The Development of the Tele-operating System for a Small Sized Excavator Coupled with Human Arm Motion

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Abstract

It is difficult, for those without experience, to operate and manipulate a mechanical excavator. There is a long learning process to gain the skills required in operating the excavator's overall swing motions as well as movements of its boom, arm and bucket. In addition it is dangerous to operate such excavators on an inclined plane as this can lead to instability and puts the operator at great risk. In this study, a simple light weight tele-operation system has been developed for the excavator for dealing with these problems. Three sensors are attached to the operator's arm, in order to detect his movements. The operating commands for the actuators of an excavator will be transmitted via Bluetooth wireless communications. The new tele-operation system developed is simple, cost effective and lighter compared to typical haptic devices using a force feedback mechanisms. The operating algorithm has been modified and verified in many test cases. Prior to testing, the algorithms have been verified using the visual simulator, OpenGL. The operating system to operate the excavator easily and safely is developed and the control algorithm verified by tests.

1. Introduction

An excavator is a machine for digging, material handling, demolition, general grading and mining. Excavators can be divided into two groups, namely large sized and small sized machines. Untrained operators such as farmers and less skilled engineers frequently operate small sized excavators without a license, although full trained and licensed persons and skilled operators are allowed to operate large sized excavators. The small sized excavators can be used in a small farm, an orchard and an urban alleyway. In such working conditions, tele-operation systems can be more useful in a small sized excavator and previous studies have focused on developing an unmanned excavator because of this and also for safety reasons [1, 2].

Moreover, when users and owners of small excavators are not proficient operators, it can be a difficult and long process to master the skills required. The operator manipulates an excavator directly by using two joysticks.

However, unskilled operators require a long period of training in order to gain the necessary experience and to understand the correlations between the movement of the excavator and control of the joysticks. In view of these issues beginners have lots of trouble in becoming proficient excavator operators. What is more difficult is to detect a load exerted on the tip of the bucket and the operator has to estimate this from other feedback from the machine; these can include aspects such as how fast the bucket is moving, the load being carried from the engine's response and the resistance from the joysticks.

The objective of this paper is to develop a simple yet effective control system for small sized excavators. The rationale for this work is, firstly because of the high risk involved in operating the small excavators in poor, narrow or potentially unstable (inclined) conditions, and secondly to ensure users can easily gain the necessary skills for operation. Unskilled owners and operators can use small excavators without license but because of their lack of expertise they have difficulty in working the excavators quickly and efficiently.

There have been several haptic and master/slave control systems. In summary; Tokyo University and KIST have developed master/slave systems with robotic arms [3, 4]; Chiba University developed a master/slave robot hand operated by the haptic glove in Japan [5]; Georgia Institute of Technology (GIT) developed a system to control backhoes in America [6], using a commercial haptic device; and the Phantom. Keio University has also developed a master/slave robot hand to be controlled by haptic device [7].

By using haptic devices, the developed systems have the added advantages of accurate motion control together with force feedback. The excavator and robot hand, or arm, can reach the intended positions accurately by using the position feedback. These devices can sense the force feedback and transfer this sensation to the operators by generating repulsive forces at the user interface; in this way the devices can also reflect the feedback to the operators giving an indication of their manipulation accuracy.

Unfortunately haptic devices are usually heavy and burdensome, and so are not easily applied to the actual

driving systems. In addition, manipulation of the excavator and robot arm, or hand, can be difficult as the haptic devices can restrict, and disturb, the motion of the operators. In case of the Phantom, the system is made even more difficult to manipulate whilst the operator is walking around.

The system described in this paper has few sensors as it relies on the operators' observation of motion and using this visual feedback to make the necessary adjustments in manipulating the excavator. Even with the use of haptic devices, operators need to maintain close visual observation to ensure safety when working with the excavators. In the new proposed system, because there are no additional devices, the master part which attaches to the operator's arm, is inexpensive to build, quite light weight and so the operators can use it more effectively than the conventional haptic devices, in performing the manipulating.

The development was supported by the Doosan Infracore Co., Ltd. which is the largest manufacturer of heavy machinery in Korea. Initial discussions with them focused on important and frequently used functions of the excavators. This led to several mechanisms and methods of feedback to be considered in the conceptual design phase. Together with engineers, conclusion was reached that the motions of overall swinging as well as the movements of the boom, arm and bucket are more important than the other functions. Force feedback control and other actuator motions for traveling, dozing, etc. were excluded when considering the design (development) priority.

2. System Configuration

The hardware for the system is set up to detect the movement of the operator's arm and to make the operation commands for the excavator. The configuration of the system is shown in Fig. 1, and it can be seen that the whole system is largely divided into a master part and a slave part. The master part is composed of three sensors and an industrial computer to collect data from the sensors and make the commands to be sent to the slave part by using the inputs from the operator. The slave part is composed of the actuators in the excavator, including proportional valves, and an embedded computer to control the actuators. These two parts are wirelessly connected through serial modules using industrial Bluetooth.
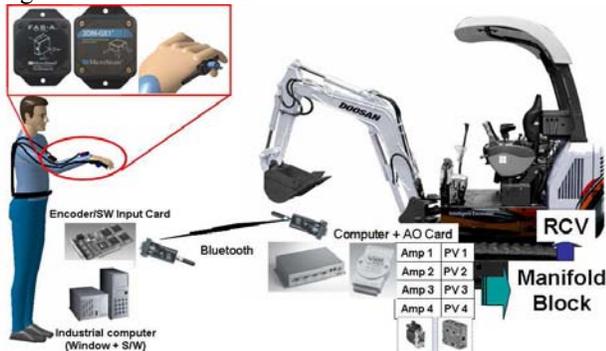

Fig. 1 Configuration of the system hardware

The coordinate system of the excavator and the operator has been determined and can be seen in Fig. 2. The origin of the coordinate systems (X, Y, Z) of the human body is on the shoulder. The X-axis faces the front, the Z-axis is skyward and the Y -axis is to the left side. The coordinates on the hand (x', y', z') are also shown in Fig. 2. The origin of the coordinates of the excavator is at the center of a swing bearing with the direction of each axis being the same as those on the operator.
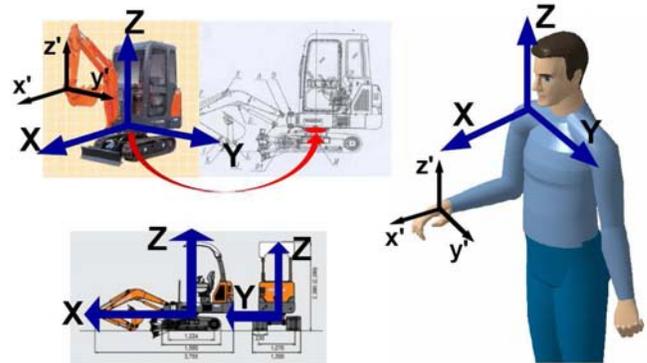

Fig. 2 The coordinate system of the excavator and the operator

2.1. The Master Part

The orientation sensor, also known as the inertia measuring unit (IMU), measures the Euler angle of the wrist to calculate its orientation [8–10], therefore the sensor should be located on the wrist. The data can be collected through an RS-232 cable, which has a microprocessor, every 100 milliseconds. The swing, boom and arm motion are determined by the data from the orientation sensor.

The inclinometer measures the upper arm's angle with respect to gravity; it can measure the angle through 360 degrees continuously, and communicate with the computer through an RS-232 every 100 milliseconds. The arm's motion is also determined by its data.

The bucket is manipulated by the angle between the palm and the little finger. Hence, the angle is measured using a small encoder device and rotary encoder. The encoder device is designed and manufactured by aluminum, with a weight of less than 20 g. The rotary encoder is one of the smallest available, with a resolution of 300 pulses per revolution. Its output is a two phase square wave, A and B. The signal is detected by an I/O board for the square waved encoder. The rotary encoder and device are combined and attached to the glove by sewing.
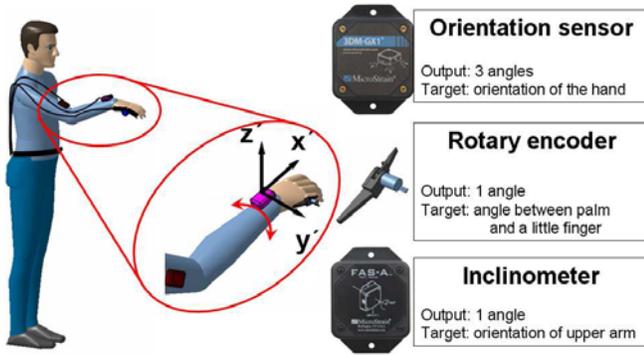
Fig. 3 Sensors of the master part

2.2. The Slave Part

The slave part is the modified excavator which is operated by the master part. Specifically, the actuators for the boom, arm and bucket and the swing motor are the elements of the slave part. These boom, arm, bucket actuators and swing motor are driven as follows: when the joysticks are manipulated, the remote control valves (RCV) are adjusted, then, the RCV controls the main control valve (MCV). Therefore, there are two ways to modify the hydraulic systems of the excavator. The first is to change the MCV into a solenoid valve block. The second is to change the RCV into a solenoid valve block. To modify the RCV is the most effective, because it is safe and inexpensive as it uses the existing hydraulic system. Moreover, the valve block which is added to the RCV includes the existing joystick operation. Hence the excavator can be controlled by both the current joysticks and the developed tele-operation system as required.

The four proportional valves are attached to the valve block and each valve corresponds to the swing motor, boom, arm and bucket actuators. The software makes operation commands by the operating algorithm with sensor data. The commands control the modified valves and oil flow rate. Fig. 4 shows the appearance of the modified excavator. The upper right side of the figure shows the control box, which includes the embedded computer and four amplifiers to control the proportional valves. The bottom of the figure shows the manifold which includes the four proportional valves.

Fig. 4 The modified excavator with additional valves and a control box

3. Algorithm

The three sensors work independently whilst the computer receives the data from the sensors respectively, every 100 milliseconds. When the swing mode is on, only the swing motion works. Otherwise, the other motions (boom, arm and bucket) work. Each motion is executed by commands after estimating the corresponding variable.

3.1. System on/off

The operator cannot continuously operate the excavator with his/her hands held high as this soon becomes tiring. When the operator wants to work or take a rest, 'SYSTEM ON' and 'SY STEM OFF' signal can activate and deactivate the operating system in the software. The X-axis rotation angle (roll) of the orientation sensor is used for turning the system ON and OFF. The operating system can be switched ON or OFF when the operator twists his/her wrist. When the system is ON, all the values of the sensors become zero.

Fig. 5 System ON/OFF

3.2. Swing and Bucket

When the system is ON, the Z-axis rotation angle (yaw) of the orientation sensor is set as zero. ±20 degrees of the origin (yaw=0) from side to side is set as the dead band of the swing motion as shown in equation (1). Equation (1) also denotes the general range which a human arm can reach from side to side. The swing motion of the excavator is stopped if the operator's arm is in this dead band of the swing motion. Turning to the left makes the excavator's arm move swing to the left and turning to the right makes the excavator's arm move swing to the right. Fig. 6 illustrates the swing operation.

$$-20° \leq \theta_{dead\_swing} \leq 20°$$
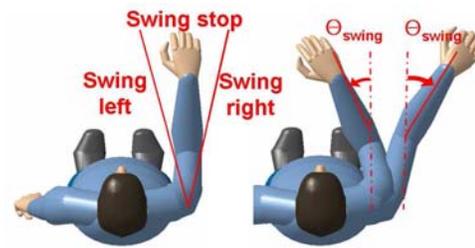$$-60° \leq \theta_{swing} \leq 60° \qquad (1)$$

Fig. 6 Swing operation

The swing motion is separated from the other motions

(boom, arm and bucket) and as such, when it is in operation, the other motions are stopped. If it is not separated from others, unintended swing motion can happen. For example, when the operator pulls his/her arm, the excavator can swing to the left. Pulling arm makes his/her wrist twisted. It should be separated from other motions to prevent unintended motion. The specific method for the separation is as follows.

When the computer reads the yaw value of the orientation sensor every 100 milliseconds, the computer checks the swing mode. If the variation of the yaw value of the orientation sensor is bigger than the determine value, the swing mode is set as ON. After the swing motion is stopped, i.e., is within the dead band of the swing motion, it is set as OFF.

$$-6° \leq \theta_{dead\_bucket} \leq 6°$$
$$-20° \leq \theta_{bucket} \leq 70° \qquad (2)$$

When the system is ON, the angle of the rotary encoder is set to zero. The dead band of the bucket motion is set to ±6 degrees of the position in up and down directions as shown in equation (2). Equation (2) also denotes the general range which a human hand can reach up and down. The bucket motion of the excavator is stopped if the arm of the operator is within the dead band. The bucket motion can be started only when the swing motion is turned off and Fig. 7 illustrates the bucket motion's operational commands.
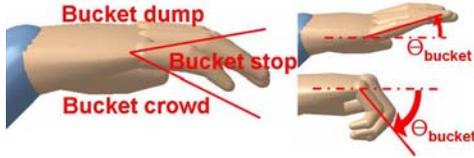

Fig. 7 Bucket operation

3.3. Boom and Arm

When the swing mode is turned off, the boom motion can start. The Y–axis rotation angle (pitch) of the orientation sensor controls the boom's motion. The boom and arm operation is also set to zero when the operating system is turned ON. The dead band is ±3 degrees up and down. When the human arm is up, the excavator's arm is also up and the same applies to the down motion. Equation (3) shows the dead band of the boom and arm motions and equations (3) also denotes the general ranges which a human arm can normally reach up and down, or back and forth.

$$-3° \leq \theta_{dead\_boom}, \theta_{dead\_arm} \leq 3°$$
$$-65° \leq \theta_{boom} \leq 65° \qquad (3)$$
$$-60° \leq \theta_{arm} \leq 60°$$

The arm motion can also start, as with the boom, when the swing mode is turned off. The operating angle is determined by using the pitch of the orientation sensor and the upper arm's angle from the inclinometer. The detailed formula is as follows.

$$\theta_{boom} = \beta$$

$$\theta_{arm} = \alpha + (90° - \beta) \qquad (4)$$

where,

α = inclinometer
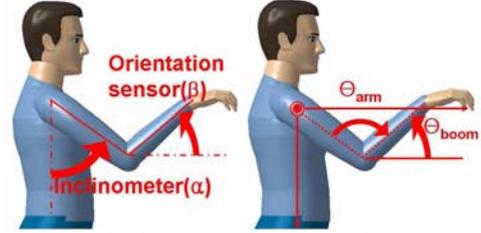β = pitch of orientation sensor

Fig. 8 Boom and arm operation

In case of the boom and arm motion, the dead band moves towards the position of the operator's arm. Fig. 9 describes the moving dead band of the arm's motion and the moving speed of the dead band is determined by trial and error and depends on actual speed of each of the excavator's motions in the boom and arm.
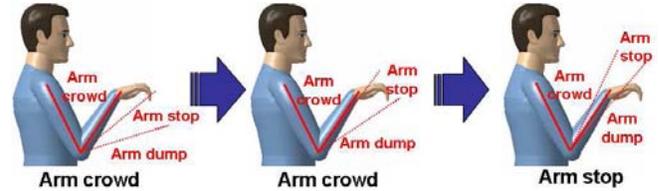

Fig. 9 Moving dead band of boom and arm motion

4. Simulation

The algorithm has been modified and improved through numerous tests. Therefore, it is necessary to verify it by using the simulation before the actual experiments with a real excavator. The simulator, which is designed by OpenGL, has been used to verify the modified algorithm visually and the simulator shows the virtual excavator on the screen to check the feasibility of the advanced algorithm.

During the simulations, several operators manipulated an imaginary (virtual) excavator, with sensors. The computer could save the data of the sensors and variables to make the operational commands while they manipulated the virtual excavator. The operators manipulated the imaginary excavator horizontally without swing and bucket motion. They moved their arms, on which the sensors attached, back and forth to manipulate it with only boom and arm motions. Then trajectories of the virtual excavator could be obtained from the data and variables by calculations and Fig. 10 shows the results of the horizontal trajectory tests. The calculations of the imaginary bucket position at the tests were executed according to the ideal hydraulic cylinders' performances at the maximum engine speed, from 2500 rpm to 3000 rpm. Fig. 10 shows that the tele-operation system can perform accurate motions within ±50 mm (up and down errors) under the ideal conditions.
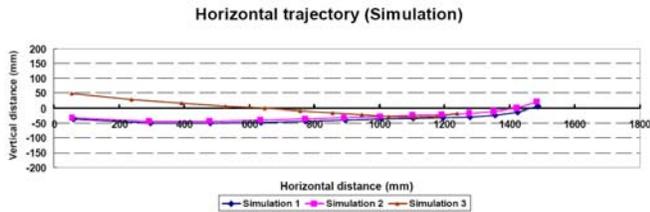
Fig. 10 The simulation results of the horizontal trajectory test

5. Experimental Results

The horizontal trajectory tests were done to check the accuracy of the system where the operator tries to manipulate the joint of arm and bucket to move it horizontally. Because it was cold winter, the tests were carried out after 30 minutes warming-up at the maximum engine speed, from 2500 rpm to 3000 rpm. The tests were also done at the maximum engine speed. The experiments are executed without swing and bucket motion and recorded on a small camcorder. Then the position of the joint of arm and bucket can be obtained from the movie clip which is taken by the camcorder sequentially.

Fig. 11 shows a graph of the results obtained from the tests. From the results, if an unskilled operator wants to move bucket horizontally, they can do it within ±80 mm (up and down errors). It is not easy that beginners move the bucket horizontally, because they should control the joystick levers of the excavator carefully to manipulate boom and arm motions at the same time. It is also a reasonable value compared with the load-independent control system [11]. The control system moves 1200 mm horizontal stroke with ±50 mm up and down errors. It is about ±4% errors compared with the horizontal stroke. Error of the tele-operation system is about ±5.5%. However, the load-independent control system moves its bucket tip at speeds of about 2m/min because it moves autonomously without operator's manipulation. In case of the tele-operation system, it takes 3 seconds for the horizontal stroke, about 30m/min.
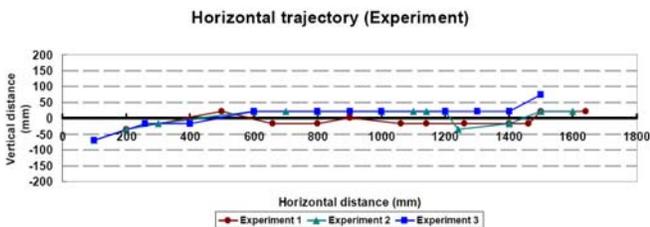

Fig. 11 The experimental results of the horizontal trajectory test

The system has been tested in simulation studies to perform the horizontal trajectory test and results gave a horizontal motion of within ±50 mm (up and down errors). However, in real excavator tests of the developed system the results show that the horizontal motion achieved was within ±80 mm, as seen in Fig. 11. The difference is due to the imprecision of the hydraulic cylinders and that the modelling has only been based on kinematic analysis. The hydraulic cylinders are not very precise actuators because temperature and humidity effects can affect its performance.

Variations in ambient temperature, fluid viscosity and flow rate changes can affect the performance of the hydraulic system, and all of these have not been included in the simulation results. However the results are sufficient to indicate that good manipulation of the excavator to positions where the operator wants to reach is possible. The developed system has shown sufficiently good results and that efficient manipulation of the excavator is possible by using visual feedback from the operator, rather than including these effects in the hydraulic system.

The separated motions, e.g. swing, boom, arm and bucket motions, of the developed system move at a similar speed. Most of the motions perform nearly 90% of the joystick control except for the boom-up motion. In other words, the excavator can move as fast as usual operations. Combined operations also show that the developed system can work as fast as usual manipulations. It takes about 15 seconds to dig out ground, swing 90 degrees, and dump it by using the tele-operation system. It is almost 87% speed of a skilled operator with a joystick controller. It takes about 13 seconds that a skilled operator does the same work by using joysticks.

Fig. 12 is the screen shot of the movie clip, which the operator uses to work the developed tele-operation system. The operator can manipulate the excavator easily and safely at a distance as seen in Fig. 12. The excavator can gather up and dig out soft ground by using tele-operation commands. The operators who participated in the experiments were unskilled excavator users. The results also show that, when the ground is soft, the system performs satisfactorily. However, because currently there is no force feedback implemented in the design, when the ground is hard, the actual excavator's motion cannot closely follow the operator's movements.

Fig. 12 The real manipulation with the developed system

6. Conclusions

The tele-operation system for the excavator with movements of a human arm has been developed so that unskilled operators can manipulate small sized excavators easily, intuitively and safely from a distance. Two problems are solved by this research, namely the high risk involved in the operation, and the difficult unintuitive manipulation methods provided by using joysticks. The developed system

is largely divided into hardware and software components. The hardware is further divided into the master part and the slave parts. In the slave part, proportional solenoid valves are attached to the existing RCV so that the excavator can be operated with both joysticks and the new developed tele-operation system. In the case of the master part, three sensors, which are attached to the human arm, detect the movements of the arm and passes the sensors readings to makes the operational commands in a computer. Finally, the computer transmits the commands to the embedded computer on the modified excavator.

Although the simulation results show that the horizontal motion achieved was within ±50 mm, the results of real excavator were within ±80 mm. The difference is due to the imprecision of the hydraulic cylinders, not included in the simulation. However, the developed system has shown sufficiently good results and that efficient manipulation of the excavator is possible by using visual feedback from the operator.

In spite of light weight and simplicity, the system is not ready to be portable for users and owners because it has additional equipments, e.g. an industrial computer and a power supply. If the master part has self contained power, for example battery, and microprocessor, operators can move easily with it on his arm. The system will be improved to be enough small and portable to manipulate the excavator everywhere.

7. Acknowledgements

8. References

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