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Design of Autonomous Underwater Vehicle

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Abstract There are concerns about the impact that global warming will have on our environment, and which will inevitably result in expanding deserts and rising water levels. While a lot of underwater vehicles are utilized, AUVs (Autonomous Underwater Vehicle) were considered and chosen, as the most suitable tool for conduction survey concerning these global environmental problems. AUVs can comprehensive survey because the vehicle does not have to be connected to the support vessel by tether cable. When such underwater vehicles are made, it is necessary to consider about the following things. 1) Seawater and Water Pressure Environment, 2) Sink, 3) There are no Gas or Battery Charge Stations, 4) Global Positioning System cannot use, 5) Radio waves cannot use. In the paper, outline of above and how deal about it are explained.

1. Introduction

The ocean occupied approximately 71% of surface of the earth still have a lot of unknown parts. Therefore various studies and development about the ocean such as marine environment, submarine earthquake, ocean life, marine resources research and so on are carried out. The collection of ocean data by survey and observation in the actual sea is indispensable for the studies and the development. Because the ocean has low transparency and cannot observe the whole deep sea in detail from the surface, so, survey and observation with the ship is not enough. However the water pressure cannot step into the deep sea easily because 1 atmospheric pressure is increasing every 10m diving.

Various underwater apparatuses such as manned submersible, unmanned underwater vehicle and so on are developed as tools to survey and observation the deep sea since the Bathyscape invented by Prof. Auguste Piccard was launched in 1948. The manned submersibles such as "ALVIN", "NAUTILE", "MIRS" and "SHINKAI6500" are good at the visual observation and sampling in small range. The towed vehicles are good at wide area survey. The Remotely Operated Vehicles (ROVs) are good at detailed observation and sampling in small range. The Autonomous Underwater Vehicles (AUVs) such as "Autosub", "Hugin", "Thesus" and "URASHIMA" and so on are good at wide area detailed survey because the vehicles does not have to be connected to the support vessel by tether cable and can close to seafloor. The development of AUVs is enabled with recent advanced computing and other various advanced technologies shown in figure 1.

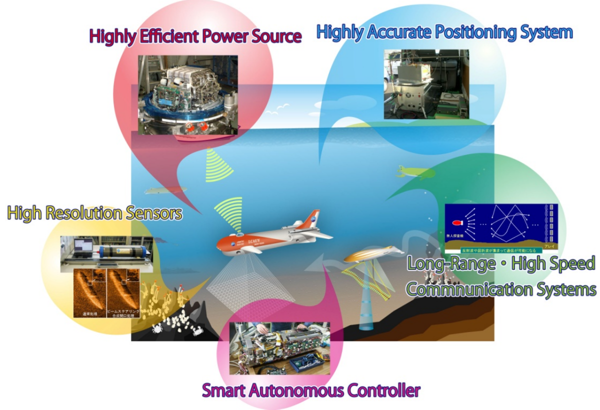

Figure 1. The Elemental Technologies for Autonomous Underwater Vehicle

It is necessary to consider about following things on developing Autonomous Underwater Vehicle: 1) Seawater and Water Pressure Environment, 2) Sink, 3) There is No Gas or Battery Charge Stations, 4) Global Positioning System Cannot Use, 5) Radio Waves Cannot Use and 6) Autonomous.

2. Sea Water and Water Pressure Environment

The ocean is the environment that, as you know, filled with seawater. Because viscosity of seawater is high, the ocean is hard to move in comparison with the atmosphere. And the remarkable characteristic of the ocean is the environment where 1 atmospheric pressure increases by every 10 meters diving. Therefore, the water pressure grows big so as to go into the deep sea and will increase strong external force as things are destroyed.

All of underwater vehicles are controlled by electronics. However, the elements of most of electronics are not exposed to seawater to short-circuit. In addition there are the elements of electronics broken by high water pressure. Therefore, solid pressure vessels are necessary to use the electronics in underwater. The pressure vessels are required to be enough strong for water pressure in the working depth, lightweight, not corroded and so on. A cylindrical shape or a ball type is most suitable for the shape of the pressure vessel. The water pressure increases according to depth, and so the hull of pressure vessel needs to increase thickness to add to strength depending on depth. However the strong pressure vessels become very heavy weight. It is not good with an aspect of energy efficiency for a deep and long cruising range underwater vehicle so that the pressure vessels hold a big part of the weight of the body. Therefore light and strong structure material for pressure vessel is important.

Generally, Aluminum alloy, Titanium alloy and High Tensile Strength Steel are used as a material of pressure vessel in JAMSTEC. The aluminum alloy is light weight, high strength, reasonable value, but surface treatment is necessary to use it in the sea. The aluminum alloy has the following characteristic: the specific gravity is 2.7, good workability, not become magnetized, resists low temperature, easy to weld and so on. Because navigation systems are not influenced, it is good that the aluminum alloy does not become magnetized. It is important that heat conductivity of the aluminum alloy is good because of heat radiation of the electronics in the pressure vessel. The aluminum alloy has various kinds from 1000 series to 8000 series. 5000, 6000 or 7000 series of the aluminum alloy is mainly used in JAMSTEC. As for 5000 series aluminum alloy, the strength is ordinary, but corrosion resistance is high. As for 7000 series aluminum alloy, the strength is high, but corrosion resistance is ordinary. The performance of the aluminum alloy of 6000 series is the middle of 5000 series and 7000series. Corrosion measures are necessary to use the aluminum alloy in the sea. Effective means to resist seawater and corrosion is surface treatment. The surface treatments of the aluminum alloy are anodizing, TUFRAM^R, electrolysis nickel plating, electroless nickel plating, painting. The TUFRAM^R is a technique to make surface enhancement coating of General Magnaplate.

The titanium alloy is light weight, high strength, maintenance free, but expensive. The titanium alloy has the following characteristic: the specific gravity is 4.5, high corrosion resistance, low electric conductivity, low heat conductance, not becomes magnetized, low workability. Particularly, the specific strength of the Ti-6Al-4V alloy is the strongest level. The titanium alloy does not need the surface treatment even if used in the sea.

The high tensile strength steel is high strength, moderate value, but heavy weight and surface treatment is necessary to use it in the sea. The specific gravity of the high tensile strength steel is about 7.9. The high tensile strength steel has more than 490Mpa tensile strength.

The pressure vessel is designed with materials mentioned above. The parameter that is necessary for the pressure vessel design is buckling stress and yield stress, and yield stress becomes dominant in the high pressure environment of the deep sea. The specifications of the pressure vessel design are the maximum working depth, the pressure vessel inside diameter and length, safety factors. And it is necessary to be considered about corrosion and electrolytic corrosion. The metal corrosion in the seawater goes based on the electrochemic reaction. The materials are made surface treatment to protect against the corrosion so that they do not touch the seawater directly. The electrolytic corrosion is a corrosion phenomenon to occur when two kinds of different metal comes into contact in seawater. The high metals of the ionization tendency melt in seawater, and the metals melting become quicker in the corrosion speed than case alone. As protecting against the electrolytic corrosion, some insulator such as resin or rubber is attached to metal contact surface, or sacrifice electrodes are attached to metal.

The development of the new type pressure vessel by different materials is carried out to reduce the weight of the underwater vehicles in JAMSTEC. One of the materials is magnesium alloy, and the other is Super Carbon Fiber. In late years, many magnesium alloys are developed as the parts of cars, aircraft and mobile devices. The specific gravity of the magnesium alloy is 1.8 that is about 1/3 of the titanium or about 2/3 of aluminum. The magnesium alloy is the most lightweight in metal structure materials, and the specific strength is strongest. The pressure vessel made by magnesium alloy shown in figure 2 was produced experimentally, and strength of it was evaluated. The size of it is 90mm inside diameter, 130mm length and 9mm thickness. The pressurization test for it was performed with hyperbaric chamber. At the pressurization test, the shrinkage of the pressure vessel was measured by strain gages. The water pressure was pressurized in 2MPa per minute to 40Mega Pascal, maintained 20 minutes at 40MPa and deceased pressure in 2MPa per minute. The relations of water pressure and strain of tube part of the pressure vessel are shown in figure 3. As a result of pressurization test, it was confirmed that the pressure vessel made by magnesium alloy was not broken by water pressure more than 40Mpa. There is the possibility that the magnesium alloy contributes to the lightweighting of the vehicle. However, there are a lot of problems that must be settled to use the magnesium alloy in underwater. The most important problem is corrosion by seawater and electrochemic corrosion.

The Super Carbon Fiber (SCF) is Carbon fiber Reinforced Plastic (CFRP) rod having high moment of bending and high pulling strength developed in Kyushu University. A pressure vessel made by aluminum alloy is reinforced with SCF. Consumption of aluminum decreases by this method and can reduce the weight of the pressure vessel. A hull thickness of the aluminum and a diameter of the SCF were calculated by finite element analysis, and a pressure vessel is designed. The hybrid pressure vessel type 1 is shown in figure 4. The size of it is 100mm inside diameter, 150mm length and 4mm thickness. The performance of the prototype pressure vessel was evaluated in a pressurization test with hyperbaric chamber. At the pressurization test, the shrinkage of the pressure vessel was measured by strain gages. The water pressure was pressurized in 3MPa per minute. The time series of water pressure and strain of tube part of the pressure vessel are shown in figure 5. At the result of pressurization test, the hybrid pressure vessel type 1 was broken at 58.74Mpa. Here, a pressure vessel made by aluminum alloy of the thickness of 4mm is broken in 10Mpa by the calculated result. It was confirmed that reinforcement with the SCF was effective. The second unit was designed again. And the hybrid pressure vessel type 2 was produced experimentally. The strength of it is going to be evaluated in near future. The hybrid pressure vessel is still the way of the development, and various problems are left.

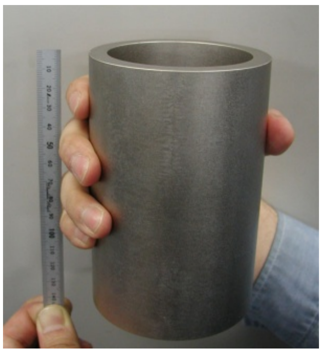

Figure 2. The Prototype Pressure Vessel made by Mg Alloy (Tube Part)

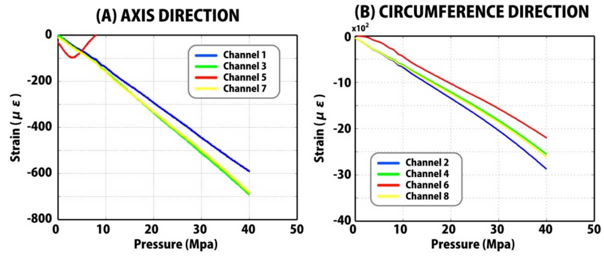

Figure 3. The Relation of Water Pressure v.s. Strain

Figure 4. The Prototype Hybrid Pressure Vessel Type 1

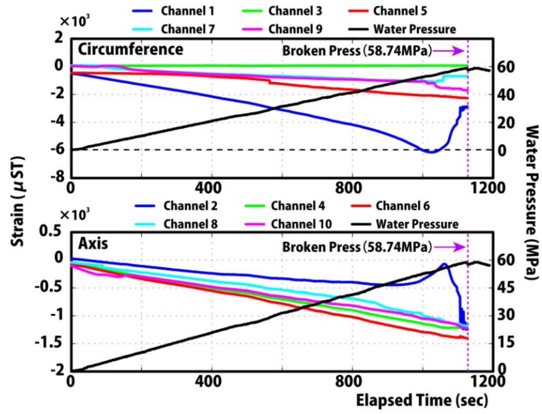

Figure 5. The Time Series of the Strain of the Hybrid Pressure Vessel

3. Sink - Fat to Underwater Vehicles ?

The deep underwater vehicles became heavy weight even if use lightweight materials for frames and pressure vessels. Some materials need to be able to float a heavy body to use a deep underwater vehicle like a space shuttle many times. Therefore it is necessary to add buoyancy materials such as the human fat to a deep underwater vehicle.

The buoyancy materials include gasoline, wood, expandable polystyrene and syntactic foam. The characteristic of the gasoline is lighter than seawater and not broken by water pressure because of liquid. Its specific gravity is around 0.8 from 0.75. However, it is large-capacity need to use it as the buoyancy material. And it is flammable. The volume of gasoline changes by water pressure and temperature. Therefore, the handling of gasoline is difficult. The characteristic of the wood is light weight, cheapness, good processing. However, it is destroyed by the water pressure, and weight increases including water. Therefore, the wood is not suitable as a buoyancy material for the deep sea. The expandable polystyrene is super light. However, it is compressed by water pressure and loses buoyancy. Therefore, the expandable polystyrene is not suitable as a material for the deep sea.

The syntactic foam consists of grass micro balloons and epoxy resin. It has high compressive strength against water pressure. Its specific gravity is around 0.65 from 0.3, and it is chosen depending on maximum working depth of the vehicles. This buoyancy material is machined in various forms with a saw or a drill. And it is filled clearances of pressure vessels of the body like human fat.

4. There is No Gas or Battery Charge Station

The underwater power source is one of very important elements to operate underwater vehicle particularly AUV for a long time. Because there is no energy supply places in underwater. Many research and development about the underwater power source are performed. When the research and development of the power source, following things need to be considered: small and light weight, put in a pressure vessel or resist against water pressure, work against low water temperature, vibration, noise, reliability and for maintenance. The power source has heaviest weight with the components of the vehicle. When the power source becomes big in proportion to the scale up of the body, maneuverability and energy efficiency worsen. Therefore it is important that the power source is small and light weight. Low vibration and low noise environment is important not to interfere acoustic equipments such as observation devices or communications devices. 1) Primary Batteries, 2) Secondary Batteries, 3) Internal Combustion Engines, 4) External Combustion Engines, 5) Radioisotope Batteries, 6) Small Nuclear Reactors and 7) Fuel Cells are considered as underwater power source. 1) The primary battery has simple structure consisting of an anode, a cathode and electrolyte. It can expose to water pressure. It is small and light weight. It has high energy density. It can be used once. The use of the primary battery takes running cost. It is used as a power supply for independent devices such as transponders. 2) The secondary battery also has simple structure consist of an anode, a cathode and electrolyte. It also can expose to water pressure. It can be used repeatedly. Running cost is low. It has high reliability. The secondary battery must not be overcharged or overdischarged. The secondary battery for underwater vehicles includes lead batteries, silver zinc batteries and lithium-ion batteries. The secondary battery is easy to be treated and most suitable as a battery for the deep underwater vehicle. 3) The close cycle diesel engine is the only internal combustion engine in the practical use as underwater power source. It is robust for environmental change. It is a reasonable system. It must be put in a pressure vessel. Protections against vibration and noise are required to use it as underwater power source. 4) The external combustion engine is the system which converts thermal energy into kinetic energy. The stirling engine is a kind of the external combustion engine. The conversion efficiency from thermal energy to kinetic energy of the stirling engine is high. It has small vibration and noise. It can work without depending on the kind of heat source. It cannot response to sudden changes. It must be put in a pressure vessel. 5) The radioisotope converts the energy that occurred by the nuclear decay of the radioactive element into electricity by a thermoelectric transducer. AS for the radioisotope, long-term power supply is possible. It works calmly. It is maintenance free. It must be put in a pressure vessel. 6) As for the small nuclear reactor, long-term power supply is possible. It is suitable for underwater power source. However, it is difficult to handle. 7) The fuel cell is a kind of electric generator using the chemical reaction of hydrogen combines with hydrogen. It is able to generate electricity directly from chemical reaction without any combustion or intermediate steps. There are various kinds of fuel cell, but the solid Polymer Electrolyte Fuel Cell (PEFC) system is most suitable for underwater power sources. The research and development of the Lithium-ion Secondary Battery and Fuel Cell are carried out in JAMSTEC.

At first, it is the lithium-ion secondary battery. Electric Power storage is an important technology for all equipment of the underwater vehicle because environmental pressure is high, the temperature is 5 degrees Celsius or less, and conditions are unsuitable for many chemical reactions in the deep sea. Battery capacity is mainly dependent on its mass; this means that the cruising range is proportional to the mass of the battery. To solve this problem, a high energy density battery and its enclosures are being developed. Concretely, batteries are enclosed with oil, to equate environmental pressure and to be insulated in seawater. This is called the oil compensated method, and is applied to various batteries. Secondary batteries that have been put to practical use in the sea are shown in Figure 6. Typical cells are lead-acid, nickel-cadmium, silver-zinc and lithium-ion. The vertical and horizontal axes in the figure indicate the energy density in weight and volume respectively. The Lithium-ion battery has many merits more than other batteries as follows: 1) Energy density is very high, this is the most important factor when choosing a battery, 2) operating voltage is also high, 3) no need to revitalize according to its memory, 4) safety, 5) maintenance free, 6) emits no gas when charging 7) longer life-time than the other batteries. The one of actual use Lithium-ion battery is shown in Figure 7. The oil-filled 300Ah Lithium-Ion battery for the vehicle was developed in 2000. The battery has three groups in parallel. One group has 120V and 100Ah. The energy density of the battery is 150Wh/kg. The more high energy density Lithium-ion battery is under development now.

Next, it is the Closed Cycle Fuel Cell system. Usually, many underwater vehicles used rechargeable battery such that the lithium-ion battery or the silver-zinc battery for a power source. However the case of long term working type untethered underwater vehicle, it needs many electric power supplies in proportion to operation time. To extend operating time, the battery must become heavier and lager. But it makes worse the maneuverability and energy efficiency of the vehicle. So the development of the fuel cell for underwater power sources is planned. The fuel cell is a kind of electric generator using the chemical reaction of hydrogen and oxygen. It is able to generate electricity directly from chemical reaction without any combustion or intermediate steps. The solid Polymer Electrolyte Fuel Cell (PEFC) system of the underwater vehicle is shown in Figure 8. Its system has two stacks of generator cells in series. As each stack generates 2kW electricity and total output is 4kW. Among various fuel cell systems considered, PEFC system is most suitable for underwater vehicles. Because of the PEFC system generates electricity at efficiency over 50% and at low temperature about 60 degrees centigrade. The other kinds of fuel cell system generate electricity at over 100 degrees centigrade. It is difficult to handle in an underwater vehicle and does negative influence on other electrical devices installed in the pressure vessel. And though the fuel cell is a kind of electric generator, mechanical noise and vibration is very small because the system need not using turbine. In the case of using the acoustic telemetry or other acoustic devices, it is good in small noise circumstance. The fuel cell system for underwater power source is required to closed circle type because of using environment is water. Recently, storing hydrogen with metal hydride has come into practical use. The metal hydride can store hydrogen at low pressure and it is controlled quite simply. When the alloy charges hydrogen, it is an exothermic reaction. On the other hand, discharging hydrogen is an endothermic reaction. In the vehicle, the heat which requires an exothermic reaction as discharging hydrogen use the exhaust heat from the fuel cell. In case of operation, the fuel cell system and metal hydride is put in each pressure vessel. Then, the pressure vessels and oxygen gas tank are put in the vehicle. The oxygen needs to be stored because using environment is seawater. And generated water is stored in the bottom of pressure vessel for fuel cell. The reasons to keep generated water are two. The first reason is because much energy is need generated water in high pressure environment. The second reason is to keep balance of weight and buoyancy. If the generated water is released outside of the vehicle, the balance changes and need additional energy to keep its depth.

Based on results obtained in sea trials, the research and development to improve the performance of fuel cell system is pushed forward now. The fuel cell system for underwater vehicles must be satisfied high efficiency, high reliability, perfectly closed system, small system and long life. A result obtained by generation experiment of a developed cell "HGC (High Grade Cell)" is shown in figure 9. The result of past cell that used as power source of AUV named "URASHIMA" is also shown for comparison. The generation experiment was operated at 300kPaA pressure. The I-V curves are shown in figure. In all the operating condition (0A to 20A), cell voltage of the HGC was more superior to that of URASHIMA's cell.

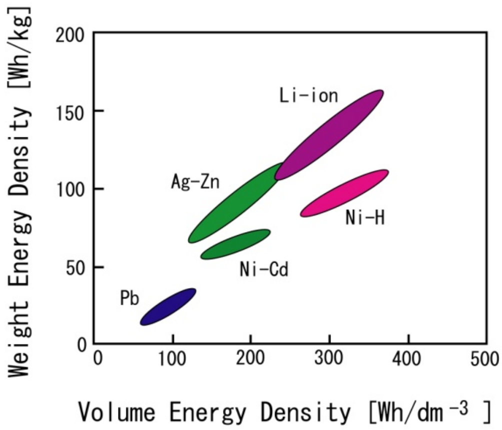

Figure 6. Volume Energy Density v.s. Weight Energy Density of Several Batteries

Figure 7. The Lithium-Ion Battery for AUV

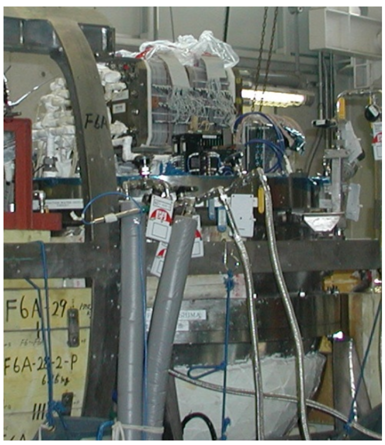

Figure 8. The Closed Cycle Fuel Cell system for AUV

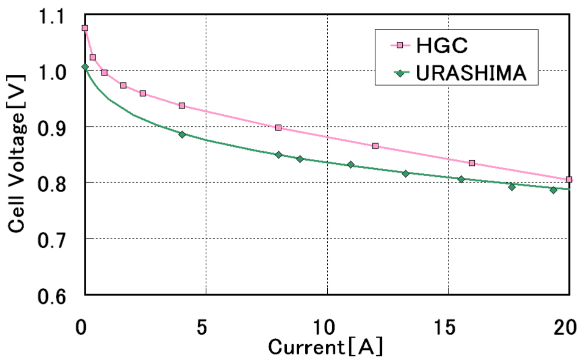

Figure 9. The I-V curves of the HGC and URASHIMA's cell

5. Where is The Vehicle Now?

The positional information of the vehicle is indispensable to obtain the marine data with the meaning. However, the positional information with the Global Positioning System is not available because radio waves are not usable in underwater. The vehicle itself calculates its position using Inertial Navigation System (INS) and velocity log, or the vehicle is informed its position by a support vessel or a transponder with acoustic navigation system. One of Inertial Navigation Systems is shown in figure 10. The INS calculates absolute position of the moving body in real time. The Type of the INS applied in JAMSTEC is the strap-down. The strap-down method is fellow method that inertia sensors are fixed to the moving body, the sensor output is counted backward, and the rate of change is estimated. The INS developing in JAMSTEC is composed of a sensor unit and an arithmetical unit. The senor unit is composed of three gyroscopes and three accelerometers. The gyroscope is a measure detecting an angle and an angular velocity of an object. It has five kinds of methods that are rate gyros, vibrating structure gyros, gas rate gyros, fiber optic gyros and ring laser gyros. The rate gyro uses a spinning top. The vibrating structure gyro uses the resonance such as tuning forks. As for the gas rate gyro, gas is sprayed on the heat rays in a housing. Heat rays temperature detects that spray is curved by Coriolis force when the housing turns around. As for the fiber optic gyro and ring laser gyro, laser beams is made to go around by mirrors or in a fiber in the housing. The phenomenon that timings from the emission to receiving of the laser changed when the housing turns around is used. Among five kinds of gyros, the ring laser gyro is one of optical rate gyro that has high precision and a wide dynamic range. The arithmetical unit defines the three-dimensional coordinate system inside it (INS coordinate system), and an accelerometer and a gyro are set on each axis of it. The outputs of the accelerometers are processed by the coordinate transform matrix which is constructed by the output from the gyros. These are integrated twice. Consequently, the current absolute position of the moving body is calculated. The current posture of it is calculated by the coordinate transform matrix. The coordinate transform matrix expresses the posture relationship between the INS coordinate system and the Earth coordinate system. The several algorithms to reduce calculations error of the INS is developing in JAMSTEC.

The vehicle is capable of cruising dozens of times owing to the internal power supply systems. However it is very difficult for it to cruise with high precision for a long time autonomously, dependent only on the INS, because the position data calculated from INS includes an error factor, and the error increases with the passage of time. Therefore the vehicle has a hybrid system which combines the INS and the velocity log. This hybrid system enables the vehicle to get more accurate position data than using only the INS. The velocity in underwater is measured by following four measures, Pitot tube velocity log, rotor type velocity logs, electromagnetic velocity logs, Doppler Velocity Logs (DVLs). The Pitot tube velocity log has good accuracy in middle range speed measurement. It is influenced by turbulence and bubble, and precision deteriorates. In addition, it is affected by temperature and density of the seawater. It has some errors when the vehicle turns. Anything should not attach to its sensor part. So, the pitot tube velocity log is not suitable for the underwater velocity log. The rotor type velocity log is good in the measurement of the low speed range. It is affected by turbulence. The influence of temperature and the density of the seawater on it is small. Its measurement accuracy is low. So, the rotor type velocity log is not suitable for the cruising type underwater vehicles. The electromagnetic velocity log has effective ranges from slight low speed to high speed. It is highly precise. It is affected by turbulence. It is not influenced by temperature and density of the seawater. It has some errors when the vehicle turns. So, the electromagnetic velocity log is not suitable for the cruising type underwater vehicles. The Doppler velocity log has effective ranges from low speed to high speed. It has small influence of the turbulence and small error when the vehicle turns. Also, it can measure against water or seafloor alternatively and correct influence of temperature and the density of the seawater. The Doppler Velocity Log is suitable for the cruising type underwater vehicle.

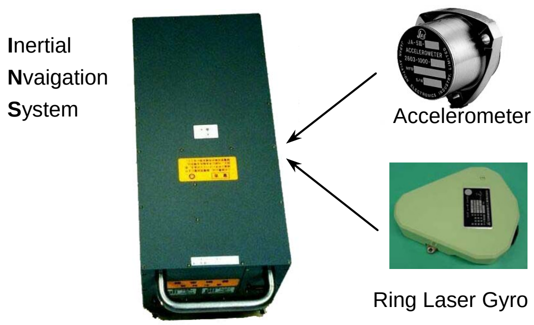

Figure 10. The Inertial Navigation System

6. Radio Waves Cannot Use

Radio wave is a not usable in the sea. However, it is necessary for the vehicle to communicate with the support vessel. The acoustic telemetry is the only effective method in the underwater communication method. So, the vehicle communicates with the support vessel by acoustic telemetry. There are analog communication and digital communication for acoustic telemetry. It is digital communication to have the communication of various data. The underwater acoustic communication methods are Frequency Shift Keying (FSK), Phase Shift Keying (PSK), Quadrature Amplitude Modulation (QAM). The FSK can transmit data of 1byte as two different (high and low) frequency. The PSK can transmit data of 3 byte as different phase. The QAM can transmit data of 8 byte that mapped phase and amplitude onto different signal points. For example, a picture shown in figure 11 is transmitted from an autonomous underwater vehicle at 3,518m depth to the support vessel by using QAM acoustic communication. The picture was taken by TV camera of the vehicle. The picture was transmitted every 8 seconds by 521 dots (horizontal resolving power) x 224 lines (vertical scanning lines) by using quality priority mode.
The underwater acoustic technology using time-reversal communication pushes forward a study of long-distance communications and a long-distance acoustic navigation in JAMSTEC.

Figure 11. TV Image Transmitted via Acoustic Telemetry from 3,518m

7. Smart Control System

A smart control system need for autonomous underwater vehicles to cruise in safely and precisely for long time. The system needs to control about the devices such as thruster, INS, rearranging of the information of the vehicle, and motion of the body. The computer of the vehicle needs to do the information processing of a lot of devices. A distributed processing system is necessary, so that processing does not concentrate on one CPU.

On the other hand, The Autonomous underwater vehicles can move freely, because they do not need cable for power supply and communications. So, the vehicles are able to maneuver precisely by a high-performance controller. JAMSTEC's AUV is a vehicle designed for scientific surveys. These surveys require precise maneuvering of the vehicle for detailed investigations. The vehicle equips some acoustic observation devices such as side scan sonar, sub-bottom profiler and multi beam echo sounder. These devices need stable cruising, maintaining depth or altitude, maintaining direction or survey line and so on. To satisfy these demands, an advances control system is one of the solutions for high-performance maneuverability. An accurate mathematical model based on vehicle dynamics is needed for design of the high-performance controller. The dynamic model of a vehicle in 6 degrees of freedom is described by two coordinate frames as indicated in figure 12. The notations for the motions of the vehicle are described by the following vectors:

$$\begin{aligned} \eta &= [x,\ y,\ z,\ \phi,\ \theta,\ \psi]^T \\ \nu &= [u,\ v,\ w,\ p,\ q,\ r]^T \\ \tau &= [F_x,\ F_y,\ F_z,\ M_x,\ M_y,\ M_z]^T \end{aligned} \qquad (1)$$

Here η denotes the position and orientation vector with coordinates in the earth-fixed frame, ν denotes the linear and angular velocity vector with coordinates in the body-fixed frame and τ is used to describe the forces and moments acting on the vehicle in the body-fixed frame. The vector $\delta = [\delta_H, \delta_V]^T$ consists of horizontal and vertical rudder deflections δ_H and δ_V, respectively. With this notation, the nonlinear equations of motion of the vehicle in 6 degrees of freedom are described as follows.
Dynamic equations of motion:

$$M\dot{\nu} = \tau \qquad (2)$$

Kinematic equations:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\ \cos\theta\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \times \begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad (3)$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix} \times \begin{bmatrix} p \\ q \\ r \end{bmatrix} \qquad (4)$$

Where

$$M = \begin{bmatrix} m + A_{11} & 0 & 0 & 0 & mz_G & 0 \\ 0 & m + A_{22} & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m + A_{33} & 0 & -mx_G & 0 \\ 0 & -mz_G & 0 & I_{xx} + A_{44} & 0 & 0 \\ mz_G & 0 & -mx_G & 0 & I_{yy} + A_{55} & 0 \\ 0 & mx_G & 0 & 0 & 0 & I_{zz} + A_{66} \end{bmatrix} \qquad (5)$$

$$F_x = -(m+A_{33})qw + (m+A_{22})rv + mx_G q^2 + mx_G r^2 - mz_G pr$$
$$-(m-\rho\nabla)g\sin\theta - R + X_{vv}v^2 + X_{ww}w^2$$
$$+ \text{(Steering force of Rudder and elevator)} + \text{Thrust} \quad (6)$$

$$F_y = (m+A_{33})pw - (m+A_{11})ur - mx_G pq - mz_G qr$$
$$+(m-\rho\nabla)g\sin\phi\cos\theta$$
$$+Y_v v + Y_r r + Y_{vv}v|v| + Y_{rr}r|r| + Y_{vr}v|r|$$
$$+ \text{(Steering force of Rudder and elevator)} \quad (7)$$

$$F_z = (m+A_{11})uq - (m+A_{22})vp - mx_G pr + mz_G p^2 + mz_G q^2$$
$$+(m-\rho\nabla)g\cos\phi\cos\theta$$
$$+Z_w w + Z_q q + Z_{ww}w|w| + Z_{qq}q|q| + Z_{wq}w|q|$$
$$+\text{(Steering force of Rudder and elevator)} \quad (8)$$

$$M_x = ((I_{yy}+A_{55})-(I_{zz}+A_{66}))qr + (A_{22}-A_{33})vw - mz_G pw + mz_G ru$$
$$-(mz_G - \rho\nabla z_B)g\sin\phi\cos\theta$$
$$+K_v v + K_r r + K_{pp}p|p|$$
$$+\text{(Steering force of Rudder and elevator)} + \text{Torque} \quad (9)$$

$$M_y = ((I_{zz}+A_{66})-(I_{xx}+A_{44}))rp + mx_G pv - mx_G qu - mz_G qw + mz_G rv$$
$$-(mx_G - \rho\nabla x_B)g\cos\phi\cos\theta - (mz_G - \rho\nabla z_B)g\sin\theta$$
$$+M_w w + M_q q + M_{ww}w|w| + M_{qq}q|q| + M_{wq}w|q|$$
$$+ \text{(Steering force of Rudder and elevator)} \quad (10)$$

$$M_z = ((I_{xx}+A_{44})-(I_{yy}+A_{55}))pq + mx_G pw - mx_G ru$$
$$+(mx_G - \rho\nabla x_B)g\sin\phi\cos\theta$$
$$+N_v v + N_r r + N_{vv}v|v| + N_{rr}r|r| + N_{vr}v|r|$$
$$+\text{(Steering force of Rudder and elevator)} \quad (11)$$

Here M is the inertia matrix, m is the mass of the vehicle including seawater in free floating spaces, I_{xx}, I_{yy} and I_{zz} are moments of inertia about the body-fixed each axes, A_{11}, A_{22} and A_{33} are added mass and A_{44}, A_{55} and A_{66} are added inertia. $[x_G, 0, y_G]^T$ is center of gravity, $[x_B, 0, z_B]^T$ is center of buoyancy. The vehicle motion control system is designed for the mathematical model of the vehicle. The mathematical model (Eqs. (2) – (4)) is linearized about equilibrium points such as forward speed is constant and other state variables are zero. The linear system of the vehicle is obtained following equation (12).

$$\dot{\mathbf{x}} = \mathrm{A}\mathbf{x} + \mathrm{B}\mathbf{u}$$
$$\mathbf{y}_\mathrm{M} = \mathrm{C}_\mathrm{M}\mathbf{x} \quad (12)$$

Where the $\boldsymbol{x}=[\eta^T\ \nu^T]^T$ is state variable, the $\boldsymbol{u}=[n_{MT}, \delta_H, \delta_V]^T$ is control input and $\boldsymbol{y}_M=[z\ \varphi\ \theta\ \psi\ u\ v\ w\ p\ q\ r]^T$ is observed output. A robust servo system with observer is designed such as shown in figure 13 based on the linear mathematical model (Eq. (12)). The integral action is necessary to let the vehicle follow target input. The observer is used for filter effect. Where the $\boldsymbol{x}_{ob}$ is state observer, the $\boldsymbol{F}$ and $\boldsymbol{F}_I$ are gain matrix, the $\boldsymbol{z}$ is observed output, the $\boldsymbol{z}_c$ is target input and the $\boldsymbol{e}$ is error of $\boldsymbol{z}$ and $\boldsymbol{z}_c$. A control purpose is to design optimal feedback gain stabilizing an error $\boldsymbol{e}$ to zero. The technique of the optimal regulator is LQI (Liner Quadratic optimum control with Integral action) method. The quadratic performance function is follows:

$$\mathrm{J} = \int_0^\infty \{\mathrm{e}^\mathrm{T}\mathrm{Q}_\mathrm{E}\mathrm{e} + \mathrm{u}^\mathrm{T}\mathrm{R}_\mathrm{E}\mathrm{u}\}\mathrm{dt} \quad (13)$$

Where, $\boldsymbol{Q}_E$ and $\boldsymbol{R}_E$ are weight matrix.

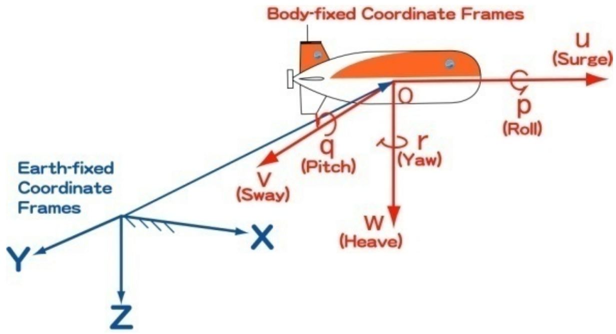

Figure 12. The Body-Fixed and The Earth-Fixed Reference Frames

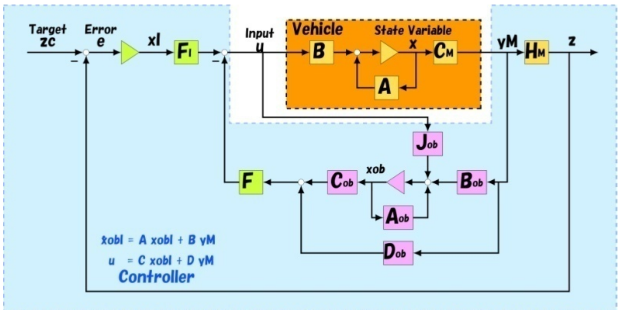

Figure 13. The Block Diagram for Robust Servo Control System with Observer

8. Navigation Modes

The autonomous underwater vehicle needs to have some navigation modes such as autonomous navigation mode and acoustic remote control mode for many scientific survey requirements. The concept is shown in figure 14. Modes are chosen according to the mission type.

The autonomous navigation mode: the working schedule is preset on the computer in the vehicle before starting observations. The schedule includes the cruising course and procedure of observation devices. The support vessel carries the vehicle to the observation area and is used for launching and recovery. The vehicle independently cruises without any information from the support vessel. When the vehicle notices some obstacles along its programmed course, it takes avoidance action by itself. In the case of long range cruising, some acoustic transponders are arranged along the cruising course for reference. The vehicle can correct its position by communication with transponders, making positioning accuracy better.

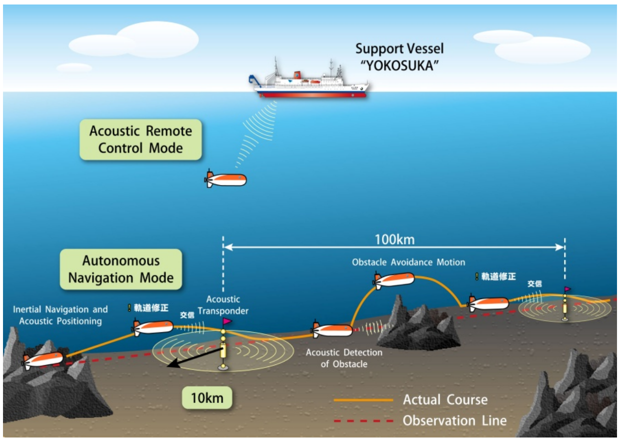

Figure 14. The Concept of The Navigation Modes

The acoustic remote control mode: the support vessel follows the vehicle and they communicate with each other during the operation. Although the working schedule is preset in the same manner as for autonomous navigation mode, a new schedule can be downlinked from the support vessel by acoustic telemetry. Images can be sent acoustically, and side-scan sonar and TV camera data can also be uplinked from the vehicle by acoustic telemetry. The images are transmitted at an interval of a few seconds. Acoustic control is able to be employed inside a 30 degree angle of conic area under the support vessel.

9. Next Dream

We started research and development of a demonstration long-range vehicle to cruise over 1,000 kilometers. It is important to improve many elemental technologies such as power source and navigation system and so on to achieve this aim. Figure 15 shows a concept image of concentrating these elemental technologies to next generation vehicle.

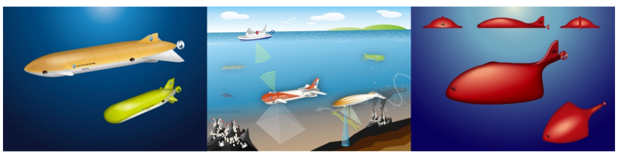

Figure 15. The Next Generation Autonomous Underwater Vehicles

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