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*Article*

# Development of a Towed Underwater Platform That Can Operate in a Marine Environment and Explore the Sea Bottom

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**Abstract:** Owing to environmental constraints, it is challenging to stably conduct various missions or surveys of the seabed for a prolonged period in the marine environment. To address this challenge, several devices and technologies are being developed. In this study, we aimed to develop an unmanned underwater vehicle (UUV)—specifically, a towed underwater platform—that can be loaded and unloaded via joint operation with an unmanned surface vehicle, which can be connected to a wired cable to obtain a stable power supply and high-speed communication. In addition, various sensors for detection are employed to investigate the marine environment and conduct missions. Furthermore, we operated the developed UUV in actual waters, reviewed the results, and examined its practical operability.

**Keywords:** towed underwater platform; unmanned underwater vehicle; depth control

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## 1. Introduction

For an extensive period from the early 2000s to recent years, increasingly small and light sensors with excellent performance have been developed and applied in marine environments alongside devices such as small-sized high-efficiency thrusters that can generate large amount of thrust [1]. The limitations associated with these sensors and devices also limit the research and exploration in marine environments [2,3], and various applied technologies have been developed worldwide to address this aspect [4–7].

Underwater platforms are being developed in various forms and can be classified into remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), depending on the existence of cables and the subject of operation. Remotely operated platforms connected via cables from floating ships can also be referred to as ROVs. In addition, the towed underwater platforms (TUPs) form a category of platforms without self-propulsion that are solely operated by the traction of the cable. A combination of the self-propelling force with the traction force of the cable can be applicable in various operating modes.

Unmanned surface vehicle (USV)–TUP interoperating technology is being developed to compensate for navigation errors in the underwater environment and to overcome battery problems and communication restrictions triggered by long-term operations [8]. Previous studies have considered the application of an efficient dynamic model-based control technology between the USVs and TUPs [9,10] and investigated the realization and control technology of cooperative operation via position measurement/adjustment between the USVs and TUPs [11].

In this study, we developed a TUP that is part of a combined USV–TUP system, which can be self-propelled in a marine environment with environmental restrictions and operated by cable traction. For the TUP production, the hardware, sensors, electric field, and software were configured, and the system performance was reviewed via a water tank test and operation in actual waters so as to examine its applicability [12].

The background for the formulation of this thesis is presented in Section 1, and in Section 2, the TUP system proposed in this study is categorized into hardware, sensors, electric field, and software. In Section 3, the attitude control algorithm is discussed, and the test performed in an aquarium environment using the developed algorithm before operations in an actual environment is presented. Subsequently, the test conducted in an actual sea area is described. In Section 4, the overall conclusion and future research directions of this study are discussed.

## 2. Towed Underwater Platform

A stable power supply and high-speed wired communication are crucial for long-term undersea exploration and investigation in marine environments [13]. Accordingly, a previous study attempted to utilize a towing cable manufactured in an underwater applicable form [14]. TUP development is divided into the development of hardware, sensors, electronics, and software. The details of each process are described in the following sections.

### 2.1. Hardware

The hardware design of the proposed TUP was realized considering functional factors. Figure 1 illustrates the overall system configuration and design results. In addition, the target specifications of the designed TUP are presented in Table 1. The TUP comprises six degrees of freedom that enable motions corresponding to roll, pitch, yaw, X, Y, and Z. Strain terminations are positioned at the front to connect the submersible cables for towing functions from the USV. To minimize interference with the movement of the cable during the vertical movement of the strain termination, a space for the cable to move is allocated inside the TUP. The outline is designed in a streamlined and flat shape, which is beneficial for maintaining posture in water. It was ultimately arranged to maintain posture and control the water depth using the front, rear, left, right, and vertical rudder, and six thrusters. The size and area of the rudder were selected via an analysis based on the design model to generate the drag force acting on the hull and the force required to reach the target water depth. The pressure-resistant box in which the electrical system is mounted is manufactured by reflecting the structure, such that it can withstand water pressure within a 5-bar environment (i.e., at a 50 m depth). The total buoyancy was designed and applied to operate with a positive buoyancy, and it was possible to adjust the weight of the thruster drum to balance it. Regarding the magnet sensor, it was designed to be detachable if necessary. In Figure 2, the actual production results are presented based on the designed contents.

**Table 1.** TUP Specifications.

| Item | Value |
|---|---|
| Size | 800 × 1800 × 320 mm |
| Weight (in air) | 150 kg |
| Search depth | 50 m |
| Search radius | 50 m |
| Operating depth | 50 m |
| Sensor types | 12 |

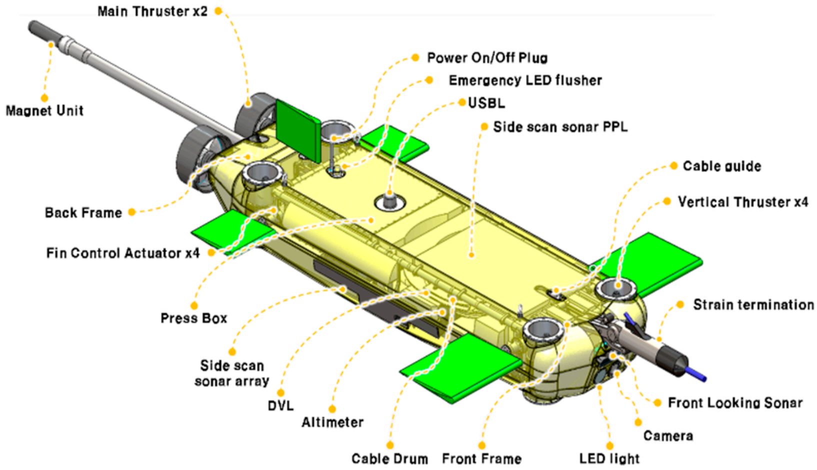


**Figure 1.** TUP design.

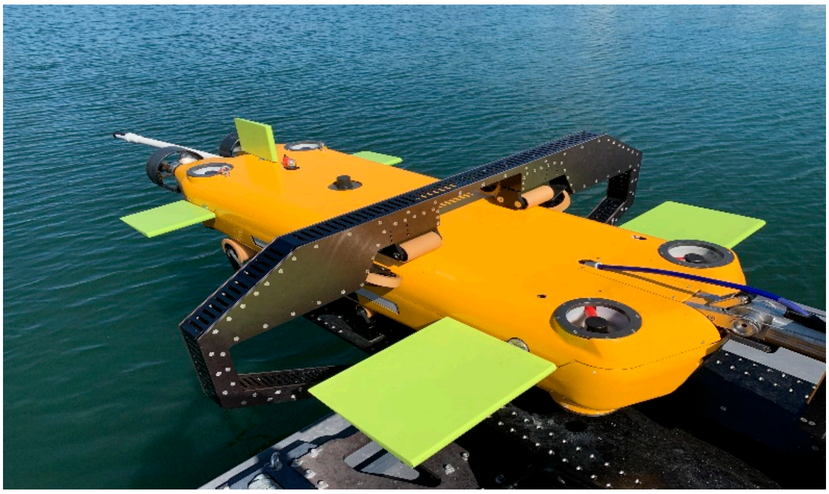


**Figure 2.** TUP implementation.

### *2.2. Sensors*

The sensors mounted on the TUP were configured and applied as presented in Table 2. In addition, the position arrangement of the sensor is illustrated in Figure 3. For its smooth operation, the sensors were arranged considering the location where interference was minimal, and no functional problem was identified in the operation of the sensors. Regarding the side scan sonar (SSS) equipment for the subsea topography survey, antennas were positioned on the left and right sides of the lower end of the TUP, and the control board had a dedicated pressure box in the TUP. The front looking sonar (FLS) was placed in the front to detect obstacles and objects identified in the front. To monitor the underwater environment, two sets of cameras and light-emitting diode (LED) lights were positioned in front and at the bottom, respectively. A magnet sensor was mounted on the rear to detect metals such as mines/torpedoes. To measure the speed of the designed TUP, the Doppler velocity logger (DVL) sensor was installed on the lower surface to calculate the relative speed according to the flow rate and position of the TUP. To measure the depth and altitude of the TUP, a depth sensor and an altimeter were mounted on the bottom of the TUP. A temperature sensor installed inside the depth sensor was adopted as a temperature sensor to measure the water temperature. To measure the position of the TUP underwater, an inertial measurement unit (IMU), attitude heading reference system (AHRS), and ultra-short baseline (USBL) transponder were placed on the upper surface of the pressure box. An LED flasher that could be operated in the case of an emergency was positioned at the top.

**Table 2.** TUP sensor specifications.

| Item | Model | Specification |
|---|---|---|
| SSS | Solstice Sidescan Sonar 8200 | 200-m scan range |
| FLS | Oculus M750d | 120 × 40-m scan range |
| USBL | Nano AvTrak6 OEM | 995-m depth rating |
| Magnetometer | OFG Self-Compensating Magnetometr System | 100 m, ±65 μT |
| DVL | DVL1000~300 m | 00.01 mm/s, 2–75 m altitude |
| Altimeter | Micron Echosounder | 0.1–120-m range |
| Depth | 4080BT010-FL1 | 0–10 bar |
| Temperature | 4080BT010-FL1 | −40–150 °C |
| IMU | Honeywell HG1700AG | Gyro 1 °/h, Acc 1 m·g |
| AHRS | 3DM-GX5-35 | Accelerometer: +/−8 g,<br>Gyroscope: 300 °/s,<br>Magnetometer: +/−8 Gauss |
| Camera | Ealge IPF 300 | 300-m depth rating, FHD |
| Light | Dragonfish T1K | 6000 K |

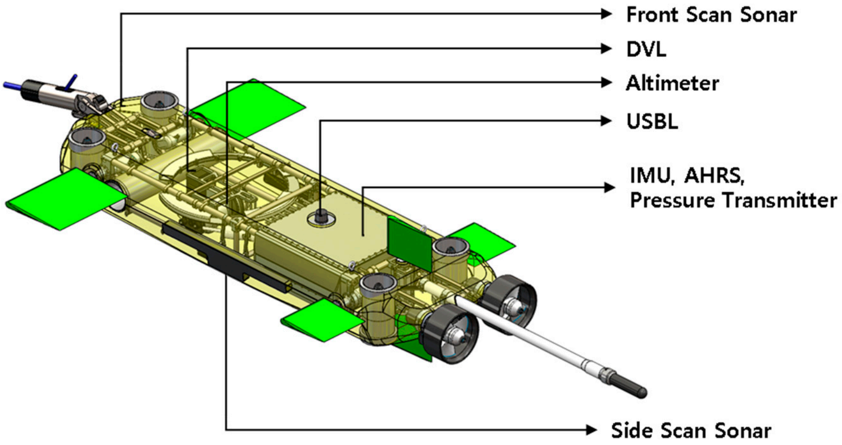


**Figure 3.** TUP sensor design.

### *2.3. Electronic Design*

The central processing unit mounted in the pressure-resistant box comprised dual communications based on optical communication. To stably transmit large-sized images of SSS at high speeds, optical communication equipment was applied. In addition, communication between the control module and the drive/sensor in the TUP was configured to transmit/receive data through two serial devices. For power management and efficient voltage distribution, the 110 V power supplied from the USV was configured to be supplied according to the voltage of each internal component by employing a DC–DC converter inside. For the driving module and sensor, connectors and receptacles that can be used underwater were applied. Figure 4 illustrates the overall electronic configuration of the TUP. The USV and junction box were connected by a towing cable; in addition, power supply and communication could be obtained from the USV. In the junction box, the converted power was supplied to the driving and sensor units according to each component. The sensor unit transmitted to and received data from the serial device via the RS232 communication method, and the driver unit had an interface configured with the RS485 communication method. The FLS, SSS, IP camera, and single board computer for the control algorithm and data processing were configured using the Ethernet method. A pressure box equipped with an electric system was manufactured and installed as presented in Figure 5.

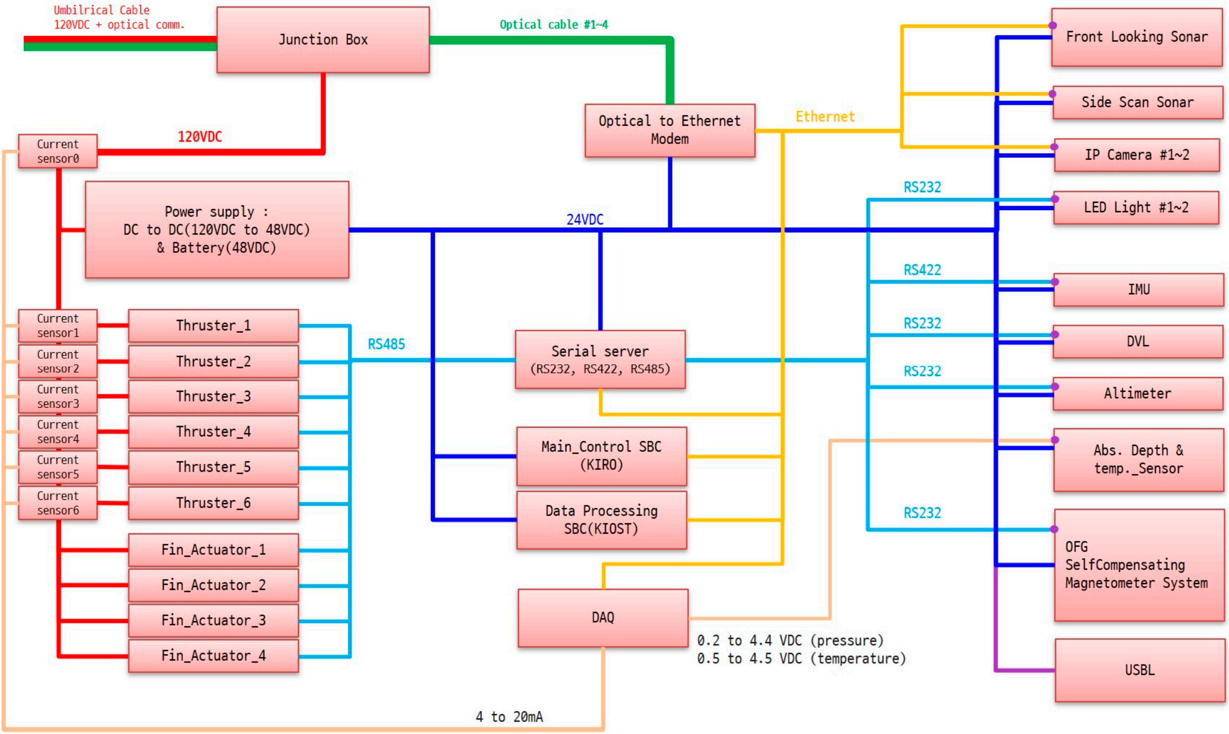


**Figure 4.** TUP electronic design.

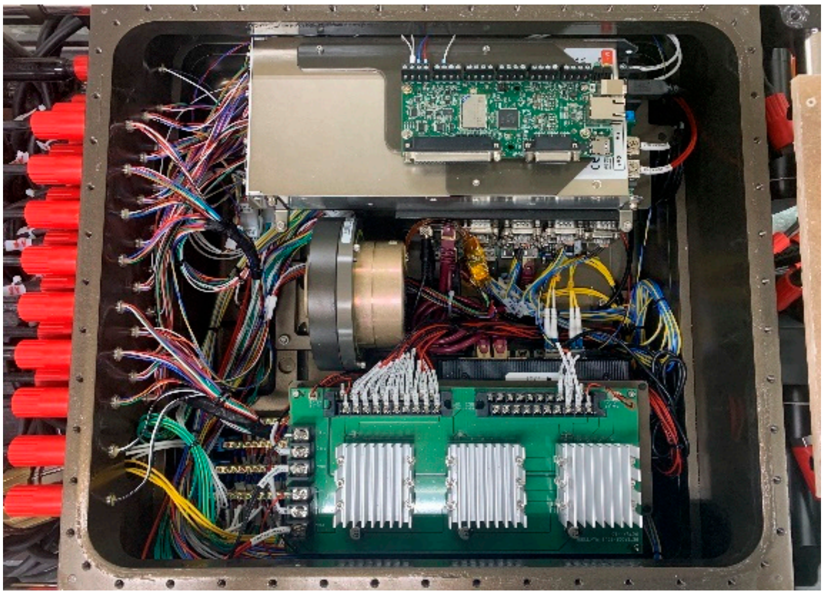


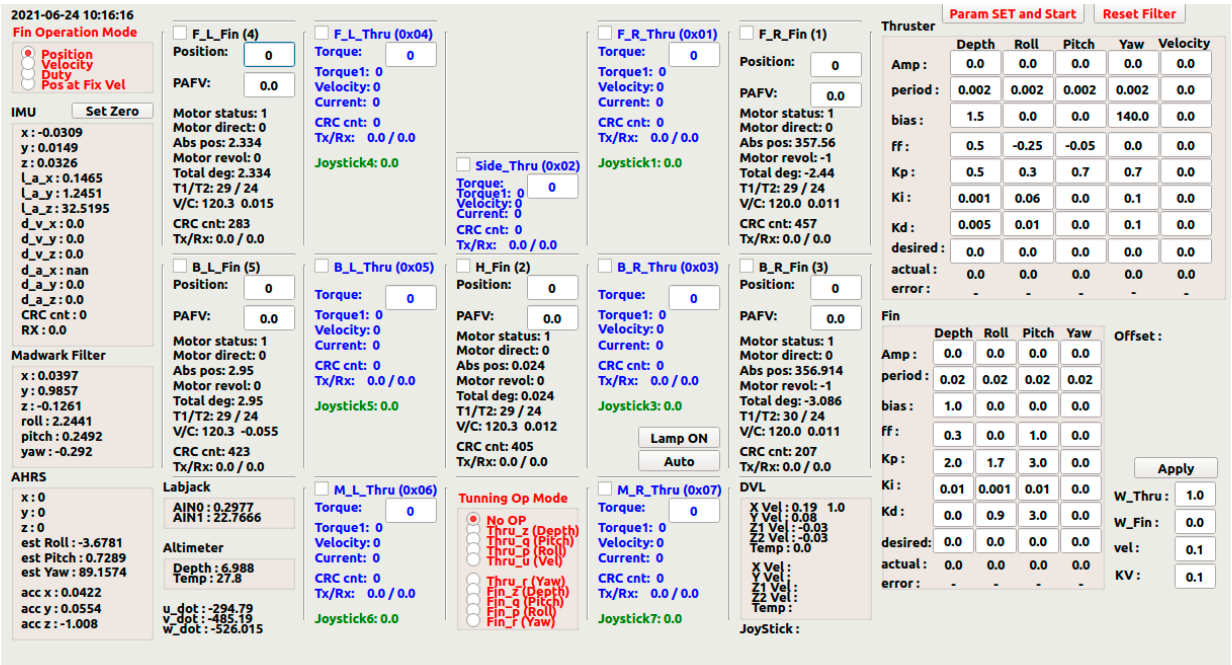
**Figure 5.** TUP pressure-resistant box.

### 2.4. Software

The main control software for the designed TUP was developed using the melodic version of the Robot Operating System (ROS) in the Ubuntu 18.04 OS environment. ROS is a trend that is being applied in various ways in the robotics and automation fields that enables virtual environment-based simulation and provides element packages for the convenience of development shared by several users.

Communication within the TUP is configured to enable the transmission and reception of data using a serial device. Two MOXA "NPort 5650-8-DT-J" products were adopted for serial devices. Each serial device supported eight serial ports, and a thruster, rudder, and sensor were connected to each port. Each port in the serial device was set to operate using the User Datagram Protocol (UDP). Topic, an ROS data transmission/reception method, provides a function to facilitate data transmission/reception between each propeller, rudder, sensor, and algorithm. The format of the transmission/reception message is the same as that of the data transmitted from the thruster, rudder, and sensor.

Figure 6 presents the software used to monitor the TUP status information and the sending/receiving messages between all nodes of the TUP. ROS provides application software such as rQT, rViz, and graphs for graph and data monitoring.



2021-06-24 10:16:16

Fin Operation Mode
● Position
○ Velocity
○ Duty
○ Pos at Fix Vel

IMU
x : -0.0309
y : 0.0149
z : 0.0326
l_a_x : 0.1465
l_a_y : 1.2451
l_a_z : 32.5195
d_v_x : 0.0
d_v_y : 0.0
d_v_z : 0.0
d_a_x : nan
d_a_y : 0.0
d_a_z : 0.0
CRC cnt : 0
RX : 0.0

Madwark Filter
x : 0.0397
y : 0.9857
z : -0.1261
roll : 2.2441
pitch : 0.2492
yaw : -0.292

AHRS
x : 0
y : 0
z : 0
est Roll : -3.6781
est Pitch : 0.7289
est Yaw : 89.1574
acc x : 0.0422
acc y : 0.0554
acc z : -1.008

☐ F_L_Fin (4)
Position: 0
PAFV: 0.0
Motor status: 1
Motor direct: 0
Abs pos: 2.334
Motor revol: 0
Total deg: 2.334
T1/T2: 29 / 24
V/C: 120.3 0.015
CRC cnt: 283
Tx/Rx: 0.0 / 0.0

☐ B_L_Fin (5)
Position: 0
PAFV: 0.0
Motor status: 1
Motor direct: 0
Abs pos: 2.95
Motor revol: 0
Total deg: 2.95
T1/T2: 29 / 24
V/C: 120.3 -0.055
CRC cnt: 423
Tx/Rx: 0.0 / 0.0

Labjack
AIN0 : 0.2977
AIN1 : 22.7666

Altimeter
Depth : 6.988
Temp : 27.8

u_dot : -294.79
v_dot : -485.19
w_dot : -526.015

☐ F_L_Thru (0x04)
Torque: 0
Torque1: 0
Velocity: 0
Current: 0
CRC cnt: 0
Tx/Rx: 0.0 / 0.0
Joystick4: 0.0

☐ B_L_Thru (0x05)
Torque: 0
Torque1: 0
Velocity: 0
Current: 0
CRC cnt: 0
Tx/Rx: 0.0 / 0.0
Joystick5: 0.0

☐ M_L_Thru (0x06)
Torque: 0
Torque1: 0
Velocity: 0
Current: 0
CRC cnt: 0
Tx/Rx: 0.0 / 0.0
Joystick6: 0.0

☐ Side_Thru (0x02)
Torque: 0
Torque1: 0
Velocity: 0
Current: 0
CRC cnt: 0
Tx/Rx: 0.0 / 0.0

☐ H_Fin (2)
Position: 0
PAFV: 0.0
Motor status: 1
Motor direct: 0
Abs pos: 0.024
Motor revol: 0
Total deg: 0.024
T1/T2: 29 / 24
V/C: 120.3 0.012
CRC cnt: 405
Tx/Rx: 0.0 / 0.0

Tunning Op Mode
● No OP
○ Thru_z (Depth)
○ Thru_q (Pitch)
○ Thru_p (Roll)
○ Thru_u (Vel)
○ Thru_r (Yaw)
○ Fin_z (Depth)
○ Fin_q (Pitch)
○ Fin_p (Roll)
○ Fin_r (Yaw)

☐ F_R_Thru (0x01)
Torque: 0
Torque1: 0
Velocity: 0
Current: 0
CRC cnt: 0
Tx/Rx: 0.0 / 0.0
Joystick1: 0.0

☐ B_R_Thru (0x03)
Torque: 0
Torque1: 0
Velocity: 0
Current: 0
CRC cnt: 0
Tx/Rx: 0.0 / 0.0
Joystick3: 0.0

☐ M_R_Thru (0x07)
Torque: 0
Torque1: 0
Velocity: 0
Current: 0
CRC cnt: 0
Tx/Rx: 0.0 / 0.0
Joystick7: 0.0

☐ F_R_Fin (1)
Position: 0
PAFV: 0.0
Motor status: 1
Motor direct: 0
Abs pos: 357.56
Motor revol: -1
Total deg: -2.44
T1/T2: 29 / 24
V/C: 120.0 0.011
CRC cnt: 457
Tx/Rx: 0.0 / 0.0

☐ B_R_Fin (3)
Position: 0
PAFV: 0.0
Motor status: 1
Motor direct: 0
Abs pos: 356.914
Motor revol: -1
Total deg: -3.086
T1/T2: 30 / 24
V/C: 120.0 0.011
CRC cnt: 207
Tx/Rx: 0.0 / 0.0

DVL
X Vel : 0.19 1.0
Y Vel : 0.08
Z1 Vel : -0.03
Z2 Vel : -0.03
Temp : 0.0
X Vel :
Y Vel :
Z1 Vel :
Z2 Vel :
Temp :

JoyStick :

Thruster

| | Depth | Roll | Pitch | Yaw | Velocity |
|---|---|---|---|---|---|
| Amp : | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| period : | 0.002 | 0.002 | 0.002 | 0.002 | 0.0 |
| bias : | 1.5 | 0.0 | 0.0 | 140.0 | 0.0 |
| ff : | 0.5 | -0.25 | -0.05 | 0.0 | 0.0 |
| Kp : | 0.5 | 0.3 | 0.7 | 0.7 | 0.0 |
| Ki : | 0.001 | 0.06 | 0.0 | 0.1 | 0.0 |
| Kd : | 0.005 | 0.01 | 0.0 | 0.1 | 0.0 |
| desired : | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| actual : | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| error : | - | - | - | - | - |

Fin

| | Depth | Roll | Pitch | Yaw |
|---|---|---|---|---|
| Amp : | 0.0 | 0.0 | 0.0 | 0.0 |
| period : | 0.02 | 0.02 | 0.02 | 0.02 |
| bias : | 1.0 | 0.0 | 0.0 | 0.0 |
| ff : | 0.3 | 0.0 | 1.0 | 0.0 |
| Kp : | 2.0 | 1.7 | 3.0 | 0.0 |
| Ki : | 0.01 | 0.001 | 0.01 | 0.0 |
| Kd : | 0.0 | 0.9 | 3.0 | 0.0 |
| desired: | 0.0 | 0.0 | 0.0 | 0.0 |
| actual : | 0.0 | 0.0 | 0.0 | 0.0 |
| error : | - | - | - | - |

Offset :
W_Thru : 1.0
W_Fin : 0.0
vel : 0.1
KV : 0.1

**Figure 6.** TUP monitoring software.

The user interface (UI) was configured as illustrated in Figure 6 to output and check messages sent and received through the driving module and sensor in the TUP. Data were transmitted and received at a set period for each node, and the UI software was developed to receive, print, and check these data. Regarding the control node for maintaining the TUP posture and controlling the depth, it was necessary to tune the proportional integral derivative (PID) gain parameter. Accordingly, each parameter was input and applied to the control loop. A function was also added to ease the PID gain-tuning process.

## 3. Experiment

### *3.1. Control*

To operate the TUP in water, a control algorithm was developed by appropriately combining the thrust and drag of the thruster and rudder, respectively. After launching in a launch and recovery system (LARS), a high weight was assigned to the thruster to maintain a fast posture in the low-speed section during the initial operation. In addition, a relatively high weight was applied to the rudder during towing. Information obtained from sensors such as the IMU, DVL, depth, and altimeter mounted on the TUP was adopted as the current status information.

A PID controller was used to follow the control input information for the roll, pitch, and depth of the TUP, and the parameters applied to the controller were empirically input and derived, such that it could be followed using a graph based on the control input versus output information. Figure 7 shows the block diagram of the entire control structure.

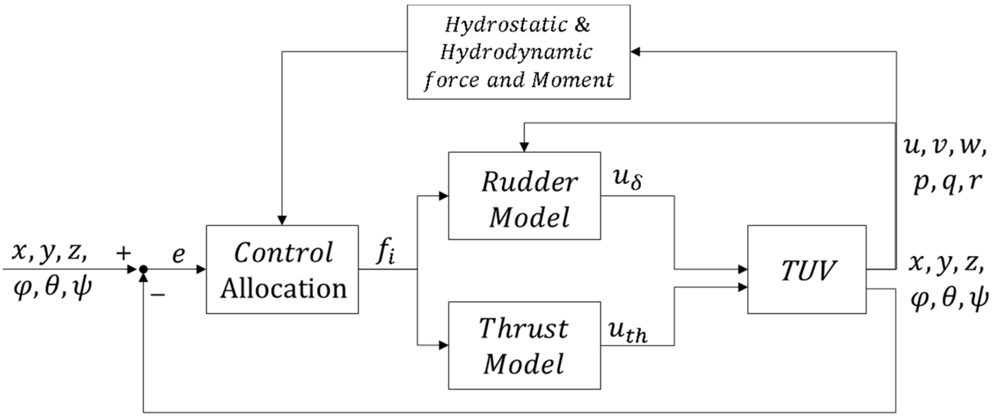


**Figure 7.** TUP control design.

### 3.2. Water Tank Test

The manufactured TUP was subjected to a functional verification test in a water tank environment before being operated in an actual marine environment. The objective of this study was to check whether the desired posture was maintained in the water according to the arrangement of the thrusters and fins, and to verify whether any problem emerged in the operation of the algorithm developed for the proper distribution of the propulsion force. As illustrated in Figure 8, the test was conducted in an engineering tank at the Underwater Robot Complex Demonstration Center located in Buk-gu, Pohang-si, Gyeongsangbuk-do. Figure 9 demonstrates that the posture of the TUP was maintained stably at a low speed of 1 knot.

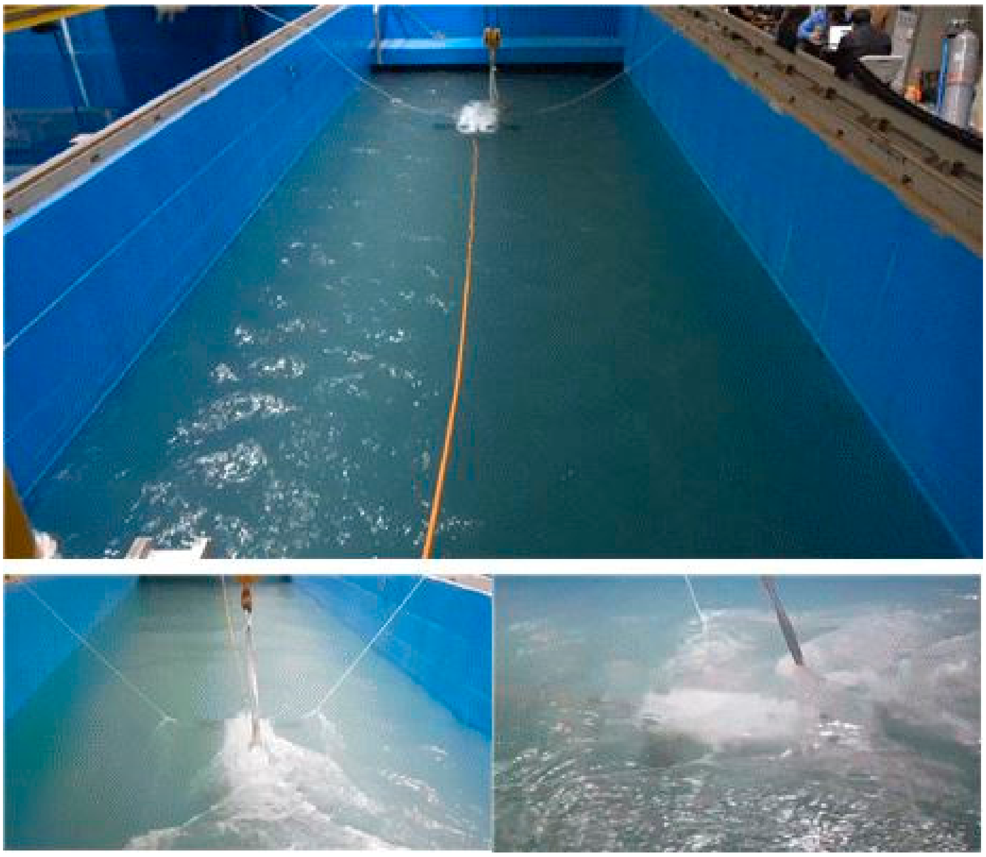
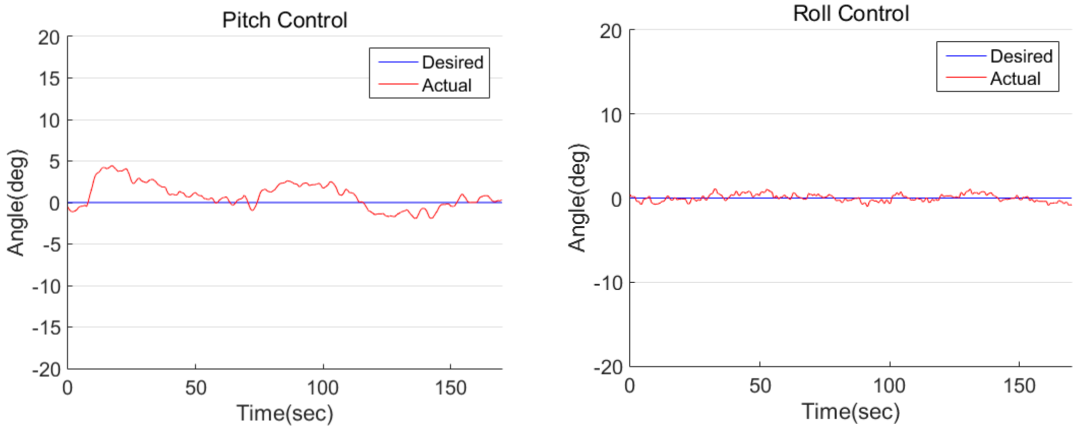
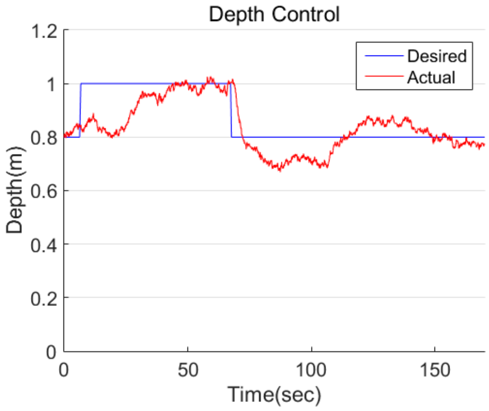


**Figure 8.** Experimental environment in water tank.



(**a**) Pitch control Result (**b**) Roll control Result



(**c**) Depth control result

**Figure 9.** TUP experiment result in water tank (1 knot).

### 3.3. Actual Experiment Environment

Because it is difficult to operate the TUP alone, the operation scenario of the entire system was defined such that it could be maneuvered underwater by combining it with the USV and LARS systems. Figure 10 illustrates the operation concept of the TUP for the actual sea area test.

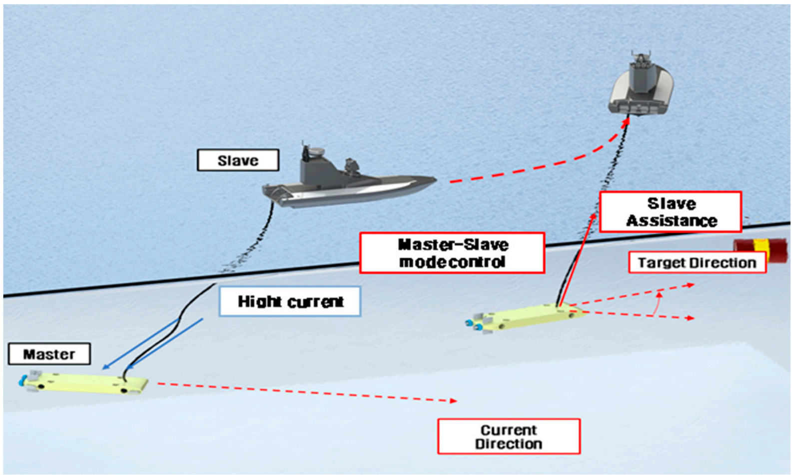
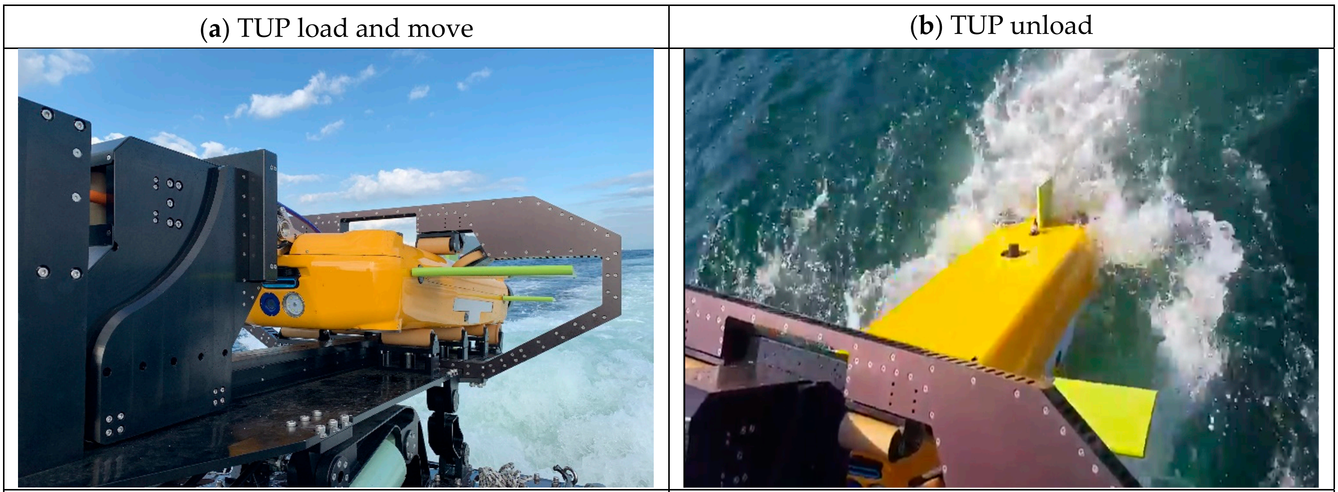
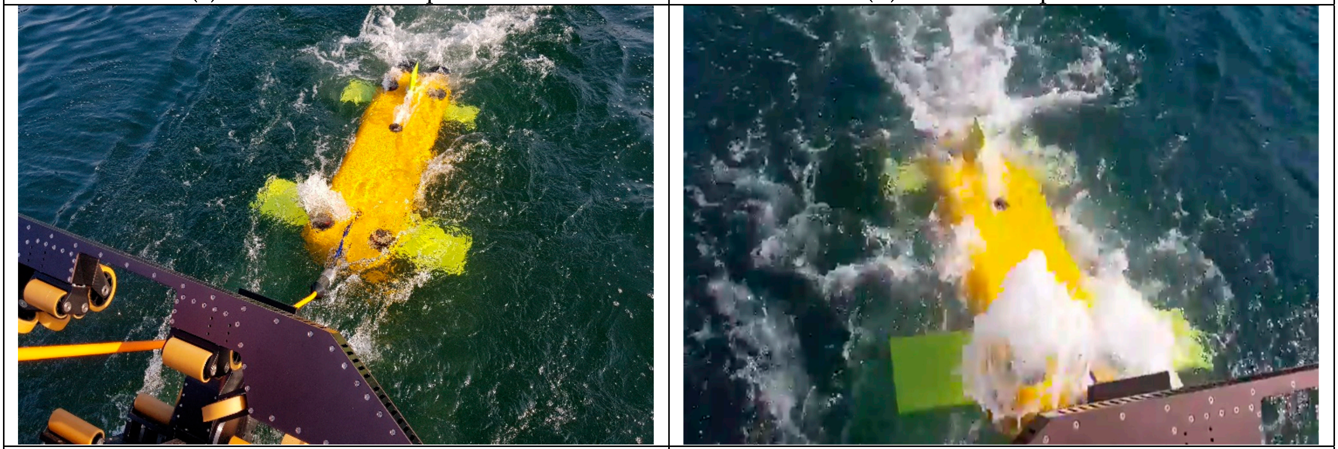


**Figure 10.** TUP operation concept.

After moving to the test area using the USV, the TUP was launched at the expected point to prepare for the mission. Before arriving at the target point, the cable length of the LARS was adjusted to the target depth beforehand to maintain the water depth and position of the TUP. The target position and depth were maintained, while the SSS information was obtained on the exploration area and object to be detected.

Figure 11 presents the results obtained from interworking with the USV and LARS systems when conducting missions from the start of the TUP operation.


(**a**) TUP load and move (**b**) TUP unload


(**c**) TUP unload complete (**d**) TUP start operation

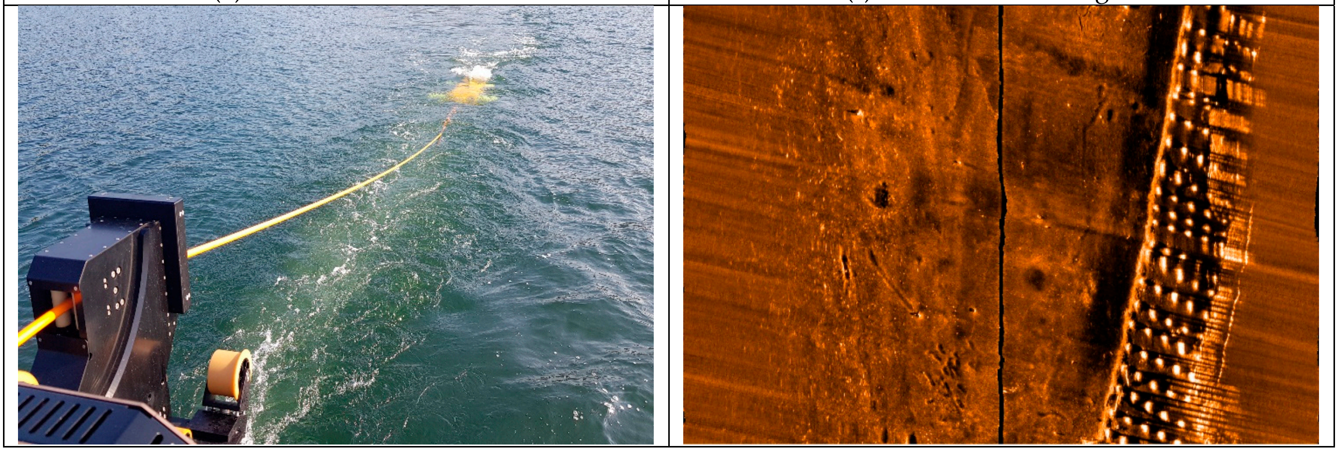
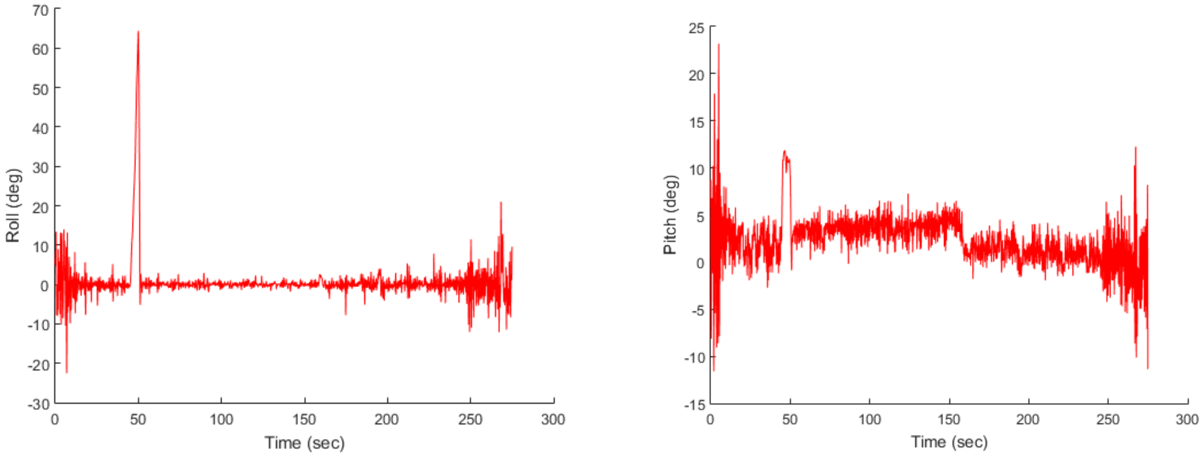

(**e**) TUP mission start (**f**) Seafloor Scan using SSS

**Figure 11.** TUP operation sequence.

The designed TUP was mounted on the USV by LARS and moved to the target point, as illustrated in Figure 11a. LARS is a system designed to automatically retrieve the TUP and perform the tug control of the TUP using the tension of the cable. When it arrives at the target point, the launch command is transmitted from the upper control unit to the LARS, and the launching process is performed according to the LARS control sequence, as shown in Figure 11b. In LARS, the mode is defined for each cable length, and when the cable length corresponding to the launch is derived, the launch is completed, as illustrated in Figure 11c. When the launch complete status is reached, LARS sends a launch completion command to the TUP, and the TUP receives this command and executes the attitude control mode, and the operation commences, as illustrated in Figure 11d. At the target point, the water depth is measured using an altimeter mounted on the TUP. The target operating depth is defined considering the water depth, and the depth control commences, as shown in Figure 11e. When arriving at the target point and depth, the SSS information is checked, as illustrated in Figure 11f.

This experiment was conducted on 7 October 2021, off the coast of the Jangmok Port, Geoje, Gyeongnam. The weather was clear and the wind was moving in the northwest——north (morning)/south–southwest (pm) direction, the wind speed was 3–6 m/s, and the wave height determined at a position where observation was performed at 0.5 m. By setting the target depth of the TUP to 20 m, it was confirmed that maintaining the water depth is possible. As illustrated in Figures 12 and 13, the error for the roll posture occurs up to a maximum/minimum of 64.3° to −22.5°, with an average of 0.67°. The error for the pitch posture occurs up to the maximum/minimum of 23.1 to −11.5°, with an average of 2.29°.



(**a**) Roll control result (**b**) Pitch control result

**Figure 12.** TUP roll and pitch control results.

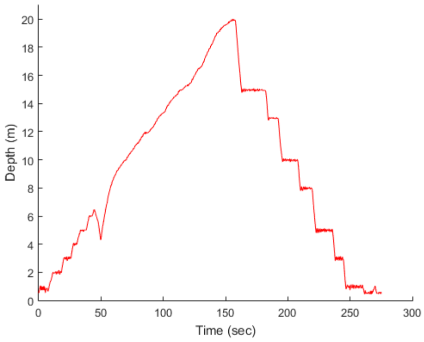


**Figure 13.** TUP depth control results.

## 4. Conclusions

In this study, we developed an ROV that can be operated by its own driving force and a TUP as part of a USV–TUP interoperating system that can be self-propelled in marine environments with environmental restrictions and operated via cable traction. Hardware, sensors, electric field, and software were reviewed for the production of the TUP. To examine the operability of the developed system, we reviewed the performance of the test in a water tank environment and performed posture maintenance in actual water. It was verified that posture maintenance is normally achieved at the target depth and that the seafloor topographic information can then be obtained.

In future investigations, we intend to conduct research to maintain and control posture in an environment with strong currents and to increase its utility by conducting research to enable operation in master–slave and slave–master modes in the USV–TUP system.

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