Motion Control of Excavator with Tele-Operated System

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Abstract

The number of dismantling sites for buildings has been rapidly increased and these processes are very dangerous. So many research papers have been published addressing the development of a remote controller for the dismantling equipments. In this paper, a novel concept of applying tele-operated device is proposed for the remote control of excavator-like dismantling equipment. As a tele-operated system, this controller is designed to improve the operability of the excavator. This paper also includes all the necessary kinematic analysis to design the tele-operated system. In order to explore the feasibility of the device, modeling of the tele-operated system is used to demonstrate its convenience. Then, the hydraulic system of excavator which uses the proportional valve system is also studied. And basic motion control simulations to the real excavator working at construction site are conducted with designed tele-operated system. And operator can control the real excavator intuitively with this new model of tele-operated system.

Keywords: Haptic Device, Excavator, Inverse Kinematics, Dismantling Process, Hydraulic System

Notations

Z_{e1} : Axis of swing joint
Z_{e2} : Axis of boom joint
Z_{e3} : Axis of arm joint
Z_{e4} : Axis of bucket joint
a_2 : Distance between Z_{e2} and Z_{e3} (Length of boom)
a_3 : Distance between Z_{e3} and Z_{e4} (Length of arm)
r_{24} : Distance between Z_{e2} and Z_{e4}
θ_{ei} : Rotational angle of each link of excavator (i=1, 2, 3, 4)

1. Introduction

The construction technology has been developed for thousands of years, so the latest buildings are about several hundred meters high. Furthermore, how tall buildings can be stably constructed has been a main theme in architecture. Recently, however, how to dismantle an old high-rise building has also been focused by many researchers. Dismantling methods have been also developed for centuries, and among these methods, mechanical dismantling has been very common. For example, the excavator which is used to construct a new designed building is also utilized for the heavy equipment for dismantling processes. Especially crusher and breaker are the attachments for the excavator to crack the building to pieces. This excavator which is equipped with the attachment can be easily seen at dismantling sites. However dismantling processes are very dangerous, so many safety-related accidents happen in many sites. Furthermore, operator has to ride on the excavator and this makes the dismantling process more dangerous. Therefore, remote control device is necessary to guarantee an operator's safety.

There have been some recent researches related to the tele-operation of the excavator. First, kinematics analysis and simulation of construction devices were conducted by Frimpong and Stentz. Furthermore, Frankel studied remote control of excavator with commercial haptic device, Phantom. Finally, haptic device of excavator which was operated in underwater was studied by Hirabayashi and Sasaki. And last, Phantom device is also studied by Kim and Feygin. And another tele-operating system for excavator is conducted by Oh.

In this paper, tele-operated device for dismantling process is main subject. This device is designed based on the kinematics of the excavator, which can cover 3-dimensional workspace. This kinematics analysis of the excavator is studied. This paper also includes all the necessary kinematic analysis to design the tele-operated device. In order to explore the feasibility of the device, modeling of this device is used to demonstrate its convenience. Then, the hydraulic system of excavator which uses the proportional valve system is also studied. And last, basic motion control simulations to the real excavator with sensor feedback mechanism are conducted with designed tele-operated system. As a result, this device can be proposed to confirm the feasibility of the tele-operated system. And one hand control can be possible to move the real excavator with this new model.

2. Kinematics of Excavator

In the world, there are many kinds of backhoes. However, in this paper, excavator whose motions are called like swing, boom, arm, and bucket, is chosen. This excavator may be easily seen in many construction sites. Based on this motion, Figure 1 shows 4 coordinates of each links of the excavator. First, swing joint axis of excavator is represented by Z_{e1}, and the remaining three joint axes, boom, arm, bucket are also declared.

After the modeling of excavator, forward and inverse kinematics analysis is necessary. When the haptic devices are designed, the inverse kinematics analysis is more important. Because the operator wants to control the pose of last link, bucket which should be determined by the tele-operated system. With this reason, according to the bucket's pose, four joint angles of excavator are controlled by the inverse kinematics analysis. These joint angles can be calculated with following equations.

$$\theta_{e2} = \tan^{-1}\left(\frac{r_{24}(y)}{r_{24}(x)}\right) + \cos^{-1}\left(\frac{a_2^{\,2} + r_{24}^{\,2} - a_3^{\,2}}{2a_2 r_{24}}\right) \qquad (1)$$

$$\theta_{e3} = \pi + \cos^{-1}\left(\frac{a_2^{\,2} + a_3^{\,2} - r_{13}^{\,2}}{2a_2 a_3}\right) \qquad (2)$$

Degree of freedom of excavator is four, at the same time, bucket can move in 3-dimensional space. In other words, the bucket movement can be represented with haptic stylus in 3D space. However, when the real digging operations are examined, it is observed that the swing motion is nearly not used. That is, the main motion of excavator is controlled by 3 DOF without swing, which determines the bucket's 2D motion. The swing motion is usually used to move the dug earth to other side. If the swing motion is separated from the digging motion and can be controlled by the haptic device's another reserved joint, operator can control the excavator more easily.

Therefore, inverse kinematics analysis of excavator which is 2-dimensional kinematics problem to control the boom and arm is necessary. However, with this control method, 2D plane motion of bucket joint cannot be controlled intuitively. The position of bucket joint can be acquired with the two angles of boom and arm. So, if operator wants to control the only boom angle or arm angle, it is difficult to control each angle with this 2D plane control method. So, design concept of tele-operated system will be shown next chapter.

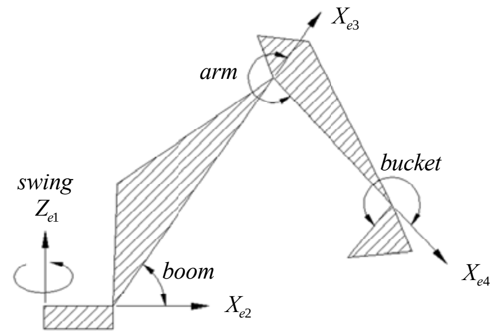


Figure 1 Kinematic model of excavator

3. Design of Tele-Operated System

In previous research, a haptic device was designed, such that operator can work with intuitive bucket control. So, novice operator can use the excavator easily unlike the conventional controller. The degree of freedom of haptic device is 4, because the excavator has 4 degrees of freedom. First, swing and bucket control is directly connected to two joints of haptic device. And 2-dimensional position control is mapped with the position of the bucket joint. But this method makes the control somewhat unintuitive. So new concept design is proposed like Figure 2 and Figure 3. This is not a fine design, but shows the concept design of tele-operated device. And Figure 4 is a last drawing of haptic device. Operator put ones elbow on the table of the tele-operation system. And grab the haptic stylus and move ones arm freely. This motion controls the full motion of the excavator. First, d_{h1} controls the boom motion. Second, θ_{h4} which represents the angle of wrist of operator controls the bucket motion directly. And the angle θ_{h3} between the lower arm and horizontal plane controls the arm angle of excavator. And last θ_{h2} controls the swing motion of excavator. With this design concept, operator can control the each angle directly.

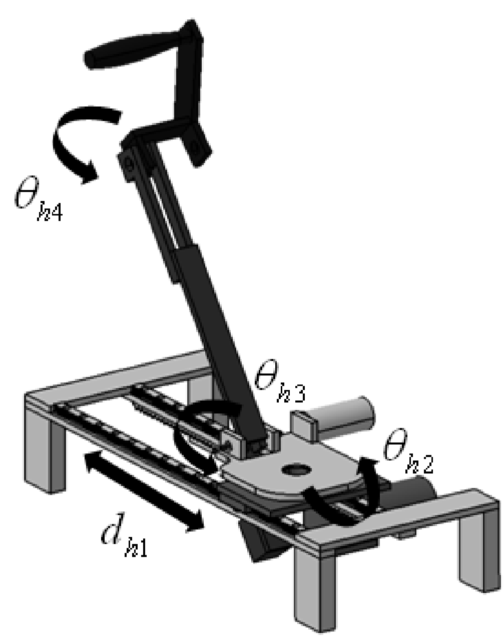
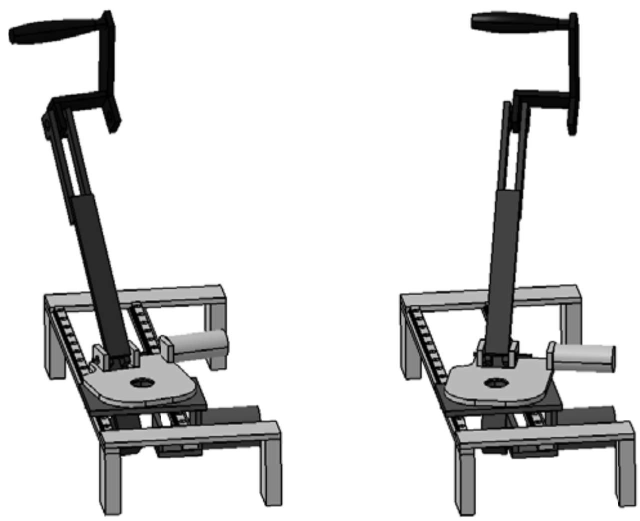


Figure 2 Design concept of tele-operated system



(a) Swing to the left direction (b) Swing to the right direction

Figure 3 Swing motion control of excavator with tele-operated system

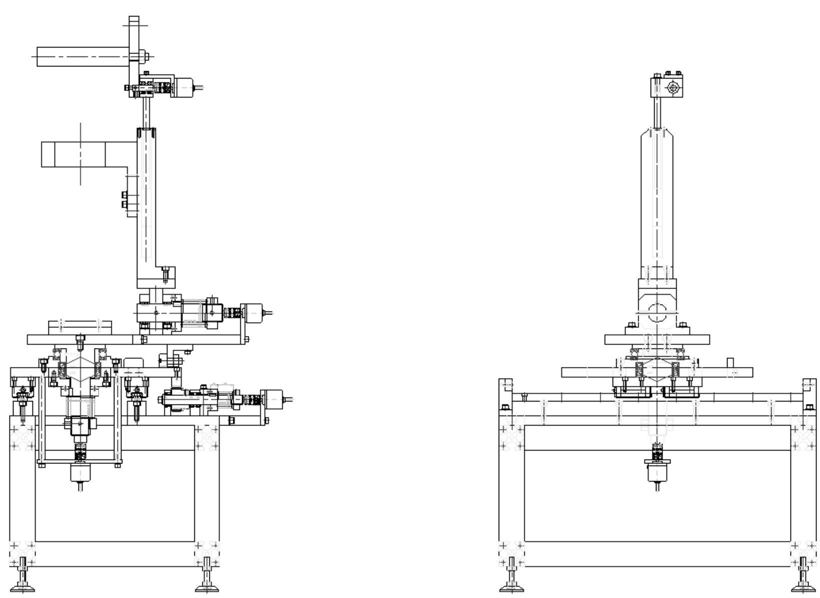


Figure 4 Final design of tele-operated system before manufacturing

4. Control of Excavator

There are some sensors to feedback control. Inclinometers and gyro sensor are used to feedback pose value of excavator. DAQ 6024E board (NI) is used to get the values of sensors. Industrial PC is also set up on the excavator and values of sensors can be monitored. This feedback mechanism circuit is shown in Figure 5.

Three inclinometers and one gyro sensor are necessary. Inclinometers are attached to get the angle value of each link, boom, arm and bucket. And gyro sensor is installed on the base frame of excavator to get the pose. The angles of links are acquired with Visual C++ program through DAQ board, and then these values are used to control the motion of the excavator. PI control result is shown in Figure 6. The reference inputs are 70 degree (boom) and 200 degree (arm). If controller has only P controller, there is steady state error which is about 5 degrees. But there is almost 1 degree of steady state error with PI controller. However friction of boom joint is larger than that of arm joint, control result of boom is not excellent in this paper.

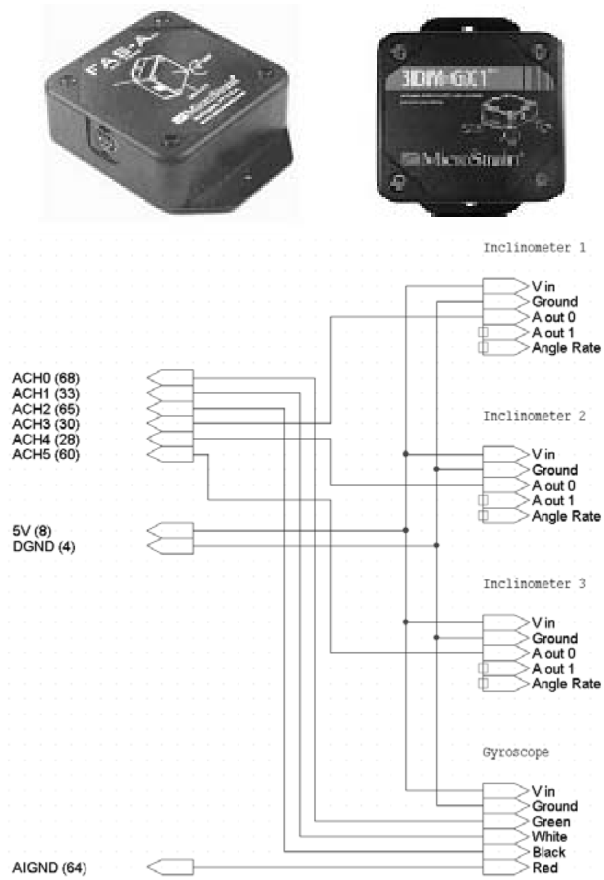
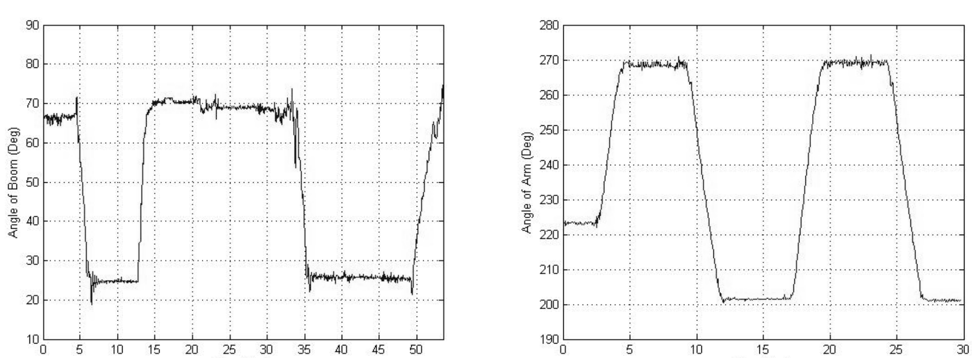


Figure 5 Picture of sensor and circuit of sensor feedback with DAQ board

For the control of excavator, hydraulic system should be studied first. Figure 7 is the picture of real excavator whose name is SOLAR 015. Main hydraulic control valve system has 9 degrees of freedom in Solar 015. So, there are 9 hydraulic ports in control system. And among these ports, first, fourth, fifth and eighth control valve is pilot valve and these control the main links of excavator (swing, boom, arm and bucket). Pilot valves are controlled with the joystick of excavator installed on the both side of operator seat. This is original model of excavator but it has to be remodeled with some equipment. First, proportional valve system which is shown in Figure 8 is adapted to control electrically. There are 8 proportional valves connected to the pilot valves of main hydraulic valve. So with these proportional valves, operator can control the excavator electrically from remote sites.



(a) Boom angle control result (b) Arm angle control result

(Ref=70degree) (Ref=270degree)

Figure 6 Angle control result of excavator with PI controller

Figure 7 Picture of excavator which is SOLAR 015

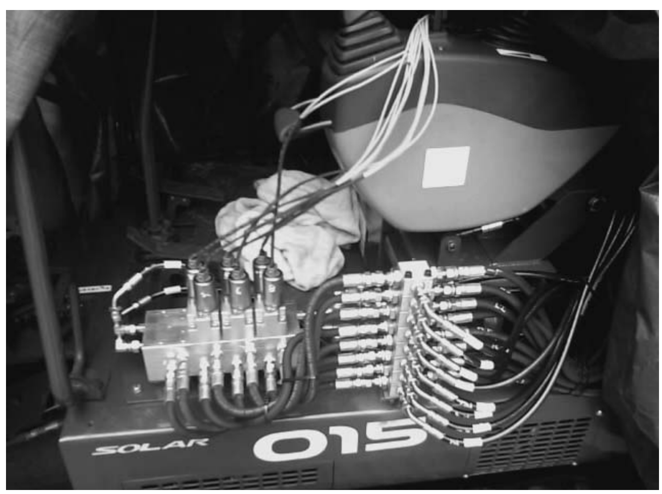


Figure 8 Proportional valve systems to control the excavator

Figure 9 Remote controller of excavator (joystick and receiver)

Basically, this proportional valve can be controlled with wireless joystick system, and this joystick system is shown in Figure 9. This is same as the joystick of excavator. And RF transmitter module is installed inside of this joystick and the excavator is equipped with RF receiver module. So operator can control the excavator with this wireless joystick system at the remote sites. And to use the original joystick of excavator, 8 shuttle valves are also equipped. Operator can use both the remote joystick and excavator joystick to operate the excavator.

In this paper, main object is to make the tele-operated system, so, another system should be added. First, electrical control unit should be adapted, and analog signal can be transferred to the proportional valve. DAQ 6024 board (National Instrument) is used to make the analog signal from 0V to 3V. When the input signal is 1.5V to the RF module, link of excavator doesn't move. If 3V is connected, link moves one direction, and 0V makes opposite direction movement. There are 2 analog output channels in DAQ 6024 board, boom and arm control valve is connected to this analog output channel. So, full control of excavator, 2 DAQ boards are necessary. In the future, more developed DAQ board should be installed to minimize the system. And control program is made with visual C++. And this program can get the value of inclinometer. It uses the input channel of DAQ board. And there is also PI controller to move the boom and arm to desired position. This is required to control the motion of excavator directly. Simulation results of this PI control was shown in Figure 6.

5. Conclusions

In this paper, new concept of tele-operated system was designed to control the excavator. First, kinematics of excavator was analyzed and hydraulic system of excavator is studied. Next sensor feedback mechanism is also included to get the angles of each link. Last, motion simulation is shown with the SOLAR 015 excavator. With this result, tele-operated system is proven to be very simple method. In the future, haptic device will be manufactured and the more intuitive and comfortable control of excavator will be researched.

Acknowledgement

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