Visual Investigation of Underwater Structures by the AUV and Sea Trials

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***Abstract*- To investigate underwater structures such as piles and caissons in harbors, and risers and jackets of deep-sea oilfields by taking visual images, Autonomous Underwater Vehicles (AUV's) have advantages that they have no umbilical cable which may get entangled in the structures and surrounding obstacles. The authors have proposed a navigation method for AUV's to observe such objects using a laser ranging system that consists of TV camera and laser pointing devices in previous papers. This ranging system provides precise distance to the target object so that the vehicle can trace the shape of the target object keeping constant distance and attitude. The method was implemented in the testbed AUV "Tri-Dog 1," and proved experimentally through tank tests in 2001. Following the success of the tank tests, the authors have carried out sea trials in 2002 at the port of Kamaishi, Japan, which has huge breakwaters. This paper describes the result of the sea trials and our perspectives. Based on the proposed system, AUV's will be able to carry out autonomous investigation of underwater structures in the near future.**

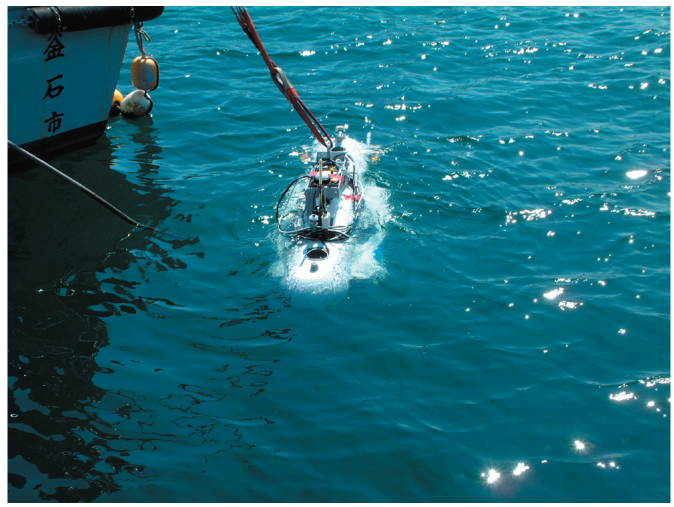

Fig. 1. Tri-Dog 1 at the sea.

I. INTRODUCTION

Since Autonomous Underwater Vehicles (AUV's) have an advantage that they can swim freely without the restriction of a tethered cable they are very useful for ocean observation. It can be said that AUV's are increasingly finding practical application worldwide [1][2][3][4]. For investigation of underwater oilfields and resources, seabed observations are already being commercially executed by AUV's using side scan sonar, multi narrow beam sonar, sub-bottom profiler and etc. [5][6][7].

There is a great demand for AUV's not only for wide area survey but also for investigation of artificial underwater structures such as piles and caissons in harbors, and risers and jackets of deep-sea oilfields. Periodical inspection is necessary for underwater structures. These works have normally been done by human divers and Remotely Operated Vehicles (ROV's). However, diver operations are risky jobs and are not applicable in very deep sea environments, while ROV's have problems of an umbilical cable that may get entangled with the underwater structures. It is expected that the demand for the development of highly intelligent AUV's to undertake these complicated missions would increase greatly over the next few years.

From this perspective, the authors have proposed a navigation method for AUV's to observe such kind of underwater structures using a laser ranging system that consists of a TV camera and laser pointing devices as reported in previous papers [8][9]. The laser ranging system provides precise distance to the target object so that the vehicle can trace the shape of the target object keeping constant distance and attitude. The method was implemented in the testbed AUV "Tri-Dog 1,"[10] and proved experimentally through tank tests in 2001. Based on the success of the tank tests, the authors have carried out sea trials (Fig. 1) in 2002 at the port of Kamaishi, Japan, which has huge breakwaters. This paper describes the investigation method, the result of the sea trials, and perspectives of our future works.

II. INVESTIGATION METHOD

The autonomous investigation method of underwater structures by AUV's is implemented by initially detecting the target objects, localizing them, and then approaching them by taking video images while closely tracing the shape of the target objects. Proper sensing and navigation methods are required to be developed to realize this behavior. Assuming that the visibility is adequate for visual investigation of underwater structures, a simple laser ranging system that consists of laser pointers and a color TV camera is introduced for sensing. For navigation, a navigation method based on the relative position

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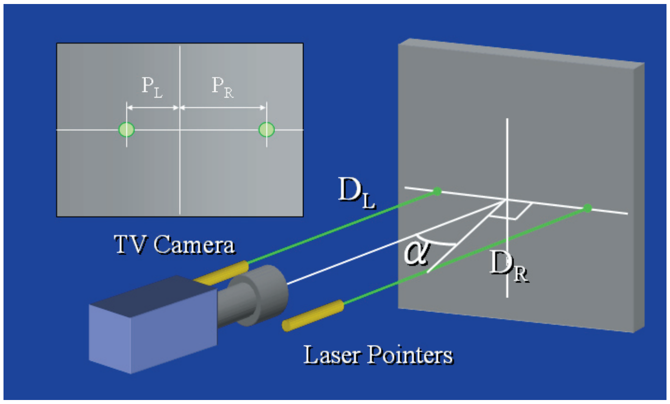

Fig. 2. Laser ranging system.

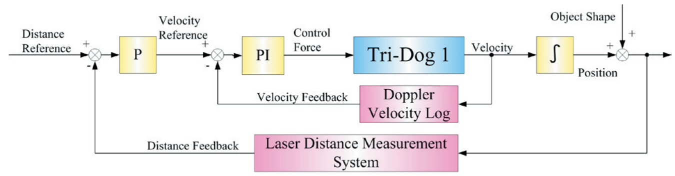

Fig. 4. Control block diagram for surge motion.

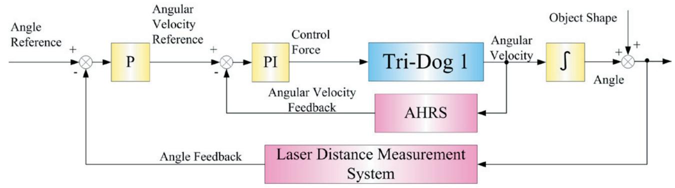

Fig. 5. Control block diagram for yaw motion.

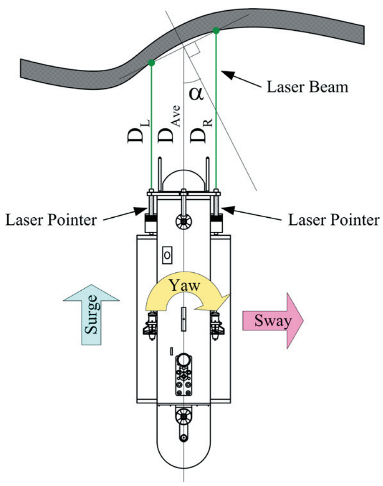

Fig. 3. Motion control for tracing the surface.

to the target objects is introduced.

As shown in Fig. 2, green laser pointing devices are fixed parallel to one another beside the TV camera. Distances D_R and D_L are calculated by using triangulation from pixel positions P_R and P_L of the camera image through image processing. Thus, the angle α between the object surface and the vehicle orientation can be determined. In order to eliminate errors caused by distortion of the camera lens and the acrylic dome and to find the relation between distances and pixel positions, calibration has to be done by preliminary experiment in the test tank. The parallel mounted laser pointers can also be used as a ruler to measure the size of the objects. Although the underwater image-based sensor tends to encounter problems of lighting and optical backscatter, it provides pinpoint and precise distance data when the target object is visible. The vehicle approaches close to the target object within few meters. It is assumed that the visibility is adequate, since the objective of this paper is visual investigation.

The dead reckoning navigation and acoustic navigation such as long base-line navigation system have difficulty to provide accurate enough position data for the AUV to trace the shape of the target objects. Thus, once the vehicle finds the target object, it changes navigation basis from absolute position to relative position to the object, so as to trace the surface of the target object precisely.

To trace the surface shape of the target objects, the vehicle controls its motion in 4-degrees of freedom independently as shown in Fig. 3. The surge velocity is controlled referencing the distance D_{Ave}, and the yaw angular velocity is controlled referencing the attitude angle α. The sway velocity is controlled as a constant velocity, and the heave is controlled for keeping constant depth. PID controllers are used for achieving the above controls. The schematic block diagrams for surge and yaw motion control are shown in Fig. 4 and Fig. 5 respectively.

III. SEA TRIALS

A. Port of Kamaishi

The port of Kamaishi is located in Iwate Prefecture, the northern part of Japan. A deeply indented coastline is facing the Pacific Ocean. The mouth depth of the port reaches down to 63m. It has huge breakwaters and rock mound underneath (Fig. 6 and Fig. 7). This caisson-type breakwater is the deepest one in the world. These caissons are constructed in the base of construction. The newly constructed caissons are put temporarily in the area of the base before they will be set on the rock mound. The area is covered by breakwaters and the flow and waves are relatively calm.

The authors chose two investigation targets. One is the caisson which is temporarily put on the construction base. The other one is the caisson which is arranged as a breakwater at the mouth of the port.

B. Testbed AUV

The proposed investigation method is implemented in the testbed AUV "Tri-Dog 1" to hold sea trials. The general arrangement and the specifications of the vehicle are shown in Fig. 8 and Table 1 respectively. The Doppler Velocity Log (DVL) is used for measuring bottom-locked velocity of surge

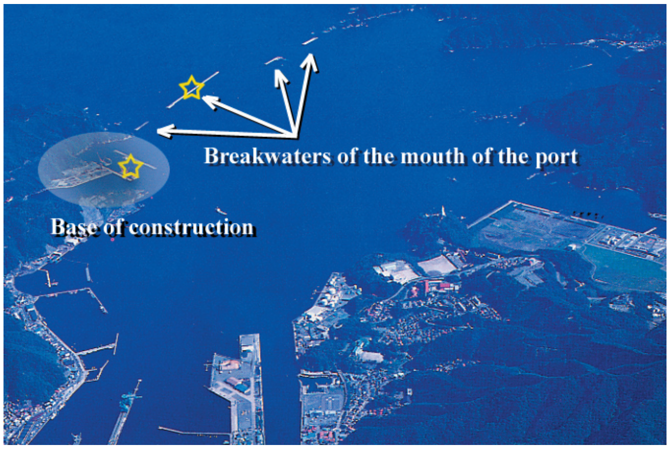

Fig. 6. The port of Kamaishi.
(copy from the bulletin of the port)

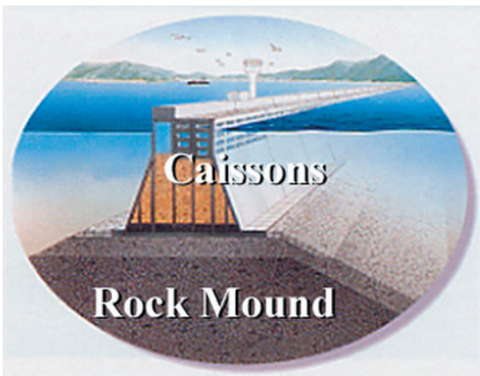

Fig. 7. Breakwater of the mouth of the port.
(copy from the bulletin of the port)

TABLE I
DIMENSIONS AND SPECIFICATIONS OF THE TRI-DOG 1

Length overall	1.85m
Breadth overall	0.58m
Depth	0.53m (0.90m include antennas)
Dry weight	170kg (approximately)
Operating depth	100m max
Maximum speed	1.4knots
Duration	more than 2.5hours
Structures	Aluminum Pressure Hulls
	(Main Cylinder x1, Battery Cylinder x2)
Actuators	100W Thrusters x6
	(Rotation, Amp. feedback)
Processors	Intel Pentium MMX 233MHz x3
	(High Level, Low Level, Vision)
Sensors	Attitude and Heading Reference System
	Doppler Velocity Log
	Electromagnetic Flow Meter
	Pressure Sensor (Depth Sensor)
	Real Time Kinematics GPS
	Acoustic Ranging Sensor x8
	CCD Camera with Pan & Tilt Mechanism
	Laser Pointer x3
Communications	Acoustic Command Link
	Wireless LAN
	430MHz Wireless Modem for RTK-GPS
Lights	24W Arc Lamp x2
Batteries	25.2V Ni-Cd Battery 20Ah x4

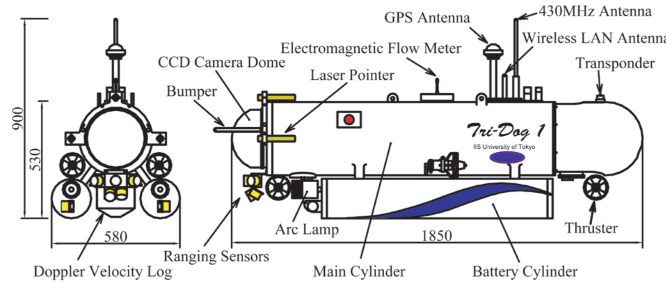

Fig. 8. General arrangement of the Tri-Dog 1.

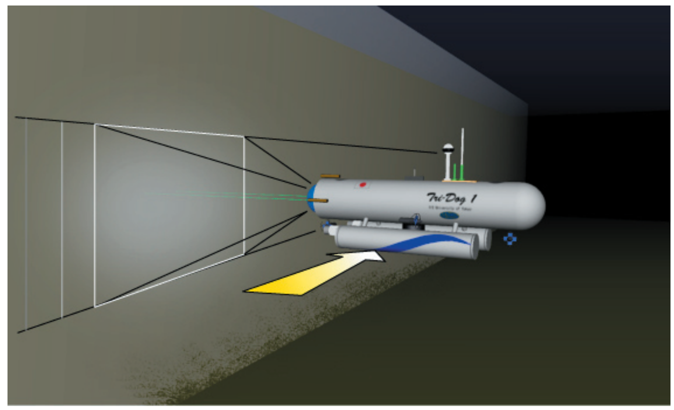

Fig. 9. Tri-Dog 1 investigating the surface of the caisson.

and sway motion. The pressure sensor is utilized as a depth sensor. The Attitude and Heading Reference System (AHRS) which contains vibration gyroscope is used to measure angular velocity of yaw motion. The accuracy of the laser ranging system is within 3.2cm for ranges between 0.65m and 2m. It is designed to maintain the vehicle at about 1m distance from the target object while taking video images.

Fig. 9 is the imaginary picture of the Tri-Dog 1 which is investigating the surface of the caisson.

C. Preliminary Investigation

In order to survey environmental conditions such as visibility, waves and flow of the target area, the preliminary investigation using small size Remotely Operated Vehicle (ROV) had been done in July 2002. The same laser pointing device of the Tri-Dog 1 was attached to the ROV, and it was examined whether the reflected point of the laser beam on the target object is visible or not for image processing. At the same time, the controllability under complicated flow around the caisson was examined by the ROV operator (the first author).

As shown in Fig. 10, the visibilities around both targets were good enough for the reflected point of the laser beam to be detected by image processing. The controllability of the ROV in the area of construction base was good and the ROV's motion could be controlled as intended by the operator. The flow and waves were almost negligible in the area. But, the flow and waves near the surface around breakwaters of

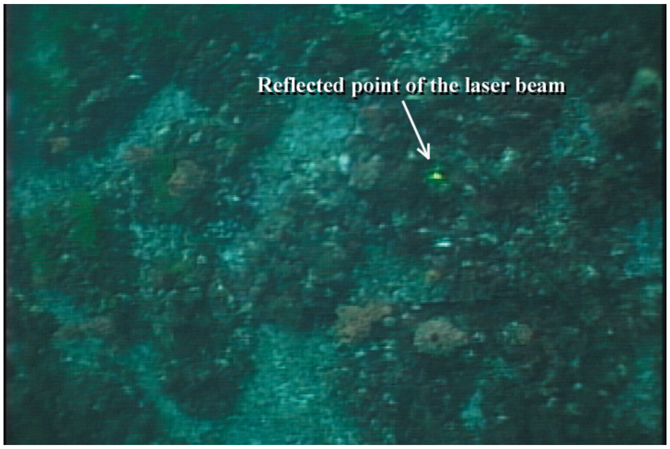

Fig. 10. Video image taken by ROV during preliminary investigation.

Fig. 11. Sea trial at the construction base.

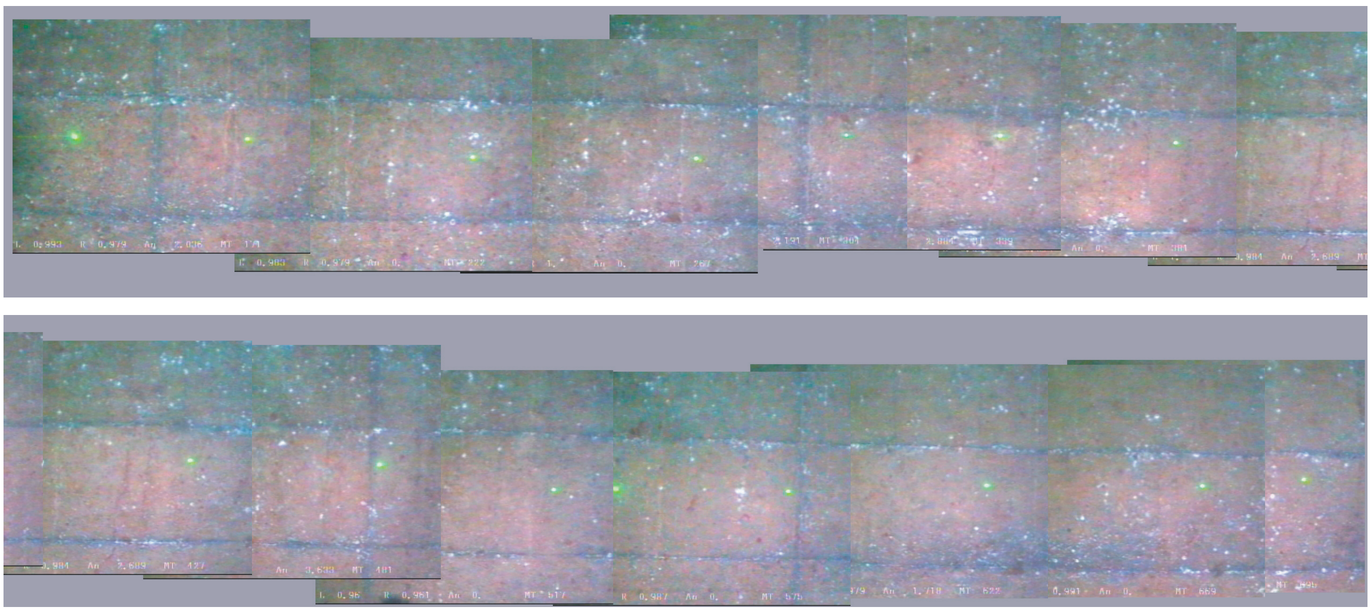

Fig. 12. Mosaic image of the caisson at 20m depth.

the mouth of the port were strong for small vehicles, and it was difficult to control its motion when the vehicle is near the surface. Once the vehicle dives deeply, the effect of the flow and waves become negligible.

D. Results

Considering the results of the preliminary investigation, the cables for the Ethernet and the NTSC video signal are connected for the safety of the AUV, and the authors made the vehicle investigate both target caissons in September 2002.

The investigation test at the base of construction (Fig. 11) was successfully done by demonstrating that the vehicle moved horizontally keeping constant distance and angle to take the image of the surface of the caisson. The effect of the waves and currents was almost negligible and so good results were obtained. Fig. 12 shows the mosaic image of the caisson as a result of the experiment.

However, during the trial of the breakwater caisson (Fig. 13), the fluctuations by waves and flow were so strong that the vehicle was unable to control itself. It is expected that if the vehicle dives deeply it will be able to control its motion. But, the vehicle drifted strongly due to the flow before descent, and could not keep its direction to the caisson. The breakwater has a slit between each caisson (Fig. 14), and the flow which comes from the sea through the slit is very strong and cyclically changes its direction (Fig. 15). The vehicle may face danger if it comes too close to the slit. Therefore, it was decided to quit the trials at the breakwater.

In the matter of the visibility of water around caissons, the reflected points of laser beams can be detected only within 2m distance because of the turbidity of the warm season during September in Japan. It was different from preliminary investigation during July. The dynamic range of the laser ranging system becomes quite narrow and it becomes difficult to find the target object. Once the vehicle can find the target, the method works well. But, under the disturbance of the flow, the

Fig. 13. Sea trial at the breakwater of the mouth of the port.

Fig. 14. Slit between caissons.

Fig. 15. Strong cyclic flow caused by the slit.

vehicle easily lost the target.

For image processing, it is better to have uniform lighting condition. While the vehicle cruises relatively deep, where there is no effect due to the change of natural sunlight, the laser ranging system works very well. Fig. 16 shows the image of the caisson that is taken at 20m depth. But in the case of

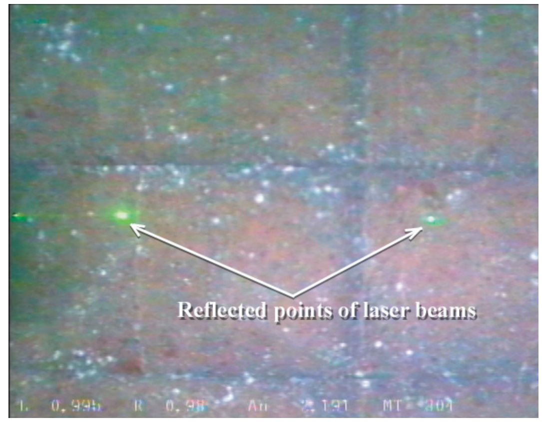

Fig. 16. Detectable reflected points of laser beams on the caisson.

Fig. 17. Undetectable reflected points of laser beams on the caisson.

very shallow water strong natural sunshine disturbs distance measurement seriously. Fig. 17 shows the image taken during the breakwater trial. The reflected points of laser beams cannot be detected by using both color and intensity extractions.

IV. CONCLUSION AND PERSPECTIVES

The visual investigation method of the AUV for underwater structures is proposed. The method was implemented in the testbed AUV "Tri-Dog 1" and the sea trial was executed at the port of Kamaishi, which has the deepest caisson-type breakwaters of the world. The method works well at the calm area by collecting images of the caisson automatically. The sea trials provide us precious knowledge to develop further AUV systems for investigation of underwater structures.

About the issue of sensing, the results of real sea trials show that the fusion of acoustic sensor and image-based sensor would be necessary for the ocean-going vehicle.

The AUV "Tri-Dog 1" is a testbed vehicle which has been designed for shallow water and test tank. The AUV for investigation of underwater structures should have strong enough thrusters to maintain the controllability even under complicated flow around the structures. The shape of the vehicle also should be designed considering that issue.

AUV's will be able to have an ability to investigate

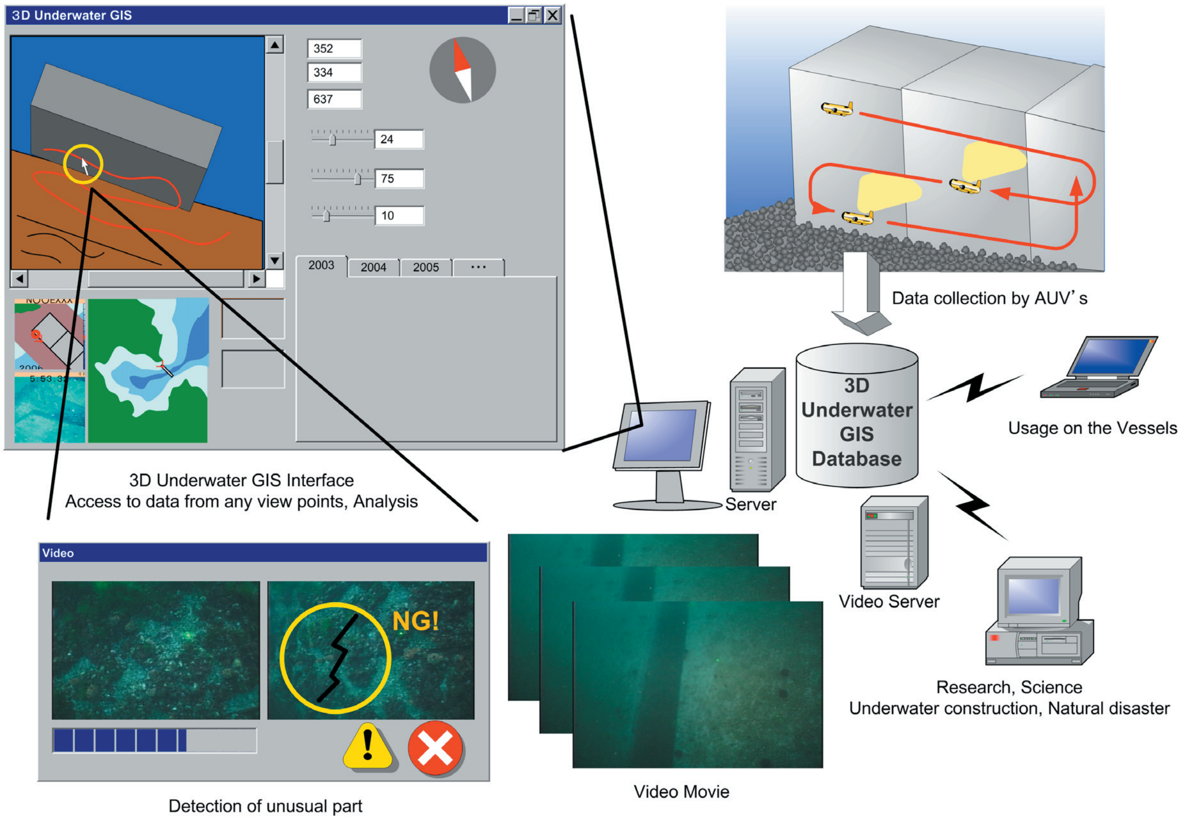

Fig. 18. Conceptual drawing of the 3D Underwater GIS.

underwater structures in the near future. The collected data by the vehicle will be huge and varied. The expected data types are image (including acoustic image), movie, position, chemical data, temperature, conductivity ...etc. Therefore, a data management system will be necessary. The authors plan to develop three-dimensional Underwater Geographic Information System (3D Underwater GIS). As shown in Fig. 18, the 3D Underwater GIS Database manages various kinds of data simultaneously, and the user can access the data using interface program which has ability to provide texture-mapped 3D graphics and non-linear video image. The system is expected to have connectivity to other GIS databases so as to provide useful information to researchers, scientists, constructors and so on.

The authors also plan to do sea trials again in 2003.

ACKNOWLEDGMENTS

The authors wish to thank Mr. Akira Uezono, the former Director of Construction and Control Systems Department of the Port and Airport Research Institute for his management to provide us an opportunity to do sea trials. The authors wish to thank Kamaishi Port Construction Office, Tohoku Regional Development Bureau, Ministry of Land, Infrastructure and Transport, and TOA CORPORATION for kindly providing us the opportunity and full support for the sea trials. The authors also thank Ura Laboratory members of the University of Tokyo for their help in preparation for the experiments.

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