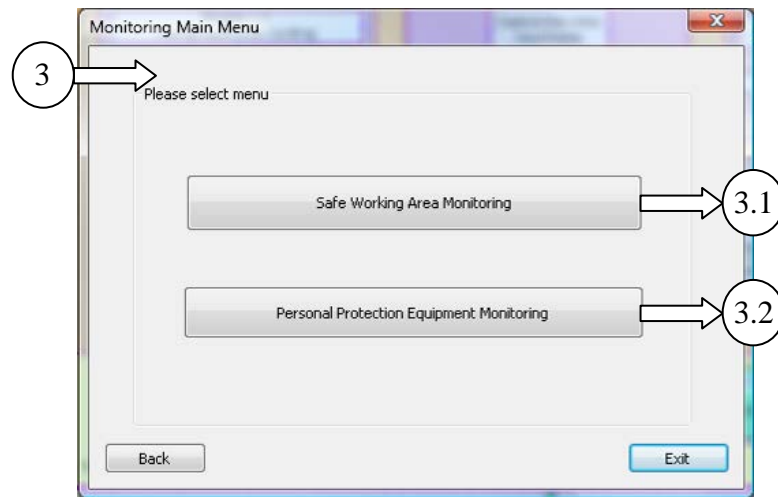


Figure 6.47 User interface of monitoring module

6.2.3.1 Sub-module of safe work area monitoring

The first sub-module of the monitoring module was safe work area monitoring, which was developed to assist the in-charge personnel when they inspect safety at the construction site. This sub-module was separated into two applications: monitoring for safety measures and monitoring for safety signs as presented in Figure 6.48.

In the first application, normally the in-charge personnel monitor the safety measures at the construction site by using simple checklists according to the safety plan. However, the safety measures are not specified in the checklists or drawings concerning type, number, and size for assisting the site personnel in monitoring. Hence, the idea for improving the monitoring process by providing efficient tools was initiated. The four steps for developing the prototype application were done as shown in Figure 6.49. In the preparation step, the 3D models of safety measures were created as described in the previous chapter. Simultaneously, the sets of markers were also prepared. Then text files containing the list of markers and 3D models of safety measures were created and loaded into the prototype application. Later, the application processes according to the ARToolKit steps and renders the 3D models of the safety measures for the markers in accordance with the defined list.

Figure 6.50 presents the user interface of the safety measure monitoring where the user can press the AR display button to view the output result. Additionally, the layout of marker was displayed, as shown in Figure 6.51, after the user pressed the button to view it.

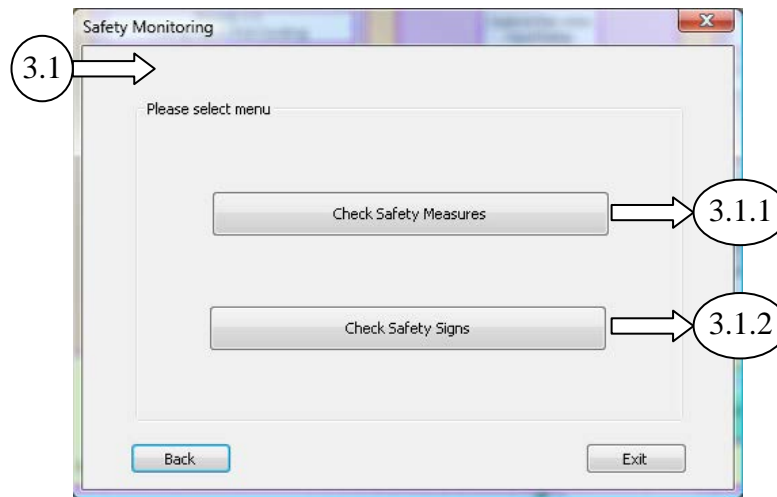


Figure 6.48 User interface of sub-module of safe work area monitoring

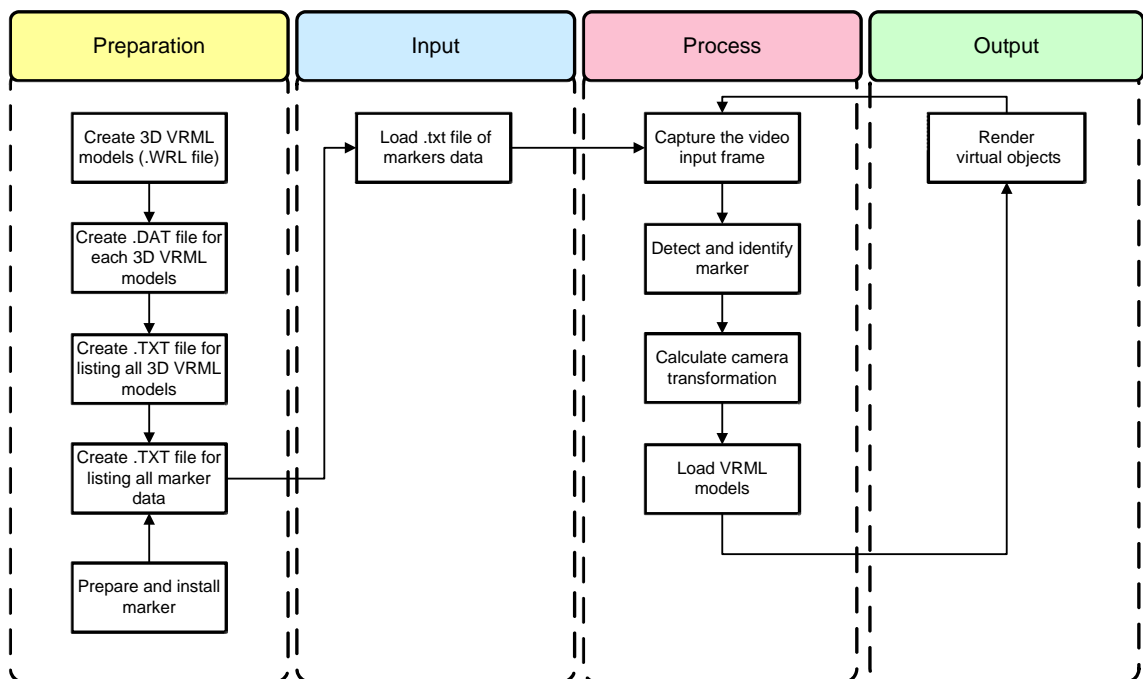


Figure 6.49 Flowchart of application of safety measure monitoring

An example of an output window of safety measure monitoring is illustrated in Figure 6.52. In this figure, 3D models of guardrails were rendered with information, such as shape and size. Due to the requirements of the laws and regulations, not only should guardrails be installed to protect against fall hazards, but

toe boards should also be installed to prevent falling object hazards, as demonstrated in the example.

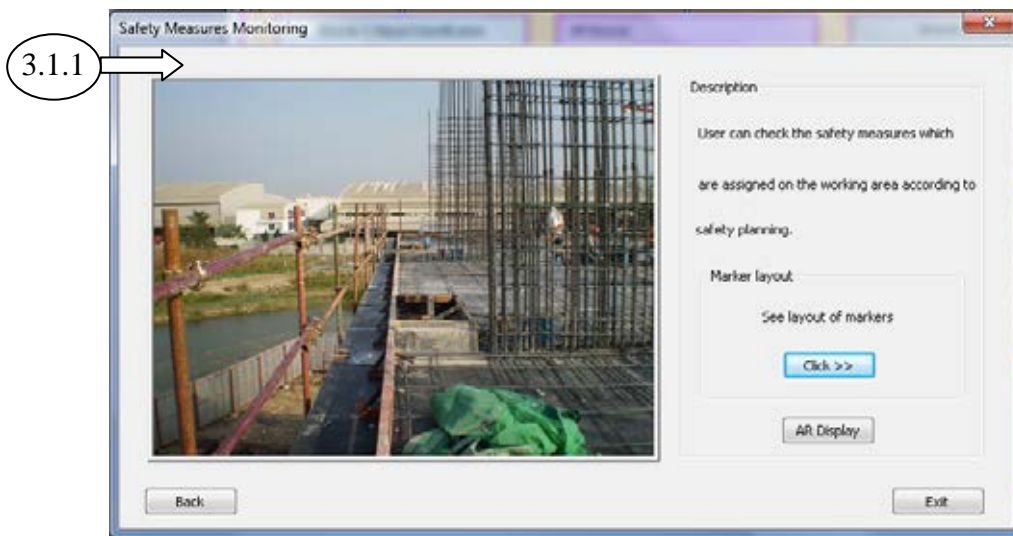


Figure 6.50 User interface of safety measure monitoring

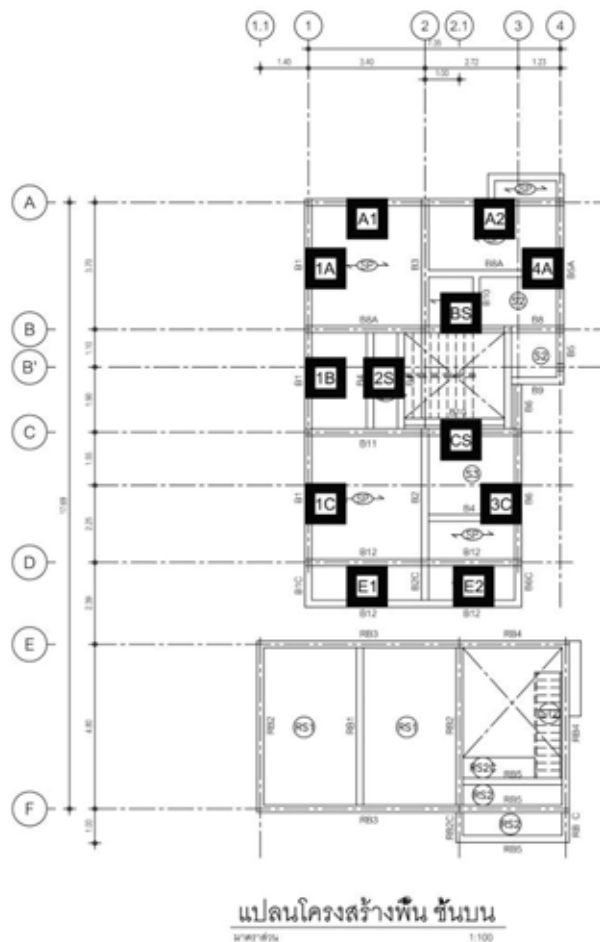


Figure 6.51 Example of marker layout on the 2nd floor plan of building

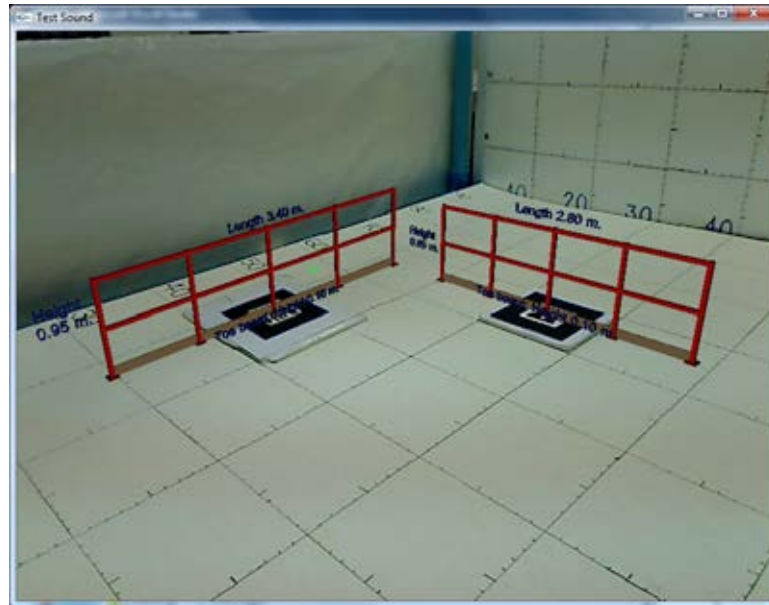


Figure 6.52 Example of output window for safety measure monitoring

The second application of the safe work area monitoring sub-module is safety sign monitoring. To prevent accidents at a construction site, providing safety measures are not the only effective approach; providing safety signs also helps. As seen in the previous discussion, the safety signs should be monitored by the in-charge personnel to ensure that safety signs are installed at the proper location to warn the involved personnel. These signs should be particularly designated when safety planning is developed. Later, it is effortless for the safety inspectors that check for and monitor unsafe conditions. Therefore, a prototype application was developed for this purpose.

Four steps in developing the AR application for safety sign monitoring were performed. At the beginning, 2D image files representing each safety sign were created and a text file containing the lists of markers and images was arranged in the preparation step. Each marker represented one image of a safety sign. Then the text file was loaded into the application which subsequently performed the ARToolkit processes. After detecting the marker and calculating the camera transformation, the 2D image of safety sign was displayed in accordance with the pattern on the marker. The user interface for running this application is presented in Figure 6.54. The user could press the AR Display button to view the output window. Finally, the prototype application rendered the output window as shown in Figure 6.55. In this figure, three safety sign images (dangerous area, construction area, and walkway) were displayed. After the safety inspectors see the virtual safety signs, they can check the real safety signs in the area and also monitor the workers as to whether they performed the tasks as the safety signs recommended.

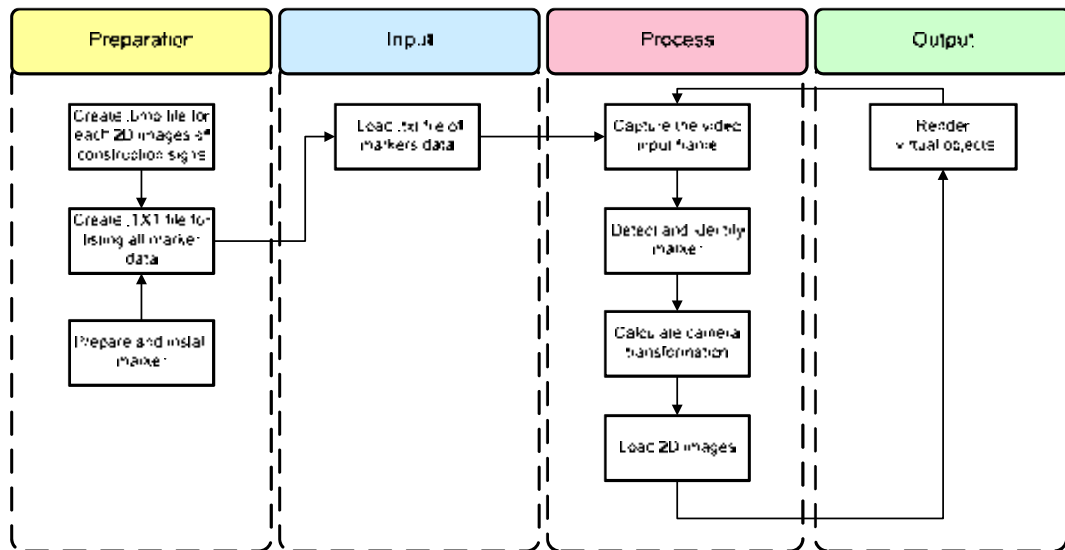


Figure 6.53 Flowchart of application for safety sign monitoring



Figure 6.54 User interface of safety sign monitoring

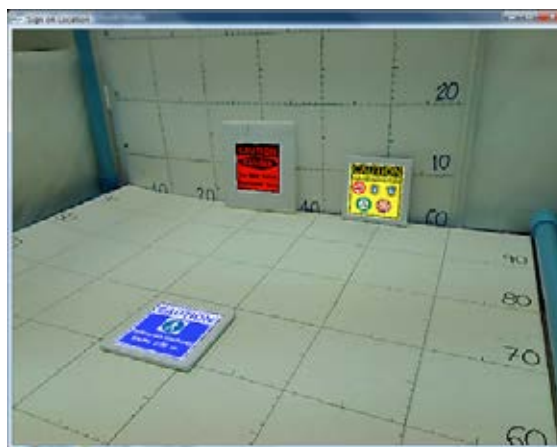


Figure 6.55 Example of output window for safety sign monitoring

6.2.3.2 Sub-module of personal protective equipment monitoring

Personal protective equipment monitoring was the second sub-module of monitoring module developed for assisting the superintendents in monitoring the proper personal protective equipment of the workers in the work areas. The workers can be instructed by the supervisors to wear the appropriate equipment before starting or continuing their work. In this prototype application, fall hazards when workers perform construction activities were mainly focused on.

This application also consists of the following four steps: preparation, input, process, and output, as shown in Figure 6.56. For the preparation step, markers and 2D images containing the workers' information were prepared as with other applications. Furthermore, a database containing information on the individual worker, such as injury records, training course, current job and location, and required personal protective equipment for current job, was created by using MySQL Workbench. Afterwards, a text file containing the list of marker files and 2D image files were loaded while the database file was retrieved.

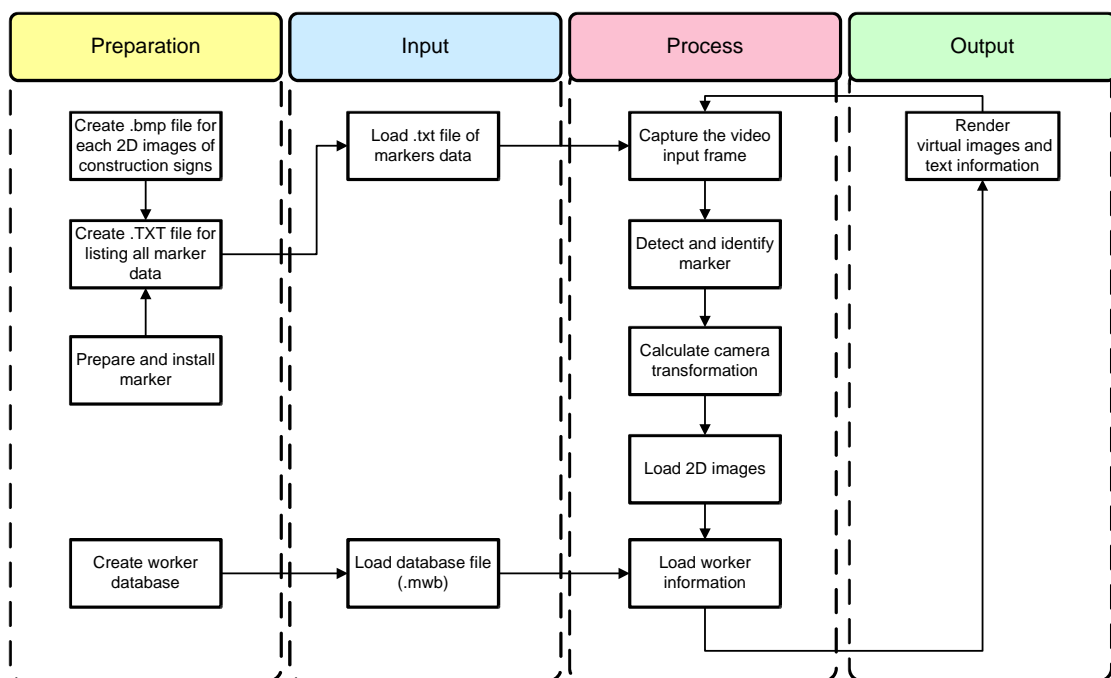


Figure 6.56 Flowchart of application for personal protective equipment monitoring

The markers were printed out and installed on the workers' clothes. The user interface of the personal protective equipment sub-module is presented in Figure 6.57. The user could update both marker file and database file by pressing the buttons in the interface. The application processes for rendering the virtual information of the workers according to ARToolKit steps were capturing the video input frame,

detecting and identifying the markers, calculating camera transformation, and loading 2D images files and worker information into the database file. Then, the output windows were displayed, as shown in Figure 6.58 and Figure 6.59. Worker information, such as name, age, position, was also provided both in the 2D image and the text information on the screen. The safety inspectors could compare the photo of the worker and other information on the 2D image with the text information on the screen to identify the worker.

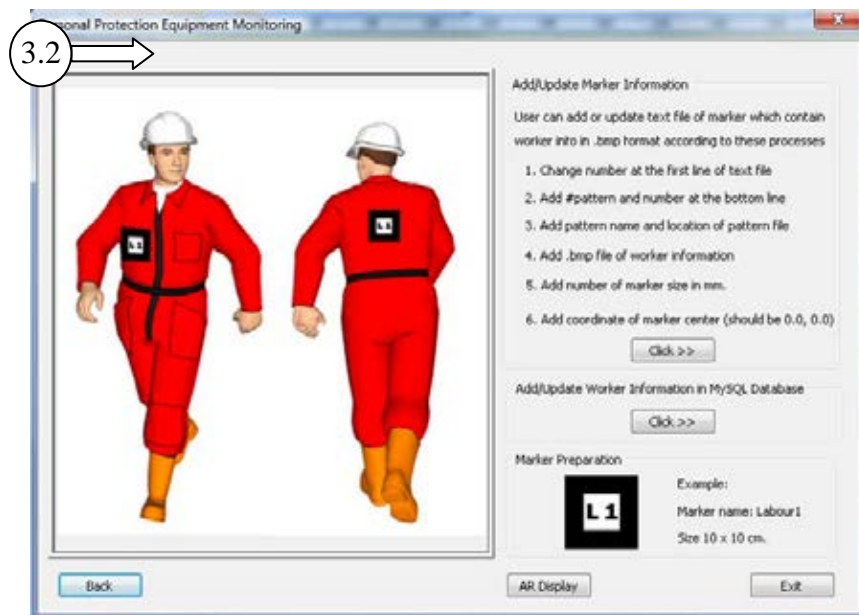


Figure 6.57 User interface of personal protective equipment monitoring



Figure 6.58 Example of output window for personal protection equipment

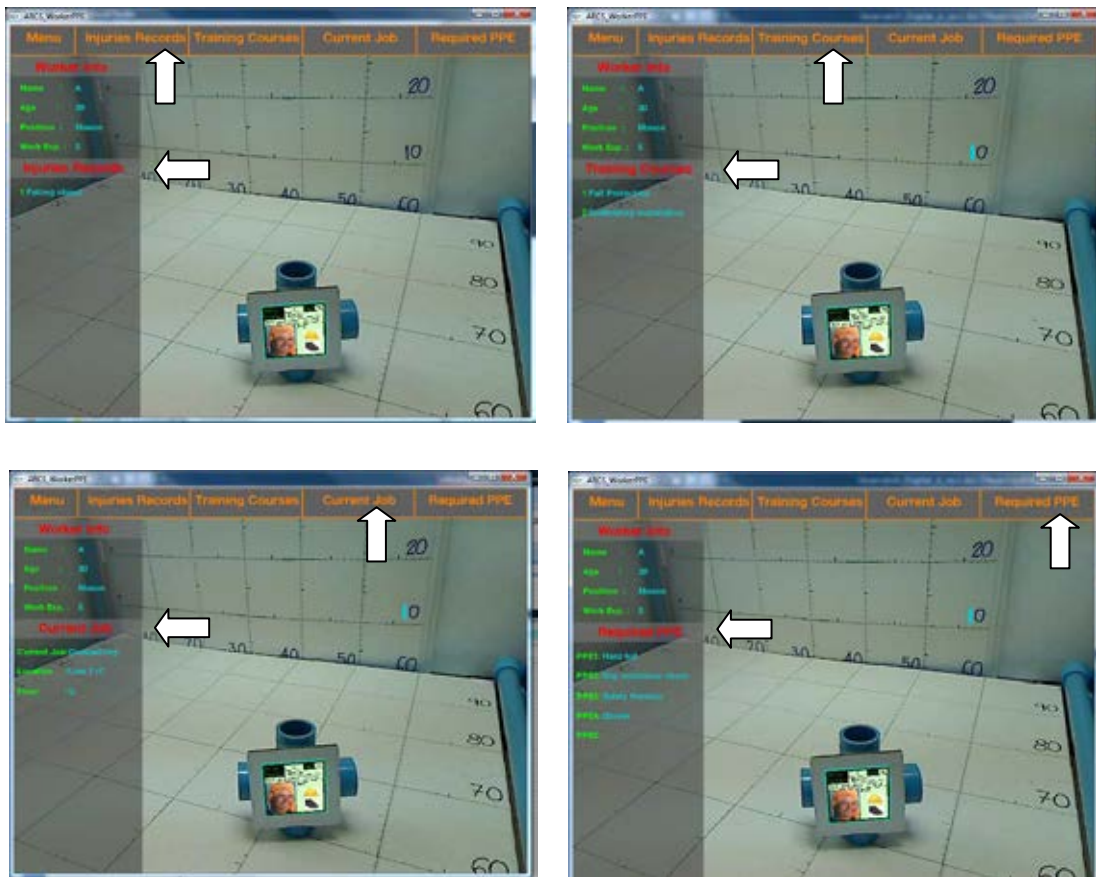


Figure 6.59 Example of output windows for presenting worker information

6.2.4 Training Module

Commonly, safety management consists of three main tasks: hazard identification, safety measure planning, and control (Benjaoran and Bhokha, 2009). Nevertheless, another important task that should be performed to achieve the goal of safety management is training. Therefore, the last module in this proposed system was training module, which was divided into two sub-modules, as shown in Figure 6.60. The first sub-module was safe assembly and the second sub-module was training media for a safe working process. Each sub-module is described as follows.

6.2.4.1 Sub-module of safe assembly

To safely perform construction activities, all involved participants should have sufficient knowledge about those activities. They also should understand the method and procedure for executing the activities. Moreover, they should know and be able to identify in advance the hazards which can occur while carrying out those tasks. Hence, all applications of this sub-module were developed to support the training process which could improve the safety at the construction site. This sub-module provides the visualized information which the user can immediately understand and communicate with others.

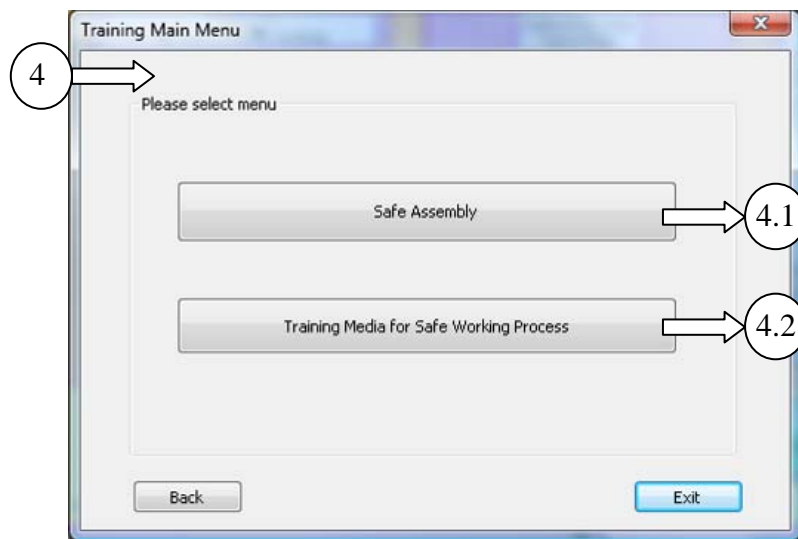


Figure 6.60 User interface for training module

The first sub-module was divided into three applications according to the approach for providing the information, which were comprised of step-by-step safe assembly, all-in-one safe assembly, and solid and transparent safe assembly, as shown in Figure 6.61. A flow chart of the applications of the safe assembly sub-module is presented in Figure 6.62. All applications of this sub-module contained the same steps, which are preparation, input, process, and output. However, the preparation process associated with the 3D models and text files was different. These differences are described as follows.



Figure 6.61 User interface for safe assembly sub-module

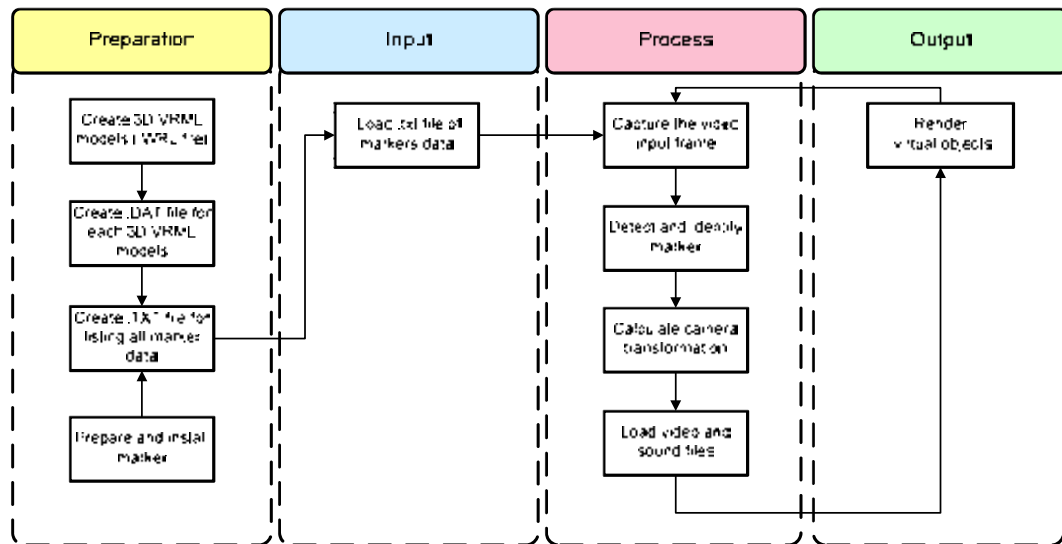


Figure 6.62 Flowchart of prototype application for safety assembly

The first application aimed to produce a training approach which could present the construction method step-by-step. The processes, such as installation, assembly, construction, or dismantlement, should be divided into many stages for easy understanding. In this application, 3D models were created according to the divided stages of the construction method. Then a set of 3D model files was orderly listed and matched with the list of marker files in the text file, which was loaded into the prototype application. The user interface of the step-by-step safe assembly is presented in Figure 6.63.

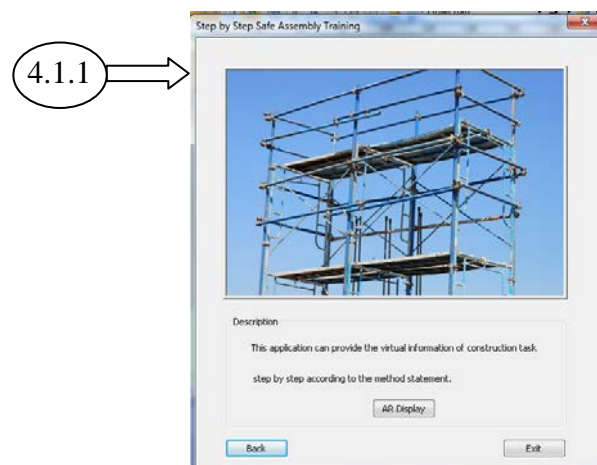


Figure 6.63 User interface for step-by-step safe assembly application

The user could press the AR Display to visualize the output window, as shown in Figure 6.65 and Figure 6.65. In this prototype application, the construction method for installing scaffolding was selected to be a case study. The application

instructed the involved person in how to assemble the scaffolding. One set of scaffolding consisted of two vertical frames, two cross-braces, and one work frame. As a result, the set of 3D models for this installation consisted of five 3D model files. The sequences of creating the list of the 3D model files of the scaffolding are presented as follows.

1. Left vertical frame
2. Right vertical frame
3. Front cross brace
4. Back cross brace
5. Work frame

After the user pressed the AR Display button in the user interface for step-by-step safe assembly, the application displayed the output window as shown in Figure 6.65. The first 3D model was rendered on the output screen. To visualize the next step of the assembly, the user could click the mouse in the rectangular area at the top left of the output screen which contained the menu function. After that, the other two menus, which were the previous step and the next step, appeared. The user could click these buttons to go forward or backward in the assembly steps.

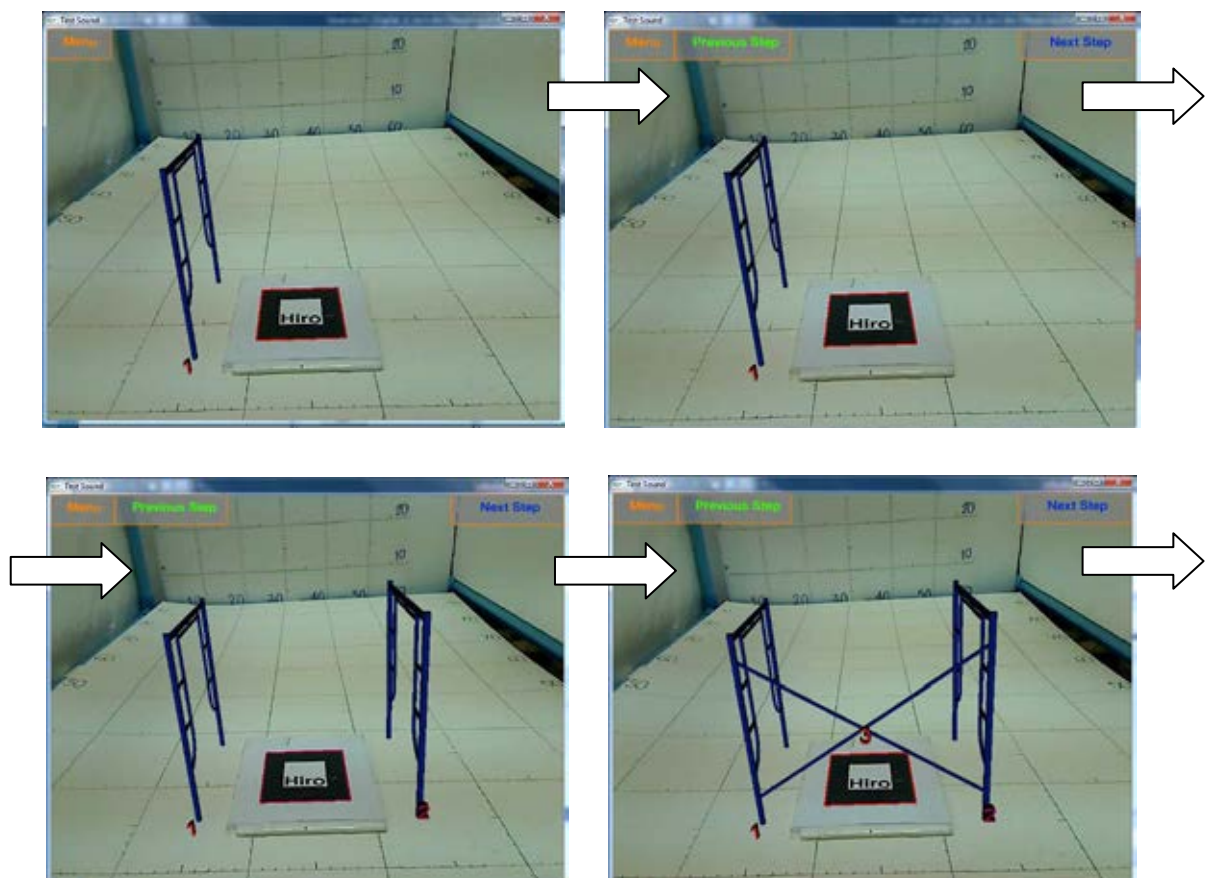


Figure 6.64 Example of output windows for step by step safe assembly (step 1 to 3)

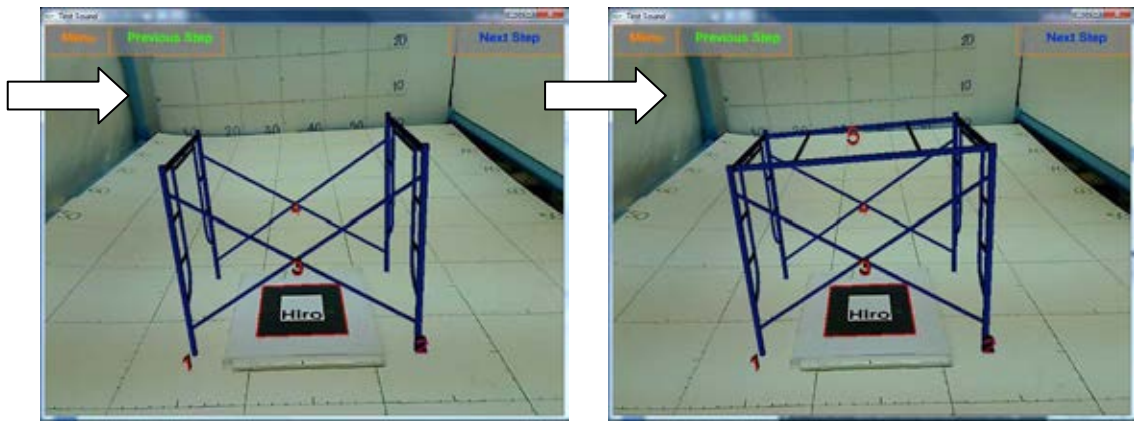


Figure 6.65 Example of output windows for step by step safe assembly (step 4 to 5)

The second application of the safe assembly sub-module was the all-in-one safe assembly, whose purpose was to present the construction method in one animation file. Sometimes, site personnel require all of the information of construction method statements for executing the construction activities. Thus, the preparation in this application was different from that in the previous training application. 3D models of the building components and temporary structures were created as animation files. Then the animation files were listed together with the marker files, and both of them were stored in the text file, which consequently was loaded into the application. The user interface for the all-in-one safe assembly is shown in Figure 6.66. The installation of the prefabricated panels was selected to be a case study. An example of an output window is demonstrated in Figure 6.67.

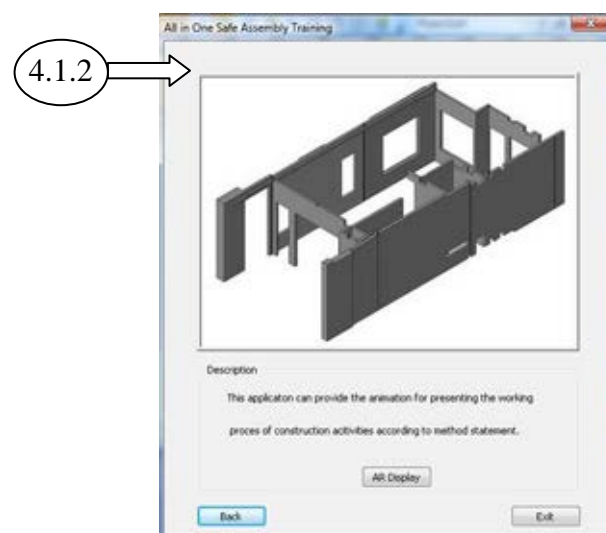


Figure 6.66 User interface for the all-in-one safe assembly application

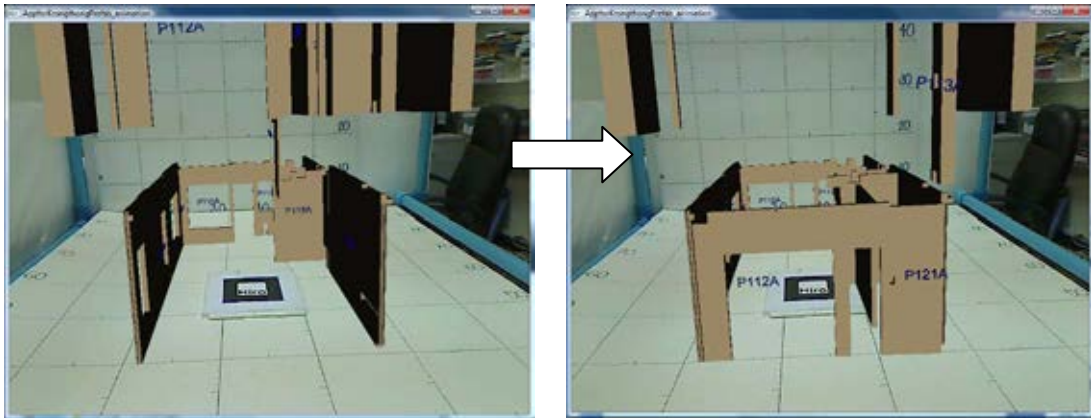


Figure 6.67 Example of output windows for all-in-one safe assembly

The last application of this sub-module was solid and transparent safe assembly, which aimed to provide invisible information on the construction activities. When performing construction activities at the site, the construction personnel traditionally use 2D drawings to support their tasks. They mentally combine and generate the related information by themselves because some information, such as utilities work, is separated from the structural or architectural work. Then they communicate their understanding with the other associated participants. However, these tasks are difficult and may lead to mistakes. Therefore, this prototype application attempted to provide invisible information for supporting the training process before beginning the construction activities. The user interface of this application is shown in Figure 6.68.

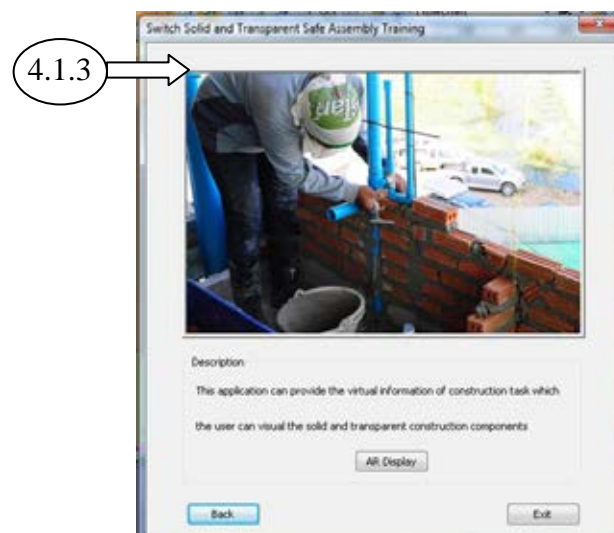


Figure 6.68 User interface for solid and transparent safe assembly application

In the preparation process, the 3D models were created by using CAD software. These models were assigned the characteristics of being solid or transparent. Then the sets of 3D model files were listed and matched with the list of marker files in the text file. This text file was loaded in the prototype application. A bathroom containing sanitary pipes was selected to be a case study in this prototype application. Three sets of 3D models of the bathroom were created. The first solid 3D models represented all of the bathroom components, such as walls, floor, sanitary ware, and sanitary pipes. The second 3D models which represented the walls, floor, and sanitary ware were transparent. And the last 3D models illustrated the sanitary ware and sanitary pipes. These three sets of 3D models were matched with one marker file. When the user pressed the AR Display button in the user interface, the output window of this application was displayed as shown in Figure 6.69.

An example of output windows are illustrated below. The first set of 3D models was rendered at the beginning. The user could click the menu in the rectangular area at the top left of the output screen. Then the other two rectangular menus containing the commands named previous model and next model appeared. The user could click both menus to change the displayed 3D models.

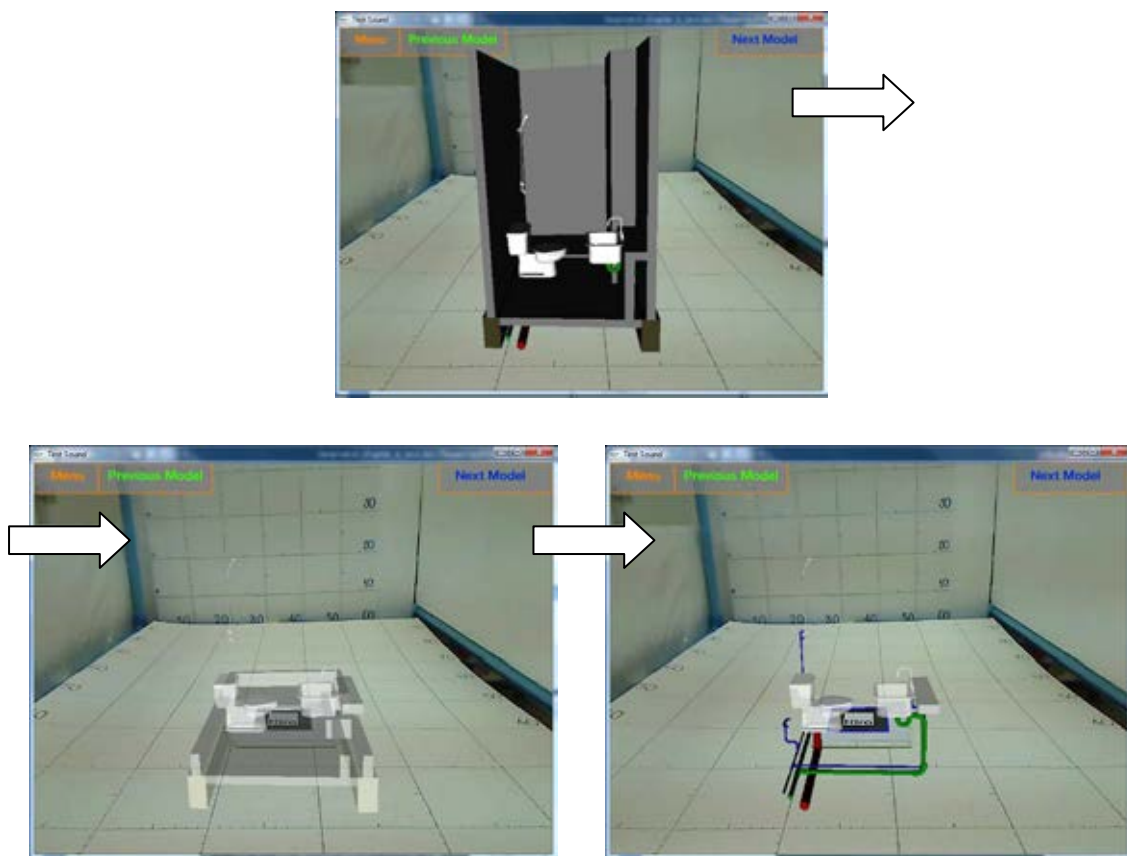


Figure 6.69 Example of output windows for switch solid and transparent safe assembly

6.2.4.2 Sub-module of training media for safe working process

Not only was a training approach by using the 3D model presentation developed in this proposed system, but other media such as video and audio also were used to improve the safety training at the construction site. Occasionally, the work method for some special construction activities was complicated and required more explanation so that only 3D model presentation was not enough. The engineer could use this application, which contained a description of the safety training for special construction tasks, and communicate the information among the project participants at the real construction site.

A flowchart of the training media for a safe working process is presented in Figure 6.70. In the preparation process of this sub-module, the video and audio files were arranged and matched with the marker files. The types of video and audio files were .avi and .wmv respectively. The text file which contained the lists of marker files and media files was loaded into the application as done in the previous application. The user interface of this application is presented in Figure 6.71 and an example of the output windows is demonstrated in Figure 6.72.

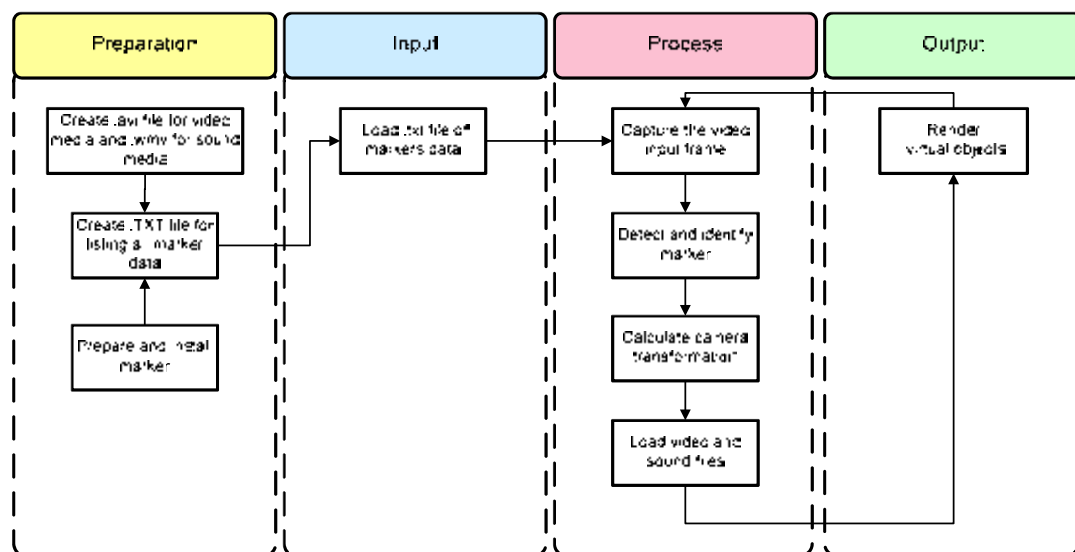


Figure 6.70 Flowchart of application for training media for safe work process

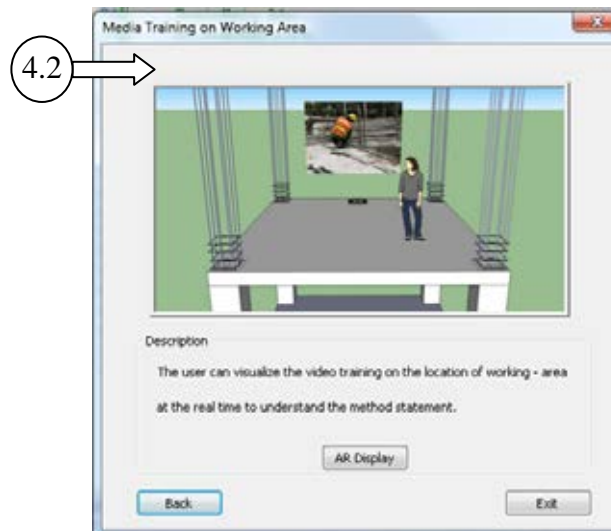


Figure 6.71 User interface for training media for safe work process

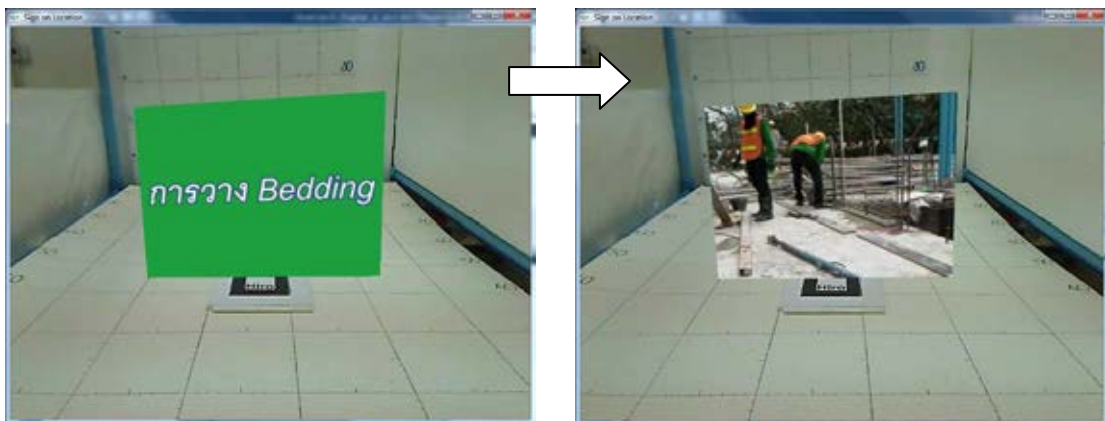


Figure 6.72 Example of output windows for training media for safe work process

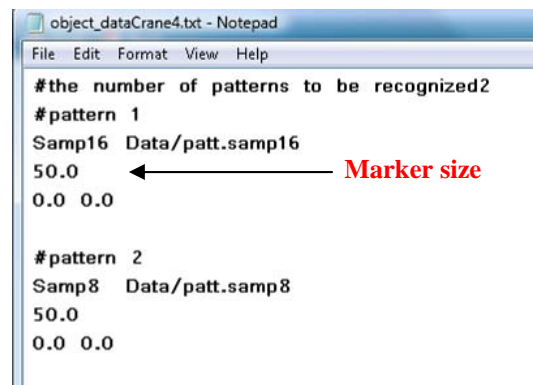
6.3 Testing the proposed system

All of the developed prototype applications in this proposed system were tested to check for the outputs and then verification and validation of the system were done and are described in the next chapter. Testing the outputs of each function was done in both the laboratory and in the real environment. The factors such as web camera installation, marker size, lighting, 3D models size, and so on were differently specified. Therefore, the testing setup is explained in this section.

6.3.1 Laboratory testing

Before this proposed system was implemented in the real environment, it was tested in the laboratory so that the preliminary outputs could be checked. Moreover, some outputs of the prototype application could be verified for accuracy in the laboratory. Many patterns of markers were created, printed out, and trained for use in this system. The patterns of the markers were designed to be unique and simple.

Normally the size of markers which are prepared for use in laboratory testing is 8 cm, as shown in [Appendix B](#). However, other sizes, for example 5 cm. and 16 cm, are also prepared and used. The marker size is a very important factor used in the camera transformation calculation. If the marker is too small and the web camera is installed far away from the marker, the camera may not be able to capture the marker and the proposed system cannot perform its functions. In addition, the unit of the marker size in the text file for use in the lab testing is in millimeters, as shown in Figure 6.73. As mentioned above, the web camera position also affected the transformation calculation. The positions of the web camera for each application are presented in Table 6.1 and Figure 6.74 demonstrates the web camera position when tested in the laboratory.



```

object_dataCrane4.txt - Notepad
File Edit Format View Help

#the number of patterns to be recognized2
#pattern 1
Samp16 Data/patt.samp16
50.0 ← Marker size
0.0 0.0

#pattern 2
Samp8 Data/patt.samp8
50.0
0.0 0.0

```

Figure 6.73 Example of marker data in text file

Lighting is one of the limitations of ARToolKit which affects the tracking process. However, OpenCV libraries, which provided a thresholding function, were implemented to solve this problem. Threshold operations are helpful and provide the most common way to segment a region of an image. Therefore, the boundaries of a black square marker can be easily detected when the marker is located on clear and light background. At the beginning, the value of the initial threshold was set at 100. In case that the marker could be detected properly, the threshold value of the binary image processing should be adjusted using the track bar of OpenCV. However, the lighting conditions in the laboratory testing were from fluorescent lamps, which was the control environment.

Table 6.1 Summary of web camera position for each prototype application

Item	Prototype application	Web camera position
1	Falling object hazard from building	On base level
2	Falling object hazard from crane to work area (camera on crane)	Above base level
3	Falling object hazard from crane to work area (camera on working level)	On base level
4	Falling object hazard from crane to workers' space (camera on crane)	Above base level
5	Falling object hazard from crane to workers' space (camera on work level)	On base level
6	Safety measure selection	On base level
7	Safe work area preparation	On base level
8	Safety measure monitoring	On base level
9	Safety sign monitoring	On base level
10	Personal protective equipment monitoring	On base level
11	Step-by-step safe assembly	On base level
12	All-in-one safe assembly	On base level
13	Solid and transparent safe assembly	On base level
14	Training media for safe work process	On base level



(a) Camera located on work level



(b) Camera located above base level

Figure 6.74 Camera set up for testing in the laboratory

Furthermore, a pipe frame was built for simulating the tower crane operation at the construction site, as shown in Figure 6.74. The fishing line hoisted with the

plummet hung on the pipe frame was used as the weight of the object, which was lifted and moved by the crane. The 10 x 10 cm. grid lines were created on foam boards and bagasse paper and used for measuring the virtual objects. For testing, the positions of the markers were set up in many postures depending on the considered application, such as being laid down on the bagasse paper, installed perpendicular with the web camera, or connected with the hoisted weight.

The testing results were shown as examples of output windows, which were demonstrated in the previous sections. All of the prototype applications could satisfactorily perform and generate the output results in response to the purposes of the application development. Nevertheless, some problems were discovered during the testing as follows.

1. The messy and inhomogeneous background also influenced the marker detection process in the module of augmented reality, in which the black square shapes were detected in the capturing frames. Consequently, it could not identify the exact marker for the considered application. Moreover, jittering problems occurred.

2. Even though the selected web camera was a high-performance device in the market, there were still some limited properties, such as field of view, the connecting cable, and the notebook clip. The field of view was too narrow and the capture frame could not cover all of the experimental area. Moreover, the connected cable was too short and the clip was not stable.

3. In the testing of the AR applications for preventing a falling object hazard from crane operation, the marker was installed at the hoisting weight, which always swung. Therefore, the web camera could not smoothly capture the marker in the input frame.

6.3.2 Real environment testing

After testing the prototype system in laboratory, real environment testing was also required for investigating the implementation of this system at the real construction site. The proposed system should be robust enough to provide the output contents in accordance with the user's augmented views. However, there were some adjustments regarding device arrangement. First, the marker size was modified to be of an adequate size so that the web camera could effortlessly detect the black square shapes. The marker sizes which were created to be tested were 20, 30, 40, 50, and 100 cm.; however, the patterns of the markers were the same as in the testing in the laboratory. The marker sizes were adjusted because the distance from the web camera was farther. In order to render the real size of the virtual building components, safety measures, work areas, worker's space, and so on, the distance from the web camera to the marker must be sufficient to cover the 3D space that the user expects to observe.

There were two approaches to the web camera installation. In the first approach, the web camera was installed on a safety helmet and connected with the laptop computer, which the user carried by using a special harness for a portable laptop, as shown in Figure 6.75(a). The position of the web camera in this approach was close to the viewing frustum of the eyes of the user. The captured viewing scenes responded to the orientation of the user's head.



(a) First approach



(b) Second approach

Figure 6.75 Camera set up for testing in the real environment

Furthermore, the user could conveniently move to change his or her viewpoint. Although this approach can provide more interactive views for the user, it contains a problem as the rapid and continuous movements of the user influence the capturing capability of the web camera. Hence, the second approach, where a web camera was installed on the tripod, was applied to reduce the mentioned problem, as shown in Figure 6.75(b). From the preliminary testing in the real environment, the following problems were discovered.

1. The unit of the markers in the text file for testing in the real condition had to be set as centimeters, which was different from the lab test. Thus, the units of the virtual objects and their scales in the developed applications had to be adjusted. Otherwise, the virtual objects would not be accurately rendered in the output windows, as shown in Figure 6.76.

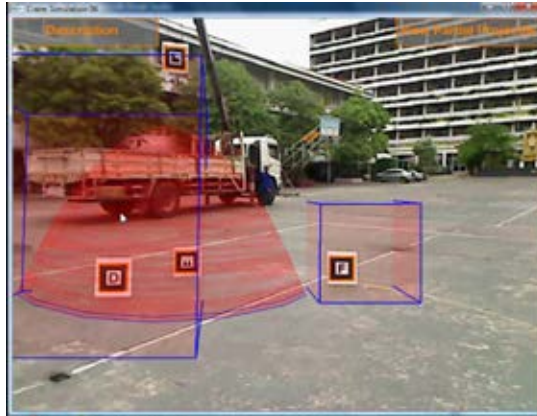


Figure 6.76 Example of the output screen in which the unit marker was wrong

2. This proposed system applied the image based on the tracking method for developing the AR application. Therefore, in case that the background was messy and contained many black square shapes, as demonstrated in Figure 6.77, the application attempted to detect all possible black shapes which might be the specified markers for the running application. This situation might have led to output errors.

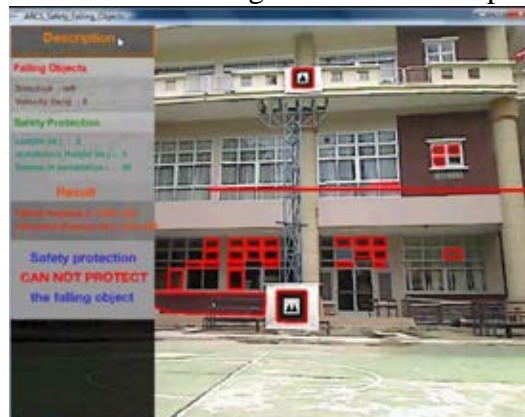


Figure 6.77 Example of messy background with many black squares

6.4 Conclusion

This chapter demonstrated the development of the VSMART System, which can support safety management at a construction site for preventing accidents caused from the hazards of falls and falling objects. Fourteen by-product applications which assisted the construction personnel in carrying out the safety management processes: design and planning for preventing the hazards of falling objects, design and planning for arrangement safe work area, monitoring, and training in the real environment were illustrated. All applications provided the AR output by using the ARToolKit. However, each application had individual procedures of preparation, input, process, and output. The calculations and algorithms in the previous chapters were also applied in the process step.

Regarding the hazards of falling objects, the following two scenarios were selected to be case studies: falling objects from the building perimeter and falling objects from crane operation. In the process of design and planning for arrangement of safe work area, the applications of safety measure selection and safe work area preparation were created. Monitoring applications of the safety measures, signs, and personnel protection equipment also were developed. Lastly, applications for training, which consisted of safe assembly and training media for safe assembly, were developed.

The proposed system was concurrently developed and tested in the laboratory, and then as an experiment in the real environment. The problems from both experiments were investigated.

Chapter VII

System Verification and Validation

7.1 Introduction

In this chapter, the VSMART System, which was developed to support construction personnel in safety management, particularly regarding construction activities performed at heights and containing hazards of falls and falling objects, was tested to prove that it could accurately and effectively perform. Even though the proposed system was able to provide the expected outputs during the development process, it had to be tested to verify accuracy and to validate the potential of the system at the real construction site. The verification process was done in both the laboratory and in the real environment. After that, this system was validated by the construction personnel. The details are described as follows.

7.2 System Verification

There are many functions that were developed in the proposed system, such as providing the visualization of possible hazards from falling objects, illustrating the unsafe work areas, and presenting virtual objects regarding safety. In order to verify the accuracy of this system, the mentioned functions are tested in this section. As described in the previous chapter, some of the factors affected the performance of the developed AR application. Due to the significant feature of AR, it can interact with the user's positions and orientations. However, too many movements influence the capturing capability of the web camera. In these experiments, the web camera was installed on a tripod to reduce jittering problems to present stable virtual objects in the output frames. The functions were tested to verify their accuracy in both the laboratory and the real environment.

7.2.1 Function for providing the visualization of possible hazards from falling objects

In high-rise building construction project, objects such as materials or tools usually drop from the building perimeter or floor opening at a higher level and strike people or property. Therefore, the in-charge personnel make an effort to prevent these kinds of accidents by providing a falling-object protection system. In this research, the AR application for supporting the process of safety measure preparation was used as a case study. The projectile path of the falling object was considered as the possible range of hazards which could occur. In the experiments, the actual falling distances were manually measured and used in the manual calculation of the horizontal distance in accordance with the projectile formulas, while the AR application measured the

falling distance and calculated the horizontal distance through computer programming.

In the laboratory testing, there were three cases of falling distance that were studied. The distances between the two markers as the falling distance were fixed at 20, 30, and 40 cm. respectively. The falling distances were measured from the center of the higher marker to the base of the lower marker. The values of velocity were repeatedly input ten times to check the results of each testing case beginning from 0.1 m/s to 1.0 m/s., as described in Table 7.1. Then the system generated a moving red sphere which represented the falling object on the output screen. The moving path of this red sphere was repeatedly rendered according to the results from the projectile calculation. The horizontal distance was calculated and measured from the center of the higher marker in the X axis, which depended on the falling direction input by the user. Furthermore, the system also provided text information on the input data, measured falling height, and the calculation results of the horizontal distance on the output screen. The compared results of the height distance measured by manual and by system programming are presented, together with the compared results of the horizontal distance calculated by manual and by system programming, in Table 7.1, and the percentages of the error of the height distance and horizontal distance are also presented. The minimum and maximum of percentages of the error of the height distance respectively were 0.67 and 3.00. Additionally, the minimum and maximum of the percentage of error of the horizontal distance were 0.04 and 1.78 respectively. The captured output windows of each testing case are shown in Figure 7.1 to Figure 7.3. The graphs from Figure 7.4 to Figure 7.6 were created from the comparison results of the falling height distance of each testing case and Figure 7.8 to Figure 7.10 were created from the comparison results of the horizontal distance. The graphs in Figure 7.7 and Figure 7.11 present the sum of percentage of the error of the falling height distance and horizontal distance of all testing cases, respectively.

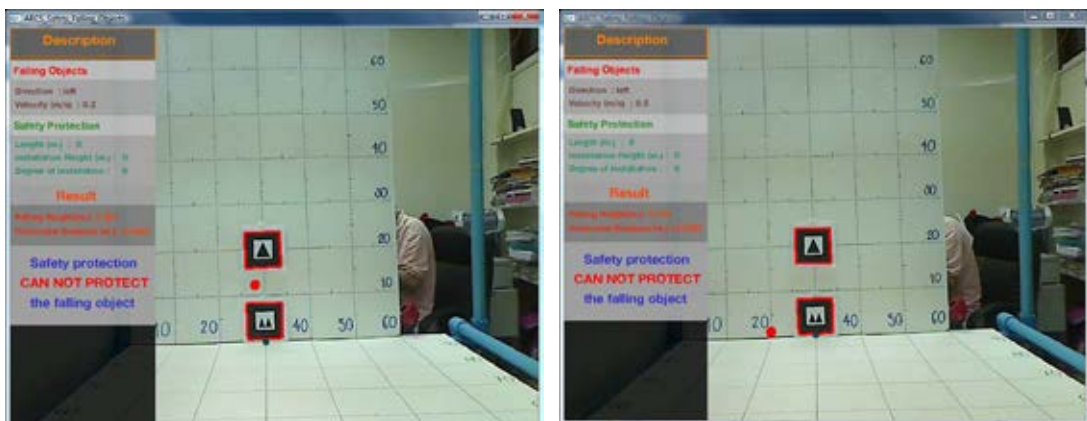


Figure 7.1 Output windows of case 1 (falling distance = 20 cm)

Table 7.1 Results of testing cases for comparing falling height distance and horizontal distance

Experiment no.	Initial Velocity (m/s)	Manual measure and calculation		Programming measure and calculation		% error	
		Height of falling object m.	Horizontal Distance m.	Height of falling object m.	Horizontal Distance m.	Height of falling object	Horizontal Distance
1	0.1	0.2	0.02	0.206	0.021	-3.00%	-1.52%
2	0.2	0.2	0.04	0.200	0.040	0.00%	-0.04%
3	0.3	0.2	0.06	0.202	0.061	-1.00%	-0.37%
4	0.4	0.2	0.08	0.196	0.080	2.00%	0.83%
5	0.5	0.2	0.10	0.194	0.100	3.00%	1.45%
6	0.6	0.2	0.12	0.194	0.119	3.00%	1.78%
7	0.7	0.2	0.14	0.196	0.139	2.00%	1.66%
8	0.8	0.2	0.16	0.194	0.159	3.00%	1.57%
9	0.9	0.2	0.18	0.194	0.179	3.00%	1.50%
10	1.00	0.2	0.20	0.197	0.201	1.50%	0.46%
11	0.1	0.3	0.02	0.298	0.025	0.67%	0.13%
12	0.2	0.3	0.05	0.297	0.049	1.00%	0.53%
13	0.3	0.3	0.07	0.296	0.074	1.33%	0.66%
14	0.4	0.3	0.10	0.298	0.099	0.67%	0.33%
15	0.5	0.3	0.12	0.297	0.123	1.00%	0.53%
16	0.6	0.3	0.15	0.298	0.148	0.67%	0.26%
17	0.7	0.3	0.17	0.303	0.174	-1.00%	-0.51%
18	0.8	0.3	0.20	0.298	0.197	0.67%	0.43%
19	0.9	0.3	0.22	0.298	0.222	0.67%	0.26%
20	1.00	0.3	0.25	0.298	0.247	0.67%	0.13%
21	0.1	0.4	0.03	0.408	0.029	-2.00%	-0.85%
22	0.2	0.4	0.06	0.410	0.058	-2.50%	-1.20%
23	0.3	0.4	0.09	0.408	0.087	-2.00%	-1.08%
24	0.4	0.4	0.11	0.408	0.115	-2.00%	-0.68%
25	0.5	0.4	0.14	0.408	0.144	-2.00%	-0.85%
26	0.6	0.4	0.17	0.408	0.173	-2.00%	-0.97%
27	0.7	0.4	0.20	0.410	0.202	-2.50%	-1.05%
28	0.8	0.4	0.23	0.407	0.231	-1.75%	-1.11%
29	0.9	0.4	0.26	0.408	0.260	-2.00%	-1.16%
30	1.00	0.4	0.29	0.410	0.289	-2.50%	-1.20%



Figure 7.2 Output windows of case 2 (falling distance = 30 cm)



Figure 7.3 Output windows of case 3 (falling distance = 40 cm)

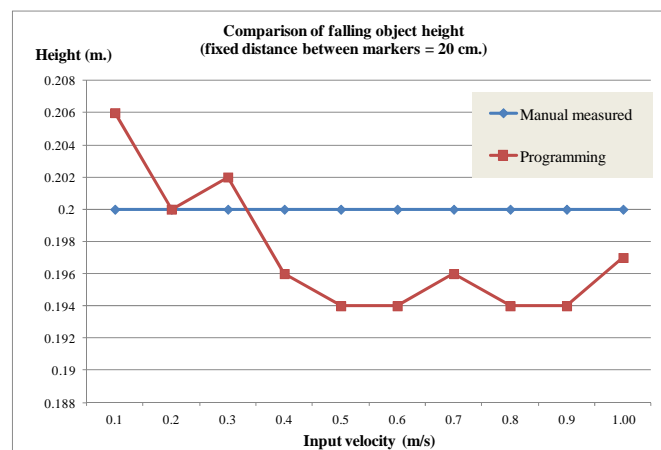


Figure 7.4 Comparison results of falling height distance for testing case 1

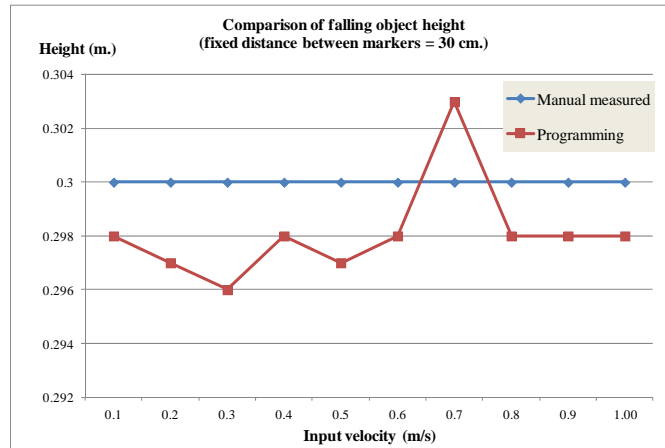


Figure 7.5 Comparison results of falling height distance for testing case 2

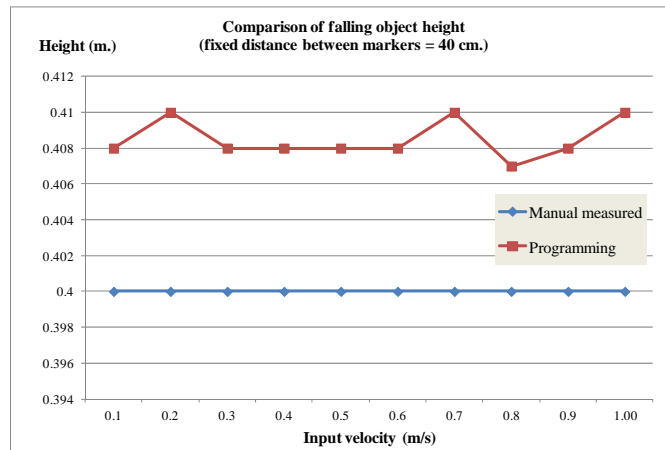


Figure 7.6 Comparison results of falling height distance for testing case 3

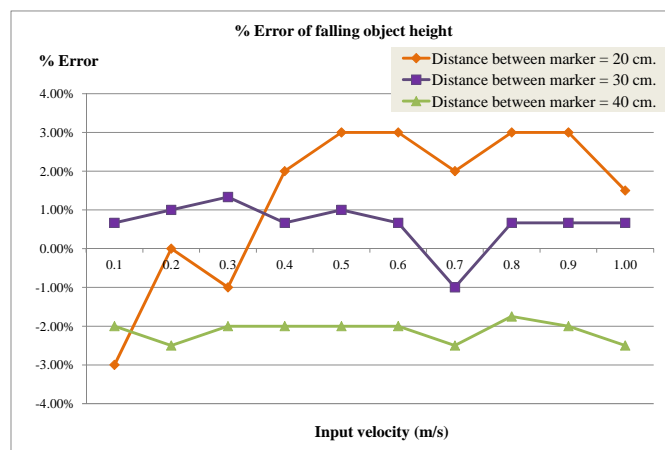


Figure 7.7 Summarization of % error of falling height distance for all cases

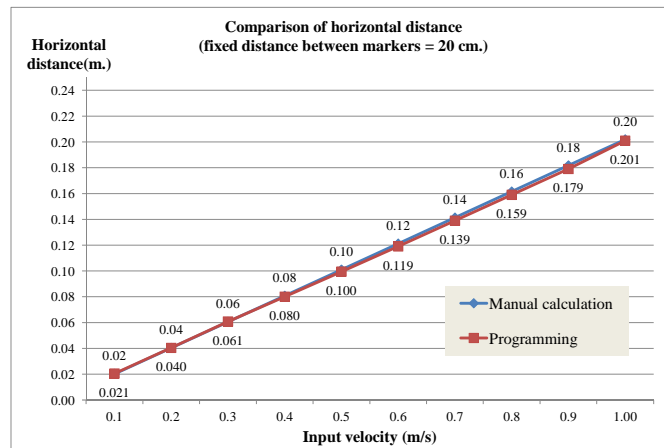


Figure 7.8 Comparison results of horizontal distance for testing case 1

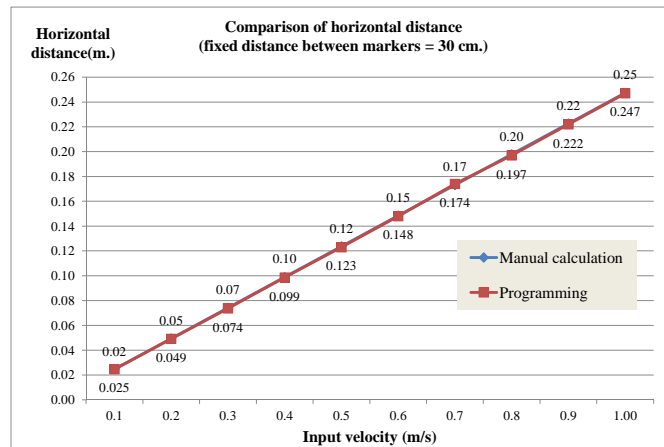


Figure 7.9 Comparison results of horizontal distance of testing case 2

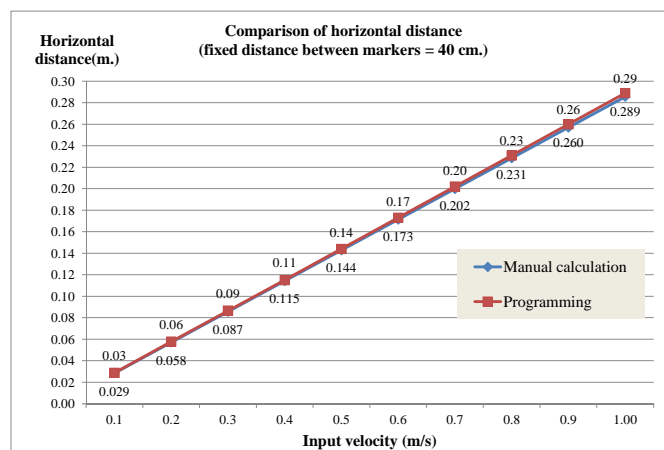


Figure 7.10 Comparison results of horizontal distance for testing case 3

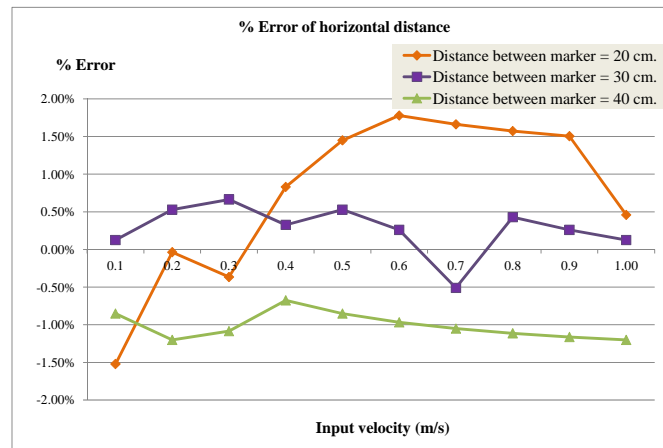


Figure 7.11 Summary of % of error of falling height distance for all cases

Not only were the measured height distances and calculated horizontal distances verified by programming; the collision detection algorithm which was used for simulating the safety measures arrangement was also tested. The height distances of falling objects were set as in the previous experiments. The velocity of the falling object was defined as 0.5 m/s for all cases. The factors which were changed consisted of length, installation height, and installation degree of safety measure. Then, the calculations for checking the protection condition of the prepared safety measure manually and by programming were performed and the results were compared, as presented in Table 7.2. The verifications of the proposed system are also presented.

In testing case 1, where the height of the falling object was 0.2 m., the two values of the length of safety measure were input as 0.06 m. and 0.08 m. The installation height of the safety measures was 0.1 m. in both cases. In addition, the input values of the degree of installation measured from the horizontal were 0° , 30° , 45° , and 60° . The testing results were denoted from case 1 to case 8. According to the manual calculation of the first four testing cases, the results indicated that the safety measure, which had a length equal to 0.06 m. and was installed at 0.1 m above the base level at all degrees of installation, could not protect against the hazards of falling objects. When checking the results from the system programming, they conformed to the manual calculation.

In the later group, the length of the safety measure was changed to 0.08 m. and other factors were input similar to the previous testing cases. The results from the manual calculations indicated that the modified length of safety measure could protect against the hazards from the falling object and the calculated results by system programming conformed to these manual calculations. Figure 7.12 to Figure 7.15 illustrate the output screens of results for each testing case.

Table 7.2 Verification results of manual and system programming calculation for safety measure preparation

Case	Height	Length of safety measure	Installation height	Degree from horizontal	Y-axis distance of safety measure	Installation height + Y-axis distance	Remaining falling distance	Velocity	Horizontal distance of falling object	X axis distance of safety measure	Manual check	Programming check	Verification
	m.	m.	m.		m.	m.	m.	m/s	m.	m.			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	
					(5) = (2) x sin (3)	(6) = (3) + (5)	(7) = (1) - (6)		(9) = sqrt(((7) x 2)/9.81) x (8)	(10) = (2) x cos (3)	Compare (9) & (10)		Correct
1	0.2	0.06	0.1	0	0.000	0.100	0.100	0.5	0.07	0.060	cannot protect	cannot protect	√
2	0.2	0.06	0.1	30	0.030	0.130	0.070	0.5	0.06	0.052	cannot protect	cannot protect	√
3	0.2	0.06	0.1	45	0.042	0.142	0.058	0.5	0.05	0.042	cannot protect	cannot protect	√
4	0.2	0.06	0.1	60	0.052	0.152	0.048	0.5	0.05	0.030	cannot protect	cannot protect	√
5	0.2	0.08	0.1	0	0.000	0.100	0.100	0.5	0.07	0.080	can protect	can protect	√
6	0.2	0.08	0.1	30	0.040	0.140	0.060	0.5	0.06	0.069	can protect	can protect	√
7	0.2	0.08	0.1	45	0.057	0.157	0.043	0.5	0.05	0.057	can protect	can protect	√
8	0.2	0.08	0.1	60	0.069	0.169	0.031	0.5	0.04	0.040	can protect	can protect	√
9	0.3	0.1	0.1	0	0.000	0.100	0.200	0.5	0.10	0.100	can protect	can protect	√
10	0.3	0.1	0.1	30	0.050	0.150	0.150	0.5	0.09	0.087	cannot protect	cannot protect	√
11	0.3	0.1	0.1	45	0.071	0.171	0.129	0.5	0.08	0.071	cannot protect	cannot protect	√
12	0.3	0.1	0.1	60	0.087	0.187	0.113	0.5	0.08	0.050	cannot protect	cannot protect	√
13	0.3	0.1	0.15	0	0.000	0.150	0.150	0.5	0.09	0.100	can protect	can protect	√
14	0.3	0.1	0.15	30	0.050	0.200	0.100	0.5	0.07	0.087	can protect	can protect	√
15	0.3	0.1	0.15	45	0.071	0.221	0.079	0.5	0.06	0.071	can protect	can protect	√
16	0.3	0.1	0.15	60	0.087	0.237	0.063	0.5	0.06	0.050	cannot protect	cannot protect	√
17	0.4	0.1	0.15	0	0.000	0.150	0.250	0.5	0.11	0.100	cannot protect	cannot protect	√
18	0.4	0.1	0.15	30	0.050	0.200	0.200	0.5	0.10	0.087	cannot protect	cannot protect	√

Table 7.2 Verification results of manual and system programming calculation for safety measure preparation (Cont'd.)

Case	Height	Length of safety measure	Installation height	Degree from horizontal	Y-axis distance of safety measure	Installation height + Y-axis distance	Remaining falling distance	Velocity	Horizontal distance of falling object	X axis distance of safety measure	Manual check	Programing check	Verification
	m.	m.	m.		m.	m.	m.	m/s	m.	m.			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	Correct
				$(5) = (2) \times \sin(3)$	$(6) = (3) + (5)$	$(7) = (1) - (6)$		$(9) = \sqrt{((7) \times 2) / 9.81} \times (8)$	$(10) = (2) \times \cos(3)$	Compare (9) & (10)			
19	0.4	0.1	0.15	45	0.071	0.221	0.179	0.5	0.10	0.071	cannot protect	cannot protect	✓
20	0.4	0.1	0.15	60	0.087	0.237	0.163	0.5	0.09	0.050	cannot protect	cannot protect	✓
21	0.4	0.15	0.15	0	0.000	0.150	0.250	0.5	0.11	0.150	can protect	can protect	✓
22	0.4	0.15	0.15	30	0.075	0.225	0.175	0.5	0.09	0.130	can protect	can protect	✓
23	0.4	0.15	0.15	45	0.106	0.256	0.144	0.5	0.09	0.106	can protect	can protect	✓
24	0.4	0.15	0.15	60	0.130	0.280	0.120	0.5	0.08	0.075	cannot protect	cannot protect	✓
25	0.4	0.1	0.2	0	0.000	0.200	0.200	0.5	0.10	0.100	cannot protect	cannot protect	✓
26	0.4	0.1	0.2	30	0.050	0.250	0.150	0.5	0.09	0.087	cannot protect	cannot protect	✓
27	0.4	0.1	0.2	45	0.071	0.271	0.129	0.5	0.08	0.071	cannot protect	cannot protect	✓
28	0.4	0.1	0.2	60	0.087	0.287	0.113	0.5	0.08	0.050	cannot protect	cannot protect	✓

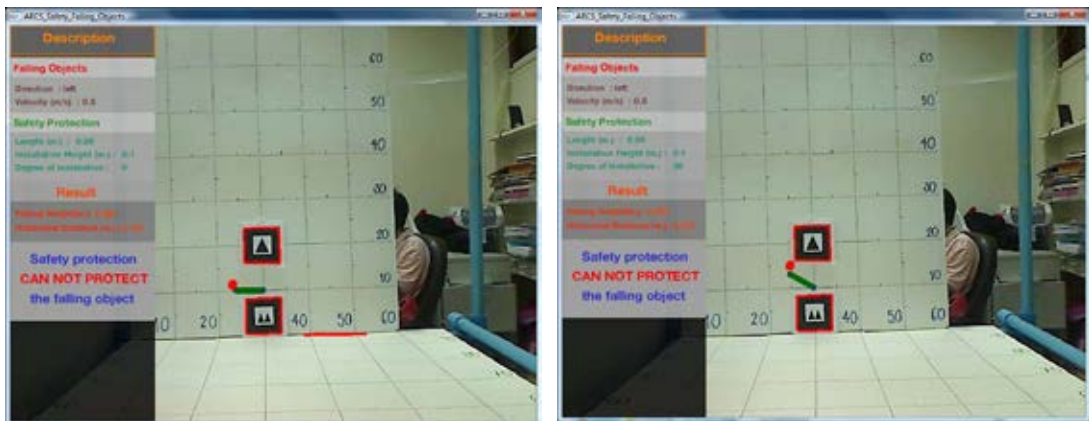


Figure 7.12 The output screens of the testing results for case 1 and case 2

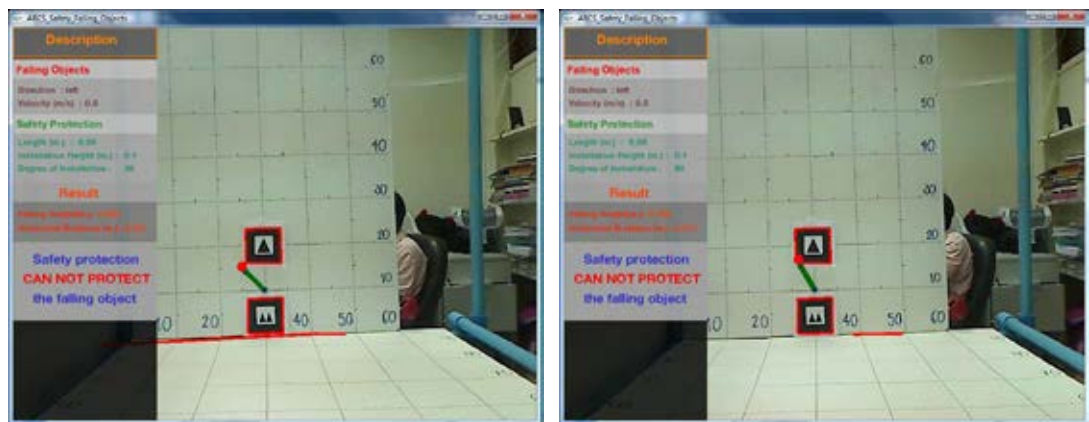


Figure 7.13 The output screens of the testing results for case 3 and case 4

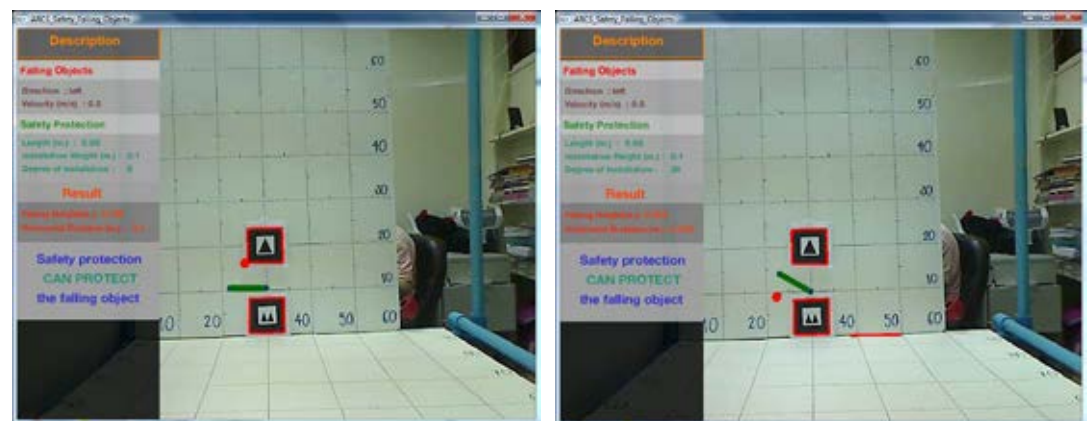


Figure 7.14 The output screens of the testing results for case 5 and case 6

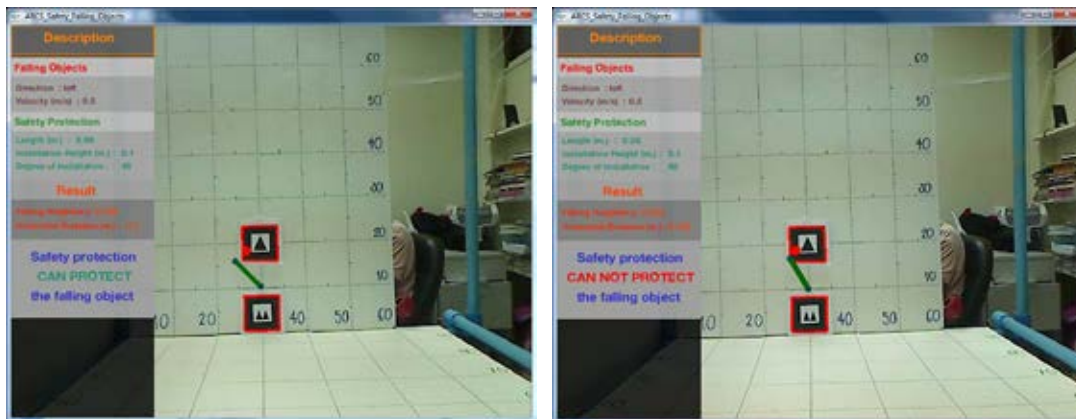


Figure 7.15 The output screens of the testing results for case 7 and case 8

Next, the height distance of the falling object was changed to 0.3 m. and the length of the safety measure was set as 0.1 m. However, two values of installation height were tested, which were 0.1 and 0.15 m., and the degrees of installation were 0° , 30° , 45° , and 60° . The results of the manual and system programming calculation are presented in case 9 to case 16 in Table 7.2. For the cases where the safety measure was installed at 0.1 m, only the case where the safety measure was installed at 0° degree could protect against the hazard of a falling object. Contrarily, all degrees of installation, except the 60° degree at which the safety measures was installed at 0.15 m, could protect the hazards of falling object.

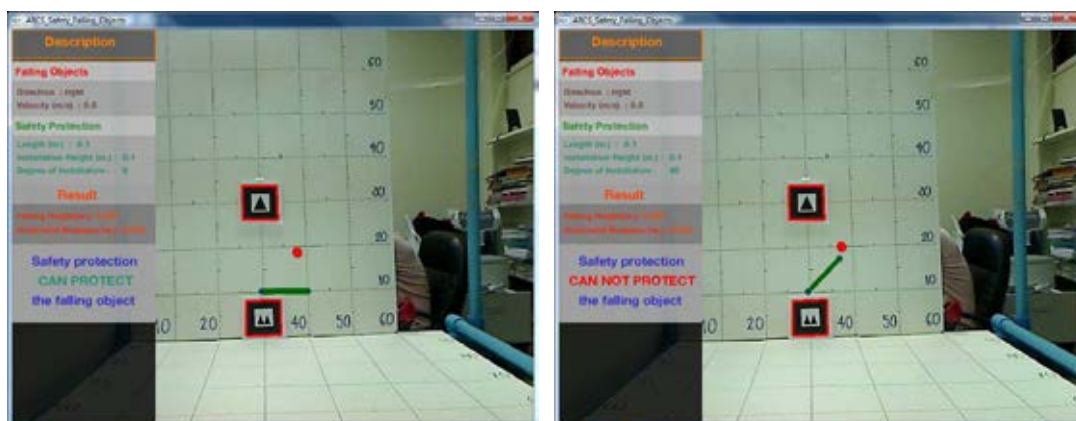


Figure 7.16 The output screens of the testing results for case 9 and case 11

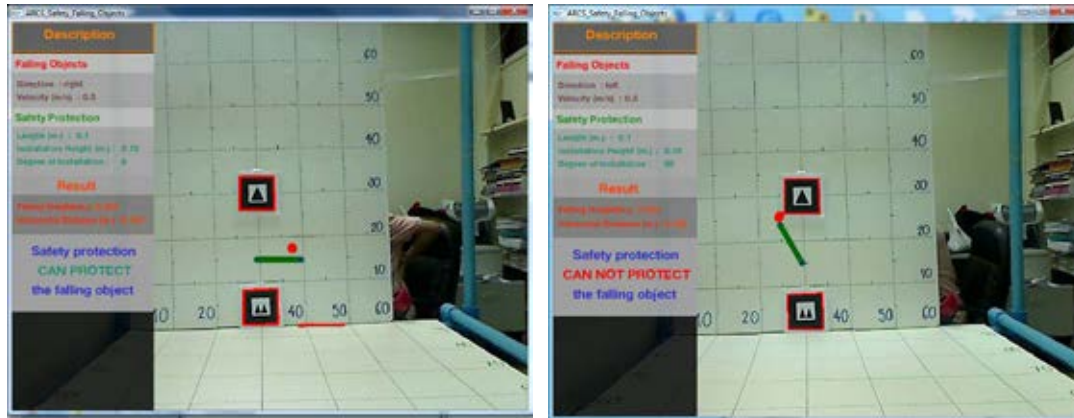


Figure 7.17 The output screens of the testing results for case 13 and case 16

Lastly, the falling height was modified to be 0.4 m. The factors which were also modified were length of safety measure and installation height. There were two values of length of safety measures, which were 0.1 and 0.15 m. The installation heights were 0.15 and 0.2 m. The degrees of installation, which were 0°, 30°, 45°, and 60°, were tested. For case 17 to case 20, the length of the safety measure was equal to 0.1 m. and the installation height was 0.15 m. The results of the system programming checks indicated that the safety measure could not protect against the hazard of falling objects for every degree of installation which complied with the manual checks. Figure 7.18 illustrates the output screen for case 17. The length of the safety measure was changed in case 21 to case 24 to 0.15 m., while the installation height was set at 0.15 m. . Only for case 24, where the safety measure was installed at 60° degrees of installation, the safety measure was not able to protect against the hazard of a falling object and the checking results of system conformed with the manual check results. Figure 7.19 demonstrates the results by system programming for case 21 and case 24. Additionally, the length and installation height of the safety measure were modified again to be 0.1 m. and 0.2 m. respectively for case 25 to case 28. According to the manual checks, the maximum distance in the X axis of the safety measure for every testing case was less than the horizontal distance of the falling object, which indicated that the safety measure could not protect against the hazard of falling objects as checked by the system program. The results of the system programming for all twenty-eight testing cases conformed to the manual checks.



Figure 7.18 The output screen of the testing results for case 17



Figure 7.19 The output screens of the testing results for case 21 and case 24

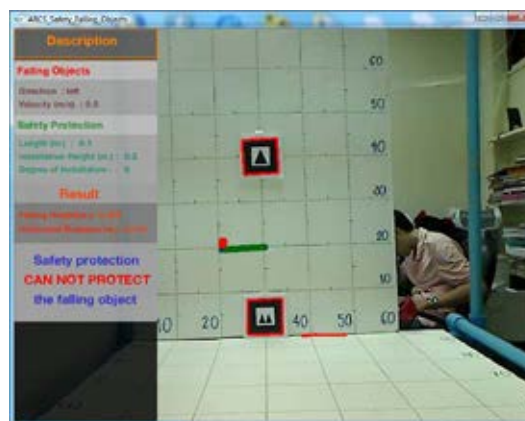


Figure 7.20 The output screen of the testing results for case 25

After testing to verify the function of providing the visualization of possible hazards from falling objects of the proposed system in the laboratory, actual environmental experiments were carried out in order to verify the system in the actual conditions. As mentioned in the previous chapter, the sizes of the marker were

adjusted to be large enough and their values in the text files were revised. The two markers whose size was 100 by 100 cm were made of fabric. One marker was installed at the higher level and another was installed at the base level. The height distance, which was measured from the ground level to the top perimeter of the white area of the higher marker, was 10.70 m. The width of the white borders was 0.4 m. Therefore, the distance measured from the center of lower marker to the center of higher marker was 8.9 m. A laptop computer and web camera were set, as demonstrated in Figure 7.21. The two arrow signs were used for identifying the expected point of the virtual falling object and a tape measure was used for measuring the virtual horizontal distance, as shown in Figure 7.22.



Figure 7.21 Device setting for real environment testing



Figure 7.22 Arrow signs and tape measure

Three situations were tested in the real environment. The input factors in each situation are presented in Table 7.3. The horizontal distances were calculated manually and were compared with the measured falling height and calculated horizontal distance via system programming, as denoted in Table 7.4. The percentage of the error for the height distance and horizontal distance was less than 2% and 1%, respectively.

Table 7.3 Input factors for providing visualization of possible hazards from falling objects in the real environment

Situation no.	Velocity (m/s)	Length of safety measure (m.)	Installation height (m.)	Degree of installation
1	1	2	5	45°
2	2	3	3	30°
3	4	3	3	30°

The checking results for each case manually and by programming for simulating the safety measure preparation are also presented in Table 7.5. Although the falling height distance measured by the programming was more than the actual distance, the results which were checked by the programming conformed to the manual calculation in every test. Figure 7.23 to Figure 7.25 demonstrate the output screens for the verification results of the function of providing visualization of possible hazards from falling objects in the real environment.



Figure 7.23 An output screen of the result for situation number 1

Table 7.4 Results of the testing cases for comparing the falling height distance and horizontal distance in the real environment

Situation number	Initial velocity	Manual measure and calculation		Programming measure and calculation		% error	
		Height of falling object	Horizontal distance	Height of falling object	Horizontal distance	Height of falling object	Horizontal distance
	(m/s)	m.	m.	m.	m.		
1	1	8.9	1.35	8.810	1.34	-1.01%	0.52%
2	2	8.9	2.69	8.850	2.69	-0.56%	0.15%
3	4	8.9	5.39	8.810	5.36	-1.01%	0.52%

Table 7.5 Verification results of for the manual and system programming calculation for safety measure preparation in the real environment

Situation	Height	Length of safety measure	Installation height	Degree from horizontal	Y-axis distance of safety measure	Installation height + Y-axis distance	Remaining falling distance	Velocity	Horizontal distance of falling object	X axis distance of safety measure	Manual check	Programming check	Verification
	m.	m.	m.		m.	m.	m.	m/s	m.	m.			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	
					$(5) = (2) \times \sin (3)$	$(6) = (3) + (5)$	$(7) = (1) - (6)$		$(9) = \sqrt{((7) \times 2) / 9.81} \times (8)$	$(10) = (2) \times \cos (3)$	Compare (9) & (10)		Correct
1	8.9	2	5	45	1.414	6.414	2.486	1	0.71	1.414	can protect	can protect	✓
2	8.9	3	3	30	1.500	4.500	4.400	2	1.89	2.598	can protect	can protect	✓
3	8.9	3	3	30	1.500	4.500	4.400	4	3.79	2.598	cannot protect	cannot protect	✓



Figure 7.24 An output screen of result for situation number 2



Figure 7.25 An output screen of the result for situation number 3

7.2.2 Function for illustrating unsafe working areas

When the workers perform construction activities at a height, they can encounter a fall hazard, which may lead them to serious accidents. Safe workplaces are essentially required to prevent the workers from a tragedy. This test part presents the verification of the function for illustrating the unsafe work areas developed in this research. The unsafe condition which was selected to be a case study was the hazard of falling objects from crane operation. When a crane lifts or moves objects at a construction site, the areas beneath its operation path must be clear and restricted. In

this study, the hazards of falling objects from cranes were calculated according to projectile formulas and represented by 3D transparent virtual objects. The work space of the worker was represented by 3D cylinder shapes. The proposed system checked for the collision of these virtual objects and alerted the related personnel regarding the hazards. In the experiments, the results of the function for illustrating the unsafe work areas by the system programming were compared manually in order to verify the proposed system. Similarly, the experiments were carried out in both the laboratory and the real environment.

In the laboratory, the following three markers were prepared: 1) a reference marker, 2) a marker for the crane, and 3) a marker for the worker. The marker sizes were 5 and 8 cm. A reference marker was placed on the test area, as demonstrated in Figure 7.26. However, other markers were placed on the top sanitary pipe fitting to determine the falling height. There were three values of falling height for testing, which were 10.2, 20, and 30 cm. These heights were measured from the top surface of the reference marker to the top surface of the crane marker. The sizes of the workers' work space were set as radius and height at 5 and 10 cm, respectively. The position of the web camera was above the testing area.

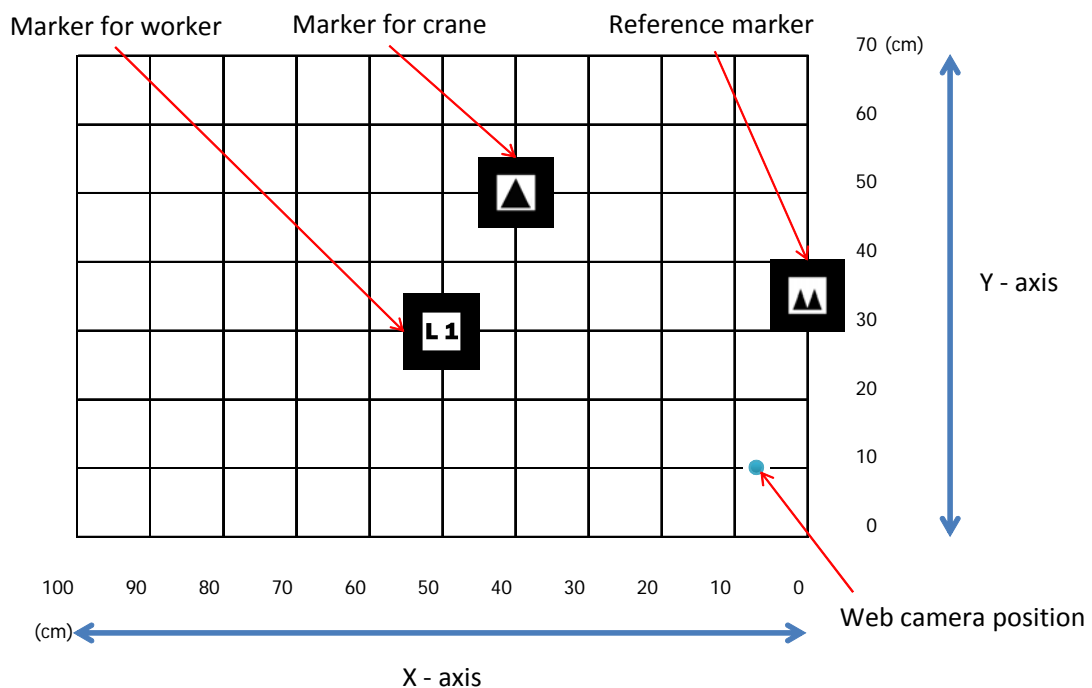


Figure 7.26 Testing area and markers for laboratory testing

The marker settings for each case are demonstrated in Figure 7.27 to Figure 7.29. The reference marker was fixed at the same position for every testing case as presented in the figures. The marker representing the crane was moved to each grid on

the test area. Then, the system measured the height of this marker and displayed it on output screen.



Figure 7.27 Examples of marker setting for case 1



Figure 7.28 Examples of marker setting for case 2



Figure 7.29 Examples of marker setting for case 3

The results of the measured falling height by programming for testing case 1, where the actual height of the falling object was determined as 10.2 cm, are presented in Table 7.6. This table also presents the percentages of the error of falling height for

each position of crane marker. In this case, there were six positions where the percentages of the error of falling height were less than 3%, as shown in the highlighted cells. The positions represented in orange cells were selected to be the feasible position for testing in the next experiment.

Table 7.6 Comparison of falling height measured manually and via system programming (case 1: actual height 10.2 cm.)

Distance from base to camera	80	cm.						
Actual height	= 10.2	cm.						
Position of reference marker	X-axis	0 cm.						
Position of reference marker	Y-axis	0.35 cm.						
(measured from the origin to center of marker)								
<u>Height measured by programming</u>								
Actual	Distance from origin in X-axis (m.)							
Distance from origin in Y-axis (m.)	origin(0,0)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	0.1020	0.1020	0.1020	0.1020	0.1020	0.1020	0.1020
	0.2	0.1020	0.1020	0.1020	0.1020	0.1020	0.1020	0.1020
	0.3	0.1020	0.1020	0.1020	0.1020	0.1020	0.1020	0.1020
	0.4	0.1020	0.1020	0.1020	0.1020	0.1020	0.1020	
	0.5	0.1020	0.1020	0.1020	0.1020	0.1020		
	0.6	0.1020	0.1020	0.1020	0.1020			
	0.7							
Program	Distance from origin in X-axis (m.)							
Distance from origin in Y-axis (m.)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	0.1200	0.1190	0.1500	0.1440	0.1430	0.1400	0.1460
	0.2	0.1110	0.1110	0.1380	0.1380	0.1310	0.1370	0.1410
	0.3	0.1070	0.1060	0.1230	0.1200	0.1230	0.1310	0.1400
	0.4	0.1010	0.1030	0.1060	0.1110	0.1130	0.1140	
	0.5	0.0930	0.0951	0.1050	0.1030	0.1010		
	0.6	0.0886	0.0873	0.0994	0.1020			
	0.7							
% Error	Distance from origin in X-axis (m.)							
Distance from origin in Y-axis (m.)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	17.65%	16.67%	47.06%	41.18%	40.20%	37.25%	43.14%
	0.2	8.82%	8.82%	35.29%	35.29%	28.43%	34.31%	38.24%
	0.3	4.90%	3.92%	20.59%	17.65%	20.59%	28.43%	37.25%
	0.4	-0.98%	0.98%	3.92%	8.82%	10.78%	11.76%	
	0.5	-8.82%	-6.76%	2.94%	0.98%	-0.98%		
	0.6	-13.14%	-14.41%	-2.55%	0.00%			
	0.7							

The meaning of the blank cells in the table is that the positions were out of range of the web camera. The graph in Figure 7.30 was created to present the height of the falling object measured by system programming, and Figure 7.31 presents the percentages of the error of the falling height distance in each position.

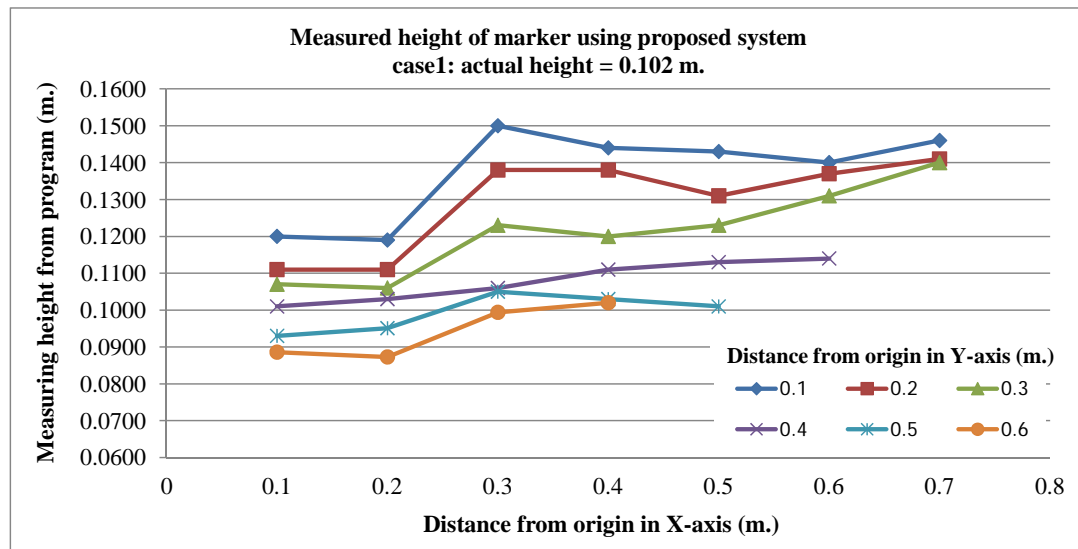


Figure 7.30 Falling height measured by system programming for case 1

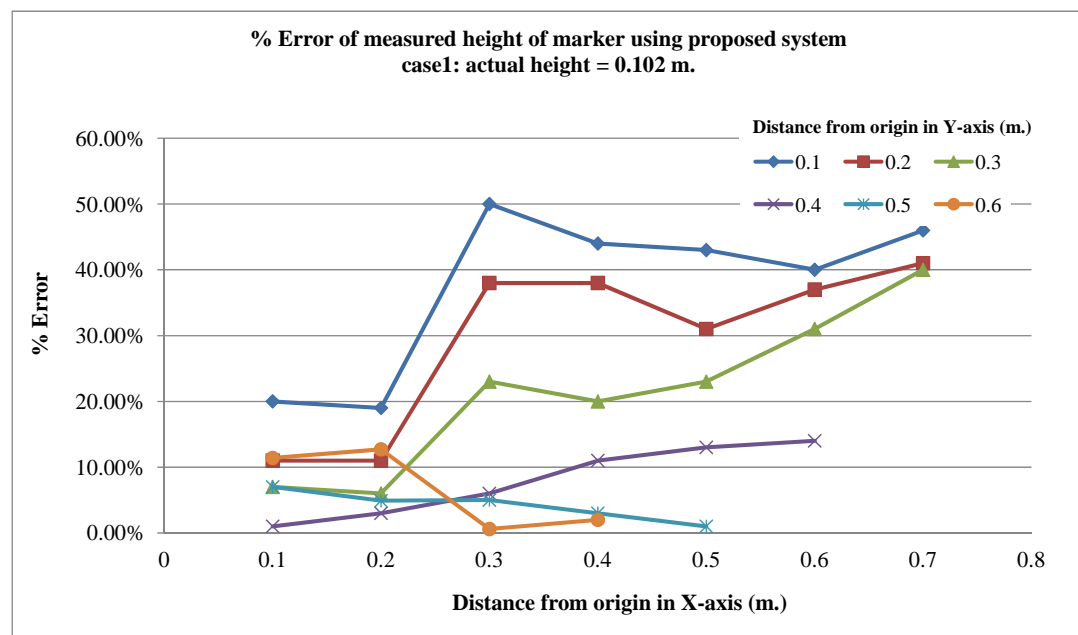


Figure 7.31 Percentage of error of falling height for case 1

In the second case, the actual height of the falling object was specified as 20 cm. Table 7.7 presents the results of the measured falling height by programming and comparison with the defined falling height. There were seven positions for which the percentages of the error of falling height were less than 3%, as shown in highlight cells. Moreover, the system could not measure the falling height of some of the positions which could be measured in the previous case.

Table 7.7 Comparison of falling height measured manually and via system programming (case 2: actual height 20 cm.)

Distance from base to camera	80	cm.						
Actual height	= 20	cm.						
Position of reference marker	X-axis	0 cm.						
Position of reference marker	Y-axis	0.35 cm.						
(measured from the origin to center of marker)								
Height measured by Programming								
Actual	Distace from origin in X-axis (m.)							
Distance from origin in Y-axis (m.)	origin(0,0)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000
	0.2	0.2000	0.2000	0.2000	0.2000	0.2000	0.2000	
	0.3	0.2000	0.2000	0.2000	0.2000	0.2000		
	0.4	0.2000	0.2000	0.2000	0.2000	0.2000		
	0.5	0.2000	0.2000	0.2000	0.2000			
	0.6			0.2000				
	0.7							
	Program	Distace from origin in X-axis (m.)						
Distance from origin in Y-axis (m.)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	0.2250	0.2270	0.2450	0.2350	0.2270	0.2390	0.2480
	0.2	0.2020	0.2150	0.2310	0.2310	0.2240	0.2330	
	0.3	0.2040	0.2080	0.2220	0.2190	0.2170		
	0.4	0.1980	0.1960	0.2090	0.2130	0.2090		
	0.5	0.1940	0.1940	0.2070	0.2080			
	0.6			0.2040				
	0.7							
	% Error	Distace from origin in X-axis (m.)						
Distance from origin in Y-axis (m.)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	12.50%	13.50%	22.50%	17.50%	13.50%	19.50%	24.00%
	0.2	1.00%	7.50%	15.50%	15.50%	12.00%	16.50%	
	0.3	2.00%	4.00%	11.00%	9.50%	8.50%		
	0.4	-1.00%	-2.00%	4.50%	6.50%	4.50%		
	0.5	-3.00%	-3.00%	3.50%	4.00%			
	0.6			2.00%				
	0.7							

The graph in Figure 7.32 was created to present the height of the falling object measured by system programming, and Figure 7.33 presents the percentages of the error of falling height distance in each position of testing case 2.

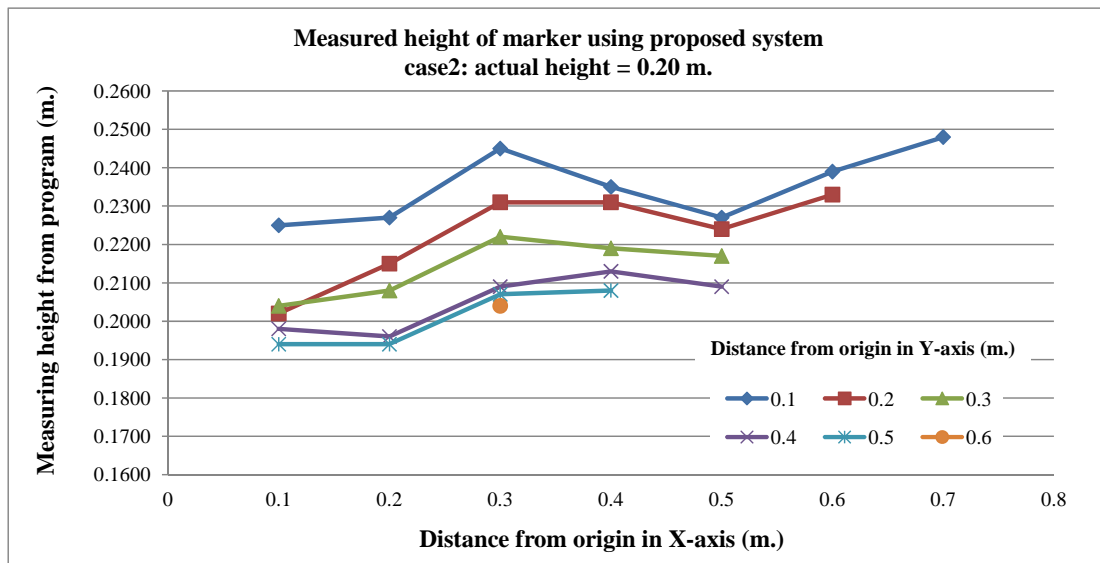


Figure 7.32 Falling height measured by system programming for case 2

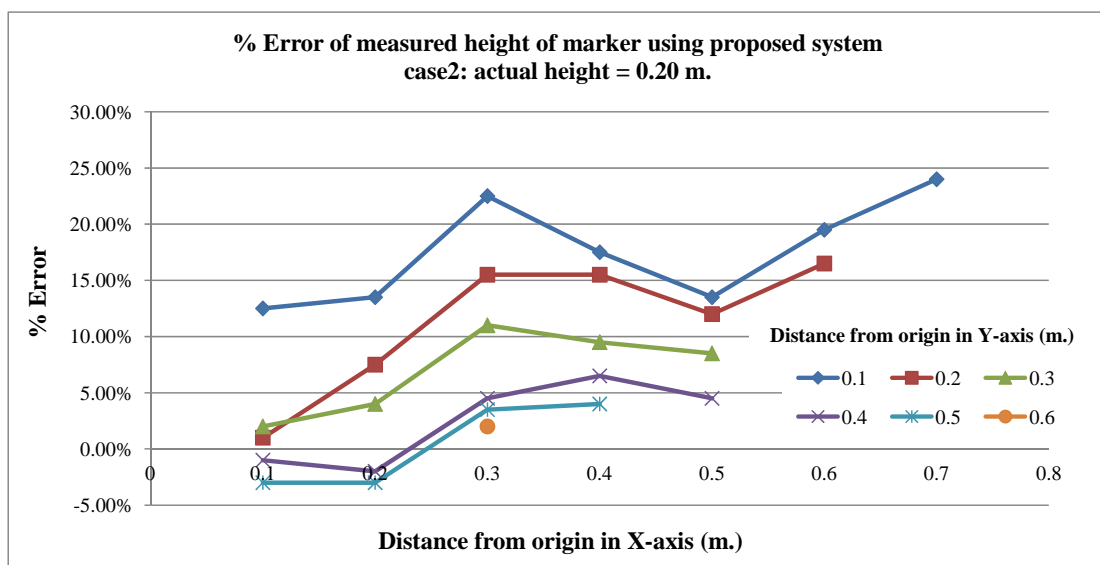


Figure 7.33 Percentage of error of falling height for case 2

Lastly, the actual height of the falling object in case 3 was defined as 30 cm. Table 7.8 presents the results of the measured falling height by programming and comparison results for testing case 3. There were only three positions for which the percentages of the error of falling height were less than 3%, as shown in highlight cells.

Table 7.8 Comparison of falling height measured manually and system programming (case3: actual height 30 cm.)

Distance from base to camera	80	cm.						
Actual height	=	30	cm.					
Position of reference marker	X-axis	0	cm.					
Position of reference marker	Y-axis	0.35	cm.					
(measured from the origin to center of marker)								
Height measured by Programming								
Base	Distance from origin in X-axis (m.)							
Distance from origin in Y-axis (m.)	origin(0,0)	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	0.3000	0.3000	0.3000	0.3000	0.3000	0.3000	
	0.2		0.3000	0.3000	0.3000	0.3000		
	0.3		0.3000	0.3000	0.3000			
	0.4	0.3000	0.3000	0.3000	0.3000			
	0.5		0.3000	0.3000				
	0.6							
	0.7							
Program	Distance from origin in X-axis (m.)							
Distance from origin in Y-axis (m.)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	0.3190	0.3300	0.3520	0.3350	0.3310	0.3470	
	0.2		0.3140	0.3340	0.3310	0.3240		
	0.3		0.3100	0.3230	0.3200			
	0.4	0.2970	0.3060	0.3170	0.3170			
	0.5		0.2980	0.3110				
	0.6							
	0.7							
% Error	Distance from origin in X-axis (m.)							
Distance from origin in Y-axis (m.)	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7
	0.1	6.33%	10.00%	17.33%	11.67%	10.33%	15.67%	
	0.2		4.67%	11.33%	10.33%	8.00%		
	0.3		3.33%	7.67%	6.67%			
	0.4	-1.00%	2.00%	5.67%	5.67%			
	0.5		-0.67%	3.67%				
	0.6							
	0.7							

The graph in Figure 7.34 was created to present the height of the falling object measured by system programming, and Figure 7.35 presents the percentages of the error of falling height distance in each position for testing case 3.

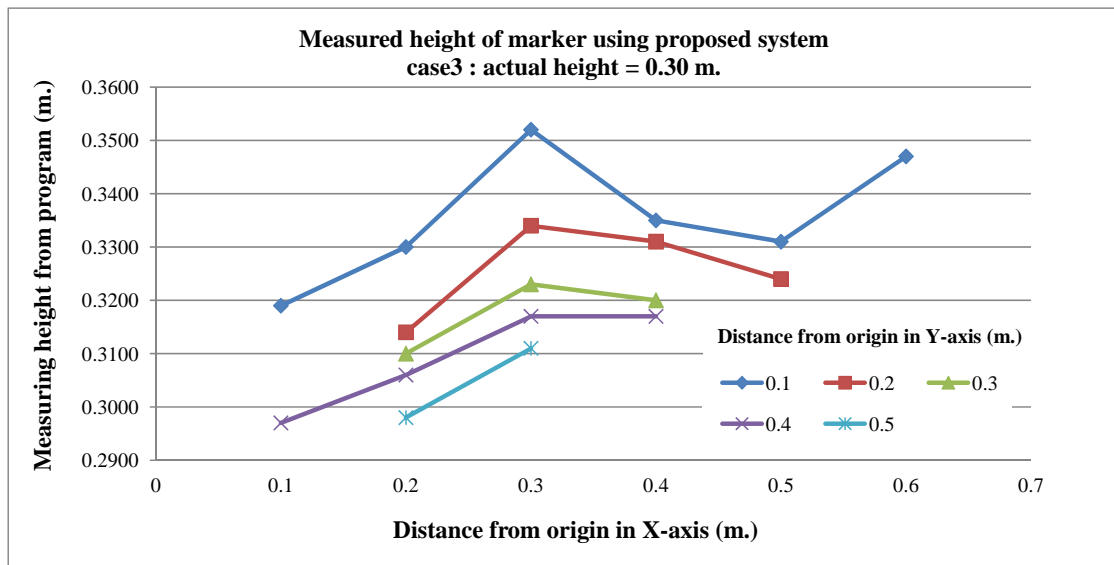


Figure 7.34 Falling height measured by system programming for case 3

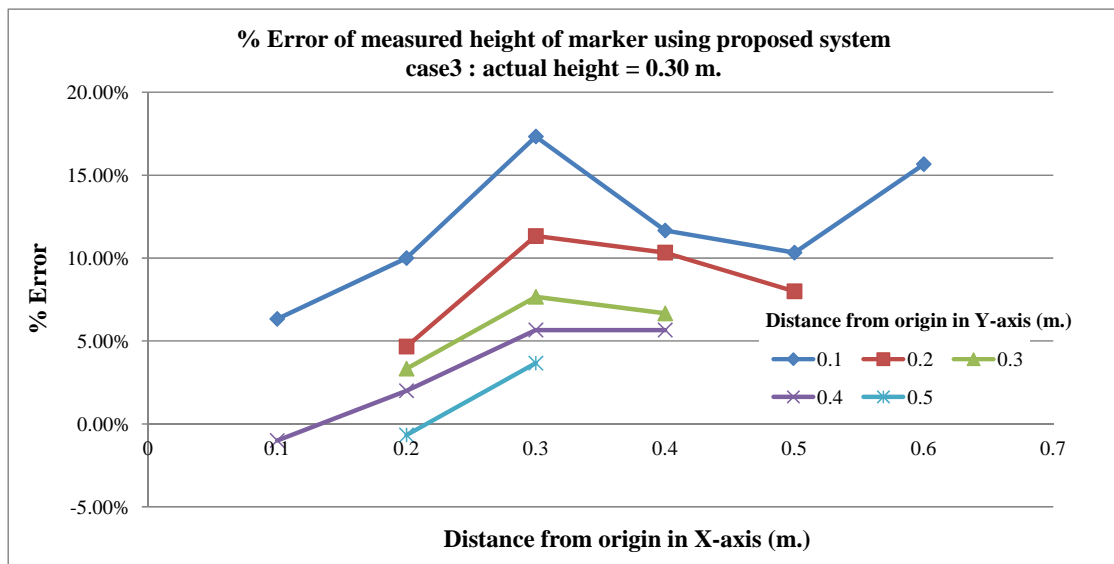


Figure 7.35 Percentage of error of falling height for case 3

The heights of the falling objects measured by system programming were used in the projectile calculation, which represented the unsafe zone from the crane operation. The results of the calculation, which were falling height and horizontal distance, were also presented as text information on the output screen. The horizontal distance as a radius of the base of the 3D parabolic shape was measured from the center of the crane marker. While the virtual unsafe area of the hazards of falling objects from the crane was displayed, the working spaces of the workers were also rendered. Not only the virtual work space of the worker, but also the 2D images contained worker information as shown in the output screen. The proposed system

calculated the distance between the markers in order to compare them with the unsafe area from the crane operation and required space for the workers. If the system could detect the collision between the virtual objects, the color of the virtual objects changed from green to red and sounded warning alerts. Examples of the output screen for each testing case are illustrated from Figure 7.36 to Figure 7.38. In Figure 7.36, the virtual objects of the hazards of falling objects from the crane and work space of the worker did not collide with each other. Thus, the color of both virtual objects was green. On the other hand, the color of the virtual objects, as presented in Figure 7.37 and Figure 7.38, was red due to the results of the collision. The meanings of these results denoted that the workers were in unsafe areas and that they would be potentially struck by a falling object.



Figure 7.36 Example of output screen for case 1



Figure 7.37 Example of output screen for case 2

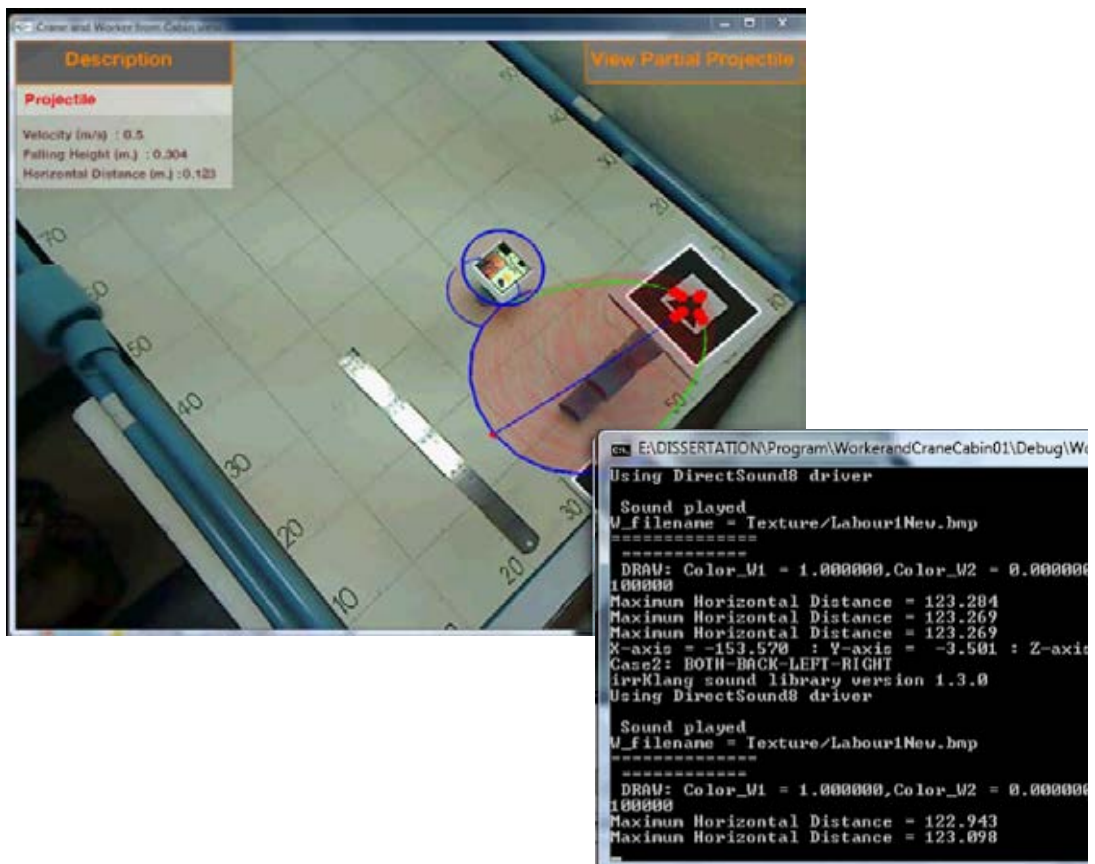


Figure 7.38 Example of output screen for case 3

Table 7.9 presents a comparison of the measured results of the distance between the crane and worker markers using actual measurement and with the system programming. The positions of the crane marker were selected from the previous test cases, as presented in Table 7.6 to Table 7.8. The two positions of each case which provided the percentage of error of falling height less than 3%, as presented in the orange cells, were chosen. Fifteen test cases were carried out. Example descriptions of the verification results in Table 7.9 are described as follows.

In case 1, the falling height was specified as 0.1 cm and the velocity of the falling object was defined as 0.5 m/s. The size of all markers was 0.8 cm. The crane marker was located at coordinates 0.2 and 0.4, measured from the origin of the test area. The horizontal distance calculated manually was equal to 0.071 m. and the radius of the workers' working space was set at 0.05 m. Thus, the minimum distance between the crane and worker markers had to be equal to 0.1207 m. Next, the system measured the falling height, which was 0.1 m. When placing the worker marker in the Y-axis on the test area for checking for the collision, the distance between the crane and worker markers, for which the system could detect a collision, was equal to 0.12 m. However, the actual distance measured by using a ruler was 0.11 m and less than the calculated distance with the system programming. The percentage of the error of the distance between the crane and worker markers for case 1 was 9.09%.

On the other hand, the falling height in case 7 was specified as 0.2 cm. The velocity and all marker sizes were determined the same as in case 1. The crane marker was located at coordinates 0.1 and 0.2, measured from the origin of the test area. The horizontal distance calculated manually was equal to 0.1 m. Hence, the minimum distance between the crane and worker markers had to be equal to 0.15 m. The worker marker was placed in the Y-axis on the test area and the distance between the crane and worker markers, where the system could detect the collision equal to 0.1526 m. and the actual distance, was 0.1530 m. Furthermore, the percentages of the error of the distance between the crane and worker markers for this case were -0.26%.

Table 7.9 Comparison of the distance between the crane and worker markers by actual measurement and by system programming

Case	Crane marker size (m.)	Worker marker size (m.)	Initial velocity (m./s)	Distance between origin and crane marker (m.)		Actual height (m.)	Horizontal distance by manual calculation (m.)	Minimum distance between crane and worker marker which is manual calculated (m.)	Height measured by program (m.)	Worker's working radius (m.)	distance between crane and worker marker measured by program (m.)				Actual distance between crane and worker marker (m.)	%error (measured by program and manual calculation)	%error (measured by program and actual)
				X-axis	Y-axis						X-axis	-X-axis	Y-axis	-Y-axis			
1	0.08	0.08	0.5	0.2	0.4	0.1	0.0707	0.1207	0.1000	0.05				0.1200	0.1100	-0.59%	9.09%
2	0.08	0.08	0.5	0.2	0.4	0.1	0.0707	0.1207	0.1010	0.05		0.1201			0.1190	-0.51%	0.92%
3	0.08	0.08	0.5	0.2	0.4	0.1	0.0707	0.1207	0.0991	0.05			0.1204		0.1200	-0.24%	0.35%
4	0.08	0.08	0.5	0.5	0.5	0.1	0.0707	0.1207	0.1000	0.05				0.1190	0.1150	-1.42%	3.48%
5	0.08	0.08	0.5	0.5	0.5	0.1	0.0707	0.1207	0.1060	0.05	0.1208				0.1200	0.07%	0.67%
6	0.08	0.08	0.5	0.1	0.2	0.2	0.1000	0.1500	0.2090	0.05		0.1501			0.1690	0.07%	-11.18%
7	0.08	0.08	0.5	0.1	0.2	0.2	0.1000	0.1500	0.2240	0.05			0.1526		0.1530	1.73%	-0.26%
8	0.08	0.08	0.5	0.3	0.6	0.2	0.1000	0.1500	0.2000	0.05				0.1516	0.1430	1.04%	5.99%
9	0.08	0.08	0.5	0.3	0.6	0.2	0.1000	0.1500	0.2000	0.05	0.1502				0.1350	0.11%	11.24%
10	0.08	0.08	0.5	0.3	0.6	0.2	0.1000	0.1500	0.2030	0.05		0.1508			0.1580	0.54%	-4.55%
11	0.08	0.05	0.5	0.1	0.4	0.3	0.1225	0.1725	0.2990	0.05				0.1711	0.1720	-0.78%	-0.51%
12	0.08	0.05	0.5	0.1	0.4	0.3	0.1225	0.1725	0.3030	0.05	0.1536				0.1780	-10.96%	-13.72%
13	0.08	0.05	0.5	0.2	0.5	0.3	0.1225	0.1725	0.3000	0.05				0.1713	0.1800	-0.66%	-4.81%
14	0.08	0.05	0.5	0.2	0.5	0.3	0.1225	0.1725	0.3010	0.05		0.1723			0.1920	-0.13%	-10.29%
15	0.08	0.05	0.5	0.2	0.5	0.3	0.1225	0.1725	0.3010	0.05	0.1719				0.1520	-0.31%	13.12%

Not only was testing employed to verify the results in the laboratory, but the system was also tested in the real environment. The pattern and size of the reference and crane markers were similar to those in the previous real environment testing. In addition, the worker marker, whose size was 0.3 m., was located as shown in Figure 7.39. However, the falling distance in this experiment was measured from the bottom boundary of the lower marker to the center of the higher marker, which equaled 9.3 m. A web camera was installed both on the ground level and above the ground level. Tape measurement was applied to measure the distance of the rendered virtual objects, as shown in Figure 7.40. In the real environment testing, the height and radius of the worker's space was set at 1.80 m. and 1.00 m., respectively.



Figure 7.39 Marker of worker setting in real environment testing



Figure 7.40 Tape measurement in real environment testing

The seven situations as presented in Table 7.10 were defined to verify the system. The two values of velocity were input into the system programming. Then,

the worker marker was placed at various positions, which can be classified into the following two patterns as further than and closer than manual calculation.

Table 7.10 Situation for verifying the function for illustrating unsafe work area in the real environment

Situation number	Velocity of falling object (m/s)	Position of web camera	Distance between crane and worker marker setting
1	1	Ground level	further than manual calculation
2	3	Ground level	closer than manual calculation
3	3	Ground level	further than manual calculation
4	1	Above ground level	closer than manual calculation
5	1	Above ground level	further than manual calculation
6	3	Above ground level	closer than manual calculation
7	3	Above ground level	further than manual calculation

The results of the experiments are presented in Table 7.11. In situation number 1, the minimum distance between the markers of the crane and the worker in XY coordinates calculated manually was 2.36 m., and both markers were placed at a position further than the manual calculation to verify the checking results, as shown in Figure 7.41. The system was able to accurately check that the worker was located in a safe working area, as illustrated in Figure 7.42. However, the velocity was changed in situation number 2, which affected the horizontal distance of the falling object. When the system checked for an unsafe condition and discovered that the worker was located in an unsafe working area, the system provided the results in the form of a change in color and a warning sound, as shown in Figure 7.43. The testing process was repeatedly done in situation number 3 but the position of the worker marker was adjusted to be further than that in the manual calculation. The result showed that the system could provide the correct information—that the worker marker was in a safe working area, as shown in Figure 7.44.

Table 7.11 The testing results for verification of the function for illustrating the unsafe working area in the real environment

Situation number	Crane marker size (m.)	Worker marker size (m.)	Initial velocity (m./s)	Actual height (m.)	Horizontal distance by manual calculation (m.)	Minimum distance between crane and worker marker which is manual calculated (m.)	Height measured by program (m.)	Horizontal distance calculated by program (m.)	Worker's working radius (m.)	Minimum distance between crane and labour marker which program must detect (m.)	%error (measured by program and manual calculation)	Actual distance setting (distance between crane and worker markers)	Unsafe working area checking by system programming	Verificaton
														Correct
1	1.00	0.30	1.0	9.30	1.36	2.36	9.20	1.37	1.00	2.37	0.24%	further than manual calculation	SAFE	✓
2	1.00	0.30	3.0	9.30	4.09	5.09	9.20	4.11	1.00	5.11	0.34%	closer than manual calculation	UNSAFE	✓
3	1.00	0.30	3.0	9.30	4.09	5.09	9.20	4.11	1.00	5.11	0.34%	further than manual calculation	SAFE	✓
4	0.30	0.30	1.0	7.20	1.20	2.20	7.05	1.20	1.00	2.20	-0.05%	closer than manual calculation	UNSAFE	✓
5	0.30	0.30	1.0	7.20	1.20	2.20	7.44	1.23	1.00	2.23	1.44%	further than manual calculation	SAFE	✓
6	0.30	0.30	3.0	7.20	3.60	4.60	7.30	3.66	1.00	4.66	1.30%	closer than manual calculation	UNSAFE	✓
7	0.30	0.30	3.0	7.20	3.60	4.60	7.23	3.64	1.00	4.64	0.92%	further than manual calculation	SAFE	✓



Figure 7.41 Example of worker marker setting for situation number 1



Figure 7.42 The output screen of situation number 1 for verifying the function to illustrate the unsafe working area



Figure 7.43 The output screen of situation number 2 for verifying the function to illustrate the unsafe working area

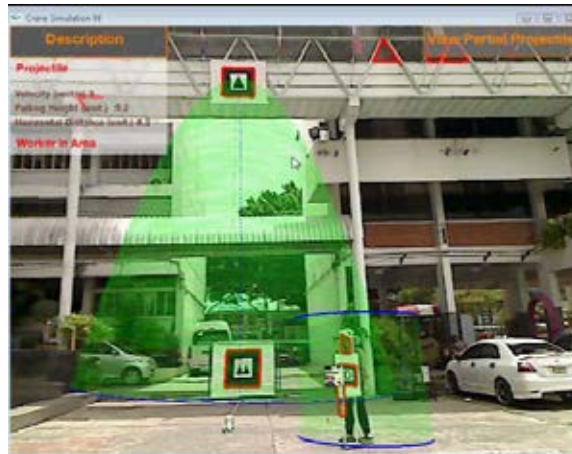


Figure 7.44 The output screen of situation number 3 for verifying the function to illustrate the unsafe working area



Figure 7.45 The output screen of situation number 4 for verifying the function to illustrate the unsafe working area



Figure 7.46 The output screen of situation number 5 for verifying the function to illustrate the unsafe working area

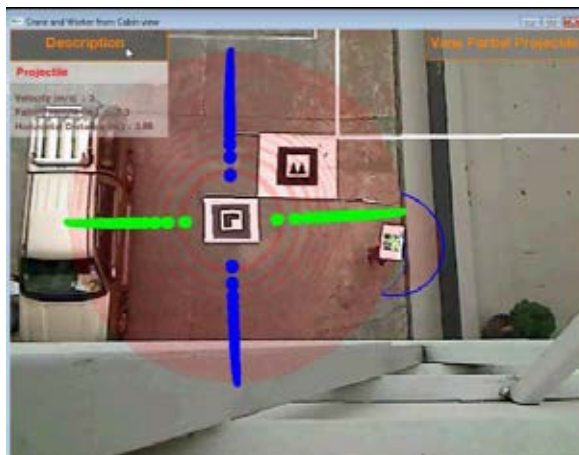


Figure 7.47 The output screen of situation number 6 for verifying the function to illustrate the unsafe working area

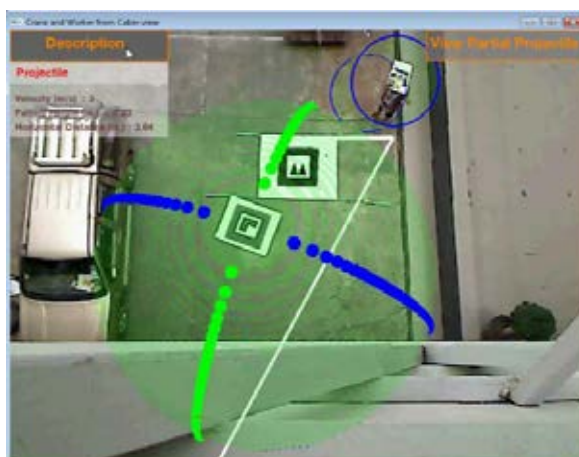


Figure 7.48 The output screen of situation number 7 for verifying the function to illustrate the unsafe working area

7.2.1 Function for presenting the virtual objects

In the laboratory testing, the outputs of the prototype applications, such as safety measure preparation and safety measure monitoring, were correctly rendered as expected. However, this proposed system intended to provide the virtual objects in a real world scene in order to support construction personnel in carrying out safety management at actual construction sites. Therefore, the testing of the function for presenting the virtual objects was carried out.

The virtual objects were created as described in the previous chapter. The marker unit in the text file and the scale of the virtual objects were points of concern. The marker size, which used in the experiments, was 0.3 m. In Figure 7.49, the guardrail with a toe board containing information about the dimension was rendered in the output screen, and Figure 7.50 demonstrates two options for a

guardrail on the stairway. Furthermore, the transparent virtual objects were also tested, as shown in Figure 7.51.



Figure 7.49 Example of 3D virtual guardrail with toe board



Figure 7.50 Examples of 3D virtual guardrails in the required position

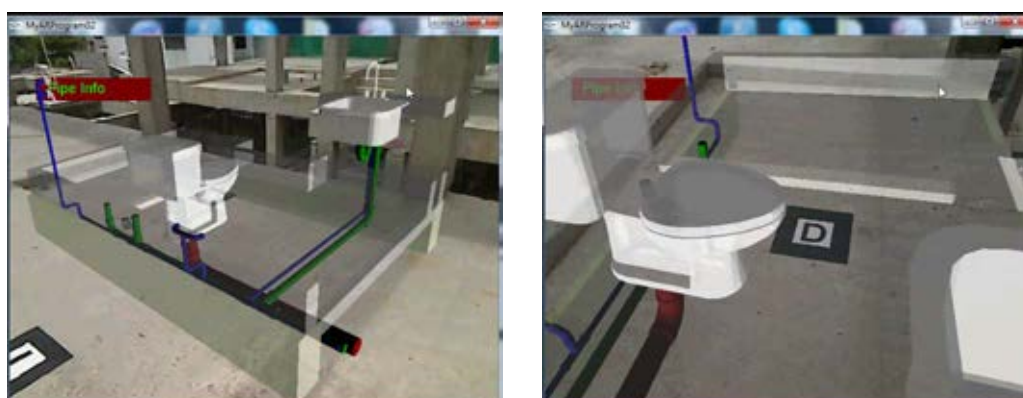


Figure 7.51 Examples of transparent virtual objects

7.3 System Validation

In order to evaluate the proposed system and to measure the improvement of construction personnel regarding situational awareness for safety, the

experiments and questionnaires were designed and implemented at the real construction site. The designed questionnaires aimed at gathering qualitative rather than quantitative feedback were applied, while observation of the subject's performance during the experiment was done. The eight-story high-rise building construction project, which was a residential building, was selected to be the sample project. The twelve site personnel that worked on this project were recruited to participate in testing and answering the questionnaires. The designed questionnaires were divided into seven parts, as presented in [Appendix D](#). The first three parts were used to survey the respondents' demographic and background information regarding visualization techniques and construction safety. The distribution of the questionnaires and the demographic profile of the respondents is presented in Table 7.12. Moreover, the proportion graphs for each variable of the respondents' demographic profile are presented in Figure 7.52 to Figure 7.54.

Table 7.12 Demographic profile of the respondents

Variables	Distribution (n = 12)
Gender	
<i>Male</i>	100%
Age (years)	
<i>Mean</i>	34.17
Education	
<i>High vocational</i>	25%
<i>Bachelor</i>	66.67%
<i>Other (Undergraduate)</i>	8.33%
Work experience (years)	
< 10	50%
10 - 20	25%
> 20	25%
<i>Business type</i>	
<i>Main contractor</i>	66.67%
..... <i>Consultant</i>	33.33%

According to the background of the respondents, only one engineer had personal experience with falling object accidents. However, 33.33% of the respondents felt that accidents would not happen to them and all of these respondents had work experience of more than ten years.

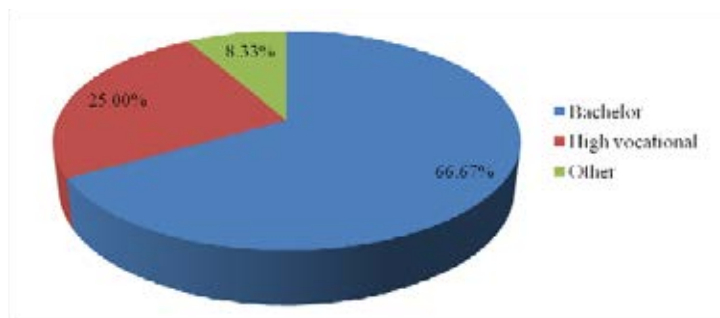


Figure 7.52 Education level of respondents

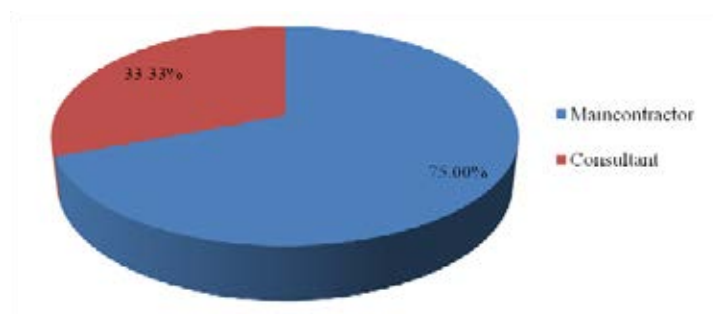


Figure 7.53 Type of company of respondents

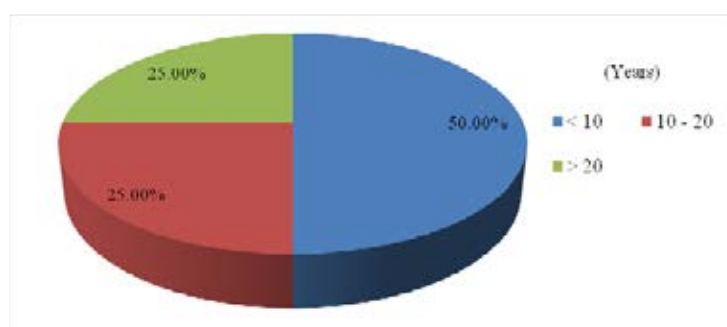


Figure 7.54 Work experience of respondents

Moreover, the subjects were asked to provide their opinions in accordance with three stages of situational awareness, which were perception, understanding, and execution about actual hazards in the real work environment. According to the questionnaire results, half of the respondents could not perceive, understand, or execute actual hazards while they were not in the real work environment. The percentages of the respondents that could perform each stage of situational awareness are presented in Figure 7.55 to Figure 7.57.

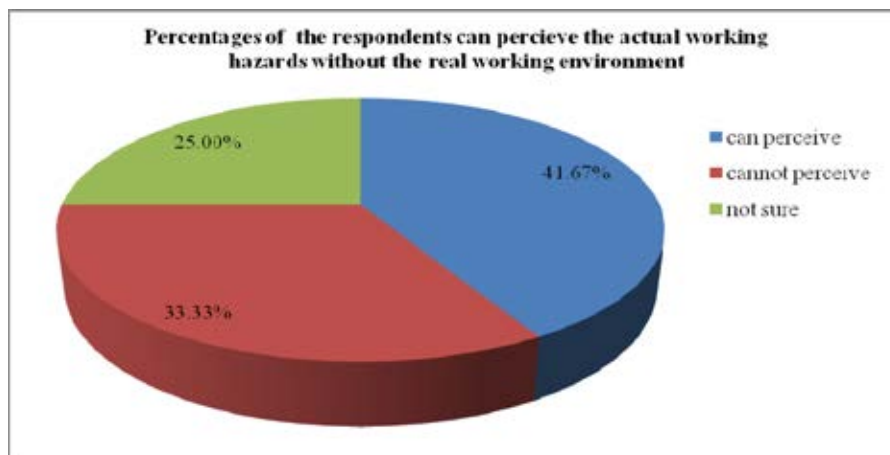


Figure 7.55 Percentages of the respondents that could perceive the actual work hazards without the real work environment

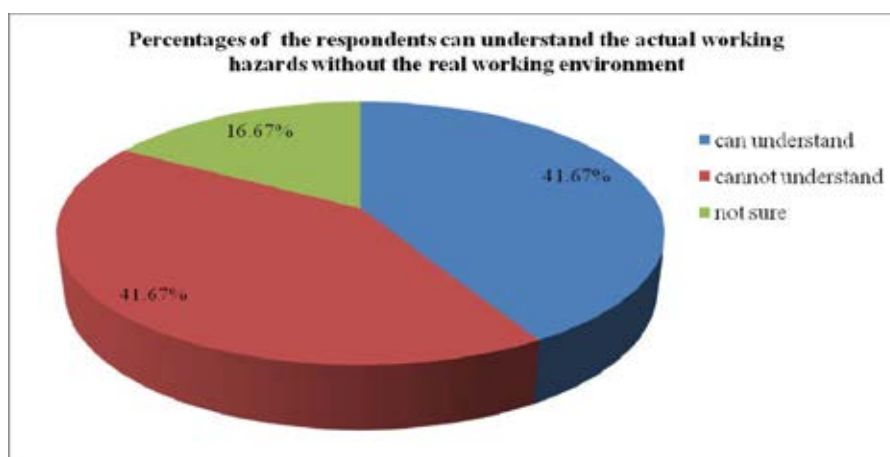


Figure 7.56 Percentages of the respondents that could understand the actual hazards without the real working environment

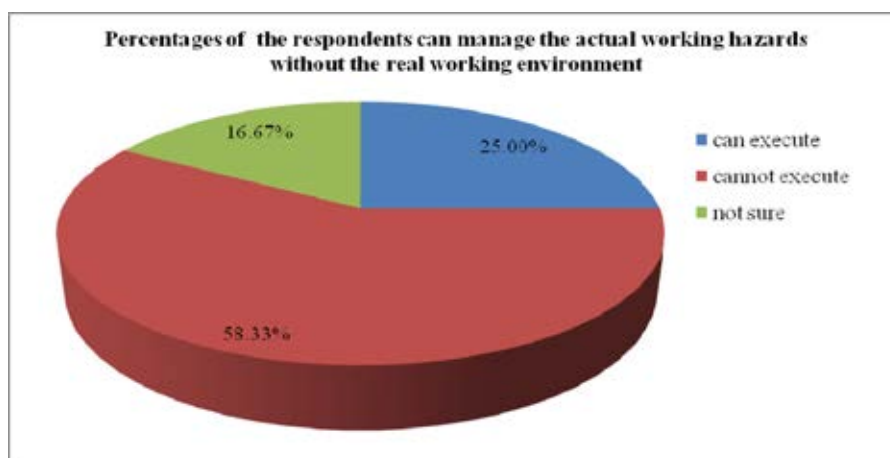


Figure 7.57 Percentages of the respondents that could execute the actual hazards without the real working environment

Then, the subjects were asked to answer the questions in the fourth part of questionnaires, which were the example situations regarding the hazards of falls and falling objects. The information for each situation was provided to the respondents by using text-based and 2D drawings in paper format to investigate the situational awareness of the respondents. Figure 7.58 demonstrates the four example situations. As the questionnaire results indicate, all of the respondents answered that they perceived the hazard of each determined situation. However, their answers about their understanding and execution in dealing with the hazards were different.

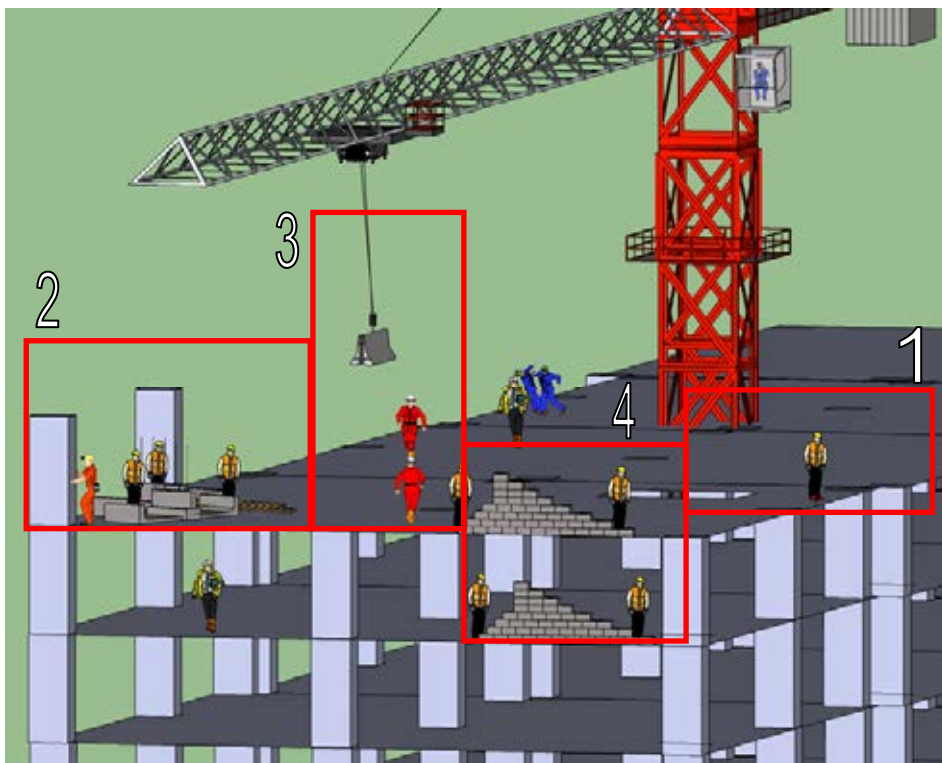


Figure 7.58 The four situations containing hazards of falls and falling objects

For situation number 1, the six respondents were able to exactly identify the fall hazards which could occur when the workers performed the construction activities. In addition, the most common method for preventing accidents offered by the respondents was installation of guardrails. Only three of the respondents stated that other safety measures, such as safety nets, fall protection systems, personnel protection safety, and safety signs for restricted areas, should be provided. The second situation was performing construction activities near the building perimeter while other adjoining work was executed. Three respondents could identify that the overlapping and confinement of the working areas tended to lead to accident occurrence. The methods for protecting the workers from this

hazard that the respondents proposed were preparation of an additional working area, such as a platform with a guardrail, and arrangement of construction activities. For situation number 3, most of the respondents could identify the hazard of this situation, which was the hazard of the falling objects from crane operation. However, the major method that the respondents indicated was inspection of the devices associated with the crane operation. Only three of the respondents stated that they did not allow the workers perform tasks beneath the crane operation path. The last determined situation was that the materials, tools, or debris were piled near the building perimeter or opening at a higher level. Most of the respondents could identify the hazard of falling objects and only one respondent provided an additional comment, which was that the horizontal distance of the falling object would increase when the height of the falling object was higher. In terms of preventing hazards, only five respondents indicated that a falling object protection system should be provided.

According to the questionnaire results, the considerations of the respondents regarding safety in each example situation were different. Then, the proposed system was implemented at a real working area at the sample construction site in order to conduct the experiment according to the four determined situations, as shown in Figure 7.59. The respondents were required to view the outputs of each situation, as demonstrated in Figure 7.60 to Figure 7.64.



Figure 7.59 Implementation of the proposed system in the sample construction project



Figure 7.60 The output of the proposed system for situation number 1

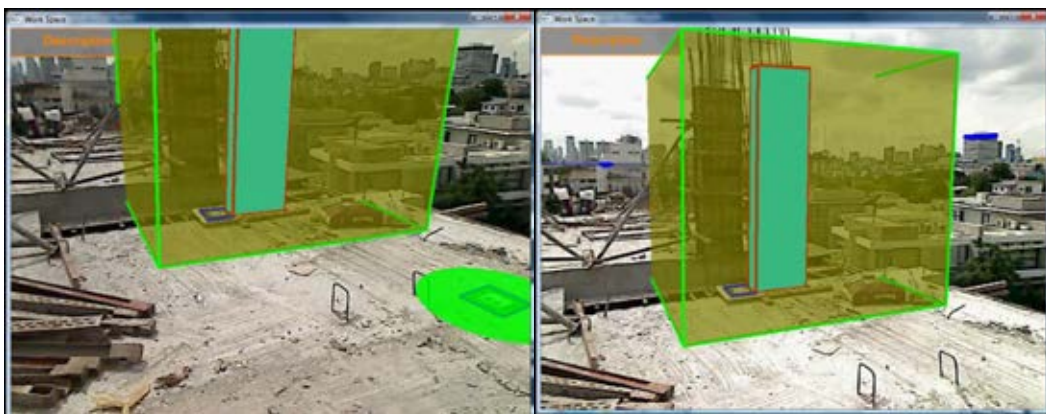


Figure 7.61 The output of the proposed system for situation number 2



Figure 7.62 The output of the proposed system for situation number 3



Figure 7.63 The output of the proposed system for situation number 3 (safe area)

Afterwards, the fifth part of the questionnaire, which was comprised of the same questions as in the fourth part, was used to ask the respondents how they felt about safety after implementation of the proposed system. The respondents indicated that they could easily understand the visualization safety information which was provided in each situation when they considered and arranged safety measures in their construction project.

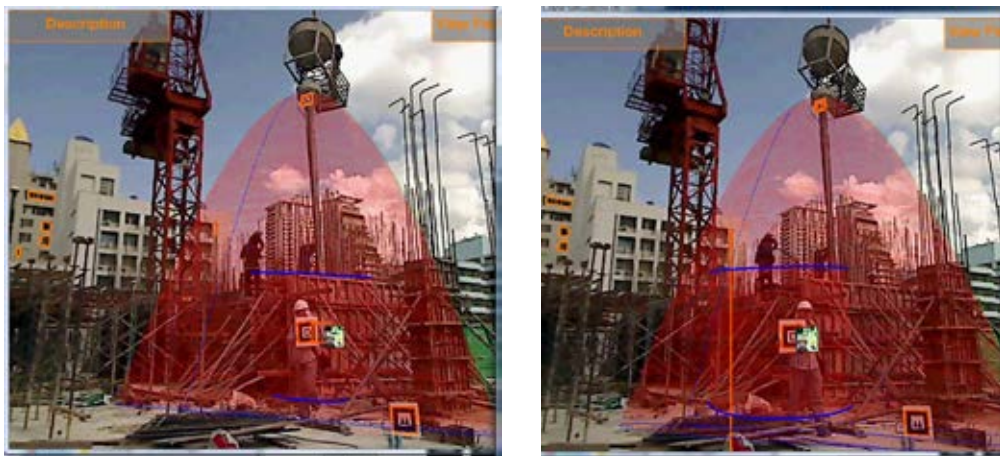


Figure 7.64 The output of the proposed system for situation number 3 (unsafe area)

The sixth part of the questionnaire dealt with the evaluation of the proposed system, where the respondents were asked to provide a score associated with the performance of the system in eleven questions. The meanings of the five scales that were used for rating consisted of 1 (poor) 2 3 4 5 (excellent). The results of this part are presented in

Table 7.13. Most of evaluation results for the proposed system in accordance with the performance of this system to support the respondents in safety management were approximately equal to 4.0/5.0, which means that the proposed system was good in terms of assisting them. Moreover, eight of the respondents had high

confidence in implementing this proposed system in their project and two of them had the highest confidence.

Moreover, the proposed system was evaluated by comparing it with the conventional method of safety management which used only 2D drawing and safety forms based on paper format. The respondents were also asked to rate the performance of the developed system compared with the traditional method in ten questions. The meanings of the five scales that were used for the rating consisted of 1 (totally disagree) 2 3 4 5 (totally agree). The results of this part are presented in Table 7.14. Most of the evaluation results of the proposed system in accordance with its performance compared with the conventional method to support the respondents in safety management were approximately equal to 4.0/5.0, which means that in the respondents' opinion the proposed system can assist them to perceive and understand the safety information for preventing the hazards of falls and falling objects better than the conventional method.

Table 7.13 Results of the evaluation of the proposed system by the respondents

Question no.	Content	Average Score
1	I felt that the developed system aided the perception of fall hazards.	4.17
2	I felt that the developed system aided the perception of falling object hazards.	4.08
3	I felt that the developed system aided the understanding of fall hazards.	4.08
4	I felt that the developed system aided the understanding of falling object hazards.	3.75
5	I felt that the developed system aided the execution of fall hazards.	4.00
6	I felt that the developed system aided the execution of falling object hazards.	4.08
7	I felt that the developed system aided the monitoring process for safety measures, safety signs, and personnel protection equipment.	4.08
8	I felt that the developed system aided in safety training.	4.08
9	I felt that the developed system could provide appropriate safety information.	4.08
10	I felt that the developed system aided the safety management at my construction project.	4.17
11	I felt that I had confidence to implement this developed system in my construction project.	4.00

Table 7.14 Comparison results between the proposed system and the conventional method

Question no.	Content	Average Score
1	I felt that the developed system aided the perception of fall hazards better than the conventional method.	4.08
2	I felt that the developed system aided the perception of falling object hazards better than the conventional method.	4.25
3	I felt that the developed system aided the understanding of fall hazards better than the conventional method.	4.50
4	I felt that the developed system aided the understanding of falling object hazards better than the conventional method.	3.83
5	I felt that the developed system aided the execution of fall hazards better than the conventional method.	4.08
6	I felt that the developed system aided the execution of falling object hazards better than the conventional method.	4.33
7	I felt that the developed system aided the monitoring process for safety measures, safety signs, and personnel protection equipment better than the conventional method.	4.17
8	I felt that the developed system aided the safety training better than the conventional method.	4.33
9	I felt that the developed system could provide the appropriate safety information better than the conventional method.	4.08
10	I felt that the developed system aided the safety management at my construction project better than the conventional method.	4.25

7.4 Discussion of the feasibility of the proposed system implementation

According to the experiments of the proposed system in the real environment and real construction project, the feasibility of the implementation in real practices was analyzed as describe below.

The major benefit of this developed system is the combination of virtual and real information and presents the tangible of unseen and unforeseen information in the real environment. Therefore, the proposed system is feasible to implement in the design and planning process, which required the visual information for understanding the results of the decision making. In the design and planning for preventing the hazards of falling objects, the trajectory of the falling objects is difficult to identify by using the 2D drawings. Although its effect to surrounding environment can be created by using virtual reality, it is expensive and time-consuming. Moreover, it cannot literally reflect the actual conditions. The capability of the designed safety measures also can be evaluated before installation. Similarly, the design and planning process for preventing against the falling objects from crane operation, none of the tools cannot provide the visualization of the hazards of falling objects while operating crane. The virtual hazards information can be used as the guidance in planning process to avoid the occurrence of accidents.

In order to design and plan for preparation of the safety measures, the evaluation of the appropriateness of safety measures typically was done after installation using the supervisors' experience accompanied with safety laws and regulations. The 3D models can be used to enhance the comprehension of the in-charge personnel. However they represent only the geometric form of the safety measures. The consideration of the appropriateness should be carried out with the information of actual work condition to produce the correct decisions. The proposed system could show the virtual safety measures according to the user's perspective. Thus, this benefit can assist the construction personnel for selecting and evaluating the proper safety measures. Not only were safety measures prepared for safe work areas, but determining the required safe working space also should be done. The tape measurement can be applied to perform this task but it requires more effort and sometimes it is too dangerous. The proposed system could easily generate and present the virtual required space. It also can check the conflict of the adjoining work which may influence to the safe condition of considered work area.

For the monitoring, even though the 2D drawing and paper format checklists can be effectively and sufficiently used, the developed system also supply the converted and combined virtual information which the construction personnel, which can easily understand and compare the measurement and specification requirements. The traditional training method consists of presentation of graphical and text information accompanied with the verbal description. As mention above, the barriers to training are language and education level of the labors. In order to provide more understanding of working method, the 3D modeling or animation can be applied. However, the mental workload to memorize such information and integrate it with the real working condition is the overburdened task for the labors. This proposed system can be the tool for helping and communicating among project participants.

Although, this system did not require the resources, such as time or cost as much as the other visualization technology, for example virtual reality to produce all construction project information, the requirements of the expertise in computer vision techniques still existed.

7.5 Conclusion

The proposed system was tested in both the laboratory and the real environment to verify the accuracy of the following three functions: 1) providing the visualization of possible hazards from falling objects, 2) illustrating unsafe work areas, and 3) presenting virtual objects. The developed algorithms were also tested. The virtual objects regarding safety were provided by combining them with

the real world scene by using augmented reality technology. The results of the verification showed that the system could generate the correct virtual information for the testing situations both in the laboratory and in the real environment.

For validation, a high-rise building construction project was selected to be the sample and twelve construction personnel, which consisted of foremen, engineers, architects, and a trainee, were chosen to be the subjects for testing. The questionnaires were applied to collect information on the respondents' backgrounds and their thoughts regarding safety before implementation of the proposed system. Then, the proposed system was implemented in the real conditions of the sample construction project according to the determined situation. The outputs for each situation were provided to the respondents and they were required to evaluate the performance of the developed system. In addition, the system was compared with the conventional method which was used in this project. The overall evaluation results indicated that the proposed system could support the construction personnel when they considered and managed safety in their construction project. Finally, the feasibility of the implementation of the proposed system in the current practices was discussed.

Chapter 8

Research Conclusion and Recommendations

8.1 Conclusion of overall research

Currently, the number of occupational injuries and accidents in the construction industry is still at a high rank compared with other industries. The improvement of safety management in this last decade has not been significantly observed. The number one and two most frequent accidents that occur at construction projects are falls and being struck by a falling object, respectively. The processes for executing safety at construction projects are separated from the main construction processes and rely on the in-charge personnel, who take responsibility for safety. These site personnel, for example engineers, superintendents, foremen, or safety officers, mentally integrate information, including project information, safety laws and regulations, and resources, by themselves. Conventionally, the information is presented based on a 2D paper format and is difficult to understand. The site personnel have to convert the paper-based information and generate a 3D mental picture. This task is tedious and burdensome. Further, it requires the sufficient knowledge and experiences of the in-charge personnel. Moreover, the inherited hazards in the actual environment are excluded from the safety execution. Thus, the processes of hazard identification, safety planning, operation, monitoring, and training do not completely reflect the real working conditions when the workers perform high-risk construction activities.

Therefore, an innovative and proactive approach for supporting construction personnel so that they can carry out safety management by using visualization technology, named augmented reality, was developed in this research. The underlying hazards in high-rise building construction project are mainly focused on to prevent accidents caused by falls from high elevations and being struck by falling objects. This purposed approach can provide virtual safety information and can be superimposed on the real world scene to reflect the actual conditions.

In order to explore the current practices, problems, and limitations of the processes of safety management, such as hazard identification, design and planning, monitoring, and training, a construction site survey containing a walkthrough of construction sites, a direct interview, and photography and video recording were applied. Most of observed construction projects did not fully implement a safety management system for preventing the hazards of falls and falling objects. Additionally, the problems that were discovered from the site observation were that the safety at the sample construction projects was executed in accordance with the minimum requirements of laws and regulations, and the numerous and various

information which was used to achieve safety was only presented in two-dimensional, text-based, and paper format. This information was difficult to convert, was complicated to understand, and it was possible to misinterpret it. Furthermore, the actual conditions in which unseen and unforeseen hazards exist usually are excluded when considering safety. Only construction personnel that had sufficient knowledge and experience could convert, interpret, integrate, and communicate the safety information. Hence, the current practices, such as design and planning for preventing against the falling object and for arrangement of safe work areas, monitoring, and training at the surveyed construction projects was poor and inefficient.

The concept of the proposed system was initiated from these mentioned problems, supported with a literature review. The proposed system, which was named Visualized Safety Management using Augmented Reality Technology System (VSMART System), uses unseen and converted essential safety information along with the actual environment by using augmented reality technology to assist the construction personnel in safety management for construction activities performed at a high elevation. The five modules, which consisted of 1) a module for design and planning for prevention of the hazard of falling object, 2) a module for design and planning for arrangement of safe work areas, 3) a module for monitoring and inspection, 4) a module for safety training, and 5) a module of augmented reality, were developed in this system.

The development and implementation of this system required a preparation process that included hardware and software. A laptop computer, a web camera, and markers were prepared. The development environments which were used for developing the augmented reality application consisted of Microsoft Visual Studio (C/C++ language), ARToolKit, DSVideo, GLUT, OpenVRML, OpenCV, IrrKlang, FreeType, and DirectX. Additionally, the 3D models of safety measures were generated by using CAD software called "Autodesk Revit Architecture." Then the created 3D models were imported into the 3D software called "Autodesk 3D Max" to modify some of the characteristics of building components or safety measures and to add more description. However, the models and animations needed to be converted into the Virtual Reality Modeling Language (VRML) format (.wrl file) so that the augmented reality application could be used. Not only 3D models but 2D images representing safety signs and worker information were also prepared. Furthermore, a database containing worker information, such as profiles, injury records, training courses, current jobs, and required personal protection equipment, was created by using MySQL Workbench.

This research applied the advantages of the computer vision technique in order to support safety management for construction. Thus, the proposed calculation and

algorithms were developed to deal with the underlying hazards. First was the projectile calculation for the falling object, which applied a basic physics formula. Secondly, the collision detection algorithms, which were classified into two types based on the safety scenario, consisted of 1) a collision detection algorithm for preparation of a falling-object protection system and 2) a collision detection algorithm for a safe working area. The proposed calculation and algorithm were implemented with the prototype applications.

As mentioned above, the VSMART System consists of four safety modules which contain fourteen prototype applications to perform the functions of safety management at the construction site. First was a module of design and planning for prevention of the hazard of falling object which comprised sub-modules to identify the hazards of falling objects from the building perimeter, from crane operation to the work area, and from crane operation to the workers' space. For preventing against the falling objects from the building perimeter, the system could provide the visualization of the effect of falling objects to the surrounding buildings and support the construction personnel in the evaluation of the appropriateness of the designed safety measures prior they were installed at the actual work condition. In the applications for prevention the hazards of falling object from crane operation, there were two viewpoints based on the position of the web camera when using the function to identify the hazards of falling objects from the crane operation. When considering the hazards of falling objects from the crane operator's viewpoint, the web camera had to be installed above all of the markers. These applications could assist the in-charge personnel to perceive the potential hazards via the visualization of cover range of falling objects calculated in accordance with the projectile formulas. The virtual hazards range could be used to plan the moving path of crane operation and to be the guidance to define the safety zone and restrict the unauthorized person.

Secondly, a module of design and planning for arrangement of safe work areas contained two sub-modules to assist the site personnel in safety measure preparation and safe work area arrangement. Similar to the previous module, the evaluation of appropriateness of safety measures in the preparation of safe work areas was done after these safety measures were installed. Thus, the first sub-module was developed to assist the process of evaluation of design safety measures in the real environment and to support the decision making process of in-charge personnel. In order to prepare the safe work areas, not only were safety measures supplied, but the construction personnel also have to define the required safe work space for constructing the building component. The application in the second module was developed to help the in-charge personnel when determining the work areas and reduce the space conflict problems.

The third module was safety monitoring, which provided the sub-modules for monitoring the safety measures, safety signs, and personal protection equipment in the construction project. Each application in this module was developed for supporting the in-charge personnel to easily retrieve the required safety information for inspection. Lastly, the safety training module comprised the sub-modules to provide information on safe working processes according to the construction method. The applications in this last module were developed to overcome the problems of memorized work load of the in-charge personnel and communication among the project participants. The proposed system was tested in order to prove the output of each function in the laboratory before testing in the real environment. However, the preliminary experiments in the real environment revealed limitations in the system implementation, such as the unit of marker size and lighting. When testing in the real environment, the unit of marker size must be set as centimeters, which was different from the lab test. The wrong setting would effect to the displayed size of the virtual objects. For the problems regarding lighting, the initial threshold in the second output screen, which was presented the binarized image of video input was set as 100. In case that the lighting condition was too bright or too dark, the threshold value of binary image processing had to be adjusted. These factors influenced the capability of the system in terms of accuracy and tracking.

Then, three developed functions in the system, which were providing the visualization of possible hazards from falling objects, illustrating unsafe work areas, and presenting virtual objects regarding safety, were verified in both the laboratory and the real environment. First, the system was tested to verify the first function and showed that the system could satisfactorily provide the results, which were the identification of the hazards of falling objects in terms of horizontal distance, and the simulation of the safety protection system preparation. Next, the identification of the unsafe work area caused by the hazard of falling objects from crane operation was verified. In the laboratory, the hazards of falling objects identified from the crane operator's viewpoint were selected to be the test cases. Three values of falling-height distance were tested. This function was tested in two scenarios when implemented in the real environment. The last function—to present safety information by rendering virtual objects—was also tested.

For validation, the proposed system was implemented with a real construction project, which was the construction of a high-rise residential building. The twelve project participants were selected to be the samples. The questionnaires were used to collect data in accordance with the respondents' backgrounds and their opinions regarding the safety aspects at this construction project and to evaluate the proposed system. The subjects were required to consider four unsafe scenarios by using only

text information and a 2D drawing. After that, the outputs of the proposed system of each unsafe scenario were provided to them for answering the questionnaires. The questionnaire results indicated that the site personnel thought that the developed system could assist them to perceive and understand the safety information for preventing the hazards of falls and falling objects better than the conventional method, and they had high confidence in implementing this system in their project. Finally, the feasibility of implementation of the proposed system in the current practices at the real construction site was discussed. It is feasible to apply this system in the design and planning process. Moreover, this system could support the monitoring and training in communication aspect.

8.2 Applications and benefits of the proposed system

The VSMART System can support construction personnel in safety management at high-rise building construction projects, particularly regarding hazards from falls and falling objects. This system can create, describe, and display real-time augmented scenes of safety information by tracking a pre-defined marker and registering the virtual objects on top of live video backgrounds of the real world. The user can observe the virtual objects representing the hazards of falling objects, unsafe workplaces, workers' working space, safety measures, safety signs, simulations of construction methods, and training media from different perspectives while they perceive the actual working conditions. The following fourteen applications were developed:

1. Design and planning for preventing of the hazards of falling objects
 - 1.1 Design and planning for preventing of the hazards of falling objects from building perimeter
 - 1.2 Planning for preventing of the hazards of falling objects from crane operation into working area (crane operator's viewpoint)
 - 1.3 Planning for preventing of the hazards of falling objects from crane operation into working area (supervisor's viewpoint)
 - 1.4 Planning for preventing of the hazards of falling objects from crane operation into worker space (crane operator's viewpoint)
 - 1.5 Planning for preventing of the hazards of falling objects from crane operation into worker space (supervisor's viewpoint)
2. Design and planning for arrangement of safe work areas
 - 2.1 Safety measure selection
 - 2.2 Safe working area preparation
3. Safety monitoring
 - 3.1 Safe working area monitoring
 - 3.1.1 Safety measure monitoring

- 3.1.2 Safety sign monitoring
- 3.2 Personal protection equipment monitoring
- 4. Safety training
 - 4.1 Safe assembly
 - 4.1.1 Step-by-step safe assembly
 - 4.1.2 All-in-one safe assembly
 - 4.1.3 Solid and transparent safe assembly
 - 4.2 Training media for safe working process

8.3 Research outcomes

- 1) The product of this research is a prototype system named the Visualized Safety Management using Augmented Reality Technology System (VSMART System), which contained prototype applications to support construction personnel in the processes of design and planning for preventing against the hazards of falling object and for arrangement of safe work areas, safety monitoring, and safety training.
- 2) Two new collision detection algorithms based on the computer vision technique to support the safety protection system arrangement for falling objects and unsafe working area identification were created.
- 3) A conceptual framework for applying augmented reality technology to the development of a safety management system for the construction industry was suggested.

8.4 Research contributions

- 1) The primary contribution of this research consisted in an innovative and proactive approach to improving the current practices of safety management in construction projects, especially construction activities performed at heights. Effective visualization associated with unsafe conditions in the interactive augmented environment was provided to enhance the perception and understanding of construction personnel. The benefits of the developed system consist of:
 - The visualized hazards of falling object from the building perimeter in cooperation with the simulation results of designed safety protection system can support the in-charge personnel in the planning of safety protection system. The potential range of the hazards of falling objects from crane operation can be visualized and used to be the guidance for specifying the unsafe zone.
 - The visualization of virtual safety measures and required safe work spaces in the real environment can help the in-charge personnel in the design and planning process for arrangement of safe work area.

- The virtual safety information were produced to support the processed of monitoring and training. Moreover, it could effectively assist them in carrying out the safety and communication among the project participants.

2) The product of this research is a prototype of the VSMART System, which can assist construction personnel in executing safety in high-rise building construction projects. Furthermore, it can be applied to other construction projects for safe management.

8.5 Recommendations and limitations

1) This system was developed to support safety management regarding the hazards of falls and falling objects at high-rise building construction projects. Other accident causations, such as electrocution or being caught in and/or between objects, were not included in this development.

2) This prototype system was developed in the individual laptop computer environment and was not connected with the network for sharing of information, such as use of a database. Only one web camera was applied for all applications in this research.

3) Image-based tracking was applied in this development. Thus, the marker had to be captured all the time in order to run the applications.

4) Some input data were required by the user, such as the velocity of the falling object.

5) Other factors which may cause or influence potential hazards, such as wind or light, were excluded from this research.

8.6 Future research

1) An advanced device for measuring some input data, such as the velocity of crane hoisting, should be applied to supply the real measured velocity of the crane hoisting movement used in the calculation. Moreover, factors such as wind and light should be included so that all of the factors that influence hazard identification can be integrated.

2) Other hazards when performing construction activities at high-rise building construction projects should be included to improve the proposed system. Moreover, the unseen hazards which influence the health of site personnel such as sound and dust should be considered.

3) At this time, sound warning can be used to alert the site personnel that use a laptop computer that runs the application. Thus, a method for warning the people that are in unsafe conditions should be developed, such as sending a short message to a mobile phone.

4) The concept of this proposed system can be applied to construction projects in other civil engineering domains, such as transportation and infrastructure. This system can provide benefits for other construction projects, such as tunneling or elevated mass rapid transit, in which unseen or unforeseen hazards exist.

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Appendix A

Examples of document for executing safety
from construction site observation

แบบประเมินผลความปลอดภัยและกฎระเบียบ
Safety system evaluate and discipline / Order
โครงการ

จำนวนอุบัติเหตุสัปดาห์ / Accident number per week คน / No คน / Persons ราย / Date 24/3/2555 (สัปดาห์ / Week 6)

ผลการประเมิน คะแนนประเมินประจำสัปดาห์ / Weekly evaluate score 83.15 %

เกณฑ์ในการผ่านประเมินคือร้อยละ.....80%.....

รายการ Item	รายละเอียด / Description	HR / Result			รายการที่พึงแก้ไข Area for Improvement	ถึงไม่ถึงกำหนดการ
		ปฏิบัติตาม Practice	ปฏิบัติตามไม่ครบ Incomplete	ไม่ปฏิบัติตาม Not Practice		
A	กฎระเบียบ / Discipline / order					
1	ต้องใส่บัตรก่อนเข้าหน่วยงาน Put the ID, Card on before enter job site.	1				
2	สวมใส่รองเท้าบู๊ตนิรภัย (Safety Shoes) หมวกนิรภัย และเครื่องแต่งกายรัดกุม / PPE Wear safety shoes, safety hat and uniforms in job site.		1		ไม่สวมใส่รองเท้าบู๊ตนิรภัย	
3	ห้ามสูบบุหรี่ภายในหน่วยงานและนำไฟแช็กเข้าหน่วยงาน ยกเว้นพื้นที่อนุญาตเท่านั้น No smoking in job site and bring cigarette lighter in site except area permitted	1				
4	ห้ามดื่มสุราและไมอนุญาตให้ผู้ที่เสพยาหรือมีอาการมึนเมา เข้ามาในหน่วยงาน No alcohol, not allow drunk people in to job site.	1				
5	ห้ามพกพาอาวุธในหน่วยงาน No weapon allow in job site.	1				
6	ไม่อนุญาตพนันหรือเล่นไพ่ในหน่วยงาน No gambling in job site.	1				
7	ไม่อนุญาตรับประทานอาหารในพื้นที่ทำงานยกเว้นสถานที่กำหนด No food allowed in working area except area to	1				
8	ตรวจสอบบันทึกคนงาน-รถ เข้าออกหน่วยงานก่อสร้าง Check and record worker, car permit to job site.	1				
9	จัดอบรมประจำวันทุกวัน Morning talk daily		1			
10	จัดประชุมความปลอดภัยทุก ๆ สัปดาห์ To set up site safety meeting by weekly.			1		
B	ระบบความปลอดภัย / Safety system					
1	ติดตั้งป้ายเตือน To install the warning signs.		1			
2	ใช้เข็มขัดนิรภัยขณะทำงานสูงเกิน 2.50 เมตร Fasten safety belt while working above 3 M.					1
3	จัดเตรียมจำนวนถังดับเพลิงในหน่วยงานให้เพียงพอรวมทั้งแสดงเครื่องหมายไว้และการตรวจสอบ To prepare adequate number of fire extinguisher in job site with the symbol / sign and checking.	1				
4	การป้องกันการเกิดเพลิงไหม้โดยเตรียมถังดับเพลิงในบริเวณที่ทำงานและใบอนุญาตทำงาน To prepare adequate number of fire extinguisher at working area with hot work permit.	1				
5	ตรวจสอบสายไฟฟ้าก่อนนำมาใช้งาน To inspect electric cable before using.	1				
6	ใช้ปลั๊กเชื่อมสำหรับงานไฟฟ้า To use inlet plug for electricity connection to other locations.	1				
7	จัดเตรียม BREAKER สำหรับงานก่อสร้างมีสภาพสมบูรณ์ To prepare breaker for working in good condition	1				
8	เตรียมโคมไฟแสงสว่างให้เพียงพอในการทำงาน To prepare enough lighting for working.	1				
9	จัดเตรียมตู้เชื่อมพร้อมอุปกรณ์สภาพสมบูรณ์ To prepare welding machine with accessories in good condition.	1				

Figure A-1: Checklist form for evaluating safety system from site observation

Appendix B

Example of markers pattern



Figure B-1: Marker pattern named onetri



Figure B-2: Marker pattern named twotri

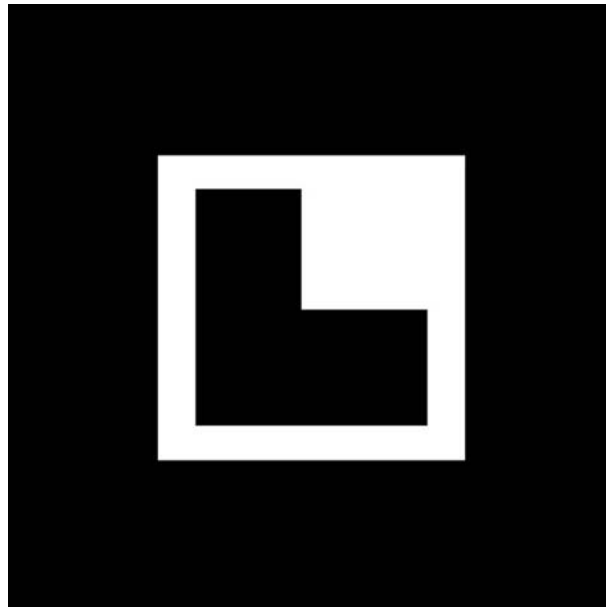


Figure B-3: Marker pattern named samp16



Figure B-4: Marker pattern named down

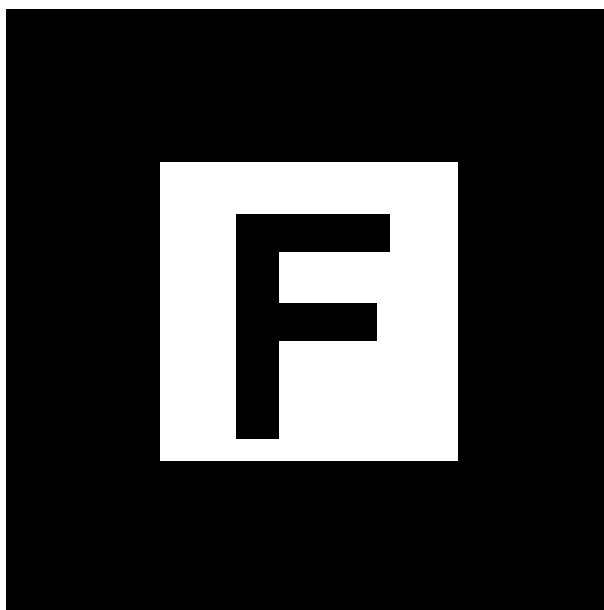


Figure B-5: Marker pattern named front



Figure B-6: Marker pattern named component

Appendix C

Human ergonomics dimensions

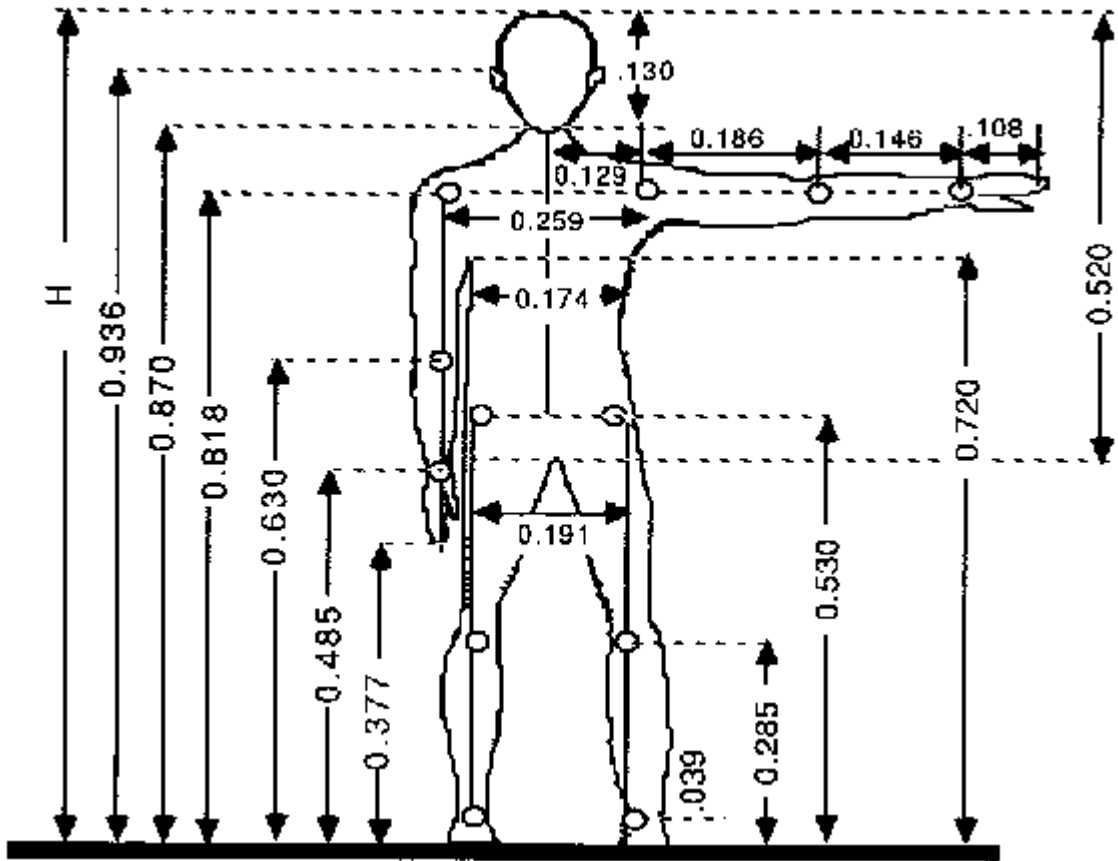


Figure C-1: Relative dimensions of the average human body (Intranont, 2005)

Appendix D

Questionnaires form

..... วิศวกรสนาม (Site Engineer)

..... วิศวกรสำนักงาน

..... เจ้าหน้าที่ความปลอดภัย

..... อื่นๆ(ระบุ

.....)

ประสบการณ์ในการทำงาน ปี

ประสบการณ์ในการทำงานอาคารสูง

ประสบการณ์ในการรับผิดชอบด้านความปลอดภัย ปี

มูลค่าโครงการปัจจุบันที่กำลังดำเนินการ.....

บาท

ลักษณะโครงการปัจจุบันที่กำลังดำเนินการ

.....

ลักษณะธุรกิจของบริษัท

.....ผู้รับเหมาบริษัทพัฒนาอสังหาริมทรัพย์บริษัทที่ปรึกษา

.....หน่วยงานราชการและรัฐวิสาหกิจ

..... อื่นๆ (ระบุ.....)

หน่วยงานที่รับผิดชอบ

..... สำนักงานใหญ่หน่วยงานโครงการ

แบบสอบถามประสบการณ์เกี่ยวกับอุบัติเหตุ

- ท่านเคยประสบอุบัติเหตุตกจากที่สูงหรือไม่
ก. เคย จำนวน ครั้ง ข. ไม่เคย
- ท่านเคยประสบอุบัติเหตุจากสิ่งของหรือวัสดุตกใส่ กระแทก หรือ ฟุ้งชน หรือไม่
ก. เคย จำนวน ครั้ง ข. ไม่เคย
- ในหน่วยงานที่ท่านเคย หรือ กำลังปฏิบัติงาน เคยเกิดอุบัติเหตุจากการตกจากที่สูงหรือไม่
ก. เคย ข. ไม่เคย ค. ไม่แน่ใจ
- ในหน่วยงานที่ท่านเคย หรือ กำลังปฏิบัติงาน เคยเกิดอุบัติเหตุจากสิ่งของหรือวัสดุตกใส่ กระแทก หรือ ฟุ้งชนหรือไม่
ก. เคย ข. ไม่เคย ค. ไม่แน่ใจ
- ท่านทราบถึงอันตรายที่เกิดขึ้นในการปฏิบัติงานในโครงการก่อสร้าง ใช่หรือไม่
ก. ใช่ ข. ไม่ใช่ ค. ไม่แน่ใจ
- ในการปฏิบัติงานในโครงการก่อสร้าง ท่านมักจะคิดว่า อุบัติเหตุจะไม่เกิดขึ้นกับท่าน ใช่หรือไม่
ก. ใช่ ข. ไม่ใช่ ค. ไม่แน่ใจ

ส่วนที่ 2 การนำ visualization techniques มาประยุกต์ใช้ในองค์กร

นิยาม

2D Drawing	หมายถึง	แบบรูปซึ่งแสดงข้อมูลใน 2 มิติ
3D Drawing	หมายถึง	แบบรูปซึ่งแสดงข้อมูลใน 3 มิติ
Virtual Reality (VR)	หมายถึง	สภาวะเสมือนจริงที่จำลองโดยเทคนิคทาง

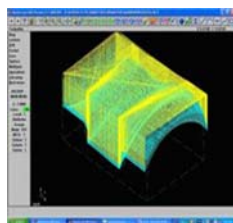
คอมพิวเตอร์

Augmented Reality (AR)	หมายถึง	การนำสภาวะเสมือนจริงผสมเข้ากับสภาพแวดล้อม
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จริง



2D Drawing



3D Drawing



Virtual Reality



Augmented Reality

คำถาม (สามารถตอบได้มากกว่า 1 ข้อ)	Visualization Techniques				None
	2D	3D	VR	AR	
1.ท่านเคยใช้ visualization techniques ไดในการปฏิบัติงาน					
2.โครงการปัจจุบันที่ท่านมีส่วนร่วม มีการใช้ visualization techniques ไดในการดำเนินงาน					
3.ท่านมีความสนใจที่จะนำ visualization techniques ได้ใช้ในการปฏิบัติงาน					

ในกรณีที่ท่านมีความสนใจ กรุณาระบุ ว่า ท่านมีความสนใจที่จะนำไปใช้ในด้านใด อย่างไร (ตัวอย่างการวางแผน การใช้เครื่องจักร, ด้านความปลอดภัย, การใช้พื้นที่ใช้สอย, ขั้นตอนการก่อสร้าง, การใช้แรงงาน)

Visualization techniques	นำไปใช้ด้าน	อย่างไร

ส่วนที่ 3 การจัดการด้านความปลอดภัย

1. ในโครงการของท่านมีการใช้เครื่องมือใดในการกระบวนการจัดการด้านความปลอดภัย

คำถาม (สามารถตอบได้มากกว่า 1 ข้อ)	Visualization Techniques				Paper forms	None
	2D	3D	VR	AR		
1.การระบุสภาพอันตรายในการทำงาน (Hazard identification)						
2.การวางแผนความปลอดภัย (Safety planning)						
3.การตรวจสอบและควบคุมความปลอดภัย (Monitoring)						
4. การฝึกอบรมด้านความปลอดภัย (Training)						

2. หน่วยงานใดและตำแหน่งใด เป็นผู้รับผิดชอบในการจัดเตรียมอุปกรณ์ด้านความปลอดภัย

.....

3. ท่านมีส่วนร่วมในการจัดการด้านความปลอดภัยในโครงการหรือไม่ อย่างไร

ก. มี คือ ข. ไม่มี

4. ท่านคิดว่า ผู้ที่ปฏิบัติงานในโครงการก่อสร้าง จำเป็นต้องทราบถึงสภาพความไม่ปลอดภัยที่อาจทำให้เกิดอุบัติเหตุ หรือไม่ อย่างไร

ก. จำเป็น เพราะ

.....

ข. ไม่จำเป็น เพราะ.....

ค. ไม่แน่ใจ

5. ท่านคิดว่า ท่านสามารถ รับทราบ สภาพความไม่ปลอดภัยที่แท้จริงในการทำงาน โดยไม่จำเป็นต้องอยู่ในสภาพแวดล้อมการทำงานจริง ได้หรือไม่

ก. ได้ ข. ไม่ได้ ค. ไม่แน่ใจ

6. ท่านคิดว่า ท่านสามารถ เข้าใจ สภาพความไม่ปลอดภัยที่แท้จริงในการทำงาน โดยไม่จำเป็นต้องอยู่ในสภาพแวดล้อมการทำงานจริง ได้หรือไม่

ก. ได้ ข. ไม่ได้ ค. ไม่แน่ใจ

7. ท่านคิดว่า ท่านสามารถ จัดการ สภาพความไม่ปลอดภัยที่แท้จริงในการทำงาน โดยไม่จำเป็นต้องอยู่ในสภาพแวดล้อมการทำงานจริง ได้หรือไม่

ก. ได้ ข. ไม่ได้ ค. ไม่แน่ใจ

8. อุปกรณ์ด้านความปลอดภัยในหน่วยงานของท่านที่ถูกจัดเตรียมไว้ อยู่ในสภาพใด
- ก. ไม่ครบถ้วนตามข้อกำหนดขั้นต่ำของกฎหมาย
- ข. ตามข้อกำหนดขั้นต่ำของกฎหมาย
- ค. ถูกปรับเปลี่ยนให้เหมาะสมกับการทำงานและปลอดภัยมากขึ้น ตามประสบการณ์ของผู้วางแผน และจัดเตรียม
9. ท่านทราบและเข้าใจถึงวิธีการใช้อุปกรณ์ด้านความปลอดภัยสำหรับป้องกันอุบัติเหตุจากการตกจากที่สูงในหน่วยงานก่อสร้างในระดับใด
- น้อยมาก น้อย ปานกลาง มาก มากที่สุด
10. ท่านทราบและเข้าใจถึงวิธีการใช้อุปกรณ์ด้านความปลอดภัยสำหรับป้องกันอุบัติเหตุจากวัสดุตกหล่นกระแทก ฟุ้งชนในหน่วยงานก่อสร้างในระดับใด
- น้อยมาก น้อย ปานกลาง มาก มากที่สุด
11. ท่านทราบและเข้าใจถึงกฎหมายและข้อกำหนดเกี่ยวกับความปลอดภัยในหน่วยงานก่อสร้างในระดับใด
- น้อยมาก น้อย ปานกลาง มาก มากที่สุด
12. ท่านคิดว่า ควรมีวิธีการสำหรับช่วยในการจัดการด้านความปลอดภัยโดยการนำเทคโนโลยี AR มาประยุกต์ใช้ หรือไม่ อย่างไร
-
-
-
-
13. ในความเห็นของท่าน เทคโนโลยี AR น่าจะนำไปใช้สำหรับการทำงานใดในโครงการก่อสร้าง เพราะเหตุใด
-
-
-
-

ส่วนที่ 4 ทดสอบการจัดการด้านความปลอดภัย จากสถานการณ์สมมติ (ก่อนใช้ระบบ)

กรุณาเลือกคำตอบโดยกาเครื่องหมายวงกลม พร้อมให้คำอธิบาย

กรณีที่1: การปฏิบัติงานบริเวณริมอาคาร หรือ ใกล้ช่องเปิดที่ระดับความสูงจากพื้นดินมากกว่า 2.00 เมตร

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

กรณีที่2: การปฏิบัติงานบริเวณขอบอาคาร ซึ่งอยู่ใกล้เคียงกับกิจกรรมก่อสร้างอื่นที่ระดับความสูงจากพื้นดินมากกว่า 2.00 เมตร

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

กรณีที่3: การปฏิบัติงานภายใต้การเคลื่อนที่ของเครน

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

กรณีที่4: วัสดุ เครื่องมือ หรือ เศษขยะ ถูกกองไว้ใกล้บริเวณขอบอาคาร หรือช่องเปิด ที่ระดับความสูงจากพื้นดินมากกว่า 2.00 เมตร

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

ส่วนที่ 5 ทดสอบการจัดการด้านความปลอดภัย จากสถานการณ์สมมติ (หลังใช้ระบบ)

กรุณาเลือกคำตอบโดยกาเครื่องหมายวงกลม พร้อมให้คำอธิบาย

กรณีที่1: การปฏิบัติงานบริเวณริมอาคาร หรือ ใกล้ช่องเปิดที่ระดับความสูงจากพื้นดินมากกว่า 2.00 เมตร

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

กรณีที่2: การปฏิบัติงานบริเวณขอบอาคาร ซึ่งอยู่ใกล้เคียงกับกิจกรรมก่อสร้างอื่นที่ระดับความสูงจากพื้นดินมากกว่า 2.00 เมตร

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

กรณีที่3: การปฏิบัติงานภายใต้การเคลื่อนที่ของเครน

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

กรณีที่4: วัสดุ เครื่องมือ หรือ เศษขยะ ถูกกองไว้ใกล้บริเวณขอบอาคาร หรือช่องเปิด ที่ระดับความสูงจากพื้นดินมากกว่า 2.00 เมตร

- 1) ท่านรับรู้สภาพความไม่ปลอดภัยหรือไม่
 - ก. ทราบ
 - ข. ไม่ทราบ
 - ค. ไม่แน่ใจ
- 2) ท่านเข้าใจหรือไม่ว่า สภาพความไม่ปลอดภัยที่เกิดขึ้น คืออะไร
 - ก. เข้าใจ คือ.....
 - ข. ไม่เข้าใจ
 - ค. ไม่แน่ใจ
- 3) ท่านจะดำเนินการอย่างไร เพื่อจัดการสภาพความไม่ปลอดภัยที่เกิดขึ้น
 - ก. ดำเนินการ โดย.....
 - ข. ไม่ดำเนินการ
 - ค. ไม่แน่ใจ

ส่วนที่ 6 การประเมินระบบต้นแบบที่พัฒนาขึ้นเพื่อสนับสนุนการจัดการความปลอดภัยในงานก่อสร้าง

กรุณาให้ประเมินระบบต้นแบบที่พัฒนาขึ้น ตามความเห็นของท่าน โดยระดับคะแนนมีความหมายดังนี้

ระดับคะแนน	1	หมายถึง	แย่มาก
ระดับคะแนน	2	หมายถึง	ค่อนข้างแย่มาก
ระดับคะแนน	3	หมายถึง	ปานกลาง
ระดับคะแนน	4	หมายถึง	ดี
ระดับคะแนน	5	หมายถึง	ดีมาก

หัวข้อการประเมินระบบ	การประเมินผล				
	1	2	3	4	5
1. ระบบช่วยให้ท่าน รับรู้ อันตรายจากการตกจากที่สูงได้	1	2	3	4	5
2. ระบบช่วยให้ท่าน รับรู้ อันตรายจากวัสดุตกหล่น กระแทก หรือ พุ่งชนได้	1	2	3	4	5
3. ระบบช่วยให้ท่าน เข้าใจ อันตรายจากการตกจากที่สูงได้	1	2	3	4	5
4. ระบบช่วยให้ท่าน เข้าใจ อันตรายจากวัสดุตกหล่น กระแทก หรือ พุ่งชนได้	1	2	3	4	5
5. ระบบช่วยให้ท่านสามารถ จัดการ อันตรายจากการตกจากที่สูงได้	1	2	3	4	5
6. ระบบช่วยให้ท่านสามารถ จัดการ อันตรายจากวัสดุตกหล่น กระแทก หรือ พุ่งชนได้	1	2	3	4	5
7. ระบบช่วยให้ท่านสามารถตรวจสอบ และควบคุม อุปกรณ์ด้านความปลอดภัย ป้ายสัญลักษณ์เกี่ยวกับความปลอดภัยและอุปกรณ์ด้านความปลอดภัยส่วนบุคคลในหน่วยงานของท่านได้	1	2	3	4	5
8. ระบบช่วยให้ท่านสามารถทำการฝึกอบรมเกี่ยวกับความปลอดภัยในการปฏิบัติงานได้	1	2	3	4	5
9. ระบบสามารถให้ข้อมูลเกี่ยวกับความปลอดภัยได้อย่างเหมาะสม	1	2	3	4	5
10. ระบบช่วยท่านให้สามารถจัดการด้านความปลอดภัยในหน่วยงานก่อสร้างได้	1	2	3	4	5

11. ท่านมีความเชื่อมั่นในการนำระบบไปใช้เพื่อจัดการด้านความปลอดภัยในงานก่อสร้าง ในระดับใด

ก. ไม่เชื่อมั่น ข. ไม่ค่อยเชื่อมั่น ค. ปานกลาง ง. เชื่อมั่น จ. เชื่อมั่นมาก

ข้อเสนอแนะเพิ่มเติม

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ส่วนที่ 7 การประเมินระบบต้นแบบที่พัฒนาขึ้นเทียบกับการใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน

กรุณาให้ประเมินเปรียบเทียบระบบต้นแบบกับการใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน ตามความเห็นของท่าน โดยระดับคะแนนมีความหมายดังนี้

ระดับคะแนน	1	หมายถึง	ไม่เห็นด้วยอย่างมาก
ระดับคะแนน	2	หมายถึง	ไม่เห็นด้วย
ระดับคะแนน	3	หมายถึง	ไม่มีความเห็น
ระดับคะแนน	4	หมายถึง	เห็นด้วย
ระดับคะแนน	5	หมายถึง	เห็นด้วยอย่างมาก

หัวข้อการประเมินระบบ	การประเมินผล				
	1	2	3	4	5
1. ระบบช่วยให้ท่าน รับรู้ อันตรายจากการตกจากที่สูง <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
2. ระบบช่วยให้ท่าน รับรู้ อันตรายจากวัสดุตกหล่น กระแทก หรือ ฟุ้งชน <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
3. ระบบช่วยให้ท่าน เข้าใจ อันตรายจากการตกจากที่สูง <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
4. ระบบช่วยให้ท่าน เข้าใจ อันตรายจากวัสดุตกหล่น กระแทก หรือ ฟุ้งชน <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
5. ระบบช่วยให้ท่านสามารถ จัดการ อันตรายจากการตกจากที่สูง <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
6. ระบบช่วยให้ท่านสามารถ จัดการ อันตรายจากวัสดุตกหล่น กระแทก หรือ ฟุ้งชน <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
7. ระบบช่วยให้ท่านสามารถตรวจสอบ และควบคุม อุปกรณ์ด้านความปลอดภัย ป้ายสัญลักษณ์เกี่ยวกับความปลอดภัยและอุปกรณ์ด้านความปลอดภัยส่วนบุคคลในหน่วยงานของท่าน <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
8. ระบบช่วยให้ท่านสามารถทำการฝึกอบรมเกี่ยวกับความปลอดภัยในการปฏิบัติงาน <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
9. ระบบสามารถให้ข้อมูลเกี่ยวกับความปลอดภัย <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5
10. ระบบช่วยท่านให้สามารถจัดการด้านความปลอดภัยในหน่วยงานก่อสร้าง <u>ดีกว่า</u> การใช้แบบรูป 2 มิติและแบบฟอร์มในการทำงาน	1	2	3	4	5

Appendix E

Raw data results of the evaluation of proposed system

Table E-1 Raw data of results of questionnaires section 6

Question no.	Content	Respondent no.												Average Score
		1	2	3	4	5	6	7	8	9	10	11	12	
1	hazards	4	4	5	4	5	3	5	4	5	4	4	3	4.17
2	I felt that the developed system aided the perception of falling object hazards	4	4	4	4	5	3	5	4	4	4	4	4	4.08
3	I felt that the developed system aided the understanding of fall hazards	4	4	5	4	5	3	5	5	5	4	3	2	4.08
4	I felt that the developed system aided the understanding of falling object hazards	4	4	4	4	5	3	4	5	4	3	3	2	3.75
5	hazards	4	3	4	4	5	4	4	4	5	4	4	3	4.00
6	I felt that the developed system aided the execution for falling object hazards	3	4	5	4	4	4	5	4	5	4	4	3	4.08
7	I felt that the developed system aided the monitoring process for safety measures, safety signs, and personnel protection equipment	4	4	5	4	4	4	5	5	4	4	4	2	4.08
8	I felt that the developed system aided the safety training	5	3	4	4	5	4	4	5	4	3	5	3	4.08
9	I felt that the developed system can provide the appropriate safety information	5	4	4	4	5	4	5	4	4	4	4	2	4.08
10	I felt that the developed system aided the safety management at my construction project	4	4	4	5	5	4	5	4	4	4	4	3	4.17
11	I felt that I have confidence to implement this developed system in my construction project	4	4	4	4	5	4	4	4	5	3	3	4	4.00

Table E-1 Raw data of results of questionnaires section 7

Question no.	Content	Respondent no.												Average Score
		1	2	3	4	5	6	7	8	9	10	11	12	
1	I felt that the developed system aided the perception of fall hazards better than the conventional method	4	4	5	5	5	4	4	4	4	3	4	3	4.08
2	I felt that the developed system aided the perception of falling object hazards better than the conventional method	4	4	5	5	5	5	4	4	4	3	4	4	4.25
3	I felt that the developed system aided the understanding of fall hazards better than the conventional method	4	4	5	5	4	5	5	5	4	4	5	4	4.50
4	I felt that the developed system aided the understanding of falling object hazards better than the conventional method	3	3	5	5	5	4	4	4	3	4	4	2	3.83
5	I felt that the developed system aided the execution for fall hazards better than the conventional method	4	4	5	5	5	5	4	4	3	4	4	2	4.08
6	I felt that the developed system aided the execution for falling object hazards better than the conventional method	3	4	5	5	5	5	5	5	4	3	4	4	4.33
7	I felt that the developed system aided the monitoring process for safety measures, safety signs, and personnel protection equipment better than the conventional method	3	4	5	5	4	5	4	4	4	4	4	4	4.17
8	I felt that the developed system aided the safety training better than the conventional method	5	4	5	5	5	5	3	3	5	4	4	4	4.33
9	I felt that the developed system can provide the appropriate safety information better than the conventional method	4	4	5	5	5	4	4	4	5	3	4	2	4.08
10	I felt that the developed system aided the safety management at my construction project better than the conventional method	4	3	5	5	5	5	4	4	5	3	4	4	4.25

Appendix F

Examples of Source Codes of the Development of VSMART System

```
-----  
--  
// Source code for safety measures monitoring  
// created by Petcharat Limsupreeyarat
```



```

// Monitor_Measures.cpp
-----
--
#include <iostream>

#ifdef _WIN32
#endif
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>

#include <afx.h>
#ifdef __APPLE__
# include <GL/glut.h>
#else
# include <GLUT/glut.h>
#endif
#include <AR/gsub.h>
#include <AR/param.h>
#include <AR/ar.h>
#include <AR/video.h>

#include <AR/arvrml.h>

#include <stdio.h>
#include <cv.h>
#include <cxcore.h>
#include <highgui.h>

#include <io.h>
#include <fcntl.h>

#include <iostream>
#include <cstdio>
#include <string.h>
#include <cstdlib>
#include <math.h>
#include <vector>

#include "object.h"

#include <stdarg.h>
#include "freetype.h"

freetype_mod::font_data our_font;

#include <tchar.h>
#include <shellapi.h>
#pragma comment(lib, "shell32.lib")

using namespace std;

#pragma comment(lib, "libAR.lib")
#pragma comment(lib, "libARgsub.lib")
#pragma comment(lib, "libARvideo.lib")
#pragma comment(lib, "opengl32.lib")
#pragma comment(lib, "glut32.lib")

#pragma comment(lib, "libarvrml.lib")
#pragma comment(lib, "openvrml.lib")

```

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#pragma comment(lib, "openvrml-gl.lib")
#pragma comment(lib, "antlrld.lib")
#pragma comment(lib, "regexd.lib")

#pragma comment(lib, "cv.lib")
#pragma comment(lib, "cvaux.lib")
#pragma comment(lib, "cxcore.lib")
#pragma comment(lib, "highgui.lib")
#pragma comment(lib, "cxts.lib")
#pragma comment(lib, "ml.lib")
#pragma comment(lib, "cvhaartraining.lib")

#pragma comment(lib, "freetype.lib")

#pragma comment(lib, "irrKlang.lib")

#pragma warning(disable : 4996)

#define COLLIDE_DIST 30000.0

IplImage *image = NULL;

/* Object Data */
Char          *model_name = "Data\\object_dataRealMo2.txt";
ObjectData_T  *object;
int           objectnum;

int           xsize, ysize;
int           thresh = 100;
int           count = 0;

#ifdef _WIN32
char          *vconf = "Data\\WDM_camera_flipV.xml";
#else
char          *vconf = "";
#endif

char          *cparam_name = "Data\\camera_para.dat";
ARParam      cparam;

//OpenCV

IplImage *img_IN;
IplImage *img_TEMP;
IplImage *img_GRAY;

// vrml variables

int           Vrml_Check_Case = 0;
int           VrmlNum;
int           TextureNum;
//-----
--
//Declare Function
//-----
--

static void    init(void);
static void    cleanup(void);
static void    keyEvent( unsigned char key, int x, int y);

```

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static void    mainLoop(void);
static void    mouseFunc(int button, int state, int x, int y);
static void    draw( ObjectData_T *object, int objectnum );
static void    setupLighting(void);
static void    setupMaterial(void);

//OpenCV
static void onTrackbar(int position);

//-----
// Main Function
//-----
int main(int argc, char **argv)

    glutInit(&argc, argv);

    init();

    arVideoCapStart();

    argMainLoop( mouseFunc, keyEvent, mainLoop );

    return (0);

}
//-----
// Init Function
//-----
static void init( void )
{
    ARParam    wparam;
    int        i;

    if( arVideoOpen( vconf ) < 0 ) exit(0);

    if( arVideoInqSize(&xsize, &ysize) < 0 ) exit(0);
    printf("Image size (x,y) = (%d,%d)\n", xsize, ysize);

    if( arParamLoad(cparam_name, 1, &wparam) < 0 ) {
        printf("Camera parameter load error !!\n");
        exit(0);
    }

    arParamChangeSize( &wparam, xsize, ysize, &cparam );
    arInitCparam( &cparam );
    printf("*** Camera Parameter ***\n");
    arParamDisp( &cparam );

    if( (object=read_ObjData(model_name, &objectnum)) == NULL )
        exit(0);
    argInit( &cparam, 1.0, 0, 0, 0, 0 );

    glutSetWindowTitle( "Safety Measures Monitoring" );

    //OpenCV
    int TrackbarInitValue = 100;
    cvNamedWindow("OpenCV");

    img_IN = cvCreateImage(cvSize(arImXsize, arImYsize),
IPL_DEPTH_8U, 4);

```

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        img_TEMP = cvCreateImage(cvSize(arImXsize, arImYsize),
IPL_DEPTH_8U, 3);
        img_GRAY = cvCreateImage(cvSize(arImXsize, arImYsize),
IPL_DEPTH_8U, 1);

        cvCreateTrackbar("Threshhold", "OpenCV", &TrackbarInitValue,
255, onTrackbar);
        cvSetTrackbarPos("Threshhold", "OpenCV", 100);

    }
    //-----
    // Mainloop Function
    //-----
    static void mainLoop(void)
    {
        ARUint8          *dataPtr;
        ARMarkerInfo     *marker_info;
        int              marker_num;
        int              i, j, k;
        double           wmat1[3][4], wmat2[3][4];
        double           scale = 0.5;

        if( (dataPtr = (ARUint8 *)arVideoGetImage()) == NULL ) {
            arUtilSleep(2);
            return;
        }
        if( count == 0 ) arUtilTimerReset();
        count++;

        arVrmlTimerUpdate();

        argDrawMode2D();
        argDispImage( dataPtr, 0, 0 );

        memcpy(img_IN->imageData, dataPtr, img_IN->imageSize);

        cvCvtColor(img_IN, img_TEMP, CV_RGBA2BGR);

        cvCvtColor(img_TEMP, img_GRAY, CV_BGR2GRAY);

        onTrackbar(thresh);
        cvShowImage("OpenCV", img_GRAY);

        if( arDetectMarker(dataPtr, thresh, &marker_info, &marker_num)
< 0 ) {
            cleanup();
            exit(0);}

        for( i = 0; i < marker_num; i++ ) {
            argDrawSquare(marker_info[i].vertex, 0, 0);
        }

        arVideoCapNext();

        argDrawMode3D();
        argDraw3dCamera(0, 0);

        glClearDepth(1.0);
        glClear(GL_DEPTH_BUFFER_BIT);

        for (i = 0; i < objectnum; i++)

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```

    {
        k = -1;
        for( j = 0; j < marker_num; j++ ) {
            if( object[i].id == marker_info[j].id ) {
                glColor3f( 0.0, 1.0, 0.0 );
                argDrawSquare(marker_info[j].vertex,0,0);

                if( k == -1 ) k = j;
                else if( marker_info[k].cf <
marker_info[j].cf ) k = j;
            }

            if( k == -1 ) {
                object[i].visible = 0;
                continue;
            }

            if( object[i].visible == 0 ) {
                arGetTransMat(&marker_info[k],
object[i].marker_center, object[i].marker_width,
object[i].trans);
                TextureNum = i;
                VrmlNum      = object[i].vrml_id;
            }
            else
                arGetTransMatCont(&marker_info[k], object[i].trans,
object[i].marker_center, object[i].marker_width,
object[i].trans);
                TextureNum = i;
                VrmlNum      = object[i].vrml_id;
            }

            object[i].visible = 1;

            draw(object, objectnum);
        }

        argSwapBuffers();
    }

static void draw( ObjectData_T *object, int objectnum )
{
    double      gl_para[16];          // ARToolkit->OpenGL
    double vrml_scale = 0.1;         ///=====for lab
    //double vrml_scale = 1.0;      ///=====real
    int         i;
    int         xpos, ypos;
    int         object_scale = 1.0; // effect to image position

    argDrawMode3D();
    argDraw3dCamera(0, 0);

    glEnable(GL_TEXTURE_2D);
    glTexEnvf(GL_TEXTURE_ENV, GL_TEXTURE_ENV_MODE, GL_DECAL);

    glEnable(GL_DEPTH_TEST);
    glDepthFunc(GL_LEQUAL);

```

```

setupLighting();
glEnable(GL_LIGHTING);
glEnable(GL_LIGHT0);
glEnable(GL_LIGHT1);

setupMaterial();

for (i = 0; i < objectnum; i++){
    xpos = - 0.5*object[i].marker_width;
    ypos = - 0.5*object[i].marker_width;
}

for (i = 0; i < objectnum; i++){
    argConvGlpara(object[TextureNum].trans, gl_para);
    glMatrixMode(GL_MODELVIEW);
    glLoadMatrixd(gl_para);

    glPushMatrix();

    glRotatef(180, 0, 1, 0);
    glScalef(object_scale,object_scale,object_scale);
    glTranslatef (xpos, ypos,0);

    glPopMatrix();
}

if (object[TextureNum].vrm1_id >= 0){
    glRotatef(90, 1, 0,0);
    glScalef(vrm1_scale, vrm1_scale, vrm1_scale);

    arVrm1Draw(Vrm1Num);
}
glDisable(GL_LIGHTING);
glDisable(GL_DEPTH_TEST);
}

//-----
// Setup lighting function
//-----
static void setupLighting(void)
{
    GLfloat    lt0_position[] = {100.0, -200.0, 200.0, 0.0};
    GLfloat    lt0_ambient[]  = {0.1, 0.1, 0.1, 1.0};

    GLfloat    lt0_diffuse[]  = {0.8, 0.8, 0.8, 1.0};

    //
    GLfloat    lt1_position[] = {-100.0, 200.0, 200.0, 0.0};
    GLfloat    lt1_ambient[]  = {0.1, 0.1, 0.1, 1.0};

    GLfloat    lt1_diffuse[]  = {0.8, 0.8, 0.8, 1.0};

    glLightfv(GL_LIGHT0, GL_POSITION, lt0_position);
    glLightfv(GL_LIGHT0, GL_AMBIENT,  lt0_ambient);
    glLightfv(GL_LIGHT0, GL_DIFFUSE,  lt0_diffuse);
}

```

```

//
glLightfv(GL_LIGHT1, GL_POSITION, ltl_position);
glLightfv(GL_LIGHT1, GL_AMBIENT, ltl_ambient);
glLightfv(GL_LIGHT1, GL_DIFFUSE, ltl_diffuse);
}
//-----
// SetupMaterial Function
//-----
static void setupMaterial(void)
{
    GLfloat    mat_ambient[]    = {0.0, 0.0, 1.0, 1.0};
    GLfloat    mat_specular[]   = {0.0, 0.0, 1.0, 1.0};
    GLfloat    mat_shininess[]  = {50.0};

    //
    glMaterialfv(GL_FRONT, GL_AMBIENT, mat_ambient);
    glMaterialfv(GL_FRONT, GL_SPECULAR, mat_specular);
    glMaterialfv(GL_FRONT, GL_SHININESS, mat_shininess);
}

//-----
// Cleanup Function
//-----
static void cleanup(void)
{
    arVideoCapStop();
    arVideoClose();
    argCleanup();
}

//-----
// mouseFunc Function
//-----
static void mouseFunc(int button, int state, int x, int y)
{
    printf("%d %d %d %d\r\n",button, state, x,y);
}

//-----
// KeyEvent Function
//-----
static void keyEvent( unsigned char key, int x, int y)
{
    if( key == 0x1b ) {
        printf("*** %f (frame/sec)\n",
(double)count/arUtilTimer());
        cleanup();
        exit(0);
    }
}

//-----
// OpenCV function
//-----

static void onTrackbar(int position)
{
    cvThreshold(img_GRAY, img_GRAY, position, 255,
CV_THRESH_BINARY);
    thresh = position;
}

```

```

}

-----
--
// Source code for safety measures monitoring
// created by Petcharat Limsupreeyarat
// object.cpp
-----
--
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <AR/ar.h>
#include <AR/arvrm1.h>
#include <irrKlang.h>;

#include "object.h"

#pragma comment(lib, "irrKlang.lib")

static char *get_buff( char *buf, int n, FILE *fp );

ObjectData_T *read_ObjData( char *name, int *objectnum )
{
    FILE          *fp;
    ObjectData_T  *object;
    char          buf[256], buf1[256], buf2[256];
    char          buf3[256], buf4[256], buf5[256],buf6[256];
    int           i;

    printf("Opening Data File %s\n",name);

    if( (fp=fopen(name, "r")) == NULL ) {
        printf("Can't find the file - quitting \n");
        return(0);
    }

    get_buff(buf, 20000, fp);
    if( sscanf(buf, "%d", objectnum) != 1 ) {
        fclose(fp); return(0);
    }

    printf("About to load %d Models\n",*objectnum);

    object = (ObjectData_T *)malloc( sizeof(ObjectData_T) *
*objectnum );

    if( object == NULL ) return(0);

    for( i = 0; i < *objectnum; i++ ) {
        object[i].visible = 0;

        get_buff(buf, 20000, fp);
        if( sscanf(buf, "%s", object[i].name) != 1 ) {
            fclose(fp); free(object); return(0);
        }

        printf("Read in No.%d \n", i+1);

        get_buff(buf, 20000, fp);

```



```

if( sscanf(buf, "%s", buf1) != 1 ) {
    fclose(fp); free(object); return(0);}

if( (object[i].id = arLoadPatt(buf1)) < 0 )
    {fclose(fp); free(object); return(0);}

    // vrml load

    get_buff(buf, 20000, fp);

    if (sscanf(buf, "%s %s", buf2, object[i].vrml_name) != 2)
    {
        return(0);}
    printf ("object[%d].vrml_name to print object.vrml_name
= %s\n",i, object[i].vrml_name);

    if (strcmp(buf2, "VRML") == 0) {
        object[i].vrml_id = arVrmlLoadFile(object[i].vrml_name);
        printf("VRML id - %d \n", object[i].vrml_id);
    } else {
        object[i].vrml_id = -1;
    }

    object[i].vrml_id_orig = object[i].vrml_id;
    object[i].visible = 0;

    get_buff(buf, 20000, fp);
    if( sscanf(buf, "%lf", &object[i].marker_width) != 1 ) {
        fclose(fp); free(object); return(0);
    }

    get_buff(buf, 20000, fp);
    if( sscanf(buf, "%lf %lf", &object[i].marker_center[0],
&object[i].marker_center[1]) != 2 ) {
        fclose(fp); free(object); return(0);
    }
}

fclose(fp);

return( object );
}

static char *get_buff( char *buf, int n, FILE *fp )
{
    char *ret;

    for(;;) {
        ret = fgets( buf, n, fp );
        if( ret == NULL ) return(NULL);
        if( buf[0] != '\n' && buf[0] != '#' ) return(ret);
    }
}

```

```
-----  
--  
// Source code for safety measures monitoring  
// created by Petcharat Limsupreeyarat  
// object.h  
-----  
--  
ifndef OBJECT_H  
#define OBJECT_H  
  
#define OBJECT_MAX 100  
  
typedef struct {  
    char name[512];  
    int id;  
    int visible;  
    int collide;  
    double marker_coord[4][2];  
    double trans[3][4];  
    char vrml_name[512];  
    int vrml_id;  
    int vrml_id_orig;  
    char sound_file[512];  
    char video_file[512];  
    char texture_name[512];  
    double marker_width;  
    double marker_center[2];  
} ObjectData_T;  
  
ObjectData_T *read_ObjData( char *name, int *objectnum );  
  
#endif
```

VITAE

Petcharat Limsupreeyarat was born on August 30, 1977 in Bangkok, Thailand. She received her high school education at Non-Formal Education Centre of Mattayom Watbuengthonglang School in Bangkok. After finished high school, she continued her Bachelor's degree in Irrigation Engineering at Faculty of Engineering, Kasetsart University, Thailand. After graduated in 1997, she worked as an estimator in a construction firm for one and half years. Then she worked as a project coordinator in a prefabricated housing developer company for one and half years. She continued studying her Master's degree in civil engineering at Kasetsart University in 2001 and graduated in 2005. While she was studying in last year of her Master's degree, she worked as a project coordinator in a real estate developer company. She continued working after she graduated for one and half years. Then, she received scholarship from Burapha University to be a lecturer after graduate Doctoral degree. Therefore, she continued studying her Doctoral degree in construction engineering and management at Chulalongkorn University in 2006. Nowadays she and her parent live in Bangkok, Thailand.