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Development of a power control system for AUVs probing for underwater mineral resources

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Abstract: Valuable mineral resources are widely distributed throughout the seabed. autonomous underwater vehicles (AUVs) are preferable to remotely-operated vehicles (ROVs) when probing for such mineral resources as the extensive exploration area makes it difficult to maintain contact with operators. AUVs depend on batteries, so their power consumption should be reduced to extend exploration time. Power for conventional marine instrument systems is incorporated in their waterproof sealing. External intermittent control of this power source until termination of exploration is challenging due to limitations imposed by the underwater environment. Thus, the AUV must have a power control system that can improve performance and maximize use of battery capacity. The authors developed such a power control system with a three-step algorithm. It automatically detects underwater operational states and can limit power, effectively decreasing power consumption by about 15%.

Keywords: power control; underwater prober; submarine mineral resources; power efficiency; energy saving

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1 Introduction

As underground resources have been exhausted in recent times, much effort has been concentrated on developing submarine mineral resources. Intelligent probing systems have been developed for the purpose of approaching the seabed and exploring the submarine manganese crust, hydrothermal deposits and other resources[1]. Remotely operated vehicles (ROVs) have some restrictions in their extreme working environment while probing undersea resources, such as the manganese crust, and hydrothermal deposits[2]. So, autonomous underwater vehicles (AUVs) have been widely used to improve probing efficiency, extend operating time and widen the exploration area[3]. The AUV's functioning depends on internal batteries, so the reduction of power consumption is one of the most important design factors. Power in conventional marine probing systems is generally provided before assembly and waterproof sealing, so external intermittent power control is difficult until the exploration is finished. Therefore, conventional power control is carried out to renovate performance and battery capacity[4-5] and implement low-consumption by dropping the supplying voltage from DC 5.0V to DC 3.3V[6]. A non-contact power supply using electro-magnetic propagation was developed to recharge a battery in an underwater earthquake detection system to extend working time[7]. Magnetic tags are used in the detection system to decrease power consumption by switching the operation mode to sleep mode. Power is controlled by attaching and detaching the magnetic tags by an operator, and continues to be consumed when the system is retrieved after finishing exploration. So, the efficiency of the power consumption can be low using the magnetic tags method[8]. Little research has focused on power saving in underwater systems by detecting the underwater operating status of the probe to control power consumption. Therefore, this study proposes a power control system and algorithms to make full use of the limited power source in the probes.

The power control system can automatically detect the underwater operating status, such as launching and recovery. Power can be supplied selectively only when the probe is submerged in the water. The algorithm has three steps:

1) Automatic detection of underwater operating status and power control.

2) Power control by exploration modes.

3) Power control in low-voltage emergency escape. The power control method was applied to a probe system. Its availability was verified in the experiment.

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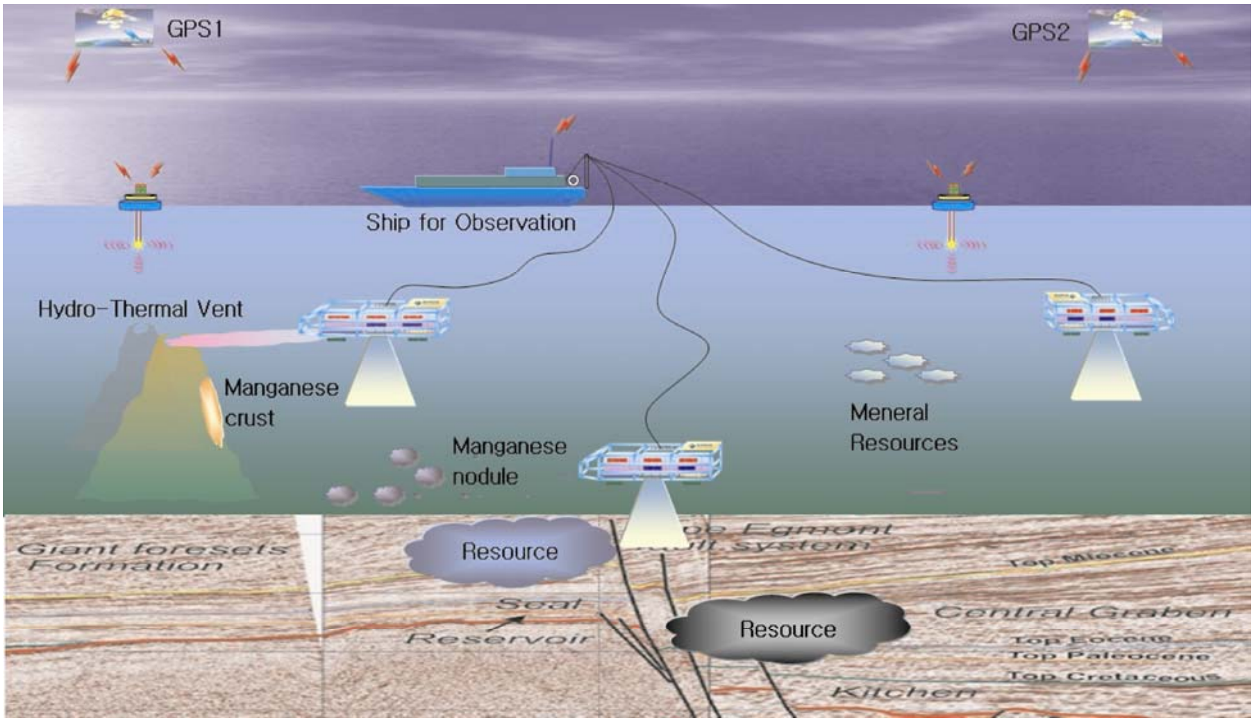

Fig.1 Operating concept of a PSUMR

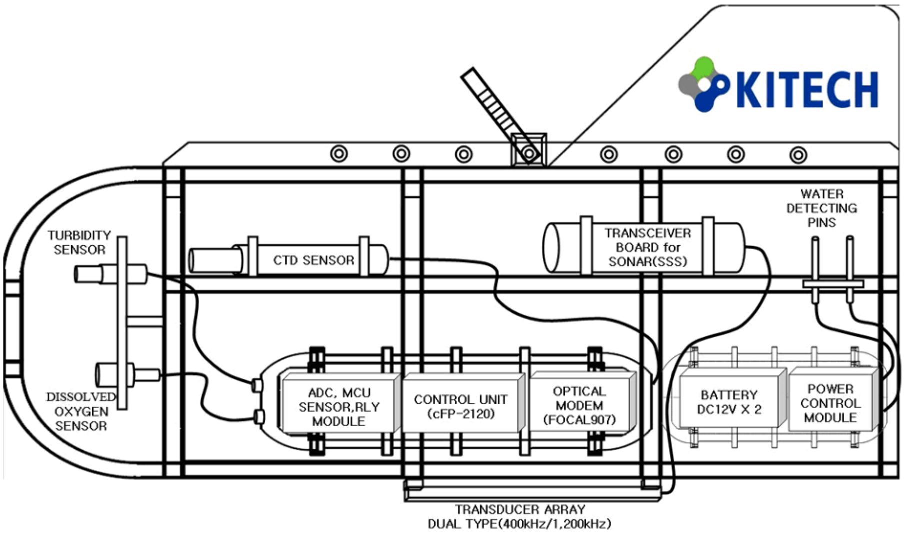

Fig.2 A schematic diagram of a probing system for underwater mineral resources

2 Probing system for underwater mineral resources

A probing system for underwater mineral resources (PSUMR) is a mechatronic unit for searching high-quality mineral resources, distributed throughout the seabed, in real time, as shown in Fig.1. Fig.2 shows the layout of the sensor modules for probing mineral resources. Conductivity temperature depth (CTD) sensor, SBE 49 Fast CAT, obtains temperature, electric conductivity, and depth of the probe. Turbidity sensor, Sea Point Turbidity Meter, 6000 Meter, detects the turbidity phenomenon around hydrothermal vents. This is increased due to the bursting mixture. This helps locate hydrothermal deposits. The dissolved oxygen sensor, Oxygen Optodes 3835, detects the deficiency layer of oxygen in the mountain slope where manganese crusts are distributed. Dual frequency (400 kHz/1 200 kHz) type side scan SONAR obtains a submarine topographical map. It is driven by a transceiver module.

PSUMR is controlled using compact field point, CFP-2120, of National Instrument Corporation. Optical MODEM (FOCAL-907) is applied to transfer digital information from sensor inputs into MCU (Main Control Unit) above the water surface. The water detection pin detects the underwater operating state of the probe. A power control system selectively supplies the essential sensor modules with electronic energy during exploration. This study was carried out to develop a power control system that detects automatically the operating state of a PSUMR and selectively supplies the probe with electronic power only when the probe is in use.

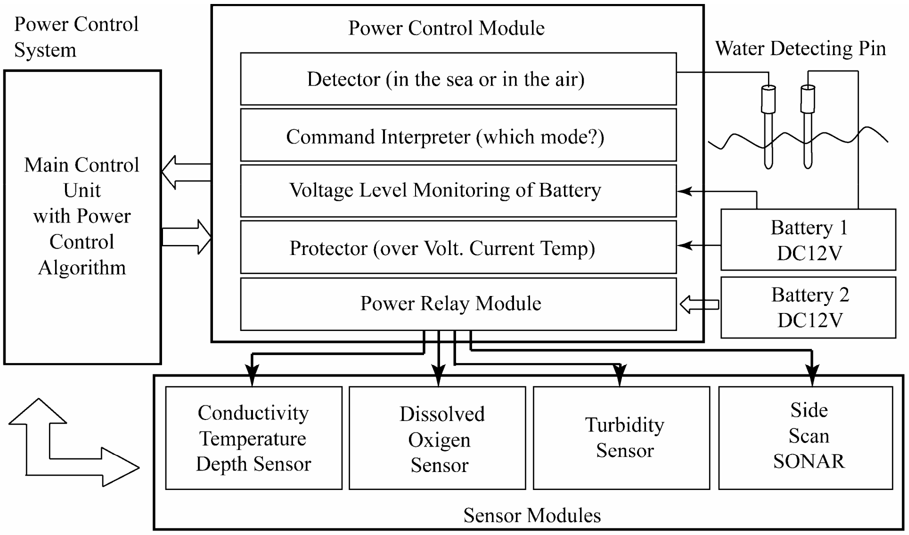

Fig.3 A schematic diagram of power control system

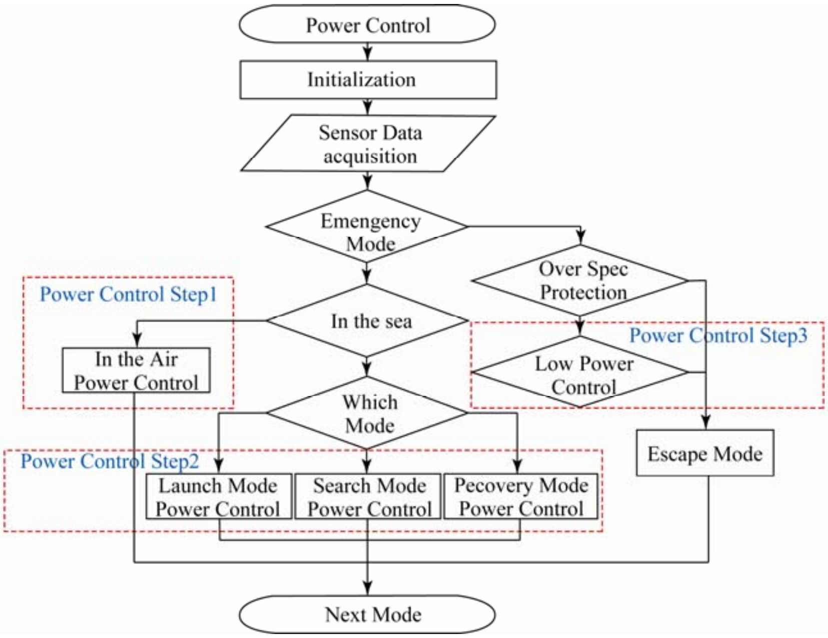

Fig.4 A flow chart for power control algorithm

3 Power control system

The power control system for a PSUMR automatically detects the underwater operational state and is configured as shown in Fig.3. The system performs a three-step power control algorithm. Fig.4 shows the execution of the power control at each step, drawn by a flow chart.

3.1 Power control by automatic detection of the underwater operating state

The first step is power control by the automatic detection of the underwater operational state. This is automatically checked if the PSUMR is in the air or underwater using the conductivity of seawater. This aims to reduce power consumption that arises unnecessarily outside the operational period. For instance, the internal power of a probe becomes isolated after the first power supplement and waterproofed housing. Unnecessary power consumption will occur while moving to the exploration area, and during recovery once exploration is complete.

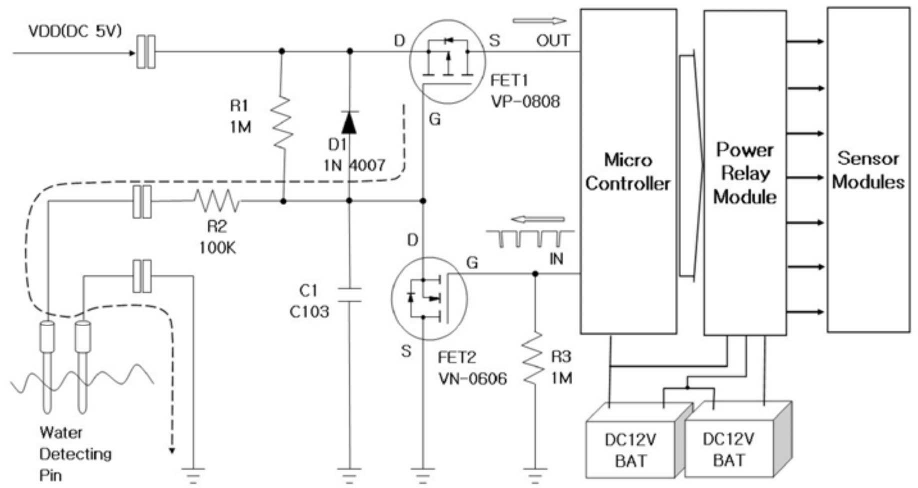

Fig.5 Automatic detection circuit of the underwater operating states

The power is supplied conditionally only when the PSUMR is functioning in the water. When a PSUMR is launched in the water, the power is supplied through the detection circuit of the underwater operational states in a PSUMR. The circuit detects the characteristics in electric conductivity of seawater and provides the power source for the PSUMR to be activated. The circuit automatically shuts off the current and cuts power consumption by detecting variation of conductivity in the air when the PSUMR is recovered. This is a selective power supply to the sensor module only while the PSUMR is submerged. The aim is to reduce power consumption.

The conductivity of seawater is detected by water detection pins, attached at a PSUMR, as shown in Fig.5. When the pins are submerged in an electrolyte, the electrolyte is dissolved in the seawater, and then it is separated into positive charges and negative charges. A direct current is supplied between two metals so that a potential difference artificially occurs. A positive charge moves to the negative pole and a negative charge moves to the positive pole while an electric current is applied to an electrolytic solution. This minute electric current is used as a voltage bias signal to drive a field effect transistor (FET, VP-0808, VN-0606), so the MCU judges whether it is underwater or in the air. Relays supply power from the control module to a probe; their basic activation state is N.C. (normal close), as shown in Fig.5. When the relays are activated, the state is switched into N.O. (normal open), so the power is shut off to sensor modules. Therefore, the power can be supplied directly in the disabled status or the relay set to “off” due to faults occurring in the power module. The power control module does not interfere with the normal work of the probe.

As the PSUMR is determined to be in seawater, the power control module (PIC16F876) conducts the control as shown in Fig.6 and Eq.(1) to stabilize electric noise and power fluctuation.

$$F_w = \sum_n [u(t-2nT_w) - u(t-(2n+0.998)T_w)] \qquad (1)$$

where, F_w is a pulse signal, t time, T_w period, u unit step function, and n the number of repetitions.

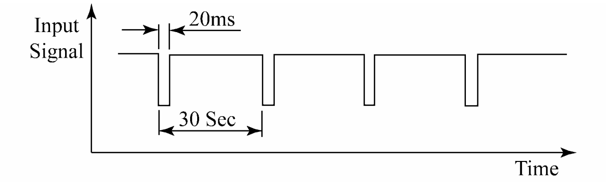

Fig.6 The pulse signal to detect the underwater operational state

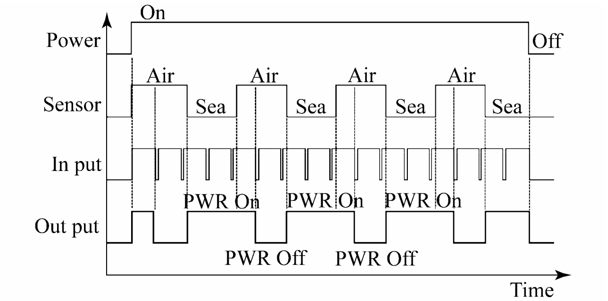

Fig.7 Dynamic characteristics of the power control after launching

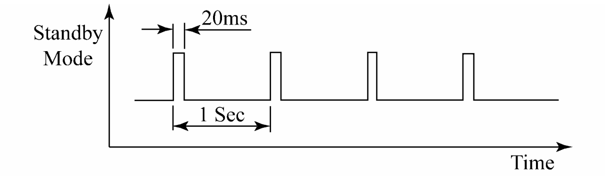

Fig.8 Transmission of exploration modes and identification information

A pulse signal is given at regular intervals (30 s) as the input of the power control circuit, so that the FETs are activated by the conductivity of seawater. When the PSUMR is exposed to air, the trigger pulse signal (20 ms) is supplied. Then, the FET1 will be turned off by the trigger and the power will be shut down. In this way, the power consumption of the sensor modules can be shut down while the probe is in the air. The time chart of Fig.7 shows the automatic detection of the power control in a PSUMR is repeatedly carried out. It can be observed that electric power is supplied immediately after a probe is launched, but it is shut off at the next cycle when the probe is in the air. The time delay is necessary to prevent a probe from being faulty due to the oscillations from the air and the underwater states when the prober is floating on the water surface.

3.2 Power control according to exploration mode

The second-step of the power control is adjusting electric power, based on exploration mode, to intermittently control power supply to each module in a PSMUR, as shown in Fig.8 and Eq.(2).

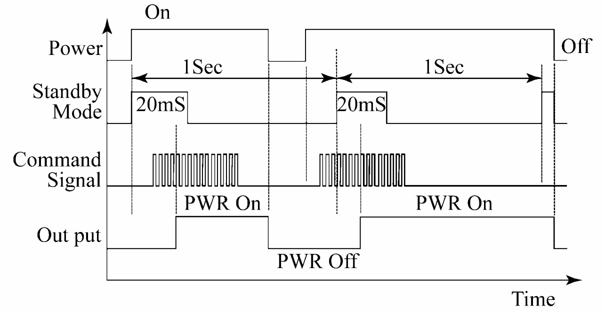

Fig.9 Dynamic characteristics of the power control based on exploration mode

$$F_p = \sum_n [u(t-2nT_p) - u(t-(2n+0.02)T_p)] \tag{2}$$

where, F_p is a pulse signal, and T_p period.

Power control by external commands and interrupt signals can be explained in Fig.9, when control signals do not arrive from an MCU in Fig.12. The power control mode is switched to the sleep mode algorithm and switches to the standby state. When command signals arrive from the MCU in Fig.12, the power control mode is switched to wake-up mode and electric power is selectively supplied to the relevant sensor modules. A probe executes safety mode before reaching the target depth for underwater resource exploration. When it reaches the exploration area for respective resources, electric power is provided to the exploration modules for the required interval. When the probe is out of the area of the target resource, the power control is switched to safety mode to reduce power consumption.

3.3 Power control in low-voltage emergency escape

The third step of power control is to adjust electric power when a PSUMR escapes from the exploration area in an emergency state due to low voltage, as shown in Fig.10. The third step of the power control algorithm aims to save power as much as possible during the recovery of a probe due to low voltage or over-drive conditions (over-voltage, over-current, over-temperature, over-moisture). Power to the low priority sensors is shut off to conserve the remaining battery energy.

The voltage in a battery is monitored using Analog Input “cFP-AI-118” from Compact Field point RT system “cFP-2120” made by National Instrument Co., Ltd. The power control is conducted by the remaining electronic energy, and the state is switched into emergency escape mode when the voltage is discharged under a preset threshold voltage (Vi<DC 8.0V). The remaining energy in a DC 12.0V battery is measured and separated into three classes.

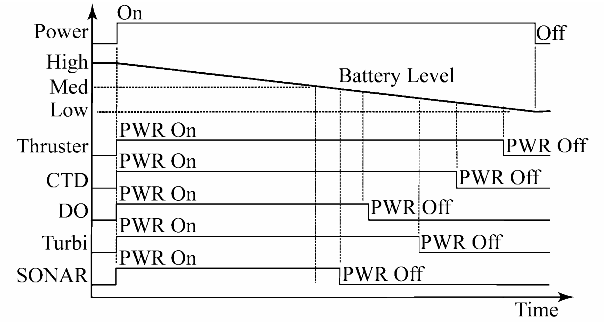

Fig.10 Characteristics of low-voltage emergency escape power control

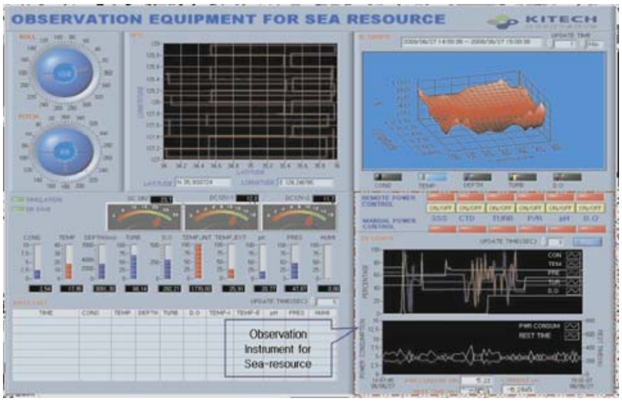

Fig.11 Configuration of a GUI for a power control system

When the voltage is between DC11.0V and DC9.0V, auxiliary electronic power is supplied to extend the interval of sampling time to probe mineral resources.

When its voltage is between DC 8.9V and DC 8.0V, data acquisition is carried out based on the priority of resource probing information. The acquisition of the probing information at low priority is stopped and power supply is cut off. When the voltage is less than DC 7.9V, the state is switched to emergency escape mode. A PSUMR disables all the functions, except essential navigation control, and conducts an emergency escape. This prevents the resource probing system from being shut down due to battery discharge of less than the cut-off voltage. When a probe escapes in an emergency, it ejects its ballast and rises to the surface using positive buoyancy.

3.4 A GUI for a power control system

Fig.11 shows a graphic user interface (GUI) for the PSUMR, constructed using Lab VIEW 8.2. The power control part at the right bottom area monitors the power consumption in a probe in real-time. The part also shows the estimated remaining operational time when a probe is exploring. The power source of the probe sensor modules are automatically controlled by the exploration modes, but the power of each sensor module can also be manually controlled, when necessary, as an operator does on a ship.

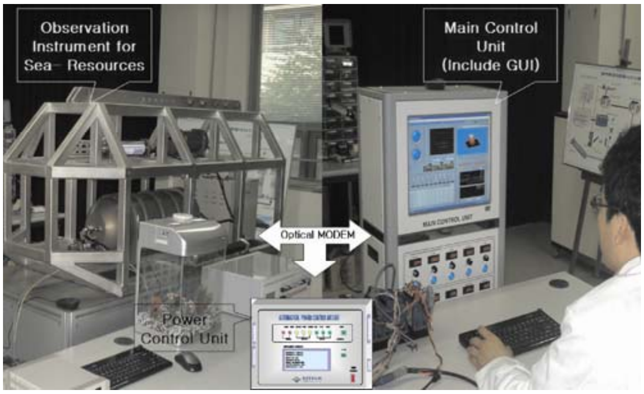

Fig.12 Configuration of experimental apparatus for a power control system

4 Experiments and considerations

4.1 Experimental conditions and procedure

An experimental system was constructed to evaluate the characteristics of a power control system in a PSUMR, as shown in Fig.12. The power control system was a Compact Field point RT System “cFP-2120”, made by National Instrument Co., Ltd. The characteristics of reduction in the power consumption were evaluated using Lab-VIEW 8.2 S/W through the simulation and the load test. The reduction in the power consumption through the proposed algorithm was measured by calculating the specified current in sensor modules attached to a probe. The simulation is carried out under the condition that the maximum current is consumed continuously, as in the non-control case. The power control system is connected to the probe as an actual load and the power control proceeded using the proposed steps. Both the simulation and the load test were conducted simultaneously. Their results are discussed in the following section.

4.2 Test results of the reduction in power consumption

The efficiency of the proposed algorithm can be evaluated by the power consumption. Better efficiency implies lower power consumption. Power consumption can be checked by averaging the power supplied in a period. The output voltage $V(t)$ from the battery can be slightly affected during operation, but in the main the load current $I(t)$ will vary. Thus, the power consumption, the load power can be defined as Eq.(3).

$$P(t) = V(t) \times I(t)[W] \tag{3}$$

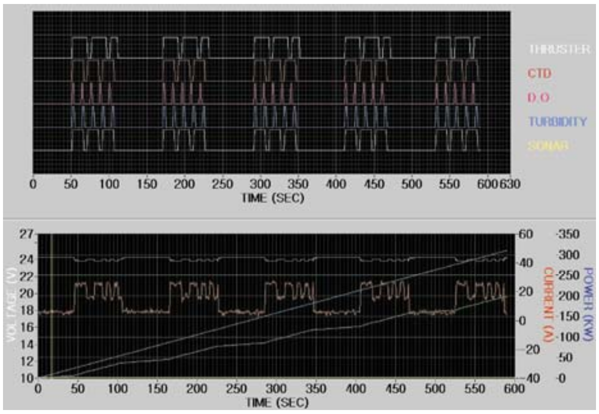

Fig.13 Configuration of experimental apparatus for a power control system

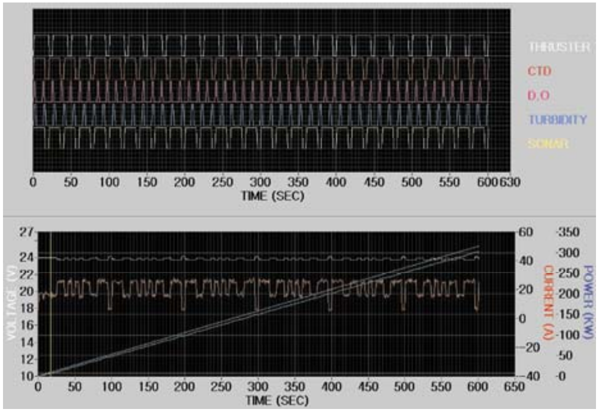

Fig.14 The characteristics of power reduction in the power control based on exploration type

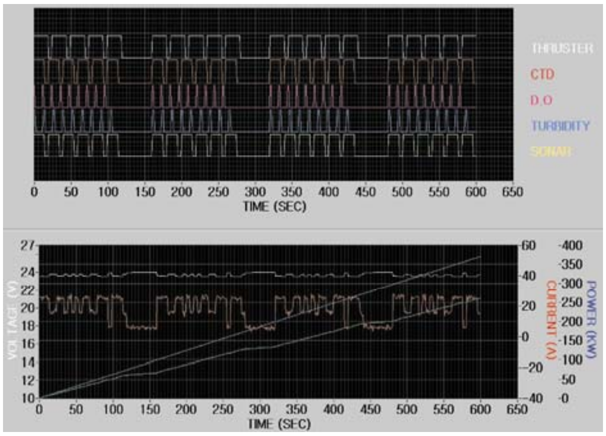

Fig.15 The characteristics of power reduction in the low-voltage emergency escape power control

The average power $\overline{P}$ in period T can be calculated as Eq.(4). $\overline{P}$ will become smaller if the power is conserved and controlled.

$$\overline{P}=\frac{\int_0^T P(t)\mathrm{d}t}{T}=\frac{\int_0^T V(t)\times I(t)\mathrm{d}t}{T}[W] \tag{4}$$

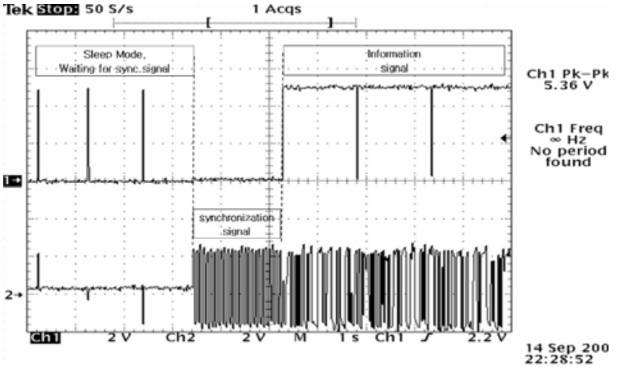

Fig.16 The characteristics of control information detection during power control

Fig.13 shows the characteristics of power consumption reduced by the first step, automatic detection of power control of the probe's operating state. Excluding the electric power of the power control module, the power supplement to the sensor modules in the PSUMR is frequently shut off. Integrated electric energy can be lowered compared to the non-control case. Power is supplied in irregular periods and controlled intermittently based on exploration mode, as shown in Fig.14. Thus, the amount of the integration, the reduction of power consumption in the second step is smaller than that in the first step. This is caused by the irregular operational time of a PSUMR compared to the non-control case. Power consumption was remarkably reduced by the power control in the low-voltage emergency escape, because the electric power supplement is shut off to low-priority sensors, as shown in Fig.15. Therefore, the effect on reducing power consumption is larger in the first step, the third step and the second step respectively, by the proposed power control system. The power consumption can be cut off during transferring and recovering the probe, excluding the underwater operation in the first step. The power supply is thoroughly shut off to the sensor modules in a probe under the low-voltage condition in the third step.

In contrast, electric power to the sensor modules is frequently controlled in the second step due to long exploration. Thus, the power-reduction effect decreased as the power reduction becomes lower, compared to the first and the third steps. Numerous on/off actions in the graphs were caused by increasing the trials during the simulation to watch the effect of consumption reduction before and after power control. The actions in a probe will rarely increase in a real situation, because auto power off is only one additional action for each sensor from full charge to discharge.

The efficiency is calculated from the non-control and the control results. All the modes in the test conserved power. The result shows that power consumption can be reduced on average 15% by the proposed algorithm. The power control system performed well in test exploration when a probe explored 50 m under the sea. The underwater test took about 8 hours operating in a 1 000 m×800 m area, scanning every 100 m (W:1 000 m) and repeating this eight times. The major characteristics of the algorithm are to stop unnecessary power consumption when not exploring. This can improve energy efficiency.

4.3 The characteristics of control information detection

The characteristics of detecting the control signal were estimated, in the process of conducting power control, to evaluate the characteristics of detecting the control signal to determine the exploration modes transmitted from MCU in Fig.12. When the synchronization signal is transmitted from the MCU to the underwater probe that is in standby mode, the power control system breaks the standby mode, receives control signals, and executes the corresponding activation, as shown in Fig.16. The control signal is transmitted 2.5 times longer than a power control cycle, so that the probe can again detect the signal, though it fails to detect the signal due to external noise. The probe correctly detected the control signal in the experiment.

4.4 An extended application to other probers

The power control system can be applied to the power control module in other underwater probes. The power relay module of this system can automatically determine if the probe is in the air or underwater. The relay module can output selectively as an independent power source with two DC24V (2 EA), DC12V (4 EA) and DC5V (2 EA) after the decision. Its maximal output is 3A Max/EA. The increase of electric capacity is possible if it is connected to a large-capacity relay.

The power control module can be easily and cheaply constructed using two FETs, as shown in Fig.5. The power control circuit can be activated just after being connected between a MCU and a battery. These algorithms and circuits are simple and small, so this does not impact the complexity and the incidence of faults.

5 Conclusion

An intelligent probing system, PSUMR, can reach the seabed and explore resources, such as hydrothermal deposits, manganese crusts, and manganese nodules. A PSUMR is supplied with power during waterproof assembly. Hence, external intermittent control of the power source is impossible before terminating exploration. Thus, power reduction is an important factor to such probes. This study presents a power control method in a probe system for the exploration of underwater mineral resources, to reduce power consumption and extend operational time. The power control algorithm comprises three steps: 1) automatic detection of the underwater operational state, 2) power control based on exploration mode, 3) low-voltage emergency escape power control.

Power control in the first step sensed the electric conductivity of seawater. Electric power was supplied to the probe only while it was operating under the sea, but power consumption was cut off while it was dormant in the air. In the second step, electric power was selectively supplied to the essential sensor modules based on exploration information, such as the types of resources, the distribution of resources and the depth of resources. Power control in the third step was carried out using the remaining energy in an internal battery for emergency escape. The efficiency of electronic power was higher than that of the non-control case. Power consumption was reduced about 15%, compared to the non-control case. This will be effective to PSUMRs operating over a long period, depending on batteries. Therefore, the power control system presented in this study can be effective for the probe systems exploring underwater mineral resources.

References

[1] GERMAN C R, YOERGER D R, JAKUBA M, et al. Hydrothermal exploration with the autonomous benthic explorer[J]. Elsevier Deep-sea Research Part I, 2008, 55: 203-219.
[2] CONTE G, SERRANI A. Robust control of a remotely operated underwater vehicle[J]. Elsevier Automatica, 1998, 34(2): 193-198.
[3] HAGEN Per Espen, Størkersen Nils, MARTHINSEN Bjørn-Erik, et al. Rapid environmental assessment with autonomous underwater vehicles[J]. Journal of Marine Systems, 2008, 69: 137-145.
[4] HASVOLD Øistein, JOHANSEN K H, VESTGAARD K. The alkaline aluminum/hydrogen peroxide power source in the Hugin II unmanned underwater vehicle[J]. Journal of Power Sources, 1999, 80: 254-260.
[5] SAWA Takao, AOKI Taro, YAMAMOTO Ikuo, et al. Performance of the fuel cell underwater vehicle URASHIMA[J]. Acoust Sci & Tech, 2005, 26(3): 249-257.
[6] NAM Heungwoo, AN Sunshin. An ultrasonic sensor based low-power acoustic modem for underwater communication in underwater wireless sensor networks[J]. EUC Workshops, 2007, LNCS 4809: 494-504.
[7] HAN Jun. Noncontact power supply for seafloor geodetic observing robot system[J]. J Mar Sci Tech, 2007, 12(3): 183-189.
[8] Acoustic Pinger and Data Storage Transmitter in one, www.sonotronics.com, (AST-03).

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Kang Won LEE received the PhD degree in precision mechanical engineering from Hanyang University, Seoul, Korea, in 1998. He is currently the manager of the Technical Service Division, KITECH. He has conducted more than 100 research projects and developed semiconductor manufacturing machines. His research interests include semiconductor manufacturing using lasers, ultrasonics, and magnetics.