Semi-autonomous Touching of Underwater Object by Unmanned Untethered Vehicle

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***Abstract*-To investigate an underwater object in detail, it is essential for underwater vehicles to touch the object. However, for the Unmanned Untethered Vehicle (UUV) touching an underwater object is not an easy task because those robots are not apt to be operated remotely via acoustic link which is slow in communication rate and results in a long time-lag. In this paper, on the basis of time-lag compensation by stored video images, ranging technique by image processing and station keeping by visual feedback, a semi-autonomous system is proposed that enables the UUV to touch an underwater object by its hand from any direction. The proposed system is demonstrated experimentally through tank tests using testbed robot Tri-Dog 1 to which a two-degree-of-freedom robot hand is fitted.**

I. INTRODUCTION

Manned Submersibles (MS) and Remotely Operated Vehicles (ROV) are operated and practically used for survey and observation in underwater environment. Manipulator systems fitted to the MS and ROV that are directly operated by the operator are well developed and are useful tools for investigation and handling. For practical surveys, Unmanned Untehered Vehicles (UUV) are also very useful. However, they are mainly used for observation by cruising over a wide area and are scarcely applied for investigation of a small area. This is mainly due to limitations of data communication between the UUV and the surface support vessel, and the UUV's intelligence and performance. Since the UUV's dynamics are not disturbed by the umbilical cable, it is expected that the UUV can operate a manipulator for investigation and handling of objects on the sea floor. The UUV with a manipulator has following advantages in comparison with ROV and MS.

- A hazardous sea area can be investigated.
- Objects in an area having a complicated topography can be investigated.
- It does not need heavy deck equipment for operation.

As a first stage of underwater manipulation, the UUV should touch the specified object. This paper proposes a semi-autonomous system that enables the UUV to touch an underwater object with the robot hand from any direction.

II. BACKGROUND

In order to let the UUV touch an underwater object, the following issues should be addressed:

1) Slow data communication rate
2) Visual recognition of the target
3) Ranging to the target
4) Station keeping
5) Robot hand control
6) Interface between the operator and the robot

1) is caused by the acoustic link which is the only wireless communication method in water. Time-lag which depends on the range is also imposed on communication between the operator and the UUV. Consequently, the UUV is required to behave automatically to the extent possible. When the operator sends a command to the UUV, this time-lag should be considered.

2) and 3) should be implemented in high reliability when the UUV touches an unknown object.

4) is required to lock the position and orientation of the UUV since the UUV is a free-floating vehicle.

5) should be done automatically based on sensory data.

6) provides a comfortable tool for the operator.

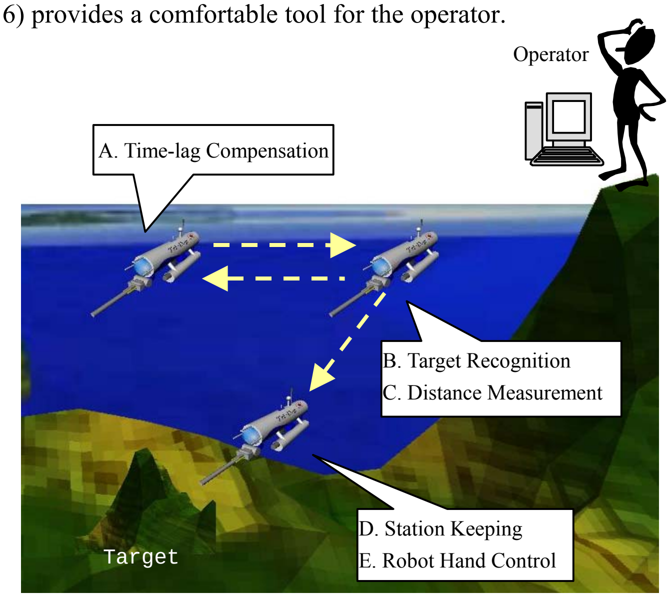

Fig. 1. Issues that must be addressed

The proposed process of target object touching is as follows:

The UUV takes video images of the surroundings and sends images to the operator via the acoustic link. The operator identifies an object in these images which he wants to investigate. The operator sends the UUV a command to specify the object. By the time the UUV receives this command, it has moved to another place because of the time-lag. The UUV should return to the place where the UUV saw the specified object (Fig. 1 A). The UUV then recognizes the object (Fig. 1 B), measures the distance to it (Fig. 1 C), goes close to it, locks the position and orientation (Fig. 1 D), controls the robot hand (Fig. 1 E) and touches the object.

III. APPROACH

A. *System Prerequisite*

The hardwear system needed in this study consists of 4 features as shown in Fig. 2.

1) a UUV with a CCD camera (Surge, sway, heave and yaw motion can be controlled.) and image processors
2) a 2-DOF hand (Tilt and linear joint can be controlled.)
3) 2 laser pointers fitted to the robot hand parallel to the arm.
4) acoustic links for command and image transmission

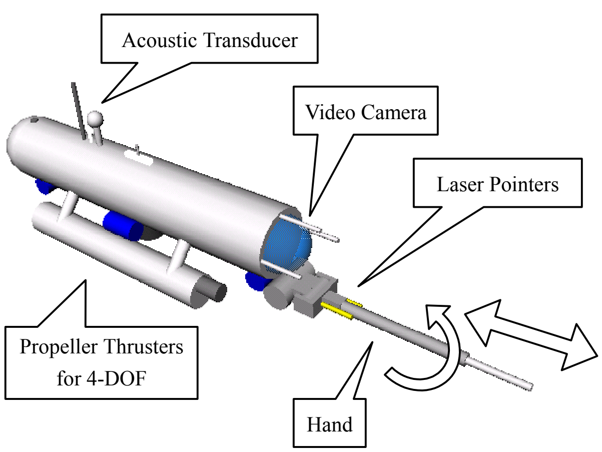

Fig. 2. UUV and 2-DOF Hand

B. *Time-lag Compensation*

The UUV periodically takes a video image and gets the position and orientation of the vehicle and stores these data with a reference number ID as shown in Fig. 3. Here, TR denotes robot time and TO operator time. The UUV sends this data package to the operator. When the operator sends a command to the UUV with this reference number, the UUV can refer to the correspond data.

The 1st command to the UUV from the operator is used to specify a target object and consists of the reference number and image coordinates of the target object as shown in Fig. 1. After receiving the 1st command, the UUV returns to the position indicated by reference number and takes the orientation by dead-reckoning navigation. The UUV always

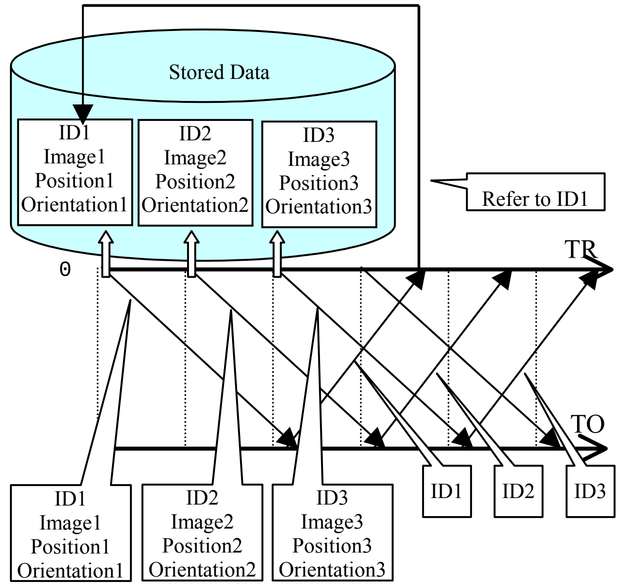

Fig. 3. Method of Time-lag Compensation

compensates the time-lag in this way when the operator sends a command to the UUV.

C. *Target Object Recognition*

After going back to the required position and taking the orientation, the UUV picks up the video image from the stored data, that the operator has indicated by reference number in the 1st command. As Fig. 5 indicates, The UUV automatically extracts a partial image of the target object from this image whose location is specified by the image coordinates of the target object in the command. The extracted image is used as the template of the target object to recognize the target in the video sequences that the UUV is taking.

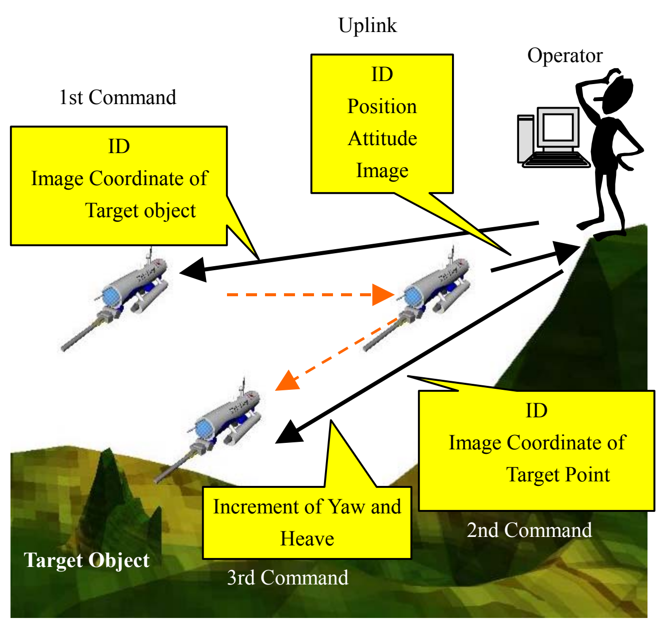

Fig. 4. Communication between the UUV and the Operator

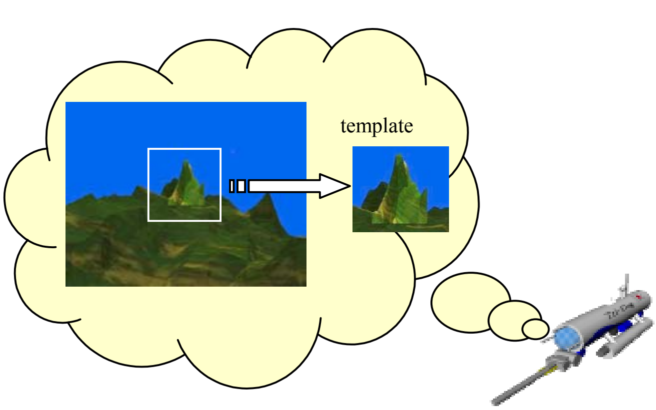

Fig. 5. The UUV makes the template of target object automatically.

D. Ranging and Directing to the target

The UUV measures the distance to the target object by pointing two laser beams from base of the arm as shown in Fig. 6 and Fig.11. Image coordinates of the reflected points of laser beams in the video image taken by the camera mounted at the head of the UUV are obtained by image processing, and the UUV calculates the distance to the reflected points based on their horizontal separation in the image.

Since the arm is located on longitudinal vertical center plane of the vehicle and the direction of the camera is in the same direction, the coordinates of the center of the reflected points in the image are always on the y axis as shown in Fig. 6. Therefore, the UUV should move so as to keep the target object on the y axis. Yaw motion is controlled to lock the target object on the y axis by visual feedback control. Then the UUV operates the robot hand to keep the center of the reflected points on the target object by tilting the robot hand using visual feedback control. The UUV also calculates the position of the target object in the robot coordinates based on the coordinates of the reflected points in the video image. The UUV then moves close to the target object by dead-reckogning navigation.

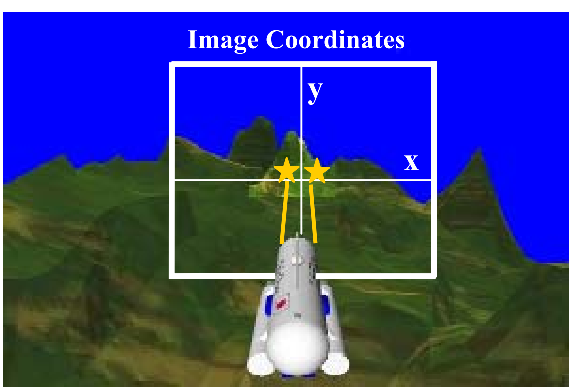

Fig. 6. The UUV measures the distance to the target by image processing

E. Station keeping

After recognizing in the user interface that the UUV is close enough to the target object, the operator sends the 2nd command (see Fig. 4) consist of the reference number and the image coordinates of the point which should be touched. By this command the operator precisely specifies the point to be touched. After receiving this command, the UUV makes a template of the image around the point, finds the point in the current image, and tracks the point. Then, the UUV starts to lock the position and orientation by keeping the distance to the reflected points constant and the target object on the y axis using visual feedback control.

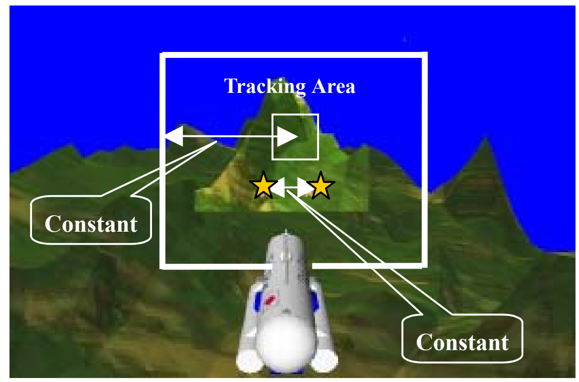

Fig. 7. The UUV locks the position by visual feedback control

F. Robot hand control

The UUV's motion and the robot hand are so controlled as to keep the center of the reflected points to be on the target point as discussed in the previous section. Since the two lasers are parallel to the arm, the UUV extends the arm and touches the target point based on the distance to the target point by controlling the linear joint. The linear joint for extension is controlled by open loop.

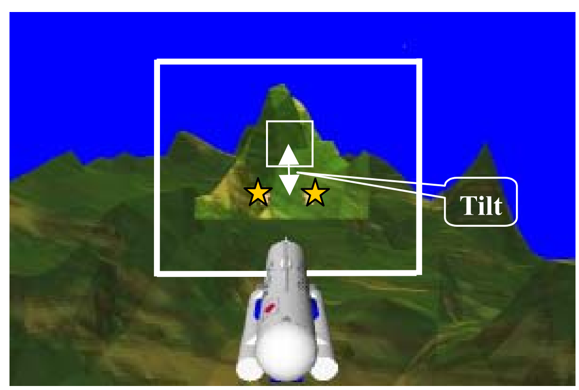

Fig. 8. The UUV controls the robot hand.

G. Angle between the robot hand and the target object

The operator can also order the UUV to touch the point from a specified direction by the 3rd command. The vertical angle can be changed by controlling the heave motion and the horizontal angle by controlling the orientation of the vehicle. The operator sends a command of increment of heading angle and depth as shown in Fig.9.

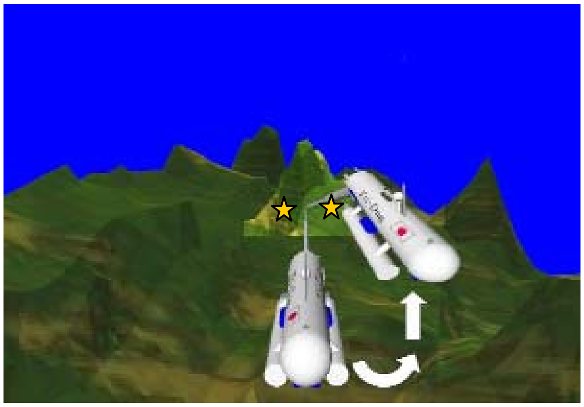

Fig. 9. The UUV changes the angle between the robot hand and the target object.

IV. USER INTERFACE

Fig. 10 shows the picture of the user interface which was developed in conformity with the operation sequence mentioned in the previous chapter. A video image which is received from the UUV in a specific interval via the acoustic image link is shown in the top panel. The target object is identified by clicking the image, which is denoted by a cross mark on the display. Below this image, there is description of the position of the UUV. The compass on the bottom right shows the heading of the UUV. These data are updated every few seconds with time-lag. Buttons on the lower left are used to send commands to the UUV. Sliders are used to change the angle between the robot hand and the target object.

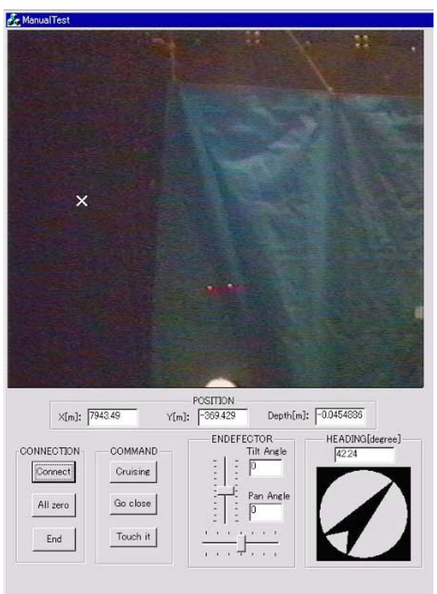

Fig. 10. User Interface

V. UUV and robot hand

Fig. 11 shows the robot hand developed to demonstrate the proposed system. The robot hand has two degrees of freedom and is equipped with two laser pointers. The robot hand has a processor and battery cell in the pressure hull and is an independent module of the UUV. This independence from the UUV provides the robot hand advantage of flexible connectivity to various UUVs. This processor communicates with the UUV through RS232C interface. The robot hand can extend from 713mm to 1085mm in length. Weight in water is about 400gf. White parts of this robot hand are made of polyethylene which is neutrally buoyant in water.

Fig. 12 shows high performance testbed vehicle Tri-Dog 1 [3] used in this study to meet the prerequisite as discussed in chapter III-A. Tri-Dog 1 provides controllability for surge, sway, heave and yaw motions. This robot has a doppler velocity log, a depth sensor, a magnetic compass and a CCD camera. The robot hand is mounted under the chin (front bottom) of Tri-Dog 1.

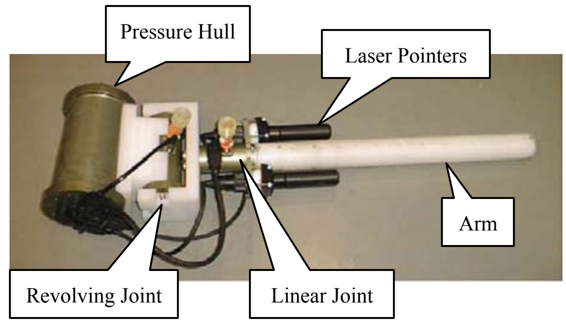

Fig. 11. Robot Hand

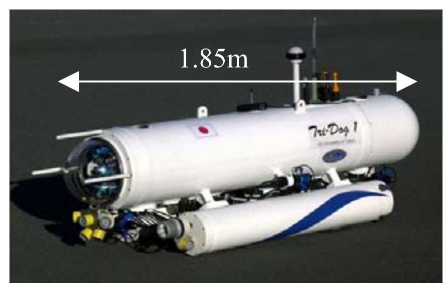

Fig. 12. Tri-Dog 1

VI. EXPERIMENTS

Tank tests have been carried out to demonstrate the performance of the proposed system. Fig. 13 shows the target object used in this test. The mission is to touch the white square (5cm*6cm) at the center of the target object. Fig. 14 shows the arrangement of the test tank.

Fig. 13. Target Object

Fig. 15 shows a sequence of images taken by the internal camera on Tri-Dog 1 and an external camera, and the user interface pictures during the experiment. The vehicle is directly connected to the interface by an umbilical cable, and the time-lag is virtually realized by program. It is assumed that the operator receives a data package from the UUV every 3 seconds with time-lag of 7 seconds.

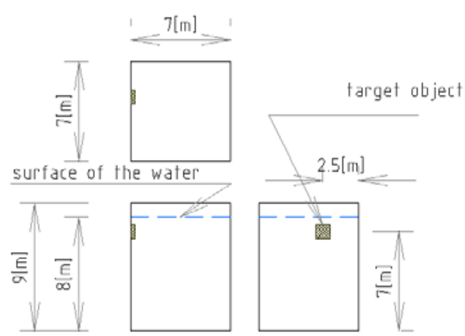

Fig. 14. Arrangement of the Test Tank and the Target Object

At the beginning of the test the UUV moves laterally facing to the wall by dead-reckoning navigation. The operator specifies the target object by clicking and pushes the command button to send the 1st command. After receiving the 1st command, the UUV compensates the time-lag, and goes back to the required position and orientation by dead-reckoning navigation. It is shown that the image on the user interface when the operator sends the 1st command is identical to that of the internal camera when the UUV comes back to the required position. Then, the UUV makes the template of the target object which is the 40 x 40 rectangular pixel region centered at the pixel specified by the operator on the user interface, and recognizes the target, measures the distance to it, and goes close to it. After the center of the white square is specified by 2nd command, the UUV locks the position and orientation, and touches the specified point by controlling the robot hand. The zoom-up feature of touching is shown in Fig. 16. After receiving the 3rd command, the UUV changes the angle between the robot hand and the target object.

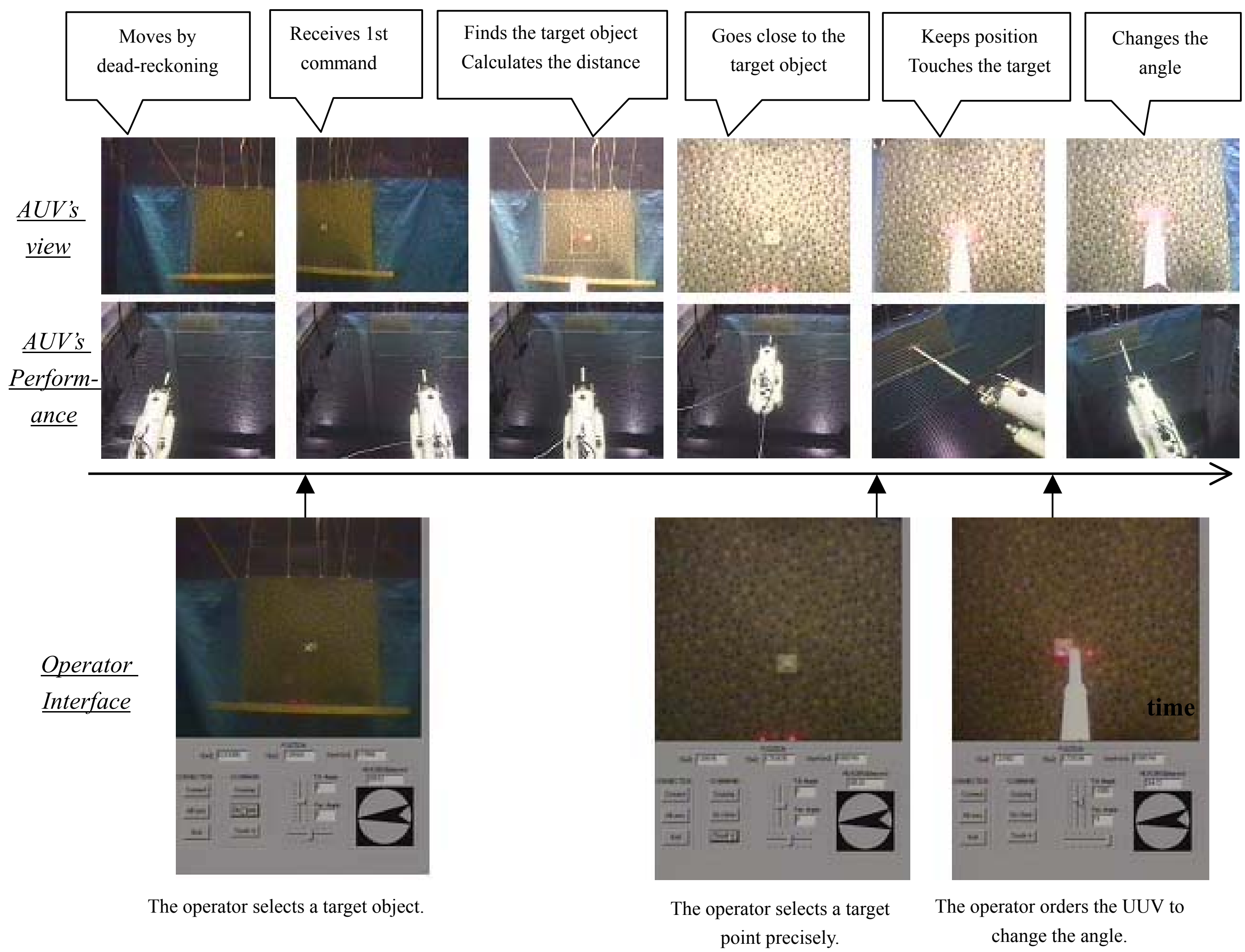

Fig. 15. Images taken by Internal and External Cameras and User Interface Pictures during Experiment

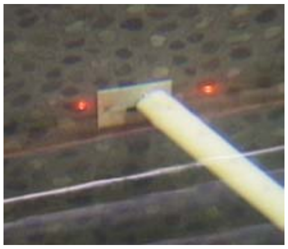

Fig. 16. The UUV touches the target object precisely.

Fig.17 shows the horizontal trajectory of the UUV during the experiment where the UUV starts at the coordinate (0,0). Fig.18 and 19 show the image coordinates of the target object during station keeping. The target object is not locked in vertical direction precisely because Tri-Dog 1 is controlled by the data from depth sensor and does not use visual feedback. The vertical fluctuation of the position, however, is compensated by tilt control of the robot hand. Since the response of the tilt control is much quicker than that of UUV's motion, vertical error of touching is negligible. On the other hand, the error in horizontal direction is larger than the vertical error since the horizontal error is significantly influenced by sway and yaw control. Initially, the horizontal error fluctuated but soon converged to zero due to the visual feedback control. When the UUV touches the target point, the distance to the target point from the CCD camera on the UUV is about 1400mm. From this distance a single pixel on image plane corresponds to 2.0mm. It can be seen that fluctuation of the horizontal position of the target in the video image is within 9 pixels, namely 18mm after 30 seconds from the start of station keeping stage. Consequently, the maximum horizontal error of touching is 18mm.

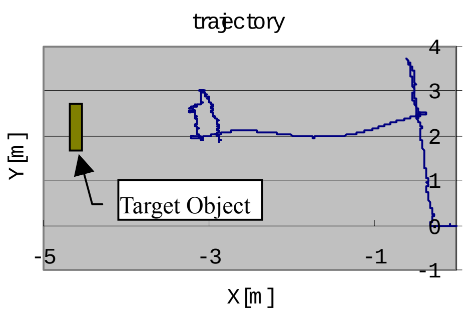

Fig. 17. Horizontal Trajectory during Tank Tests

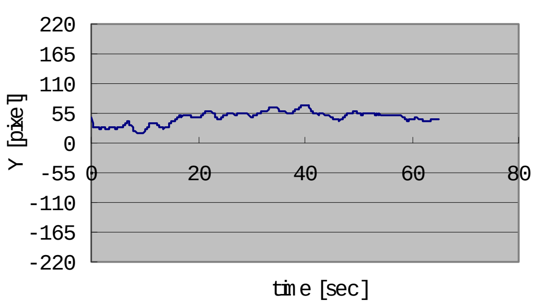

Fig. 18. x Value of Target Object in Image Coordinates during Station Keeping

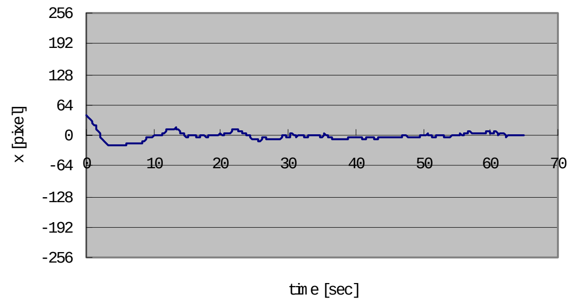

Fig. 19. y Value of Target Object in Image Coordinates during Station Keeping

VII. CONCLUSION

In this paper, We have demonstrated using Tri-Dog 1 that the UUV is able to touch an underwater object from any direction with the robot hand on the basis of time-lag compensation by the stored data, distance measurement by laser pointers and station keeping by visual feedback control. The horizontal error is less than 18mm and vertical error is much lesser. As an application of this system, by attached sensors or end effectors at the end of the robot hand, an UUV is expected to come close to hydrothermal vents or chimneys, and directly measure the plume or catch animals on them.

ACKNOWLEDGMENTS

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