DEVELOPMENT OF NEW AUV 'AQUA EXPLORER 2000' AND ITS CABLE TRACKING SENSOR

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Abstract

Submarine cable inspection is one of the promising application field for AUVs. Following the success of AQUA EXPLORER 2 (AE2), the authors developed a new AUV "AQUA EXPLORER 2000 (AE20000)" for inspection of buried submarine cables. Compared with AE2 The maximum operating depth was increased from 500m to 2,000m, and the continuous operating time was doubled to 16 hours with velocity of 1.0 m/s while the outer shape and size was the same.

The outline of AE2000 will be presented. The error analysis of the cable-tracking sensor will also be presented.

Introduction

Since the first optical submarine cable system TAT-8 was constructed in 1988 in the Atlantic Ocean, more than 500,000 km of cable had been constructed until now. At the same time, the transmission capacity per fiber was increased by more than 1,000 times from 280Mbits/s to about 1Tbits/s [(1)]. Corresponding to this expansion of submarine cable network, the construction and maintenance of the submarine cables becomes more important task for communication carriers.

Most of the cable failures are due to artificial activities such as trawling and anchoring. In order to avoid these failures, cables installed in shallow waters are buried beneath the seabed. In order to bury cables properly, inspection of the seabed before installation and inspection of burial depth of cables after installation are important.

Recently, AUVs are expected as promising tool for underwater inspections. A number of research programs are initiated, and some of the developed AUVs have already got fruitful results[(2)].

In 1994, KDD R&D Laboratories (now KDDI R&D Laboratories) succeeded in tracking of real submarine cable over 2.6 km with a small AUV 'AQUA EXPLORER 1000 (AE1000) [(3)] for the first time in the world. In 1998, AE2 [(4), (5)], the practical AUV that can inspect submarine cables, was launched. Since then two sea trials and seven commercial inspections have been successfully accomplished. The total length of the inspected cable exceeds 500km.

The inspection of the installed cables was usually done with ROVs. However in deep waters, large-sized ROVs are needed to cope with hydraulic resistance imposed on long tether cables. Large mother vessels having good maneuverability are also needed to precisely follow the vehicle that are tracking cables. Therefore the operation cost of these ROVs is not low, and these ROVs cannot be

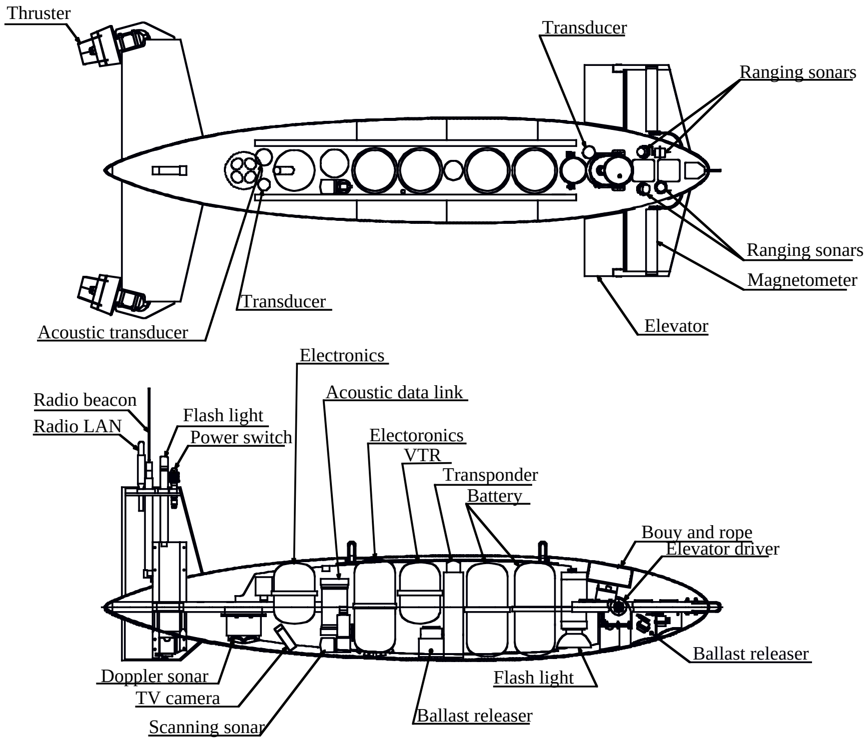

Fig.1 Mechanical configuration of AE2000

easily used for inspection.

On the other hand, small AUVs can be operated with small mother vessel. As they need no large onboard devices such as a cable drum and a winch, they can easily be mobilized and mounted on mother vessels. So, the operation cost of small AUVs is far lower than that of large-sized ROVs. Furthermore, as AUVs have no tether cable, they can swim stably even in fast water current.

Following the success of AE2, the authors developed a new AUV AE2000[6]. The control system and the shape of AE2000 is similar to its predecessor AE2, but the maximum operating depth was increased to 2,000m from 500m of AE2. The continuous operating time was enlarged by twice to about 16 hours with velocity of 1m/s. On the other hand the size and the weight are kept at the same level, that is 3 meters in length, 1.3 meters in width, 0.9 meters in height and 300kg in air. Rechargeable lithium ion battery is used for power source.

The vehicle is linked with a mother vessel through two acoustic links. One of which is for monitoring and control, and the bit-rate of which is lowered to 125 bits/s to increase the maximum transmission distance and the reliability. Another is for transmission of video image, the transmission speed of which is 16 kbits/s, but the directivity is limited to 45 degrees. It can transmit one color picture within six seconds when compressing the image data.

For the cable positioning and tracking, AC current is injected into the cable, and the generated AC magnetic field is detected with two tri-axial magnetometers installed on the vehicle. By processing the detected signal, the vehicle can know the relative location and the direction of the cable. The burial depth of the cable can be calculated using the measured location of the cable and the altitude of the vehicle measured with an acoustic altimeter.

One of the purposes of the inspection of submarine cables is to measure the buried depth of cables beneath the seafloor. Therefore the estimation of the error of the measurement is very important. The theoretical analysis of the error will be presented.

AE2000 was launched this January and the first sea test was successfully carried out this March. Following the first sea test, AE2000 was used as a test bed for the investigation [7] of tracking humpback whale.

Mechanical Design

Through the experiments and inspections of the real optical submarine cables, AE2 was proven to have adequate

Table 1 Principal specifications of AE2000

Item	Specification
Weight in air	300 kg
Dimensions	3m(Length), 1.3m(Width), 0.9m (Height)
Maximum depth	2,000m
Maximum forward velocity	1.5m/s
Maximum ascending and descending angle	+/- 30deg.
Battery	2 x 133V/11AH Rechargeable lithium batteries
Continuous operating time	16 hours with velocity of 1.0 m/s
Acoustic links	
Command/Data	125 bits/s
Video Image	16 kbits/s
Equipments	Tri-axial magnetometers, Television camera, Light,
Strobelight	
	Altitude sonar, Doppler sonar, Bottom profiler,
	Obstacle avoidance sonar, Ballast releaser, Buoy releaser,
	Wireless LAN, Radio beacon

performance needed for practical AUV inspecting submarine cables. In 1999, AE2 succeeded in tracking the submarine cable laid in the Taiwan Straight where strong sand wave and current existed, and presented that it has excellent performance of motion. In order to use this performance of motion, the authors decided not to change the outer shape of the vehicle and its control software. However the mechanical design and arrangement of equipment and the electrical design was thoroughly reviewed and refined to double its power capacity.

Fig.1 shows the mechanical configuration of the vehicle. As the design concept of AE2 was already reported [(4), (5)], only the outline is given below.

The vehicle is driven with two horizontally arranged thrusters. The heading is controlled by differentiating the thrusters. The vertical movement of the vehicle is controlled with the elevator. As the elevator is placed in the forepart of the vehicle, its sensitivity is high and the size of the elevator is small. It means that the power consumption for the control of the vertical movement is low.

When tracking submarine cables, low frequency (16 to 25 Hz) current is supplied to cables, and the generated cylindrical AC magnetic field is detected by two tri-axial magnetometers placed in the forewings. The relative position and direction of cables can be derived by processing the output of the tri-axial magnetometers. In order to increase the accuracy of positioning, the interval of the tow magnetometers is needed to be large. Moreover in order to find and locate cables earlier when approaching to cables, the magnetometers are needed to be placed in the forepart of the vehicle. Therefore the forewings are the most desirable place for the magnetometers.

Table 1 shows the principal specifications of AE2000. The weight in air was slightly increased compared with AE2 (260kg)

Cable Tracking

Fig.2 is the coordinate system that is used to calculate the cable position. xyz is the coordinate system fixed to the vehicle, the origin of which is at the center of the two tri-axial magnetometers. x'''y'''z''' is the coordinate system fixed to the submarine cable. x''y''z'' coordinate system is given by rotating x'''y'''z''' by θ around z''' axis. x'y'z' coordinate system is given by rotating x''y''z'' by β around y'' axis, and xyz coordinate system is given by rotating x'y'z' by α around x' axis. α, and β represent rolling and pitching of the vehicle, θ represents the angle between the cable and the vehicle. $\mathbf{P}_1$ and $\mathbf{P}_2$ represent the position of the two tri-axial magnetometers and L represents their interval.

Define Y and Z to be the horizontal and the vertical distance

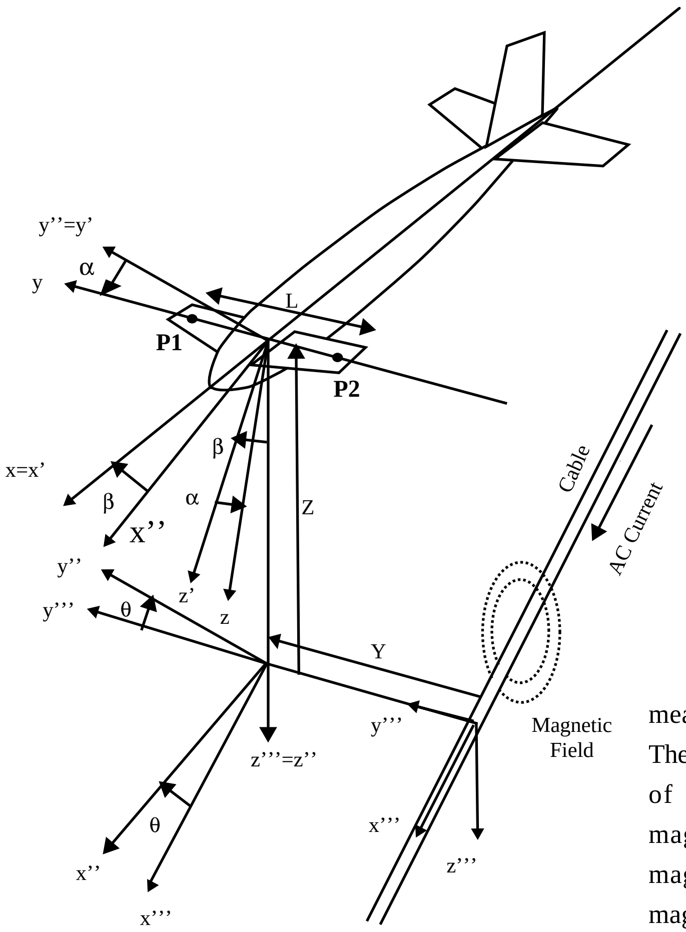

Fig.2 Coordinate system for cable tracking

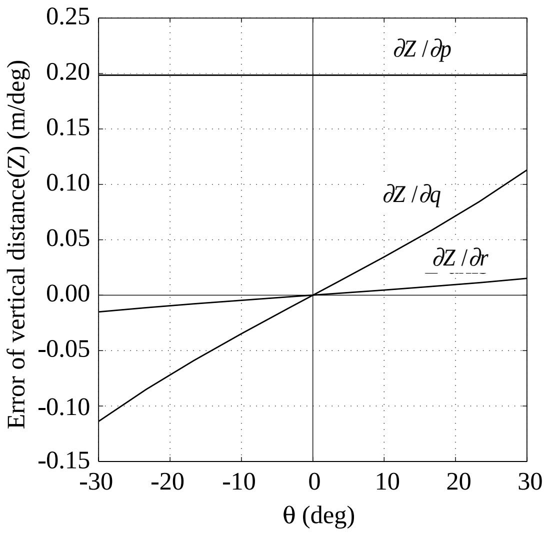

Fig.3 Error analysis of vertical distance(Z) (Y=0m, Z=3m, L=0.8m)

between the cable and the vehicle, (B_{x1}, B_{y1}, B_{z1}) and (B_{x2}, B_{y2}, B_{z2}) to be magnetic field detected by two tri-axial magnetometers, and A_i, B_i, C_i (i=1,2), K as (1) to (4), θ, Y and Z are expressed as (5) to (7). For the real operation, some approximated expression is usually used.

$$A_i = B_{xi}\cos\beta + B_{yi}\sin\alpha\sin\beta + B_{zi}\cos\alpha\sin\beta \quad (1)$$

$$B_i = B_{yi}\cos\alpha - B_{zi}\sin\alpha \quad \text{(i=1,2)} \quad (2)$$

$$C_i = -B_{xi}\sin\beta + B_{yi}\sin\alpha\cos\beta \quad (3)$$

$$K = \frac{C_1(A_2^2 + B_2^2 + C_2^2)}{C_2(A_1^2 + B_1^2 + C_1^2)} \quad (4)$$

$$\theta = \tan^{-1}\left(\frac{A_i}{B_i}\right) \quad (5)$$

$$Y = \frac{1}{2}\frac{K+1}{K-1}L(\sin\theta\sin\alpha\sin\beta + \cos\theta\cos\alpha) \quad (6)$$

$$Z = \frac{B_1}{C_1}\frac{K}{K-1}L(\tan\theta\sin\alpha\sin\beta + \cos\alpha) + \frac{1}{2}L\sin\alpha\cos\beta \quad (7)$$

As mentioned before, estimation of error in the measurement of burial depth of the cables is important. There are many source of error, for example, misalignment of magnetometers, variance of the sensitivity of magnetometers, electromagnetic noise, distortion of magnetic field due to magnetic substance around the magnetometers. In this paper, the effect of misalignment of the magnetometer is analyzed. The effect of variance of the sensitivity can be dealt in the same manner.

Assuming p, q, r to be the misalignment of the tri-axial magnetometer placed at **P1** around x, y, z axis, and assuming y_0, z_0, θ_0 to be the relative position and direction of the vehicle, the detected magnetic field at **P1** is expressed as a function of (y_0, z_0, θ_0, p, q, r). Assuming there is no misalignment in the tri-axial magnetometer placed at **P2**, the measured relative position Y, Z is also expressed as a function of (y_0, z_0, θ_0, p, q, r). The error in the estimation of Z can be evaluated by using partial differential $\partial Z/\partial p$, $\partial Z/\partial q$, $\partial Z/\partial r$.

Fig. 3 shows the calculated results of the error of Z as a function of relative direction of θ. The vertical axis corresponds to $\partial Z/\partial p$, $\partial Z/\partial q$ and $\partial Z/\partial r$. The relative height of the vehicle z_0 and the interval of the magnetometers L are assumed to be 3m and 0.8m respectively. This is because the cable is usually buried beneath the seabed about 1.0 meter, and the vehicle tracks cable with altitude of about 2 meters, and the vehicle is controlled to keep the position just above cables. From **Fig.3**, it turned out that the misalignment around x axis ($\partial Z/\partial p$) is the most sensitive, and that sensitivity of

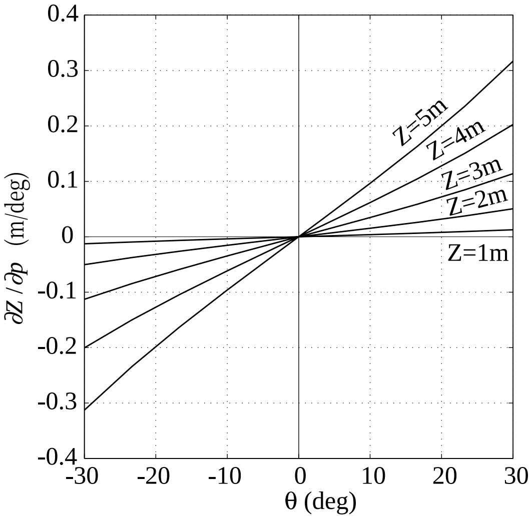

Fig.4 Error in vertical distance(Z) estimation $\partial Z/\partial p$ due to mis-alignment in x axis (Y=0m, Z=3m, L=0.8m)

Fig.5 The photograph of AE2000
Four hydrophones of the passive sonar are mounted at the end of the fore-wing

misalignment around y and z axis ($\partial Z/\partial q$ and $\partial Z/\partial r$), are proportional to θ. As the tri-axial magnetometers used for AE2000 are fixed in cylindrical housings, and the cylindrical housings are aligned in y axis, misalignment in x and z axis is relatively small. When the current is flowing crossing the laid cable, the vehicle track the cable while keeping its heading with some traverse angle to the cable in order to cope with the drag force. If the current is so strong, the angle θ exceeds 30 degrees. Assuming θ = 30 degrees and Z = 3m, and assuming the allowable error due to misalignment in x axis is 0.1m, the misalignment in x axis must be less than one degree. It seems not so easy to align the tri-axial magnetometers with accuracy of one degree. In order to realize highly accurate measurement, some calibration will be necessary to cancel the error due to misalignment.

Fig.4 shows relation between $\partial Z/\partial p$ and θ when taking the vertical distance Z as a parameter. It turned out that when the vertical distance Z is large, the error due to the misalignment in x axis also becomes large.

Sea Test

The first sea test was carried out March 2001. The performance of the cable tracking system, the acoustic link and the motion control system was confirmed. Following the first sea trial, AE2000 was used as a test bed for the investigation of tracking humpback whale. Male humpback whales are known to sing long and structured song. By detecting this song with a passive sonar mounted on the vehicle, the direction of the whale can be recognized. **Fig. 5** is a photograph of AE2000. The hydrophone of the sonar system was mounted at the end of the forewing. In the experiment, a humpback whale was found from about 5 km away, and the vehicle finally came close to the whale in about 50m. The detail of this experiment will be published [7] in November.

The second and final sea test will be done in July and August. In this test, accuracy of cable tracking system will be evaluated. Deep-sea diving test up to 2,000m will also be carried out.

Conclusion

The outline of AE2000, the newly developed AUV for inspecting buried submarine cables, was presented. It was also presented that the measurement error of the cable tracking system can be represented by partial differentials.

AE2000 is the successor of AE2. Although the shape of the vehicle is the same as that of AE2, the maximum operating depth is increased to 2,000m from 500m of AE2, and the continuous operating time was enlarged by twice. The control software and its sensors including cable tracking sensor and acoustic link are almost same as those of AE2.

The first sea test was carried out this March, and afterwards AE2000 was successfully used as a test bed for the investigation of tracking humpback whale. The second and the final sea test is scheduled to be carried out this July and August.

The theoretical analysis of the error of the cable tracking system was also presented, and it was presented that the error could be expressed by partial differentials of Z. It was also presented that assuming $\theta = 30$ degrees, $Z = 3$m and assuming the allowable error in estimation of Z is 0.1m, the misalignment of the magnetometers in x axis must be less than one degree. Some calibration will be necessary to cancel the error due to the misalignment because it seems not so easy to align the tri-axial magnetometers with the accuracy of one degree.

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