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Design of Autonomous Underwater Vehicles for Cage Aquafarms

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***Abstract* — Aquaculture systems need to provide artificial monitoring and control functions to maintain essential environmental factors within the high productivity ranges. This paper suggests that autonomous underwater vehicles (AUV) equipped with various sensors, communication devices, and navigational intelligence can perform effective and broad-range monitoring missions of cage-based aquaculture system surroundings. After explaining the target aquaculture system, we describe functional and performance requirements of AUVs for surveillance of costal cage aquafarms. It also describes several design options considered for this ongoing project as well as artificial immune-based intelligence features.**

I. Introduction

Though the consumption of fishery products has been ever increasing, fishery amounts from open wild habitats have encountered serious challenges due to several reasons including overfishing and environmental changes [1]. One of solutions is to establish aquaculture facilities where fisheries are bred, raised, and caught under high productivity settings. It has been known that the proliferation, survival and growth of marine fishes are very sensitive to environmental factors such as temperature, acidity, dissolved oxygen concentration, and pathogenic microbes [2]. Unlikely to the open wild habitats where the fishes could migrate to their preferable regions autonomously, the aquaculture systems need to provide artificial monitoring and control functions to maintain such environmental factors within high productivity ranges.

Among several types of aquaculture systems, this paper focuses on cage-based aquaculture systems operated in coastal areas. Though cultivated fishes are kept inside the cages, the afore-mentioned environmental factors are highly affected by surrounding oceanic regions since the sea water is allowed to flow through the cages. For example, mass outbreaks of death can happen if cold water suddenly flows into the cages from the sea floor. Proliferation of pathogens inside or outside cages can put critical dangers on the aquafarms while the early detection is almost impossible. The current solution is the necropsy of dead fishes to identify pathogens after the dead outbreak prevails. Since the ranges of affecting oceanic regions amount to several thousand meters depending on the factors, it is hard to deploy sufficient number of fixed sensors over the regions both in technical and economical aspects.

This paper suggests that autonomous underwater vehicles (AUV) equipped with essential sensors, communication devices, and navigational intelligence can provide acceptable solutions to this problem. After explaining the target aquaculture systems, we describe functional and performance requirements of autonomous underwater vehicles for surveillance of costal cage aquafarms. It also describes several design options considered for this ongoing project.

II. Coastal Cage Aquafarms

A. Aquaculture Types

Aquaculture is defined as the practice of using the sea, lakes, and rivers for cultivating aquatic animals and plants, especially for consumption as food. It is distinguished from fishing by active human efforts in maintaining or increasing the species involved, as opposed to simply taking them from the wild habitats. Aquaculture systems for marine products can be classified into three types according to the cultivation areas. (i) The indoor tank systems are using plastic or concrete tanks to raise fishes. The tank water is slowly circulated through pipes with pathogen filters, which are connected from the coast to the aquafarms, so that fishes can be provided with natural sea water regularly. (ii) The cage systems are using synthetic fiber cages installed several kilometers apart from the coasts. Fishes are kept inside the cages while natural sea water flows through the cages freely. Free flow of natural sea water is critical for cultivation of special fish species such as flat fishes. However, these fishes are always exposed to danger under water. (iii) Open marine ranches are designated areas in the middle of the sea where

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artificially enriched ecosystems are fostered. For example, massive marine plants and submarine structures are implanted to provide cultivated fishes with nutrients and shelters.

B. Cage Aquaculture Systems

This paper focuses on a specific type of cage aquaculture systems being used predominantly in Korea. Each farm consists of tens of beds, and each bed consists of four cells. The dimension of the cell is typically 5*5*5 meters. It is recommended that around 15 beds are deployed in a unit region of 10k square meters (Figure 1).

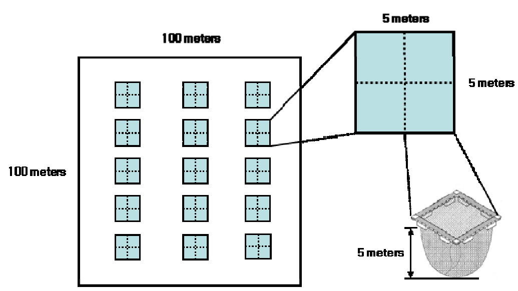

Figure 1. The typical Layout of Cage Aquafarms

C. Environmental Factors

We should consider several problems for cultivating fishes. Among them, growth promotion and prevention of mass death of fishes are absolutely important. For that, we should observe water quality at all times. To estimate water quality, we check temperature, dissolved oxygen (DO), ammonia, nitrites, nitrates, and pH and alkalinity of water. Between them, temperature is the important factor because fishes live within the optimal temperature range. If the temperature is below the threshold, they could not live any more.

The red tide is frequently occurred in Korea for June through August. They are usually not harmful. However, the excessive proliferation of zooplankton results in extensive damage to fishes caught in gill nets. Thus, it triggers mass death of fishes.

Recently, we acquire water quality data through the data logger system. It has several sensors to measure water quality. It is convenient to use within limited areas. However, we should cover relatively large area around aquafarms. Thus, it is inconvenient because users should move frequently to measure data around aquafarms.

III. DESIGN REQUIREMENTS AND PRINCIPLES

Autonomous underwater vehicles (AUVs) have been utilized for scientific, commercial and military underwater applications [3]. These vehicles require autonomous guidance and control systems to perform missions under water. For that, AUVs have their own energy sources and have many electrical devices. REMUS and GAVIA is well-known AVUs. They are used for oceanic exploration and military applications. They are used for hydrographic surveys, environmental monitoring and scientific samplings [4]. Although, these state-of-the-art AUVs have excellent functions and performance, it is inadequate to apply cage aquafarm surveillance. They are expensive approximately half million dollars and their design objective is not appropriate to ours as described below.

A. Requirements of AUVs for Cage Aquafarms

We divide Unmanned Underwater Vehicles (UUVS) into two parts according to their autonomy. One is autonomous underwater vehicles (AUVs) which can navigate under water without assistance from supervisors. The other is remotely operated vehicles (ROVs) which are supported by mother ship through a cable. Between them, AUVs are more adequate than ROVs because we need intelligent vehicles navigating autonomously around aquafarms. For that, we should consider several requirements of AUVs for surveillance of coastal cage aquafarms.

First, the accuracy of AUVs should be sustained.

(1) Exact handling in low speeds is important because AUVs should measure water quality at the target spot in low speeds.

(2) The accurate transmission of position is necessary. We do not know whether AUVs navigate adequately or not.

Second, the stability of AUVs should be obtained.

(3) AUVs turn frequently their direction to perform their mission around aquafarms. As a result, they are affected by drag force or pressure and lose their attitude. It is important to keep attitude and position stable.

Third, the efficiency of AUVs should be attained

(4) Basically, AUVs need sufficient space to equip electrical devices and batteries. In addition, they need various sensors to measure water quality and control attitude. Thus, the adequate arrangement of device is important to reduce the unnecessary space.

(5) AUVs should optimally move to the aiming point to minimize the consumption of batteries.

Fourth, the invariability of AUVs should be maintained.

(6) The deeper AUVs go under water the more pressure is exerted on the whole craft. The minimal shape change of the hull is important to keep inner devices safe because they have an important role to manage AUVs.

Fifth, the tenacity of communication systems is needed.

(7) The communication system of AUVs should be robust against noise signals to minimize error rate. It is important delivering the exact data to users.

Sixth, the accessibility of AUVs should be easy.

(8) We frequently modify control program according to missions. We adjust operational depth, pathway and sensing rate. Thus, we should easily access control system.

Seventh, the riskiness of AUVs is minimized.

(9) When AUVs navigate around aquafarms, the fishes can get stress from the light or sound of AUVs.

B. Cost Aspects of Design Principles

Existing AUVs have excellent performance. They can navigate under water from 100 to 6,000 meters. Expensive devices are equipped to navigate faster and deeper under water. However, we need not high-end AUVs for surveillance of aquafarms because our operational depth is approximately 10 meters. Thus, we can make AUVs by using devices of low price. In addition, we can minimize the cost of the waterproof hull fabrication.

IV. THE DESIGN OF SYSTEMS

A. Overall Surrounding of the Aquafarm AUV System

AUVs collect data during their missions with respect to temperature, DO, PH. These data are delivered from the intelligent vehicle to the optimal buoy communication system. Buoy communication systems transfer these data to the underwater station (Figure 2). After data processing, the underwater station sends a message to fishermen. Thus, fishermen can cope with problems which are extraordinary low temperature or low dissolved oxygen through migration of aquafarms to another place.

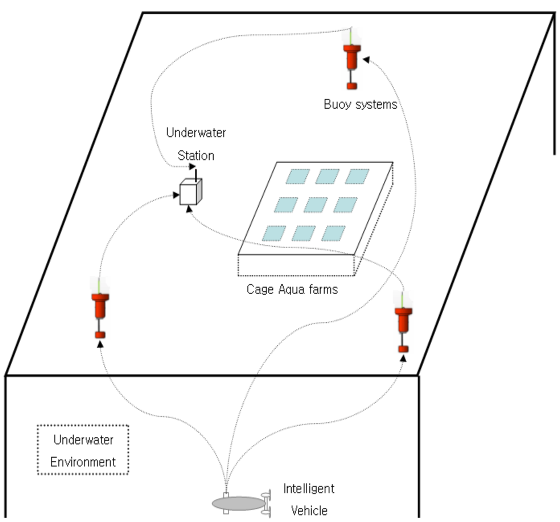

Figure 2. Overall Surrounding of Aquafarm AUVs

B. AUV/SCA systems

1) Design of AUVs

a) External shape of the hull

Generally, AUVs have several shapes sphere, cube or cylinder. According to their hull shape, they are affected differently by water. The best shape is a sphere to resist water pressure because water pushes equally from all sizes of the sphere (Figure 3).

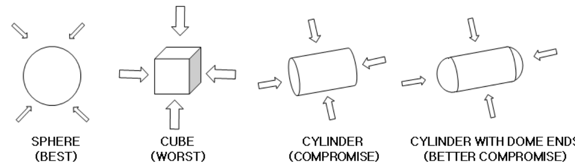

Figure 3. Pressure resistance according to shape of the hull

The streamlining hull helps decrease the drag and lowers the amount of power needed to move the vehicle at a certain speed [5].

b) Thrusters

We will equip twin thrusters with AUVs. However, they are less effective than one thruster because they need more energy sources to cruise under water. Nevertheless, we use twin thrusters because they promise the high quality of rotation. In case of our systems, we should move frequently to measure the water quality data. Thus, two thrusters are more efficient than one thruster regardless of the weak point.

c) Electrical devices

We need several sensors for the control of attitude and position of AUVs and the measurement of water quality around aquafarms. Pressure sensors are used to calculate depth along with water pressure. Sonar sensors are used to detect obstacle and topography. The magnetic compass is used to detect attitude of AUVs. These sensors are contained the electronics housing (Figure 4).

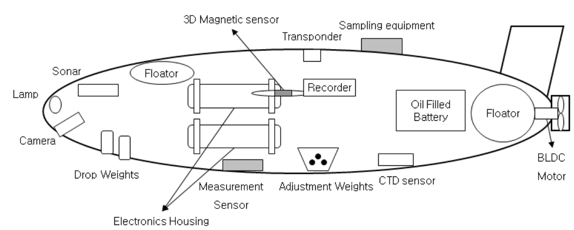

Figure 4. Internal Arrangements of Aquafarm AUVs

The microcontroller and On board PC are also contained in electronics housing. We describe the circuit of the pressure sensor whose signals are conditioned by power and operational amp (Figure 5).

a) Control of AUVs

There are several complex factors and nonlinear forces under water. Thus, it is difficult to design the accurate control model of AUVs. Their attitude information is processed by On-board PC and AUVs can correct their attitude based on information. They need control algorithms to process information. Advanced control systems have shown that autonomous diving and steering of unmanned underwater vehicles can be controlled by multivariable sliding mode control [6]. Recently, discrete-time

Quasi-sliding mode systems have been adapted for control of autonomous underwater vehicles [7]. However, these control methods have several difficulties to apply autonomous underwater vehicles. Hence, we utilize the classicalcontrol method which is PID controllers for the control of the attitude and position of the underwater vehicles.

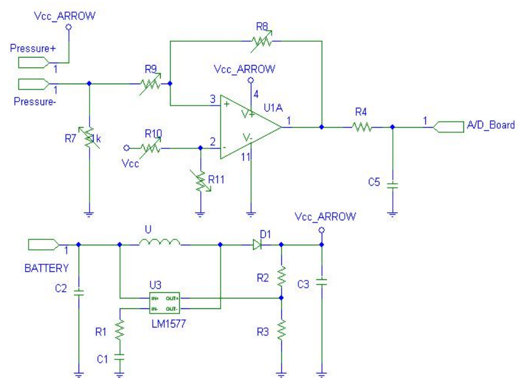

Figure 5. The circuit of the pressure sensor

2) Communication systems

a) Underwater Buoy Systems

We design underwater communication systems. We combine wireless communication systems with underwater communication systems. AUVs deliver acquired data to underwater buoy systems through ultrasound waves. These data are transferred to underwater stations (Figure 6).

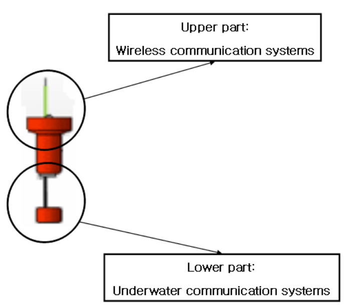

Figure 6. Underwater Buoy Systems for Communication

b) Underwater Stations

They receive data from underwater buoy systems. These data are analyzed by monitoring systems. After that, they transfer necessary information to fishermen by the mobile phone.

c) Underwater vehicles position tracking system

There are several methods to detect position of AUVs. According to the length of transponder we classify them Long Base Line (LBL), Short Base Line (SBL), Super Short Base Line (SSBL). Among them, Long Base Line (LBL) is a basic method to estimate AUV's position [8]. The mother ship calculates a relative position of AUVs comparing to three transponders. However, this method needs more equipment than others and it contains position error because of the movement of mother ship. Thus, we design the RLBL (Reverse Long Base Line) method to minimize errors and maximize efficiency. Position information is transferred by satellites to buoy systmes. Based on this information, each buoy system calculates relative position of AUVs. After that, this information is delivered to the underwater station and users know the current position of AUVs.

3) Software

a) AUVs Control program

The underwater vehicle control program directs the movement of AUVs. Users select the vehicle operation parameters such as speed and depth, and to control the data collection rate of sensors. Users give instructions to the Driving AUV Block and Sensing Block through TCP/IP protocol. The Driving Block control thrusters and a rudder. Sensors measure the attitude of AUV and water quality. These data are delivered to the Sensing Block through RS232 protocol. Water quality data are transferred to underwater station. The microcontroller gives instructions to the Driving AUV Block by using attitude data (Figure 7).

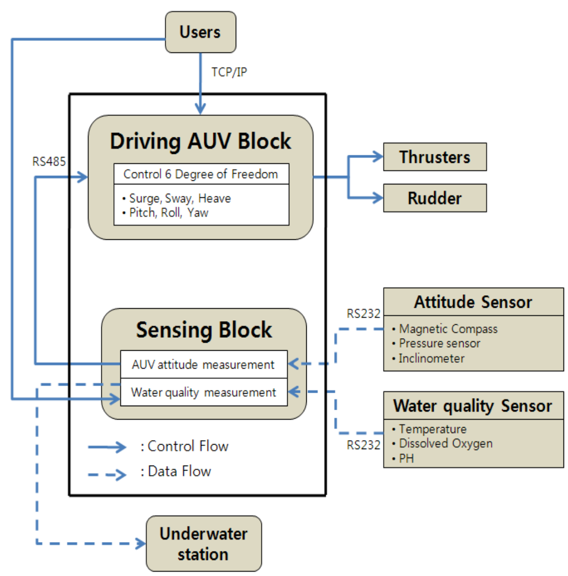

Figure 7. Architecture of the Control program

b) Simulation for the control of AUVs

The Simulation is important because it give users chances to test the performance of AUVs. It can reduce the gap between the desired output and actual output. For example, PDI controller is the classical control method. It is difficult to find optimal Proportional, Integral and Derivative gain.

Thus, we can acquire adequate gain values through the simulation of attitude and position of AUVs.

C. System development alternative & method

1) Electrical devices

Basically, we use existing electrical devices or modify devices for our purpose. For example, there are many kinds of pressure sensors. Among them, the pressure sensor should satisfy high accuracy and stability against noise. In addition, it should be operated at sealed underwater vehicles. Thus, the M5100 pressure sensor of the Schaevitz firm is useful for our systems. It can be worked all-metal sealed system and supports extended temperature range, 1% total error band and has compact outline [9].

Ahlborn firm has various sensors to measure humidity, water quality, air velocity, and temperature [10]. Among them, we select water analysis and temperature sensors. However, we have difficulties to equip sensors with AUVs because sensors are bar shape. Thus, we need reconstruction of sensors to embed them with underwater vehicles.

2) Hull design

In designing the hull, we should consider pressure resistance and drag force. They are determined by the hull shape sphere, cube or cylinder. The sphere shape has the best pressure resistance and the cylinder shape with dome ends has low drag force. We should consider the design along with their purpose. For instance, if you want low drag force, you should choose cylinder shape. On the other hand, you need more robust hull against water, you should select cube shape. Thus, we choose the streamlining hull shape because it has low drag force and moderate pressure resistance (Figure 8). We describe rough specifications of our AUVs (Table 1).

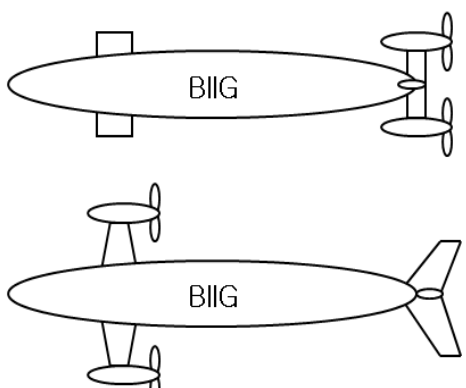

Figure 8. The hull design of AUVs

3) Thrusters

We select the Model 300 thruster of Technadyne firm [11]. To determine thrusters, we assume the value of CD (coefficient used in integrating forces and moments along hull due to local cross-flow), A (projection area of hull in xy-plane) according to the design.

From equation (3), we need 12kg bollard output to satisfy a maximum velocity 2m/s. The Model 300 thruster has 8.2kg forward thrust force and we will use two thrusters. Thus, we can accomplish a maximum velocity by using two thrusters.

TABLE I
SPECIFICATIONS OF OUR AUVS

Item	Specifications
Dimension	0.3(D)*1.5(L) m
Weight	25~30 kg
Maximum Speed	2 m/s
Operation Depth	0 ~ 10 m

m = meter, kg = kilogram, m/s = meter/second

$$Maximum\_Velocity = 2m/s \quad (1)$$

$$Thrust = Drag = \frac{1}{2}\rho \times C_D \times A \times V^2 = 118.2kg \quad (2)$$

$$Bollard\_output = Thrust / 9.81 = 12kg \quad (3)$$

$$Thrust\_Power = Thrust \times V = 236.3W \quad (4)$$

4) Energy sources

We use Lithium Polymer batteries which are rechargeable and convenient. They are more expensive than lead storage batteries. On the other hand, they guarantee both lower weight and increased run times. In addition, they can be protected from overcharging.

5) AUVs control program

We will develop control program by using C++ for the microcontroller. The C++ language possesses property of both the C language and the object oriented concept. The C language is adequate in the system programming Input-Output (I/O) control and object oriented concept help us more convenient. Object-Oriented Programming (OOP) provides reuse of code and minimizes time loss in debugging. Thus, the C++ language is more reasonable than C language.

6) Communication Systems

We divide underwater buoy systems into two parts. The upper device takes charge of wireless communication. It will be equipped with the Wireless Ethernet transceiver for data transmission to underwater stations. The lower device takes charge of underwater communication. It has been developing by ultrasound waves. We focus on the development of underwater communication systems. We should overcome some difficulties in developing systems. Scattering, diffraction and interference of waves exist under water. However, the operational depth of our system is up to 10 meters. We can minimize weak points of the wave under water. After considering that, the lower device will be equipped with Ultra sound receiver for data reception from AUVs.

D. Design of Intelligent navigation methods adapted Clonal Selection Algorithms (CSA)

1) Clonal Selection Algorithms (CSA)

The CSA is based on the artificial immune system. The

CSA is used in the field of optimization and pattern recognition. It establishes the idea that only those cells that recognize the antigens are selected to proliferate. The selected cells are subject to an affinity maturation process, which improves their affinity to the selective antigens [12].

2) Intelligent navigation

AUVs should move to the every target point to measure water quality and they occasionally move to the same tpoint. There exist many kinds of possible pathways to move around aquafarms. However, it is difficult to find the optimal pathway. Thus, we can find the best solution through CAS. First, generate possible pathways randomly from start point and calculate all affinities with respect to navigation time. Then, select pathways of high affinity. Make a lot of clones of them, and mutate. Recalculate affinities and select pathways of high affinity. Some randomly generated parameters are mixed together at this moment. These processes are iteratively performed until it converges. Finally, pathways are optimally selected by CSA. It will minimize time of navigation and the consumption of energy sources of AUVs.

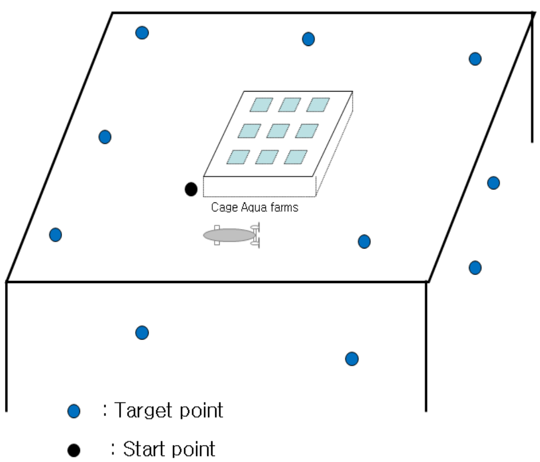

Figure 9. Intelligent navigation adapted CSA

V. Concluding Remarks

This paper has suggested autonomous underwater vehicle (AUV)-based surveillance systems for effective and broad-range monitoring missions of cage-based aquaculture system surroundings. Unlikely to the state-of-the-art AUVs, originally developed for military missions, the AUVs for aquafarms have their own engineering compromises and opportunities. It has also described artificial immune techniques for intelligent navigation and situation monitoring of the aquafarm AUVs.

Successful completion of this project will open new ways of aquafarm surveillance as well as provide cost-effective models of intelligent underwater vehicles for mission-specific applications.

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