A Study of Field Condition Feedback to a Remote Controlled Underwater Heavy Machine Operator

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Abstract –

Construction in the water is currently under way using an underwater excavator. The underwater excavator is operated by a diver. To reduce the burden on the diver, remote controlled system of underwater excavator is developed, but the current system has poor operability to use. The purpose of this study is to improve operability of remote controlled underwater heavy machine. We considered and proposed the working field condition feedback methods to the remote controlled underwater excavator operator for improving the operability. The methods were evaluated through simulation experiments.

Keywords –

Underwater excavator; Unmanned construction; Teleoperation; Operating Support; Instructions; Input Device

1 Introduction

An underwater excavator is used for constructions in harbors and dams. The underwater excavator is shown in Figure 1. It is remodeled from the land one by reloading the diesel engine to the underwater motor and hydraulic pump, and it can work underwater environment. In the underwater constructions, the excavator is operated by divers riding on it like Figure 2. So, the divers must operate it in the water for a long time. Therefore, remote controlled construction machines are needed for underwater constructions to reduce their burden, and remote controlled underwater excavators and their control systems were developed.

Figure 1. An underwater excavator [1]

Figure 2. An excavator operated by a diver [1]

In the underwater construction using current remote controlled excavator, the operator can get working field conditions only from camera images. The visibility is poor and it is insufficient for the operator to operate the excavator smoothly.

Therefore, operability of the remote control system for underwater excavators should be improved and some improvement methods were proposed [1]. However, the previously proposed remote control system has complex interfaces for showing the environment around the underwater excavator, and its operability improvement is still insufficient.

Then in this study, we propose a simple but efficient method for improving the operability of remote control system for underwater construction machines using vibration of operation lever.

In chapter 2, we analyze the cause of the insufficient operability in the underwater excavator operation. In chapter 3, we propose the simple but efficient working field condition feedback methods to the remote controlled underwater excavator operator. In chapter 4, we evaluated the operability of the proposed methods described in chapter 3 by using our developed simple simulator. In chapter 5, we conclude our study described up to chapter 4.

2 Considering about insufficient operability of underwater excavator

When the diver riding on the underwater excavator operates it, the diver relies on his seeing view, feeling shake of the excavator and hearing sounds. In the water, the diver sometimes cannot see his working field situation because of the rising clouds of dust by the excavator. In this case, the diver must operate the excavator only relying the shake and sounds. This state is shown in Figure 3.

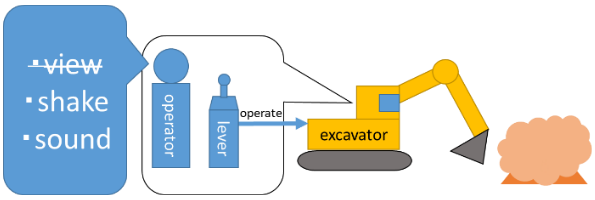

Figure 3. Excavator operated by a diver in the water

Current remote control system has some cameras on the excavator and the working field images are displayed to the operator. But, the operator cannot feel the vibration and sound of the excavator. Additionally, in the underwater work, operators cannot see the field condition when the clouds of dust soar by the operation of the excavator. Then, in the current system, operators cannot rely on not only the vibration and sounds of the excavator but also displayed images of the working field. Therefore, operators cannot operate excavators until the clouds of dust disappear. This state is shown in Figure 4.

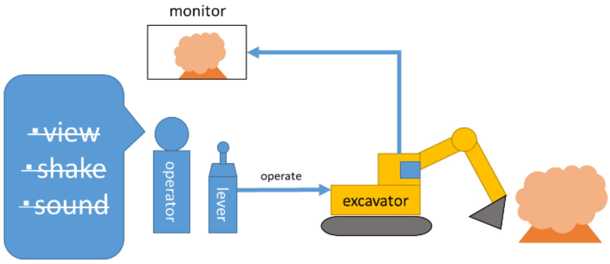

Figure 4. Excavator operated by remote control system from the operation room

3 Considering and proposal of the field condition feedback methods

This study proposes working field condition feedback methods to improve the operability for the remote controlled underwater excavator operators. Necessary information for the excavator remote control was revealed by the interview to the operators who often operate underwater excavators using remote control system. The necessary information is:

- The moment when the excavator starts moving
- The moment when the excavator hits some obstacles
- Whether the excavator reached its moving limits

In the current remote control system, some sensors are attached to the excavator, and their sensor values are sent to the operation monitors and displayed. We considered more intuitive methods are necessary to inform the working field conditions to the operators than using a display monitor. Then, we considered 3 different methods for informing the excavator conditions to the operator based on the sensor values. The methods are as follows:

- Make sounds of different types and patterns for expressing sensor values of the excavator and inform them to the operator
- Move the seat of the operator depend on the sensor values of the excavator
- Apply reaction force or vibration to the control lever of the excavator controller depend on the sensor values of the excavator.

About the first method, some current systems have a function which presents the sounds of working field picked up by a microphone on the excavator. However, further information like presenting many sounds during excavator operation may confuse the operator. About the second method, the already developed system exists [2]. It is shown in Figure 5. Although this system is effective for informing working conditions to the operator directly, it may increase the operator’s burden. Therefore, we considered that the third method, moving control lever depend on sensor values, is the most suitable for informing working conditions to the operator, then we adopted it for our study.

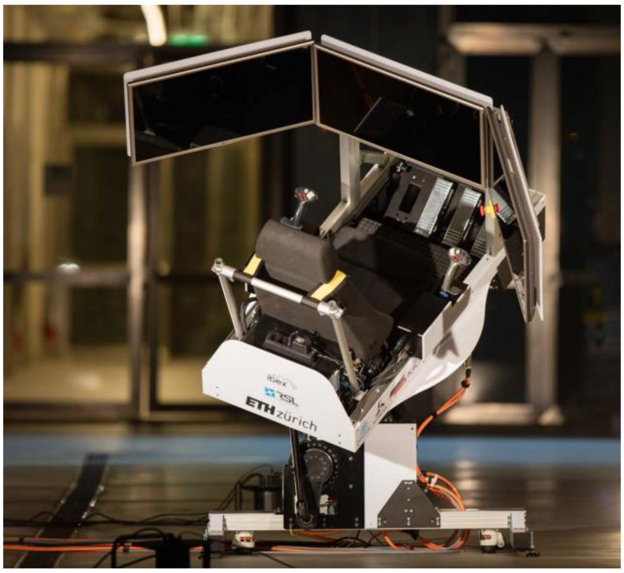

Figure 5. Moving operation seat for the remote control system [2]

We considered 3 methods to move control lever of the excavator controller for showing the sensor values of the excavator and informing working conditions to the operator. The methods are as follows:

- Applying reaction force to the control lever of the excavator controller depend on the sensor values.
- Applying breaking force to the control lever of the excavator controller depend on the sensor values.
- Vibrating the control lever of the excavator controller depend on the sensor values.

The first method was applied to the tele-operated support system of underwater excavator and confirmed that this method is good for tele-operated system when the operator cannot see the surroundings of the excavator [3]. The developed system is shown in Figure 6. Although this method is effective for informing working conditions to the operator when the operator cannot see the surroundings of the excavator, sometimes the operation may become unstable due to the delay of the feedback signal. The second method also seems effective for informing working conditions of the excavator to the operator. But, this is a passive method because breaking force acts only when the operator moves the control lever. Furthermore, the first and second methods may interfere when they are applied to the control lever at the same time. Then, we decided to adopt the third method which is vibrating the control lever depend on the sensor values.

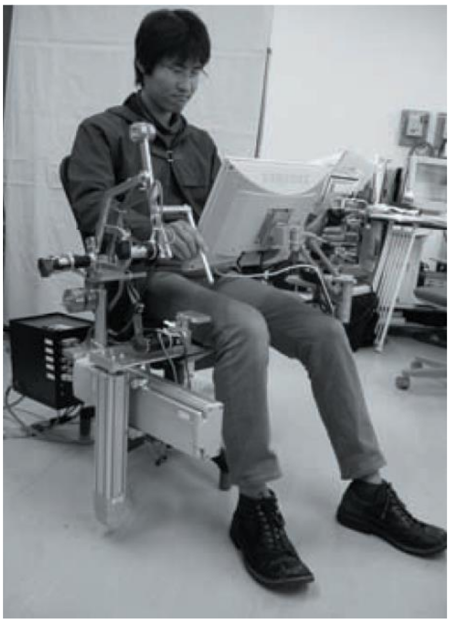

Figure 6. The operation system with force feedback controller [3]

We considered what kinds of vibration patterns of the control lever are good for operators to inform the condition of the excavator, and we proposed some vibration patterns shown in Table 1, Table 2 and Table 3. The proposed vibration patterns shown in Table 1 are for the information to the operator when the excavator starts moving. The vibration patterns in Table 2 are for the information when the excavator hits some obstacles. The vibration patterns in Table 3 are for the information whether the excavator reached its moving limits.

Table 1. Proposed vibration patterns which inform to the operator when the excavator starts moving

Method	Good point	Output
Vibrate only when the excavator starts moving	Can understand the moment when the excavator starts moving	Binary value
Vibrate while the excavator is moving	Can understand the excavator is moving or not	Binary value
Vibrate variably based on the moving speed of the excavator	Can understand the moving speed of the excavator	Analog value

Table 2. Proposed vibration patterns which inform to the operator when the excavator hits some obstacles

Method	Good point	Output
Vibrate while the excavator is loaded	Can understand the excavator is contacting something or not	Binary value
Vibrate variably based on the load of the excavator	Can understand the exerted load to the excavator	Analog value

Table 3. Proposed vibration patterns which inform to the operator whether the excavator reached its moving limits

Method	Good point	Output
Vibrate when the operator tries to move the excavator beyond moving limit	Can understand when the operator tries to move the excavator beyond the moving limit	Binary value
Vibrate variably based on the distance to the moving limit of the excavator	Can understand the distance to the moving limit of the excavator	Analog value

For informing the change of above three excavator conditions to the operator for the excavator remote control, we proposed two types of control lever vibration patterns. One is a constant vibration pattern, and another is a variably vibration pattern. The constant vibration pattern is proposed to detect the moment of condition change when the excavator starts moving or contacts something, etc. And, the variably vibration pattern is proposed to recognize the continuous condition change while the excavator is moving or receiving loads, etc. We evaluated these two types of patters through experiments using a simulator in the next chapter.

4 Evaluation of the proposed condition feedback methods

4.1 Evaluation system and method

We revealed three necessary information for the excavator remote control from the interview of skilled underwater excavator operators, and we proposed 7 vibration patterns of the control lever for informing the condition of the excavator to the operators.

To evaluate the proposed vibration patterns shown in the previous chapter, we developed a simple simulator system and made some experiments.

From the constraints of our experimental system, we evaluated the selected 4 vibration patterns of the control lever for informing the change of excavator conditions to the operator based on the sensor values shown in Table 4.

Table 4. Evaluated vibration patterns by our simple simulator system

Pattern number	Vibration pattern
1	The control lever vibrates while the excavator is moving. *The strength of the vibration changes according to the moving speed.
2	The control lever vibrates only when the excavator starts moving. *The vibration time is 0.2 sec.
3	The control lever vibrates while the excavator is loaded due to the contact of bucket and soil. *The strength of the vibration changes according to the exerted load.
4	The control lever vibrates when the operator tries to move the excavator beyond moving limit. *The vibration continues while the operator tries to move.

We made experiments to evaluate the above proposed 4 vibration patterns of the control lever. A joystick controller with vibration function and our developed simple simulator were used for the experiments. Figure 7 shows the joystick controller and its specifications are shown in Table 5. Our developed simulator is shown in Figure 8.

Figure 7. Joystick controller “PXN Thunder PRO”

Table 5. Specifications of the joystick controller [4]

Product name	PXN Thunder PRO
Model	PXN-2113
Connection	USB cable
Working current	100mA
Dimensions	22.5 x 18.5 x 18.5cm
Product Weight	About 495g

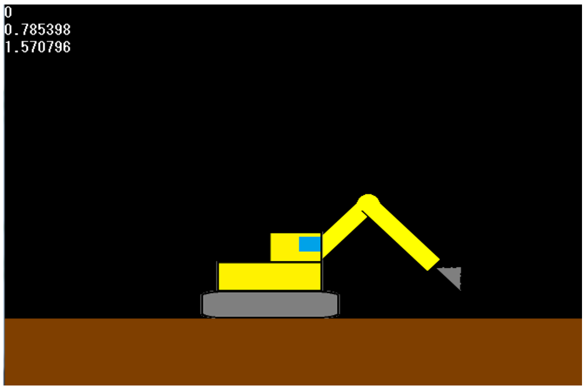

Figure 8. Simulator for the experiments

The simulator was composed of the joystick controller, a computer and a monitor. The connection of these equipment is shown in Figure 9. The computer receives a signal of tilt angle of the joystick controller and sends a signal of strength of the vibration. The monitor displays an image of the excavator like Figure 8. In the simulator, a boom of the excavator moves when the joystick controller is tilted to back or forth, and a bucket of the excavator moves when the joystick controller is tilted to left or right.

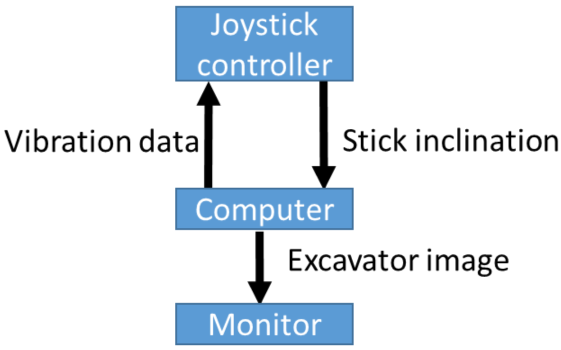

Figure 9. Equipment connection of the simulator

About the vibration pattern 1 in Table 4, the excavator in the simulator moves by tilting the joystick controller, and the moving speed of the excavator changes according to the tilt angle of the joystick controller. The joystick controller vibrates while the excavator is moving, and its vibration strength changes according to the excavator's moving speed. About the vibration pattern 2 in Table 4, the joystick controller vibrates for 0.2 sec. when the excavator starts moving by tilting the joystick controller. About the vibration pattern 3 in Table 4, when the contact of bucket and soil occurs in the simulator while the excavator is moving, the joystick controller vibrates for informing it. The strength of the joystick controller vibration shows the strength of the load exerted to the excavator bucket. About the vibration pattern 4 in Table 4, when the operator tries to move the bucket and the boom of the excavator beyond moving limit in the simulator, the joystick controller vibrates for informing it. The vibration continues until the operator stops moving the excavator to that direction.

Some subjects experienced all vibration patterns by using the simulator. After that, the subjects answered the questions about the impressions of each pattern. The questions are as follows:

- Which vibration pattern was good for operating the excavator?
- How did you feel about using these patterns?

4.2 Evaluation Results by subjects who have no experience operating excavators

Two subjects who don't have experiences operating excavators participated in the experiments. Both subjects answered that the vibration of the joystick controller to inform the collision of the excavator bucket to some obstacles is most useful for recognizing the working field conditions. And, one subject answered that the vibration of the joystick controller during excavator's moving is useful too. The answers of all subjects are shown in Table 6.

Table 6. Evaluation results by the subjects who don't have experiences operating excavators

Vibration pattern number	Evaluation
3	Easy to understand the collision of the excavator bucket to some obstacles, intuitively.
1 and 3	Good for recognizing the excavator and its working field conditions

4.3 Evaluation Results by subjects who have experiences operating excavators

Four subjects who have experiences operating excavators participated in the experiments. All subjects answered that the vibration of the joystick controller to inform the excavator’s moving condition is more useful than the vibration which informs the start of moving of the excavator. The answers of all subjects are shown in Table 7.

Table 7. Evaluation results by the subjects who have experiences operating excavators

Vibration pattern number	Evaluation
1 and 3	Good for recognizing the excavator and its working field conditions
1	Vibration pattern 1: Vibration during the movement of the excavator is OK. Vibration pattern 2: It is difficult to understand the excavator's condition only from the vibration which informs the movement start of the excavator. Vibration pattern 3: It is difficult to understand the vibration’s differences.
1 and 3	The system should have two different strength of vibration patterns which are strong and weak.
1, 3 and 4	Combining the vibration pattern 1 and 4 will inform us the posture of the excavator. The system should have different types of vibration patterns for presenting different information at the same time.

5 Conclusion

A remote controlled underwater construction machine was developed to reduce the operator’s burden. However, current developed system has insufficient operability. This paper revealed the cause of operator’s burdens for the operation of the excavator. Furthermore, more intuitive methods to inform the working field conditions to the operators than using a display monitor are considered. And, we proposed the simple but efficient working field condition feedback methods which uses the vibration of the control lever of the excavator for the remote controlled underwater excavator operator.

We considered three necessary information for the excavator remote control, and proposed 7 vibration patterns of the control lever for informing the change of excavator conditions to the operator based on the sensor values. Four different vibration patterns of the control lever were implemented to the simulator and they were evaluated through experiments.

From the results of evaluation experiments, we found that the vibration of the control lever to inform the excavator’s moving condition is more useful than the vibration which informs the start of moving of the excavator for all operators. And, the vibration of the control lever to inform the collision of the excavator bucket to some obstacles is useful for recognizing the working field conditions around the excavator for non-skilled operators.

Our study will improve the operability of remote control system for construction machines. In future work, we will evaluate more vibration patterns and some combined vibration patterns using different types of vibration patterns through simulator and actual system experiments. In addition, further study about applying other kinds of feedback methods to the construction machines will be evaluated for the improvement of the system operability.

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