Simulating Extreme Points of Crane by Robot Arm in Virtual Reality

Kuan-Lin Chen [a], King-Ho Tsang [b] , Yao-Yu Yang [b] and Shih-Chung Kang [c]

[a]Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taiwan
[b]Department of civil engineering, National Taiwan University, Taiwan
[c]Department of Civil & Environmental Engineering, University of Alberta, Canada

E-mail: m10705504@mail.ntust.edu.tw, b06501082@ntu.edu.tw, yyben@caece.net, sckang@ualberta.ca

Abstract –

Crane simulations are necessary for selecting a proper type of crane for an erection task in a construction project. However, simulating the motion of a specific crane is hardly realized because modelling a specific crane is complex. Thus, by taking advantage of a robot arm with multiple degrees of freedom, our goal is to simulate any type of retractable crane and boom crane virtually. The developed simulation process can help identify constraints of the robot arm and transform the configuration between the robot arm and a selected crane. In the experiment, by applying the developed simulation process we used a virtual robot arm to simulate a virtual retractable crane in one of the tasks of crane operator exam. The comparison of the endpoint paths of the crane and the robot arm showed the feasibility of the method. Furthermore, the method can be applied to the real robot arm for selecting a proper type of crane for the erection tasks. The erection tasks can also be easily simulated physically with a robot arm in a scaled construction site.

Keywords –

Simulation, Extreme point, Robot arm, Crane

1. Introduction

1.1. Background

In recent years, various types of cranes are used in all walks of life, especially mobile crane has high mobility and a wide range of operation suitable for many sites. Research discussed the boom control of mobile cranes, such as Autonomous Beam Assembly System [1] or Crane Operation [2] so on and so forth.

However, due to the complex kinematics and low mobility of the crane, the crane operation is difficult. There are lots of restrictions including the size of the site, the safety of the area around the site, crane rental etc. Therefore, in the past, the 3D model technology was used to simulate in advance and observe the movement behavior of the crane in the virtual space as a reference for decision-making. [3] In this paper, the method of using a virtual robot arm to simulate the extreme points motion of a crane is presented.

1.2. Crane Simulators

With the rapid development of visualization technology, many 3D simulation tools have been developed. However, these simulations in the virtual environment are limited by the software and cannot fully consider all the influencing factors, resulting in errors between the simulated objects and the reality. Especially in the erection tasks, the movement of the hanging object will be affected by complex natural factors, so the simulation results may not be accurate.

This study focuses on the use of a virtual robot arm as a tool to simulate the extreme points of crane. There are four advantages of this method. First, the researchers are able to accurately simulate any point and path. Second, the method could simplify the process for researchers to operate the crane and make research more efficient. Third, the axis of horizontal rotation and elevation are combined into one single axis. The last but not the least, the results of these simulations can be observed by actually operating the robot arm to observe the physical changes of the hanging object.

1.3. Research goal

We use the robot arm in the virtual environment to simulate the extreme point motion of the crane. This method enables operators to simulate the endpoint path of the crane before actually operating the crane. Different

from the direct simulation of the crane, the robot arm can achieve high simulation accuracy and clearly record the coordinates of each endpoint in the path, freely control the speed of movement, and the simulated movement can be actually implemented in the robot arm. This information can be used as a reference for operator decisions.

Notation

k: The ratio of maximum length of robot arm and crane boom

μ: The distance between the hoist of crane to the origin in coordinates system

R_{max} : The maximum length of robot arm.

r_{max} : The maximum length of crane boom.

r_i: The initial length of crane boom

θ_i: The initial azimuthal angle (horizontal rotation angle) of crane boom

ϕ_i: The initial polar angle of crane boom

r_T: The terminal length of crane boom

θ_T : The terminal azimuthal angle (horizontal rotation angle)

ϕ_T: The terminal polar angle

Δr: The change of length of crane boom

$\Delta\theta$: The change of azimuthal angle (horizontal rotation angle)

$\Delta\phi$: The change of polar angle

PTP: Point-To-Point form

$i(x_i, y_i, z_i)$: The initial 3D Cartesian coordinates (input of robot arm)

$T(x_T, y_T, z_T)$: The terminal 3D Cartesian coordinates (input of robot arm)

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2. Methodology

After analyzing the relationship between a crane and a robot arm, the methodology is organized as follow:

### 2.1. Operation process for simulation

We developed an operation process, that included input, analysis, transformation, simulation, output five parts to determine whether hoisting paths between robot arm and crane were the same or different for the developed simulation.

2.1.1. Simulation steps

First, we input the model of a crane and a robot arm, the coordinates of hoisting path in crane. Second, we calculate the effective simulation range of the crane and the robotic arm to ensure that the simulation path is feasible. After that, the 3D Cartesian coordinates input data of robot arm are collected. Third, simulation software is used to test the result whether the paths of the crane and the robot arm are the same. Finally, if the

hoisting path in the simulation is the same as the crane, the robot arm simulates complete. Otherwise, the method restarts and repeats the steps repeats.

Figure 1. Simulation process
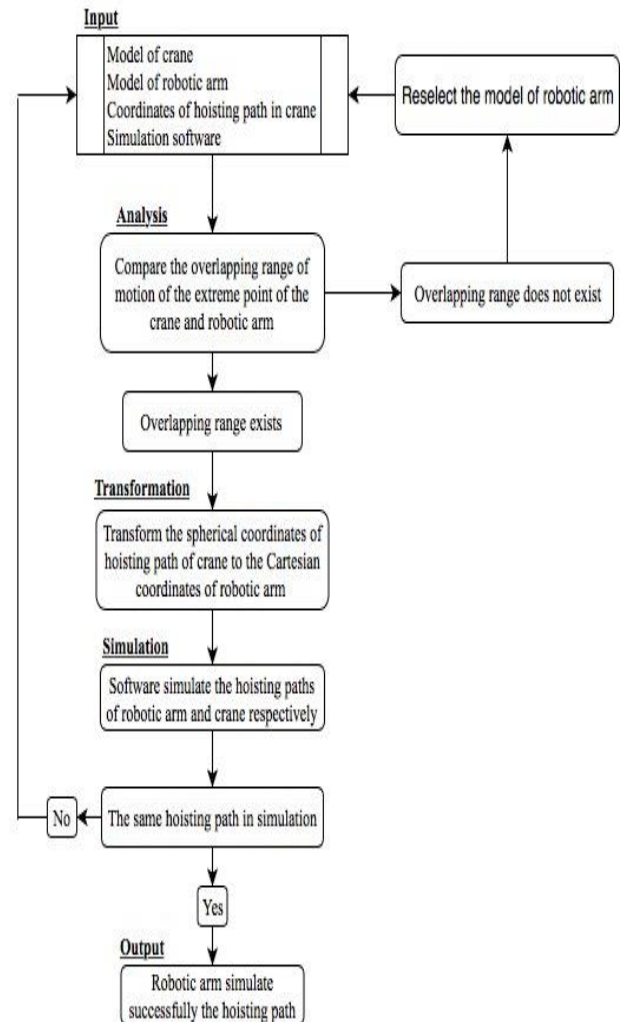
2.2. Constraint identification and assumptions

Six constraints are identified and eight assumptions regarding geometry and numerical calculation are established in this section.

2.2.1. Constraint identification

Robot arm

The upper sheave of the robot arm must be perpendicular to the ground. The form of extension and retraction of robot arm are not the same as the crane. Furthermore, one robot arm only simulates one mobile crane at each time.

Crane

The crane has two angles to be considered. The first one is the range of the elevation angle of crane: $0° \leq \phi \leq \phi_{max}$ (determined by the model of the crane). The other one is the range of the horizontal rotation angle of crane: $0° \leq \theta \leq 360°$.

2.2.2. Assumptions

Crane

Only mobile crane situation is considered. The pivot of the crane is fixed at the origin. The hook and cable of the crane are ignored. The factors of natural environment such as wind and personal factors such as the experience in operating crane are ignored. Moreover, any two of values of ϕ, θ, r change at the same time at most.

Both robot arm and crane

Robot base rotation center and pivot of crane's boom are the origins in the coordinates system. The swinging of extreme points of the crane and the swinging of the crane do not be considered. Furthermore, the motion of extreme points of the crane and the robot arm are analyzed since the extreme point is the main point we focus. Regarding the problem of the deformation of the boom and the robot arm, we assume that the deformation caused by the weight of the object can be ignored.

2.3. Configuration transformation

We derived the configuration transformation model between a retractable crane and a robot arm from their kinematic model. It consists of two parts. The first part is proportional scaling, that the virtual robot arm and crane are the same length of simulation to find their effective range of motion. In the second part, the endpoint motion of the crane is simplified into a triangular coordinate relationship, and the conversion formula is obtained by using the trig function and polar coordinate:

2.3.1. Proportional scaling

According to the model information provided by the government, the simulation condition of the equivalent ratio can be achieved through proportional conversion. The variational constant (1) is obtained by using the longest distance that can be reached by the lifting arm of the crane and the longest distance that can be reached by each axis of the robot arm at the initial Angle.

$$k = \frac{R_{max}}{r_{max}} \tag{1}$$

2.3.2. Conversion formula

The relationship between the rotation Angle of each axis of the robot arm and its motion posture in space is calculated based on forward and inverse kinematics [4]. As a tool to simulate the endpoint's path of the crane, we ensure that the A5 axis remains horizontal and that the changes in the intermediate axes are not considered. Therefore, the motion posture of the robot arm is simplified into a trig function to take the starting point and ending point of the motion of the robot arm. And it is necessary to consider that the pivot of crane and Rotation is different.

The spatial coordinates of x, y and z in the simulated environment are obtained by the transformation between the polar coordinate system and Cartesian coordinate system. As shown in figure 2, formula (2), (3) and (4) are used to calculate the initial point $i(x_i, y_i, z_i)$ of the robot arm movement in the 3D simulated environment.

$$x_i = k(r_i \sin \phi_i - \mu) \cos \theta_i \tag{2}$$
$$y_i = k(r_i \sin \phi_i - \mu) \sin \theta_i \tag{3}$$
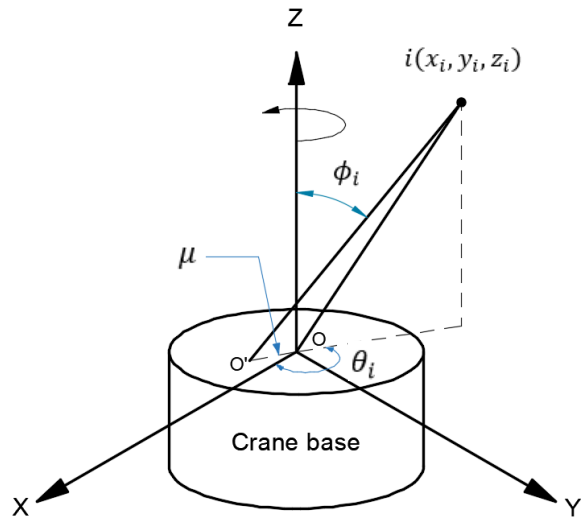$$z_i = kr_i \cos \phi_i \tag{4}$$

Figure 2. The initial point of the simulation

After obtaining each coordinate in the simulated space, formulas (5), (6) and (7) are used to calculate the length of the mechanical arm, horizontal rotation Angle and elevation Angle.

$$r_T = (r_i + \Delta r) \tag{5}$$
$$\theta_T = (\theta_i + \Delta \theta) \tag{6}$$
$$\phi_T = (\phi_i + \Delta \phi) \tag{7}$$

As shown in figure 3, equations (8), (9) and (10) can be used to calculate the extreme point to be simulated by the virtual robot arm.
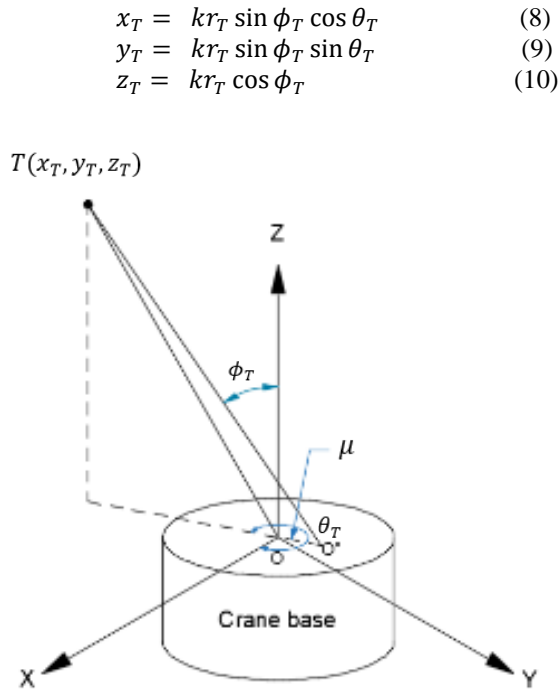
$$x_T = kr_T \sin\phi_T \cos\theta_T \qquad (8)$$
$$y_T = kr_T \sin\phi_T \sin\theta_T \qquad (9)$$
$$z_T = kr_T \cos\phi_T \qquad (10)$$


Figure 3. The end point of the simulation

3. Results

3.1. Analysis of crane and robot arm

At the present research stage, we combine the horizontal rotation of the crane and the pivot of the crane as a single pivot in the virtual robot arm for subsequent simulation to find out the effective simulation range between the virtual robot arm and the crane. Finally, the crane operator exam is taken as an example to verify the accuracy of the virtual robot arm simulating the motion of the crane extreme points.

We first analyze the motion path of the robot arm and the crane, and then compare them together. First, we assume that the robot arm is always horizontal and does not rotate at the A5 axis, and the motion range of the robot arm is not lower than the ground plane. For the crane part, it has two different Pivot Points and the height of the crane itself must be considered. The length of the crane arm is then converted to the ratio, and the effective simulation range of the two is calculated by 2D drawing software. According to figure 4, the inclined area at two different angles is shown. The sector is the movable range of the lifting arm of the mobile crane model RT-100, and the other irregular block is the movable range of the robot arm model KR16s.

Figure 4. 2D Effective simulation range
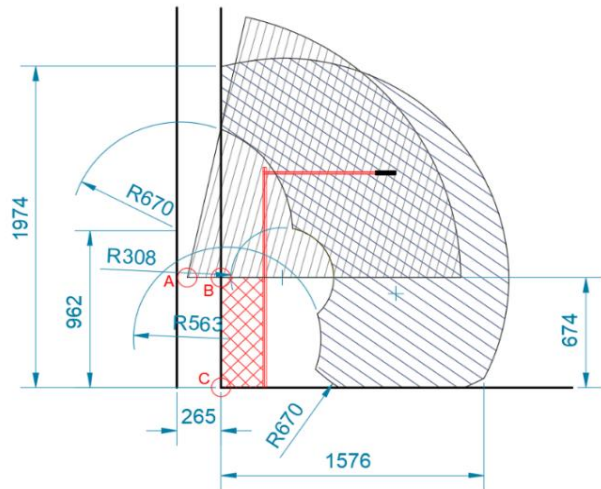
Point A: The pivot of crane
Point B: The center of Rotation
Point C: The simulated pivot of virtual robot arm
Red Area: The shape of a robot arm

Considering the crane and robot arm can rotate horizontally, 3D graphics software is used to display a complete 3D effective simulation range, as shown in figure 5.
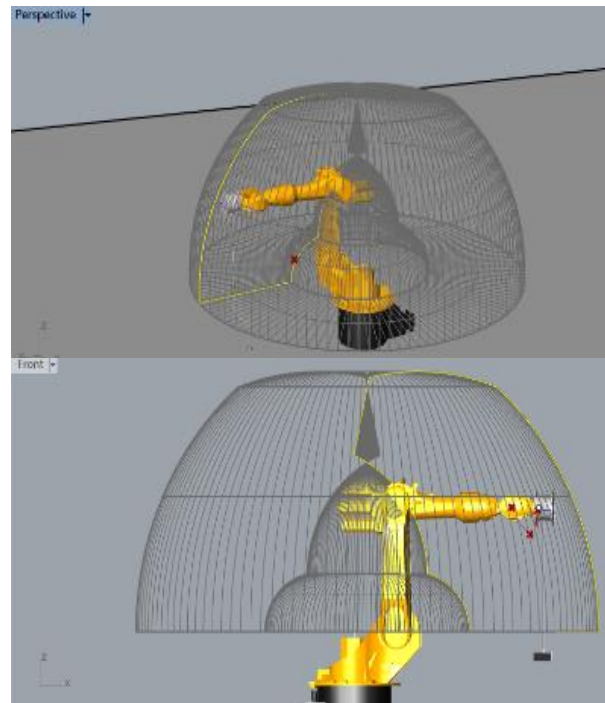

Figure 5. 3D Effective simulation range

3.2. Calculation process and simulation

According to the driving test of a mobile crane in Taiwan, we used the operation test path of the crane in the game engine, and recorded the extreme points of the boom in the space of the Coordinate points. In addition to the path, we also operate according to some examination regulations, including the following:

1. The crane is fixed in the rotation center.
2. The starting point of the crane is at point S, and the hanging object is about 2 meters high from the ground.
3. During the operation, follow the running path, pass the obstacles in sequence and return to the starting point.
4. During hoisting, the hanging object should not touch the ground.

Simulation results of crane operating model RT100 in the game engine are shown in figure 6. The red line in the space represents the route of the technical examination for the crane driver's license.
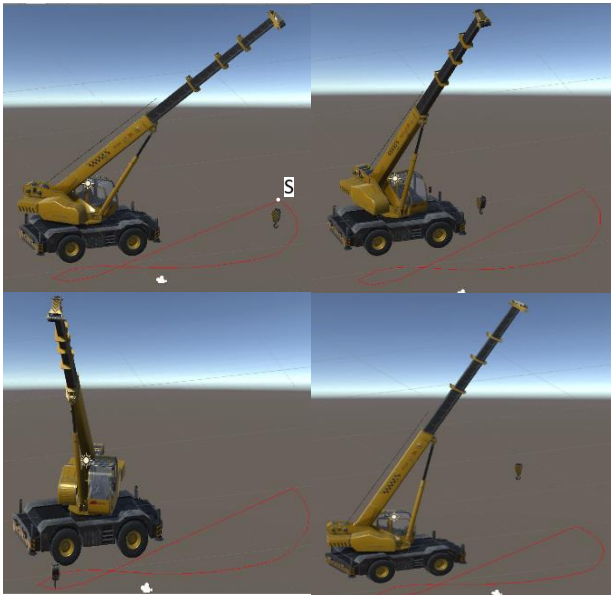

Figure 6. The crane simulates the process of the path

Next, move these Coordinate points as the crane simulates to another 3D software that can simulate a robot arm. In figure 7, you can see that the simulated path consists of red points. Some Coordinate points may appear in an area that cannot be simulated, and we can use scaling to adjust the range to be simulated. During the simulation process, it is necessary to ensure that the pose of the end of the virtual robot arm is the same as the crane. We also record the points that the end of the virtual robot arm passes through.
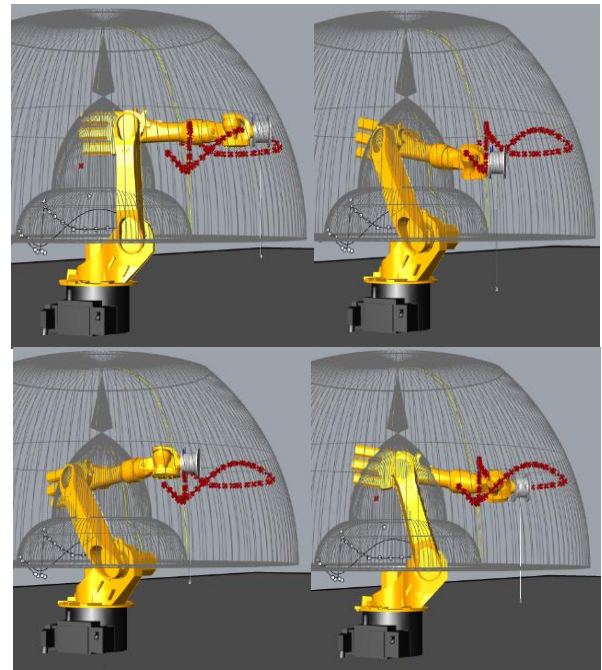

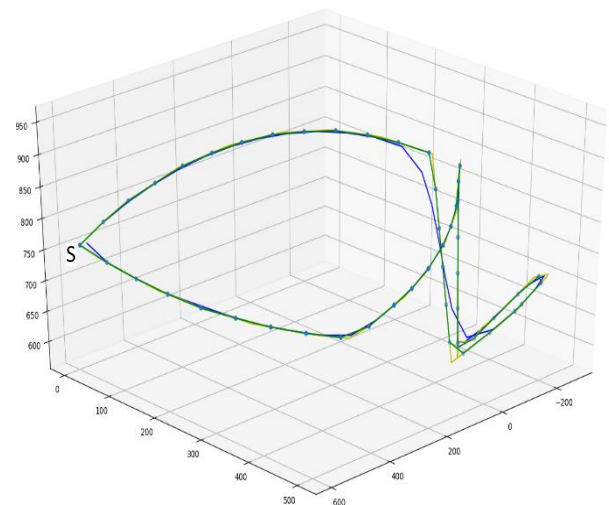Figure 7. The virtual robot arm simulates the process of the path

Figure 8. Comparison of simulated path results

We tested two different ways of simulations. The first is to use a curve made up of points as the simulation path, while the other is to use a straight line made up of points. In figure 8, we compare the simulated paths using 50 points. The yellow line represents the path of the crane. The blue lines represent curved paths of points, while green lines represent straight paths of points. Next, we increase the number of points on the straight path to 100

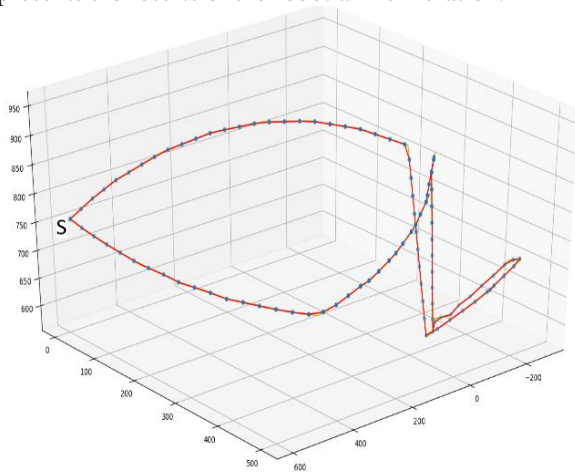and compare again, as shown in figure 9.The red line represents the results of the robot arm simulation.

Figure 9. Increase the number of points to simulate

For the 2D plane, we compared the curves, straight lines, and lines with 100 points of simulation paths.
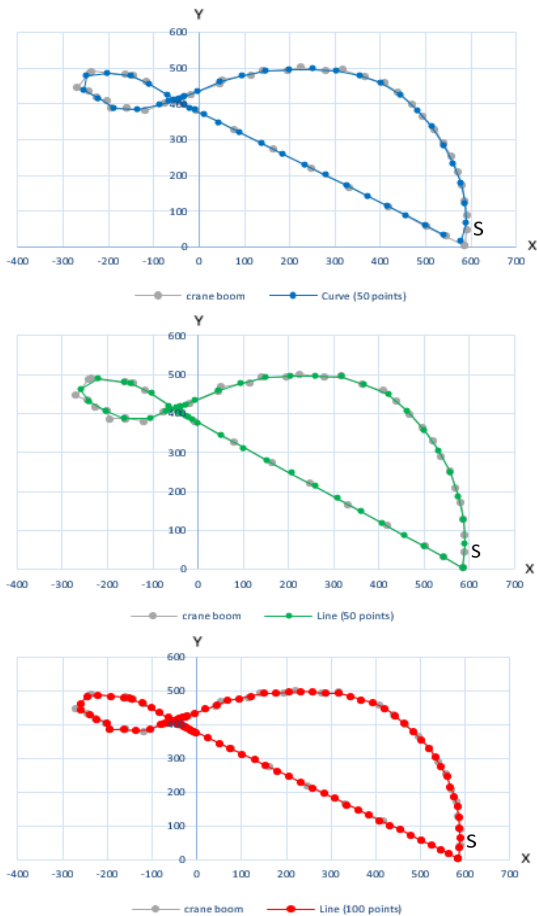

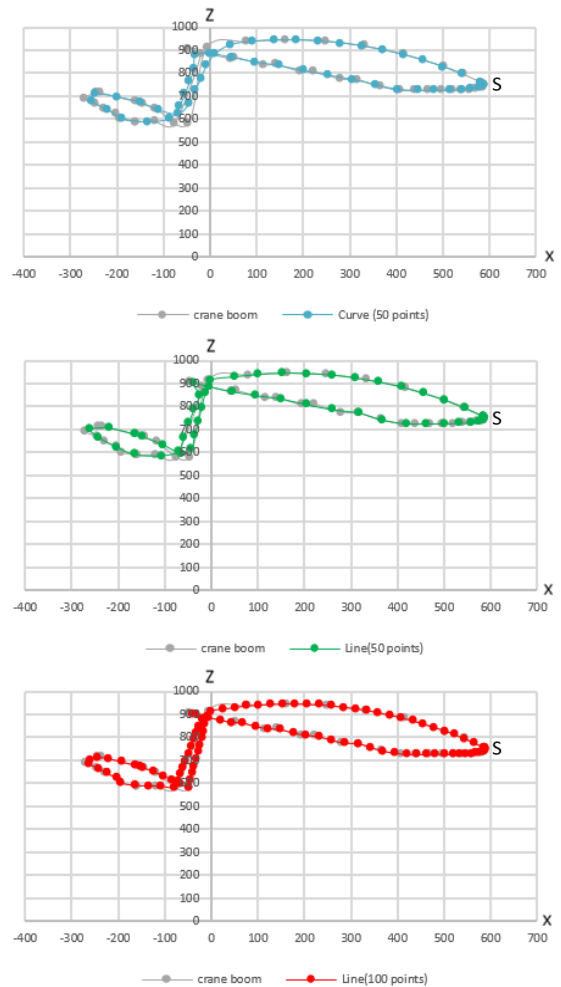Figure 10 and figure 11 are the X-Y plane and the X-Z plane, respectively.

Figure 10. Comparison of coordinate point paths in X-Y plane

Figure 11 Comparison of coordinate point paths in X-Z plane

4. Discussion

We obtained the effective simulation range based on the motion limit of the crane model rt-100 and the robot arm model K 16 RS and found that some coordinate points of the crane extreme points converted from UNITY could not be simulated by the robot arm. The reason is that we are scaling with the longest length, resulting in some points near the shortest length to be outside the effective range. In order to focus on the virtual robot arm to simulate the movement of the extreme point of the crane, the coordinates are all within the range of simulation through scaling.

During the simulation of extreme point paths, we

observed several things. If the same number of coordinate points are used for simulation, the curve path will produce a large error, while the line path will be more accurate. And when the number of simulation points is increased to 100, the accuracy of the path simulated by the robot arm can be improved. At the same time, we find that even if the number of simulation points is increased to 100, there will still be some errors when the extreme points path of the crane suddenly changes. For example, when the extreme points of a crane crashes or falls suddenly or shifts up and down. However, in the real hoisting operation, the speed of the crane movement will affect the swinging posture of the suspension. [5] Therefore, in order to simulate the real crane movement with the robot arm, the speed must also be considered. In this study, the path of the crane extreme points is analysed. Future study will discuss the time factor.

5.   Conclusion and future works

Selecting an improper type of crane for a construction project may significantly increase the erection cost. In order to select a proper type of crane, crane simulation is one of the effective methods. However, simulating multiple types of crane requires multiple types of crane models which are always lacking. We developed a simulation method with a 6-degree-of-freedom robot arm using the developed process. The simulation processes include the identification of simulation constraints and the configuration transformation between a robot arm and the crane. One of the erection tasks selected from the crane operator exam was applied to the simulations with a virtual crane and a virtual robot arm respectively. Despite the kinematic constraints for the robot arm simulating the crane, the motion paths of the extreme points of the crane and the arm are highly similar. Only with the same robot arm, the application of the method can simulate the retractable crane and the boom crane regardless of its size and detailed specification. In future work, we will take into account the problem of boom deformation and test configuration transformation with actual mobile crane and robot arm operating on site and in R-lab. In addition, we will find general configuration transformation to test the situation of the movement of the crane and the swing of hook in all crane models.

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