TELEOPERATION OF CONSTRUCTION MACHINES WITH HAPTIC INFORMATION FOR UNDERWATER APPLICATIONS

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Abstract: Mechanization is necessary for safer and more efficient underwater construction work in port areas. Teleoperated underwater construction machines are under developing. The problem is that conventional TV camera system is useless in water because of turbidity. Haptic information is introduced as the aid to control construction machines substituting for visual information. Components of control technologies are visualization of haptic image, force feedback, and similar figure controller. Leveling experiment of gravel mound was carried out successfully on land with an experimental land model of underwater backhoe.

Keywords: Underwater Construction Machine, Visualization of Haptic Image, Force Feedback, Similar Figure Controller, Leveling Experiment

1. INTRODUCTION

Composite breakwaters shown in Figure 1. are major in Japan [1]. Underwater work is necessary to construct composite breakwaters.

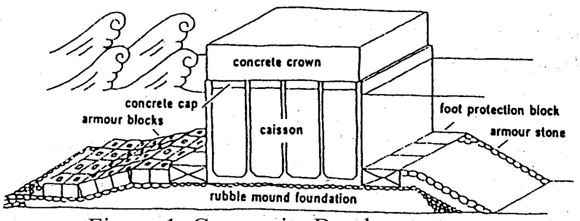

Figure 1. Composite Breakwater

Major part of underwater work in port construction sites is carried out by divers' manual labor at present shown in Figure 2. Manual labor in water is exhausting and working efficiency is not sufficient. In addition, ensuring divers' safety is difficult and diving duration is restricted in water.

Figure 2. Diver's Manual Labor

As port construction sites are moving to deeper areas because of enlargement of port scale, necessity of mechanization is increasing for safer and more efficient underwater construction work [2].

Manned underwater backhoes shown in Figure 3. have already been developed for this purpose. They are tethered watertight backhoe-type construction machines and are operated by divers boarding on. Working efficiency is improved several times by introducing manned underwater backhoes compared with divers' manual labor [3].

Figure 3. Manned Underwater Backhoe

However, there still remain two sorts of problems. The fatal problem is that visual information is hardly obtained in water because of unclear seawater or muddiness caused by construction work itself. As it is impossible to operate manned underwater backhoes without visual information, they are able to work only in transparent seawater. The solution is to utilize different information substituting for visual information. The operational problem is that ensuring operators' safety is difficult and one operator's continuous working duration is restricted due to water pressure. The solution is teleoperation of underwater backhoes from the surface.

2. CONCEPT OF TELEOPERATED UNDERWATER CONSTRUCTION MACHINES

2.1 Conventional teleoperation on land

Teleoperated land construction machines were developed for the use on dangerous construction sites such as steep slopes, soft ground and so on. In these cases, boarding operation was simply replaced by radio-control system. Only the positions of the operators are moved from the operators' seats to the places near the construction machines. It is the same that operators looking at the machines directly by naked eyes.
TV cameras have been equipped afterwards on the construction machines for long-distance teleoperation such as post-disaster construction. For example, this type of teleoperated construction machines have been in practical use for urgent removing work of volcanic ejecta which brought huge damage to wide areas near two volcanoes for these years in Japan. It is a simple combination of conventional radio-control device and TV cameras. No other sensor except GPS is equipped. Teleoperation with TV cameras is essentially equivalent to conventional radio control with human eyes.
The reason why teleoperated construction machines have been able to be used in post-disaster construction sites is that large amount of visual information, i.e., distinct real-time video images of high resolution is obtained through TV cameras in the air. Recognition of the state of the construction work by looking directly with naked eyes and that by looking through TV cameras are nearly equal. Visual images are processed in human brains in both cases. No image processing technology is required for teleoperation of construction machines as far as TV cameras are able to supply sufficient visual information.

2.2 Problems of teleoperation in water

Contrary to land construction work, visual information is generally poor undersea especially in port areas because of turbidity of seawater. Even if seawater is transparent, vision will be obscured because construction work itself makes seawater muddy. They should wait until muddiness flows off. It means TV cameras are ineffective in underwater construction sites. A control system without visual information should be developed for underwater construction machines.

2.3 Human senses and tele-existence

It is considered that man accepts information outside mainly by sense of vision. The left small part is obtained by auditory sense, tactile sensation, and the senses of smell and taste. Vision is so important for man.
Let us consider how operators boarding on conventional construction machines on land recognize the contact between end effectors and objects. General way to operate construction machines is to control flow rate of pressured oil by adjusting apertures of hydraulic bulbs with control levers. The force required to move control levers is constant independent of the actual forces acting on the objects. Operators are unable to feel the change of reaction force directly. Operators mainly recognize contacts by looking at the pushed objects moving. Operators feel vibrations of operators' seats or hear sounds of relief bulbs at the same time as they look. They are subsidiary information.
Then, in case of teleoperation, audio instruments are sometimes equipped in control rooms located in remote places to represent the ambient sound around the construction machines. However, one case of our questionnaire with interview shows that audio instrument is not in use. This fact seems to be against the concept of tele-existence that the representation of exactly equivalent circumstances of boarding operation in the control room makes operability of teleoperation better.
Presumable reasons for this fact are as follows. Concerning visual sense, field of view is limited by the viewing angle of the TV-camera lens and stereoscopic vision is not available with conventional TV cameras in contrast with wide field of view and 3-dimensional vision with naked eyes in case of boarding operation. Concerning auditory sense, represented sound is usually low-quality monaural sound not high-fidelity stereo sound. It is difficult to identify the sound of a specific machine from those of other machines in case that there are multiple construction machines on site.
Teleoperation systems with conventional TV cameras and standard audio instrument are unable to generate perfect tele-existence. It is concluded that operators tend to concentrate on processing of visual information because they rely on visual sense as main recognition means. It is for this reason that operators ignore the information other than visual information.

2.4 Introducing Haptic Information

Several types of ultrasonic imaging equipment are in the market or under developing. They are able to generate images in muddy water because ultrasonic waves are able to penetrate the water containing suspended minute particles. However, the resolutions are not sufficient for the operation of underwater construction machines. It means there is no method to obtain information from remote places underwater.

By the way, each construction work is carried out by contacts between end effectors of construction machines and objects. Instead of obtaining from remote places, obtaining information on state of execution is possible by contact points. In addition, it is reported that touch sense is dominant in form perception when vision is peripheral and blurry [4]. Tactile sense and force feedback seems to be effective for obtaining information even in the case visual sense is ineffective. Haptic sense includes both tactile sense and force feedback. It means haptic information is expected to be effective for underwater construction work.

3. COMPONENTS OF TECHNOLOGIES FOR TELEOPERATED UNDERWATER CONSTRUCTION MACHINES

3.1 Visualization of haptic image

Visualization of haptic image is to convert the information obtained by haptic sense into visual image. The positions of contact points are calculated by articulation angles of working parts of a construction machine. The configuration of the object is visualized by computer graphics.
It is hard to recognize total view of execution with haptic sense. One reason is that original form of haptic information is real-time and temporary at a time of contact. Man makes haptic image in his brain when he touches objects. However, it is disappearing from his memories as time passes. The other reason is that man excessively relies on visual sense and is accustomed to visual information. Visualization of haptic image is helpful to recognize total view of execution because it accumulates all the information obtained throughout the execution and shows it as long as needed. The other example is that sensory substitution of force feedback through the vibrotactile and auditory modalities for teleoperation tasks improved operator performances [5].
This type of representing method that the information difficult to obtain by a certain sense is substituted by other information easy to obtain by the other sense is called Augmented Reality (AR) technology
In this study, AR technology is used to visualize the positions of the contact points between the construction machine and the object by 3-D display and makes the operator to recognize the configuration of the object. The visualized haptic image of the experimental land model of teleoperated underwater backhoe is shown in figure 4. This is the side view of the backhoe and the terrain. Point of view is variable. Wire-frames show actual posture and polygons show ordered posture. The difference between the positions of wire-frames and polygons informs time-delays of hydraulic powered mechanism to the operator. The color of the bucket changes from blue to red at the moment it touches the terrain to indicate the contact obviously to the operator. Green line shows the target height of leveling. Red line shows the actual terrain obtained by haptic sense.

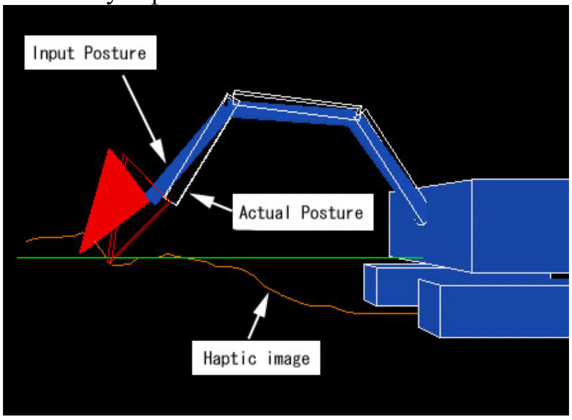

Figure 4. Visualization of Haptic Image

3.2 Force feedback

Recognition of the contact between the end effector of the construction machine and the object is necessary for operation. In the case of conventional construction machines, operators recognize contact by visual sense. Force feedback enables operators to recognize contact by feeling of hands. In other words, touch sense is used in that case.
In this study, symmetrical servo-type force feedback system is applied to hold the bucket position constant while the bucket is not touching and force-reflection-type force feedback system is applied to sense reaction force easily while touching. Transition between these two systems is automatic.

3.3 Similar figure controller

Similar figure controller has the same shape as working parts of a construction machine. It enables operators to operate construction machines by intuition compared with the conventional multi-lever type controller. Similar figure controller with force feedback system enables operators to recognize the strength and the direction of the reaction force.
In this study, similar figure controller with force feedback system is introduced to the experimental land model of teleoperated underwater backhoe shown in figure 5. The operator should hold the controller like a pencil and move it. According to the motion of the controller, the machine will move.

4. TELEOPERATED UNDERWATER BACKHOE

4.1 Experimental land model of teleoperated underwater backhoe

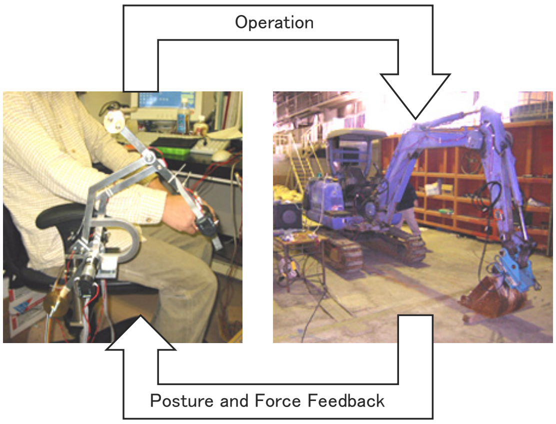

Figure 5. Similar Figure Controller

An experimental land model of teleoperated underwater backhoe shown in Figure 6. has been developed by reconstructing a conventional backhoe with a 0.09m^3 class bucket based on the test result of a small model.

Figure 6. Experimental Land Model

Electric control valves, articulation angle sensors and a reaction force sensor are added to the original machine.
Electric control valves shown in Figure 7. enable proportional control of the articulations by teleoperation. Potentiometers, one of them is shown in Figure 8., are attached at 3 axes of the arm as articulation angle sensors to obtain the attitude of the front part. A reaction force sensor attached at the joint connected with the bucket as shown in Figure 9. is able to detect contact between the bucket and the object.

4.2 Software

The software that calculates the positions of contact points by articulation angles and the rotation angle of the front part of the backhoe has also been developed. It shows the topography of the terrain to the operator by computer graphics that draws the contact points on the display.

Figure 7. Electric Control Valves

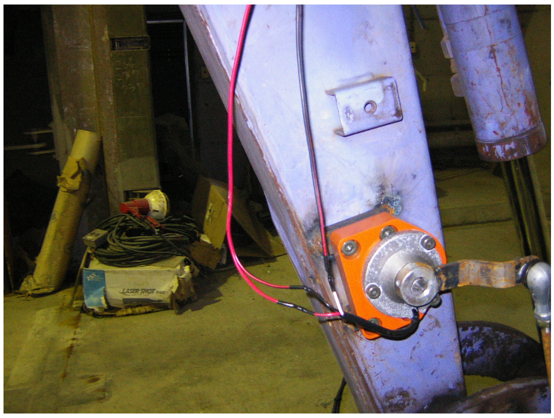

Figure 8. Articulation Angle Sensor

Figure 9. Reaction Force Sensor

It is necessary to contact many points of terrain to obtain the precise configuration of the terrain, however, small number is enough for construction work because the terrain surface is continuous due to its nature. The position of unknown point between contact points is able to be interpolated by the coordinates of contact points.
The method of interpolation is as follows. The heights of points within ±30cm horizontally distant from contact point are assumed proportional to the distance from contact point shown in Figure 4. Same algorithm is used in the first and second contact shown in Figure. 10 and Figure. 11 respectively.
Linear interpolation of ±30cm range from the contact point is proved to be most effective for teleoperation through experiments.

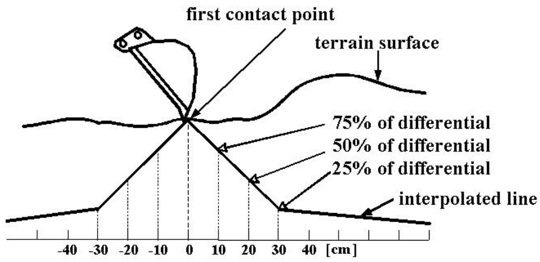

Figure 10. Interpolation at the First Contact

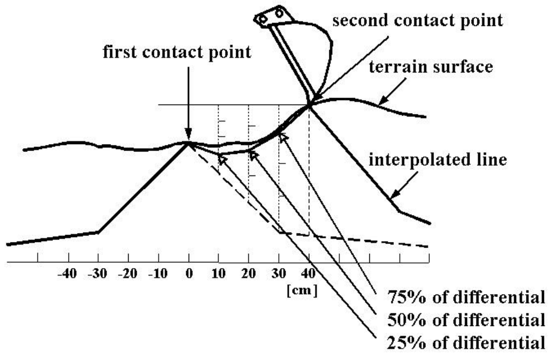

Figure 11. Interpolation at the Second Contact

5. LAND EXPERIMENTS

5.1 2-D Leveling experiment

Experiment of leveling gravel mound of unknown height to a certain height was executed with the experimental land model. Target leveling height was 600 [mm]. The size of gravel was about 150 [mm]. Leveling was 2-dimensional without rotation of upper structure and locomotion of lower structure of the machine.

In case of teleoperation, the operator was isolated in the control room where visual information by naked eyes or through TV cameras was not available. He looked at the visualized haptic image on the computer screen and moved the similar figure controller as shown in figure 12. The information available was limited to visualized haptic image and reaction force fed back to the hand. The operator touched the surface of gravel mound at first to know the rough configuration of the mound. After that, he started leveling work. It was possible to level the gravel mound only with visualized haptic image and force feedback.

Six leveling experiments were done for boarding operation and teleoperation respectively. The height of 13 points within horizontal distance of 2.3 to 3.5 [m] from the rotating axis of the front part were measured with a Totalstation. Measured values of six experiments were averaged. In case of boarding operation with visual information, averaged height is 586 [mm] and standard deviation is 21 [mm] as shown in Figure 13. In case of teleoperation with haptic information, averaged height is 608 [mm] and standard deviation is 21 [mm] as shown in Figure 14.

It is verified that the teleoperation with haptic information system has the equivalent accuracy to the conventional boarding operation. It means the accuracy of teleoperation is sufficient for practical construction work.

Figure 12. Operator in Control Room

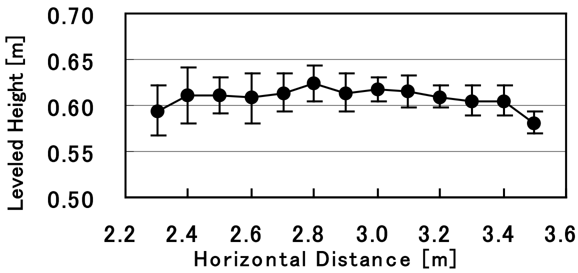

Figure 13. Leveling with Visual Information

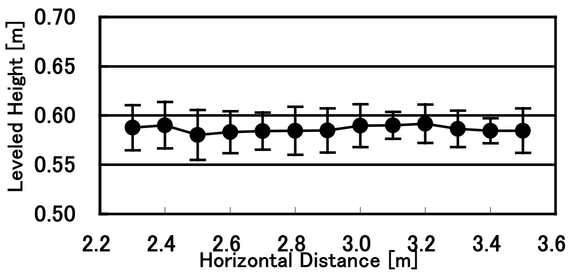

Figure 14. Leveling with Haptic Information

Experimental result was evaluated by difference between ordered height and actual height as shown in Figure 15. The height measured with a Totalstation is considered as the actual height. In case of teleoperation with haptic information, averaged error is ±28 [mm] and standard deviation is 16 [mm]. In case of boarding operation with visual information, averaged error is ±22 [mm] and standard deviation is 14mm. The averaged height of teleoperation is –23 [mm] lower than that of boarding operation.

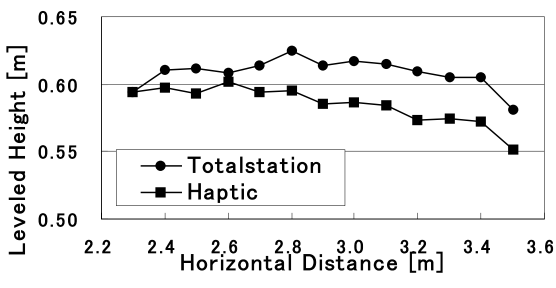

Figure 15. Totalstation and Haptic Survey

It is because the calibration of haptic information is done on the rigid surface. As the claws of the bucket are stuck in the void spaces of the gravel mound in the actual experiments, measured heights are lower than real ones. This phenomenon should be taken into consideration next time.

4.3 3-D leveling experiment

Following to 2-D experiment, the experiment of 3-dimensional leveling with rotation of upper structure and no locomotion of lower structure is being carried out successfully.
Figure 9 shows one situation that the bucket touches the gravel mound. Figure 10. shows the visualized haptic image of the same situation as that of Figure 9. Responding to rotation of upper structure, polar coordinate system is introduced.

Figure 9. Actual Image of 3-D Leveling

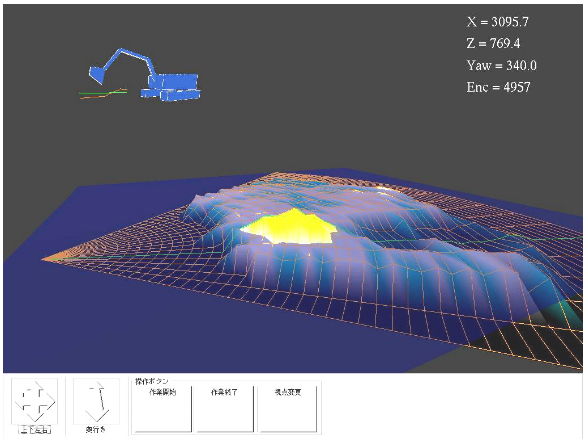

Figure 10. Visualized Haptic Image for 3-D Leveling

6. CONCLUDING REMARKS

The experiment of leveling gravel mound with a teleoperated backhoe with haptic information substituting for visual information has been successfully executed on land. It is verified that the accuracy of leveling is sufficient for practical leveling work of gravel mound.
In the next phase, the first sea trial of a teleoperated underwater backhoe with haptic information shown in Figure 11. is planned in latter half of 2004 in Kyushu Region.

Figure 11. Teleoperated Underwater Backhoe

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