AUTONOMOUS UNDERWATER TOWED VEHICLE WITH VARIOUS NAVIGATION MODES

Tetsuya Shiraishi
Construction and Control System Department
Port and Airport Research Institute
3-1-1 Nagase, Yokosuka, Kanagawa 239-0826
shiraishi-t84mv@pari.go.jp

Jin-Kyu Choi
Construction and Control System Department
Port and Airport Research Institute
3-1-1 Nagase, Yokosuka, Kanagawa 239-0826
choi@pari.go.jp

Toshinari Tanaka
Construction and Control System Department
Port and Airport Research Institute
3-1-1 Nagase, Yokosuka, Kanagawa 239-0826
tanaka_t@pari.go.jp

Abstract: This paper introduces an autonomous towed vehicle which has various navigation modes; towed mode, autonomous mode and kite mode, to stand against fast and changeable sea currents. The property assures safe and reliable observation works irrespective of a current speed. Such vehicle must be useful for port area application since in a port area sea currents are so fast and complex. The different navigation modes can guarantee safe and reliable underwater observations irrespective of the speed of a sea current. In general, the natures of AUVs and towed vehicles are mutually contradictory. This paper describes the process of development to achieve mentioned different navigation modes. The results of computer simulations, towing tank tests and the first sea trial are presented. The sea trial showed that the vehicle can be operated stably in the towed mode as well as in the autonomous mode.

Keywords: AUV, Towed vehicle, Port area, Security

1. INTRODUCTION

In various investigations of the port area and the construction management of the port facilities, it is quite important to observe underwater state, to supervise underwater operations, and to inspect the completion of the underwater construction by viewing. These works are carried out mainly by divers and partly by ROVs (Remotely Operated Vehicles) at present.

On the project of the improvement of Tokyo Bay Waterway, it is needed to observe and take pictures of underwater images to confirm the effect of the artificial fish reefs constructed by the blocks of the ruined Third Fort of Tokyo Bay and to maintain the function of the waterway. However, the current is fast and the water depth is too deep for divers to work in this area. Therefore, it is needed to research and develop a new underwater observation system in order to carry out viewing work safely and efficiently.

Consequently, we have proposed a new underwater observation system using an “Autonomous Towed Vehicle”. The results of this study can be applied as the technique of the environmental monitoring work such as the investigation of seawater property in the similar conditions of strong external forces.

A necessary function as an underwater observation system was examined for the given mission and the required conditions to achieve the stable navigation was clarified by the preliminary basic motion simulation based on the assumption values of the hydrodynamic coefficients. To obtain the hydrodynamic force derivative and the exact hydrodynamic coefficients for the development of the autonomous control software, the towing tank tests (the resistance test, the oblique motion test, the elevator angle test, and the forced oscillation test) were carried out [1]. The stability and the dynamic characteristics of the towed vehicle were reexamined in detail by the motion simulation based on the result of the towing tank test and the body of the prototype model was manufactured [2][3].

2. SYSTEM OVERVIEW

2.1 Mission

The mission given to the system is as follows.

1) Observation area

Sea area around the destroyed Third Fort of Tokyo Bay

2) Observation object

Taking a picture of image of the fish for effect confirmation of the artificial fish reefs

Taking a picture of image of sea bottom situation for maintenance of the function of the Waterway

3) Configurations of fish reefs

The reef (5 to 8m in height and about 100m×100m in area) is constructed by the destroyed blocks which are 1 to 6m cubes. And several reefs are scattered in observation area.

4) Maximum observation depth	60m
5) Maximum water current	3knots

6) Dimension and weight of vehicle

About 3m in total length and 300kg or less in weight in the air for the small support vessel

2.2 Basic System

AUVs were thought to be suitable as a basic vehicle of this system, because the given mission was the fixed form work in the comparatively wide sea area. Most of AUVs developed so far are for the mission in the deep sea and the lakes in which the flow is almost constant and not so fast. On the other hand, the ability to cruise stably for a long time with the small size body is needed to accomplish the given mission.

Therefore, we proposed the combination system of tow ship and the towed autonomous vehicle with the cable which has the function to keep the vehicle's position in fast water current and to transmit the real time image data. This system enables to perform the mission reasonably with the limited battery and equipment (towed mode, see Fig. 1). Moreover, this system was designed to be able to use without the cable below a certain current speed (untethered mode) and also planned to contain the third mode which made the towed vehicle to advance in slow speed by winding up with the winch on the anchored tow ship to keep the counter-water speed below a certain value when the current speed increases to obtain the stable images (kite mode).

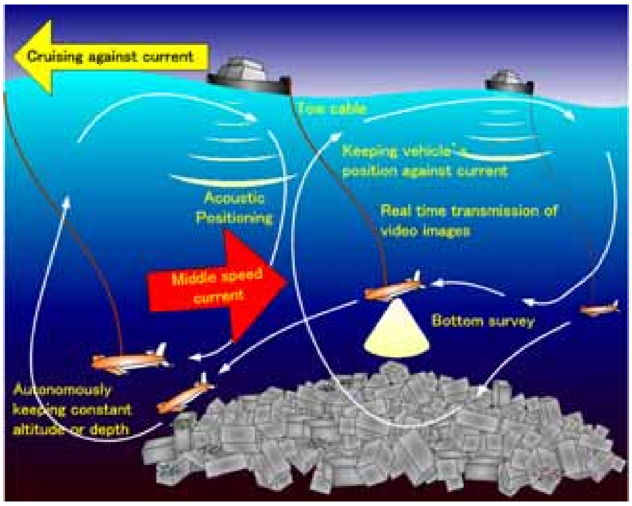

Fig. 1. Proposed underwater observation system (towed mode)

As the above-mentioned, the system operated in three modes (towed mode, untethered mode, and kite mode) according to the current speeds as shown in table 1 was proposed as a new underwater observation system.

TABLE 1.Current range on each operating mode

(UNIT ; knots)

Current speed	Mode	Towed vehicle			Tow ship		
		Thrust	Speed		Thrust	Speed	
			To water	To ground		To water	To ground
0〜2	Untethered	1〜3	1〜3	1	–	–	–
2〜3	Towed	0	3〜4	1	3〜4	3〜4	1
3〜	Kite		3+〜	0+	–	–	0

2.3 Control method

By the investigation of the motion simulations and the towing tank test, the control method to achieve the stable navigation was clarified as below. (Fig. 2~3)

1) The length of the tow cable is about 100m.
2) The forewings is necessary about 10cm longer than the base machine in the length and need the structure to be able to control the differential-motion.
3) The initial value of the elevator angle of the forewings should be 8deg.
4) The added weight of about 12kg is necessary compared with the base machine.
5) It is necessary to control heave and pitch by the parallel-motion of the forewings and to control roll by the differential-motion of the forewings. The parallel-motion means to control the elevator angle of right and left forewings in the same directions and the differential-motion means to control the elevator angle of right and left forewings in the opposite directions.
6) The connected position of the tow cable is x=0.91m,z= -0.29m on the body of the vehicle.

TABLE 2. Specifications of body of prototype

Specifications		
Fairing	Material	High density polyethylene
	Colors	Orange and white
	Specific gravity	About 1.0 or less
	Board thickness	About 5mm
Structural material	Material	High density polyethylene
	Specific gravity	About 1.0 or less
	Board thickness	About 50mm
Reinforcement	Material	Aluminum（A5083-0）
	Specific gravity	About 2.7
	Surface treatment	Black anodized aluminum and sealing
Wings	Configuration	Horizontal forewing 1 set
		Horizontal tailwing 1 set
		Vertical tailwing 1 set
	Shape	Horizontal forewing NACA0015
		Horizontal tailwing NACA0018
		Vertical tailwing NACA0024
	Material	ABS

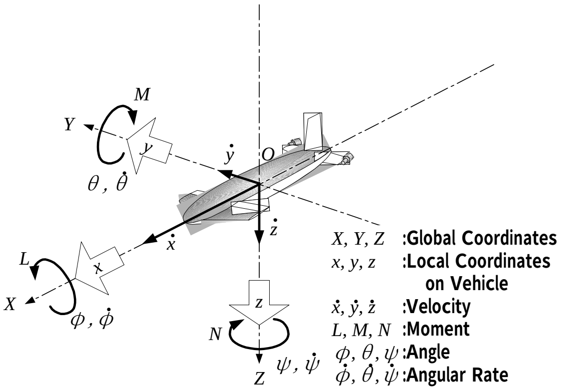

Fig. 2. System of coordinates used in the motion simulation

Fig. 3. Towing tank test

2.4 Observation Equipment

To obtain dynamic and still images of the observation objects, a digital camera (Nikon COOLPIX5400), a stroboscope (Nikon SPEEDLIGHT SB-800), and lighting devices are mounted on the vehicle, which are keeping in resisting pressure/water containers. In addition, a narrow multi-beam sonar is planned to be installed for obtaining image data in muddy water. The observation sensors are more efficiently used in the towed and kite modes since the towing cable makes data transmission more fast and reliable. In addition, four sonar sensors are planned to be installed on the front of the vehicle to detect obstacles.

Obtained dynamic and still images are displayed on the monitor placed on the mother ship and are recorded on both hard disks installed on the mother ship and in the vehicle. In the autonomous mode, especially when without a towing cable, the obtained images are recorded only on the hard disk in the vehicle.

2.5 Actuators for Motion Generation

The vehicle is equipped with fore-wings and two thrusters at tail-wings to generate translational (surge) and rotational (roll, pitch and yaw) motions. Note that the fore-wings cannot function as the input if the vehicle's speed with respect to water is zero. The rated output and the rated voltage of thrusters and the thruster force are 440 W, DC 130 V and 222 N, respectively. The dead-band and the limit of the thrusters input are 0~±18 N and ±177 N, respectively.

2.6 Positioning

The pose (position and orientation) of the vehicle is calculated from the data of a depth sensor (Druck PTX600), orientation sensors (PNI TCM2-50), DVL (Doppler Velocity Log, RD Instruments Workhorse Navigator DVL), SSBL (Super Short Base-Line, ORE 4330B) and GPS (Global Positioning System). Among them, an orientation sensor, a SSBL set (transmitter and receiver) and a GPS receiver are equipped on the mother ship. An orientation sensor is used for measuring the yaw (also denoted by heading, azimuth and bearing) of the mother ship. Another SSBL set and other sensors mentioned are installed on the vehicle.

We mainly use the depth sensor, orientation sensors and DVL for the positioning of the vehicle and their accumulated errors are modified with the data of GPS and SSBL at every pre-defined time step, because the SSBL data is inferior to the DVL data in accuracy at a single sample time. The pose of the mother ship is determined by GPS data and the orientation sensor.

The position (and orientation) data of the vehicle is transmitted from the mother ship to the vehicle or vice versa through a towing cable in the towed and kite modes, and through an acoustic link in the autonomous mode.

2.7 Motion Sensors

Three orientation sensors (NEC-TOKIN CG-16D) are equipped on the vehicle, which measure the angular velocities around the three axes of the body frame. The roll and pitch angles are directly provided by two accelerometers (TOKIMEC TA-25D-02), and the yaw angle is by an orientation sensor (PNI TCM2-50). Based on the data from these sensors, attitude (roll and pitch) and heading (yaw) controls are performed.

2.8 Power System

Lithium-ion batteries are installed on the vehicle and are always used as a main power source regardless of the navigation modes. Principal sources of power consumption are the digital camera and actuators (fore-wings and thrusters). In the towed and kite modes, continuous operating hours are about 12 hours and in the autonomous mode, about 3.4 ~ 8.5 hours corresponding with the vehicle's speed.

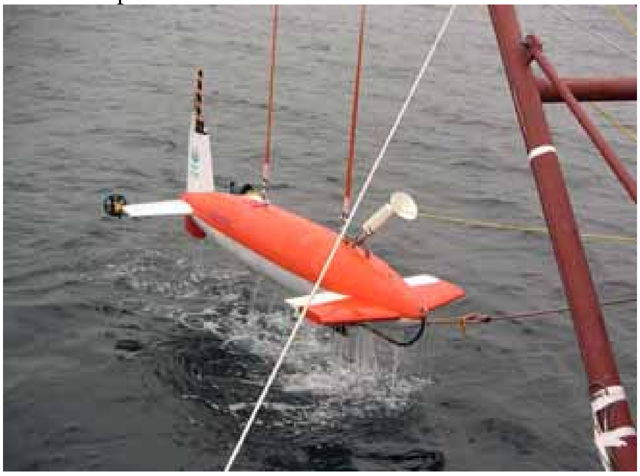

Fig. 4. Prototype model

3. FIELD TEST

After checking the operating state of each apparatus in real ocean space for the purpose of checking the fundamental performance of the manufactured prototype model, the experiment on the fundamental control performance of the prototype model was conducted.

3.1 Towed mode examination

The experiment on the control performance in real ocean space based on the control parameter obtained in the tank test was conducted. The depth of water of experiment ocean space is 60-80m, and all experiments were conducted by using a pitch and roll control. The control parameters used in examination of this system are shown in table 3 and the experimental condition in all experiment cases is shown in table 4.

TABLE 3. Control parameters

Type of Parameter	No. of Parameter set	P	I	D	Remarks
Altitude and Depth	0	10.0	0.1	5.0	AE-2 based
	1	20.0	0.2	10.0	
	2	10.0	0.1	20.0	
Pitch	Constant				AE-2 based
Roll	Constant				

TABLE 4. Experimental condition of field test

Case No.	Cable length	Towing Speed	Depth Control	Parameter set
1	16m	2kts	10m	1
2	30m	2kts	25m	1
3	50m	2kts	35m	1
4	30m	3kts	23m	1
5	50m	2kts	35m	1
6	50m	2kts	-	1
7	50m	2kts	35m	1

It was verified that the control device of this system can tow the prototype model stably by the pitch control, the roll control, and the altitude and depth control using the control rule and control parameter which were set up beforehand.

3.2 Autonomous mode test

Following towed mode examination, autonomous mode examination was conducted in the same ocean space.

The missions given in the autonomous mode examination was that after discovering a mission's start point, the model goes underwater and holding the depth of 30m, passes four way points, and resurfaces. The parameter set 0 which is the preset value of AE-2(the base machine of this prototype model) was used for the control parameter. The trail of the prototype model is shown in Fig. 5. A position is based on the integration of the measurement value by the Doppler sonar carried in the prototype model, and is displayed in the relative position with a pontoon. The given missions are performed certainly and it was verified that action with this autonomous observation system is possible. (Fig. 6)

4. CONCLUSION

From the field test, it is verified that depth control, roll and pitch control work effectively in the towed mode, and it is thought that each control parameter is suitable. The stability of the prototype model in the towed mode is also confirmed.

The stability of the vehicle in the untethered mode is confirmed in the real sea area experiments. And it is also verified that the way point control was possible in an untethered mode.

As the result, the validity of the proposed control system was proven in the real sea area experiment.

After the 9.11, the request to improving security in port area rises in our country. It is sincerely hoped that this system is used to improve security in port area as well as to inspect port facilities.

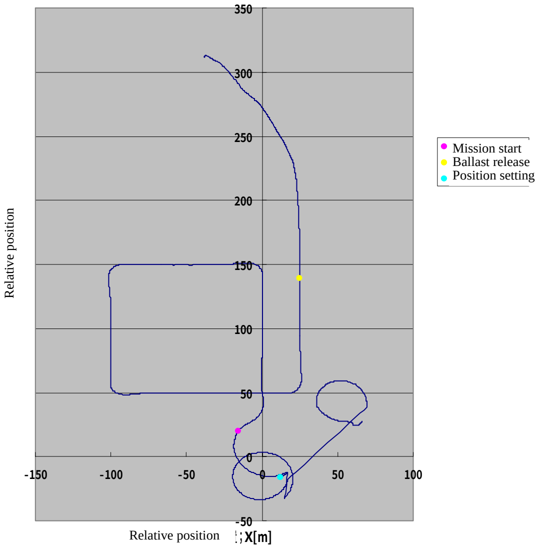

Fig. 5. The trail of the prototype model

Fig. 6. A pictture of seabottom taken by the prototype model

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