Development of an Intelligent Autonomous Underwater Vehicle, P-SURO

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***Abstract*-P-SURO is a prototype autonomous underwater vehicle (AUV), which is under development as a test-bed for developing underwater technologies such as underwater vision, underwater navigation, and guidance. This vehicle is a hovering type with four thrusters mounted to steer its 6DOF underwater motion, a color camera is mounted at the vehicle's nose for underwater vision, and an AHRS combined with one depth sensor and three range sonars construct an inertial navigation system. In this paper, we report the details of constructions of the vehicle system, and its three core modules - vision module, navigation module, and control module.**

I. INTRODUCTION

According to their external characteristics, AUVs can be classified into two types: torpedo type and hovering type. Most of the commercial AUVs developed so far, such as REMUS AUV [1] and HUGIN AUV [2], are all torpedo type. These type of vehicles have good straight line performance due to their streamlined shape [3], and therefore, suitable for rapid surveillance for large area of open space. On the contrary, due to high level of slow speed maneuverability, hovering type vehicles are often used for accurate underwater explorations as well as maintenance of complicate underwater structures. To fulfill their underwater missions, hovering vehicles may need various basis functions such as accurate underwater localization, obstacle avoidance, and flexible maneuverability, and so on. On the other hand, because of limited underwater communications, recently, how to improve the autonomy of an AUV has become one of most intense research area in the underwater vehicle community.

In April 2009, the Pohang Institute of Intelligent Robotics (PIRO) launched a project developing some basis underwater technologies such as underwater vision, underwater navigation, and vehicle guidance. As a test-bed vehicle, hovering type P-SURO (PIRO-Smart Underwater RObot) AUV, see Fig. 1, has four thrusters and takes only two kinds of motion in the water: ascend/descend in the vertical plane with two vertical thrusters and 3DOF motion in the horizontal plane using two horizontal thrusters[1]. There are three communication channels provided for the vehicle to contact with surface unit. On the surface, the vehicle communicates with surface unit through RF channel while an acoustic channel is used in the water. For the convenience of early development, underwater Ethernet cable can be connected to the vehicle. A color camera mounted at the nose provides underwater vision, from which path planning and obstacle avoidance algorithms will be derived. Also, there are three range sonars (forward, backward, and downward) assisting vehicle's local navigation as well as obstacle avoidance. An AHRS combined with depth sensor consists of inertial navigation system, while 1-axis gyro and accelerometer provide motion information to guide the vehicle's 3DOF motion in the horizontal plane.

In this paper, we report the details of the development, especially on the construction of three core modules - vision, navigation, and control modules. The remainder of this paper is organized as follows. The vehicle's general specifications and hardware configurations are presented in Section II, and in Section III, we discuss the details of constructions for three core modules. Some basin test results are also presented in Section IV. And a brief conclusion and some future works are discussed in Section V.

Fig. 1. Perspective view of P-SURO.

II. VEHICLE OVERVIEW

A. General Specifications

As aforementioned, P-SURO AUV is developed for being a test-bed for development of various underwater technologies, such as underwater vision, navigation, and guidance. On the other hand, most of experimental tests will be performed in an engineering basin in the PIRO, which dimension is about 12(L)×8(W)×6(D)m. Under these considerations, the vehicle is required to be small size with easiness of various algorithm tests. Designed specifications of the vehicle are as Table. 1.

[1] In the horizontal plane, the vehicle is always controlled to keep zero pitch angle using two vertical thrusters.

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Table. 1. General specifications of P-SURO.

Item	Specifications
Depth rating	100m
Weight	53kg
Dimension	1.05(L)×0.5(W)×0.3(H)m
Max. speed	FW: 2.5knot; BW, UP/DW: 1.5knot
Battery system	1.1kW, Lithium Ion
Duration	2.5hrs
Thrust system	4×BTD156(SeaBotix Inc.)
Payload	≤4kg

B. Mechanical System

For the convenience of maintenance, and also under the stability consideration, the battery system is separated from electronic system and set into the battery pressure hull alone, see Fig. 2. Remained electronic systems including inertial sensors, RF and acoustic modems are all mounted in the electronics pressure hull. Main frame is made of aluminum (AL-6061) while fixed parts for camera, range sonars are made of POM. To increase the hydrodynamic mobility in the horizontal plane, the open frame of vehicle is closed in a two-piece of FRP (Fiber-Reinforced Plastic) shell.

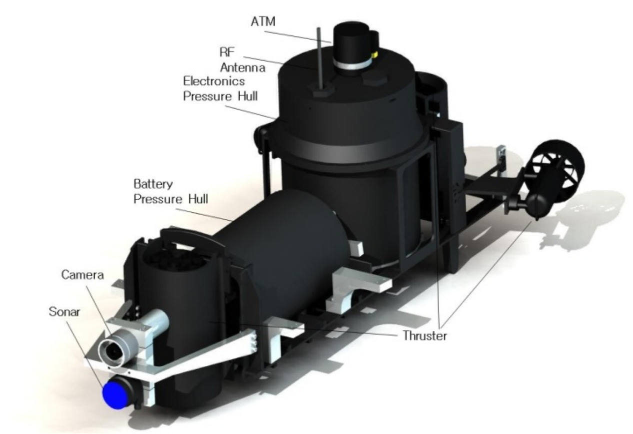

Fig. 2. Mechanical arrangement for P-SURO.

C. Computer System

Computer system for P-SURO AUV can be divided into three modules: vision, navigation and control modules. Each of them consists of PC104 type SBC (Single Board Computer), which provides 4 RS232 channels plus 4 USB channels (see Fig. 3). And serial communication channels (RS232 and RS422/485) can be easily extended using proper USB to Serial converters. Moreover, PC104 type PCM3718HG board is applied for the convenience of analog input and digital I/O interface. In addition, there are two peripheral boards designed to include DC/DC converter system, magnetic switch circuit, leakage detection circuit, and so on.

Windows Embedded CE 6.0 is ported in the navigation and control modules, while Windows 2000 OS is used in the vision module for the convenience of developing underwater vision algorithm. Compare to the commercial RTOS such as RT Linux, VxWorks, and QNX, WinCE has price competitiveness though its real-time performance may be lower than others. Each of navigation and control modules consists of PCM3353 SBC with AMD GeodeTM LX800 CPU, according to which we developed corresponding WinCE 6.0 BSP (Board Support Package).

On-board computer system communicates with surface unit through two channels. On the surface, they exchange data through RF channel, and maintain the data link in the water using ATM (Acoustic Telemetry Modem). For this ATM, its maximum data rate is 1200bits/s. For this reason, an additional TCP/IP channel is added on the vehicle for the convenience of early development. Three modules combined with surface unit consist of star-topology network with the control module at the center point.

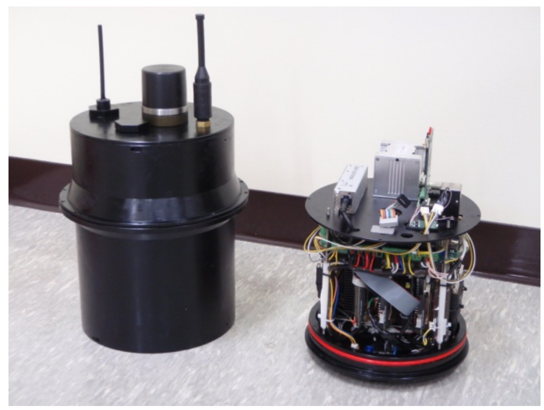

Fig. 3. Electronic system and its pressure hull.

D. Sensor System

A video color camera mounted at the vehicle nose provides vision image from which we can extract the vehicle's local positioning and attitude information. The camera also provides information for pattern-recognition based obstacle avoidance process.

As aforementioned, P-SURO is a test-bed for developing various underwater core technologies and mainly operated in an engineering basin in the PIRO. Under this consideration, we construct a relatively simple inertial navigation system which consists of one AHRS sensor, one depth sensor, and three range sonars (forward, backward, and downward). These sonar array can provide accurate local positioning information in the case where the vehicle takes specific attitude.

Throughout its underwater mission, P-SURO always takes only two kinds of motions: One is descent/ascent motion in the vertical plane, and the other one is 3DOF maneuvering in the horizontal plane. However, there are only two thrusters can be used to steer the vehicle's horizontal motion (see Fig. 2). Therefore, to speak strictly, P-SURO is an underactuated system in the horizontal plane. How to construct the stable nonlinear controller for this kind of underactuated system is one of most interesting research topics in the control community [4]. For the control purpose, there are two sensors mounted in the electronics pressure hull. 1-axis gyro provides the vehicle's yaw angular rate, while 1-axis accelerometer provides forward acceleration measurement.

Table. 2. Sensor system for P-SURO.

Sensor Model (Maker)	Specifications
Super SeaSpy (Tritech)	- >480 TV lines - 1/3" Interline Transfer CCD - Composite output
Micron Echo Sounder (Tritech)	- Operating frequency: 500KHz - Beamwidth: 6^o conical - Operating range: 50m
AHRS (Innalabs)	- Update rate: 1-100Hz - Heading accuracy: 1.0 deg - Attitude accuracy: <0.4 deg
CVG25 (Innalabs)	- Measurement range: ±200deg/sec - Bandwidth: 50Hz - Bias stability: 1.5deg/hr
AL-15M2.5 (Innalabs)	- Input range: ±2.5g - Bias: <4mg - Bandwidth: 300Hz
PR-36XW (Keller)	- Depth rating: 100m - Accuracy: 0.1% FS - Output rate: 100Hz
UWM2000H (LinkQuest)	- Payload data rate: 300-1200bits/sec - Working range: 1200m - Bandwidth: 210deg (omni-directional)
LinkWiser[TM]-HP400 (Cellution)	- Half-duplex - Operating frequency: 400-470MHz - Air data rate: 4.8kbps

III. Development of Core Modules

A. Underwater Vision Module

The main purpose of underwater vision system for P-SURO is to provide localization information for the vehicle's path planning task. Robot vision has become one of most hot issue in the past decades. So far, various patterns and corresponding recognition methods have been developed [5]. One of these patterns is shown in Fig. 4, which consists of two rectangles and two sets of four dots with the same cross-ratio. The large number in the center is used for distinguish the pattern.

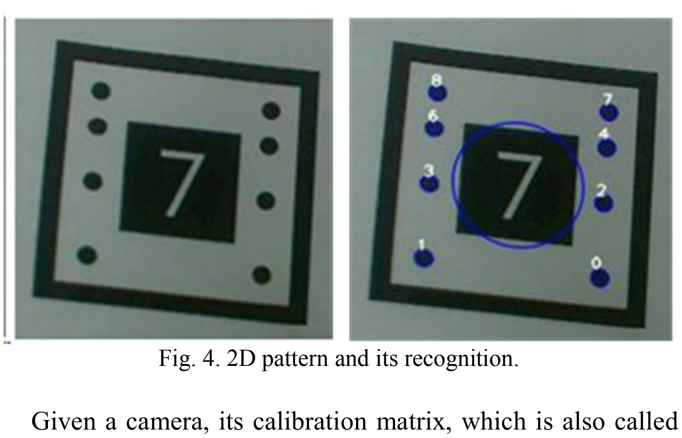

Fig. 4. 2D pattern and its recognition.

Given a camera, its calibration matrix, which is also called as perspective projection matrix, is defined as

$$P = A \cdot Rt, \tag{1}$$

where A is camera intrinsic parameter, which is always can be pre-determined for a given camera, and Rt denotes the camera external parameter. For the calibration matrix P, it can be determined by recognizing certain specifically designed patterns such as in Fig. 4. Consequently, we can get the vehicle's pose and translation information Rt using (1).

B. Underwater Navigation Module

P-SURO has an AHRS inertial sensor and one depth sensor consisting the strapdown inertial navigation system (SDINS) [6],[7]. AHRS provides angular rate and acceleration measurements as well as the roll, pitch and yaw measurements of the vehicle, all in the earth-fixed frame. 1-axis of gyro and accelerometer are also mounted for the vehicle's horizontal navigation.

To prevent the accumulation of inertial navigation error due to the inherent bias terms in the gyro and accelerometer measurements, there are two kinds of aiding method designed for P-SURO. One is range-aiding using three range sonars, each of them mounted at forward, backward, and downward. The accuracy of these sonars is $\pm 5mm$. Another aiding method is using underwater vision system. As aforementioned, P-SURO is a hovering type vehicle, and one of its main applications is maintenance of underwater structures. In this case, through recognition of pre-designed specific patterns, we can get precise localization information (position and attitude) which provides useful aids to the inertial navigation system. Block diagram of constructed navigation system for P-SURO is depicted as in Fig. 6.

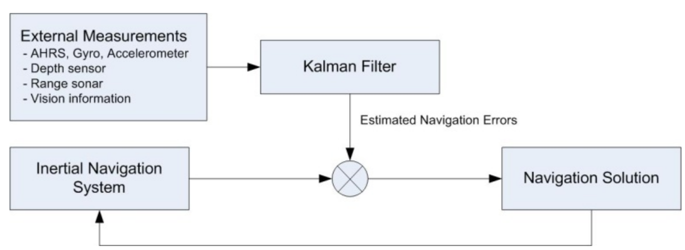

Fig. 5. Block diagram of navigation system with range sonar and vision aiding.

C. Control Module

As aforementioned, the maneuvering of P-SURO consists of series of vertical descent, ascent and 3DOF horizontal motion. In the horizontal plane, the vehicle's kinematics and dynamics can be expressed as following [4],[8],[9]

$$\begin{bmatrix}\dot{x}\\ \dot{y}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}cos\psi & -sin\psi & 0\\ sin\psi & cos\psi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}u\\ v\\ r\end{bmatrix},$$
$$\begin{bmatrix}\dot{u}\\ \dot{v}\\ \dot{r}\end{bmatrix} = \begin{bmatrix}f_u(u,v,r)\\ f_v(u,v,r)\\ f_r(u,v,r)\end{bmatrix} + \begin{bmatrix}b_l & b_r\\ 0 & 0\\ c_l & c_r\end{bmatrix}\begin{bmatrix}\tau_l\\ \tau_r\end{bmatrix} + \begin{bmatrix}d_u\\ d_v\\ d_r\end{bmatrix}, \tag{2}$$

where (x, y) is the coordinate of the vehicle and ψ is the yaw angle in the earth-fixed frame; u and v denote the velocities in the surge and sway direction, and r is angular rate in yaw direction, each in the body-fixed frame; f_u, f_v, and f_r denote the nonlinear dynamics (for details, refer to [9]); τ_l and τ_r are control inputs of thrusters with b_l, b_r, c_l, and c_r control gains; d_u, d_v, and d_r are uncertainty terms including modeling errors, disturbances, measurement noise, etc.

Since the sway force is unavailable, the most difficulty in the tracking control of this kind of system is how to properly handle the sway dynamics in its tracking phase. Recently, tracking of underactuated system has become one of most intense research area in the control community, and a number of research works have been done do far (see [4],[10] and references therein). However, research for general form of tracking scheme is still under way.

One of the main purposes of P-SURO is to develop a test-bed vehicle for demonstration and upgrade of the previous research works ([4], [10] and references therein) through practical applications.

IV. Vehicle Demonstration through Basin Tests

A. Ballasting Test

At first assembling, P-SURO was weighed at 47.5kg in the air and 14.2kg in the water. To maintain zero weight and keep balance in the water, we manufactured buoyancy material (a kind of urethane foam with 0.18 specific gravity) and added total of 2.75kg lead ingots additionally. After all, the weight of P-SURO in the air is 53kg and the maximum payload is about 4kg.

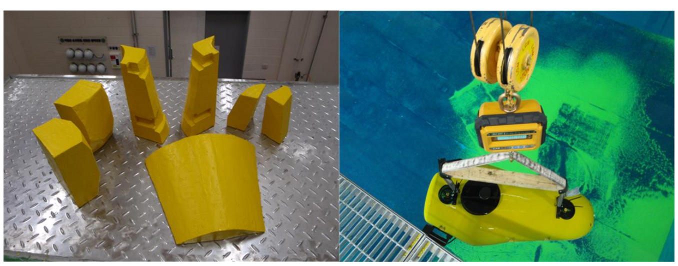

Fig. 6. Manufactured buoyancy material and ballasting test.

B. Propulsion Test

The dynamic stability of an AUV determines how the vehicle behaves when disturbed while initially travelling on a straight course [13]. To test the straight-line stability of the P-SURO, we took the following propulsion test. Under initial rest state, we applied different horizontal propulsions (same rpm command to both of horizontal thrusters) to the vehicle to observe its mechanical response. In the test, two vertical thrusters are applied with zero rpm command. Test results are shown in Fig. 7, from which we can see the vehicle has somewhat poor straight-line stability. When the two horizontal thrusters are commanded with 930 rpm and 1800rpm, the vehicle turns to the left with increased down pitch angle. However, when we increase the rpm to 3000, the vehicle turned to the right instead of left. This kind of phenomenon will be further investigated in our upcoming basin test.

To observe the vehicle's rotating behavior in the horizontal plane, we took the following propulsion test. The applied rpm commands for horizontal thrusters were determined as: for right turn motion, $C_{lRPM} = 1800 + \Delta RPM$ with left thruster and $C_{rRPM} = 1800 - \Delta RPM$ with right thruster, and for left turn motion, $C_{lRPM} = 1800 - \Delta RPM$ for left and $C_{lRPM} = 1800 + \Delta RPM$ for right thruster. And throughout the test, two vertical thrusters were controlled by auto pitch angle keeping algorithm. Test results are shown in Fig. 8 and 9.

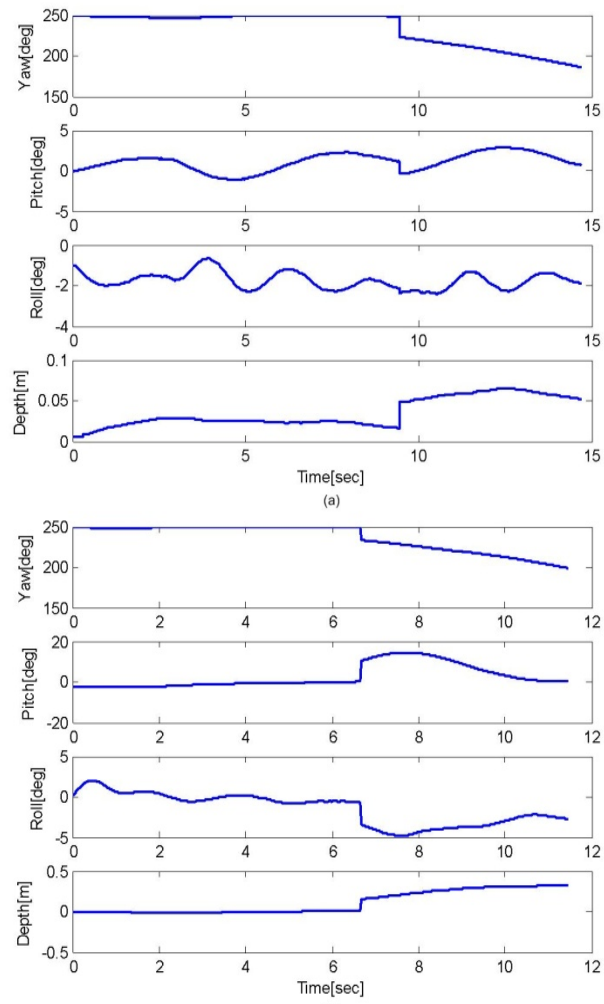

Fig. 7. Propulsion test. (a) Case of 930rpm, (b) of 1800rpm.

C. Vision Test

The PIRO basin has four specifically designed glass windows in its vertical side wall. We attached papers with numbers written in it on one glass window, and dived the vehicle to the point and test the vision algorithm. In the test, the vehicle was controlled by auto heading keeping and auto depth keeping algorithm. For recognition of number patterns, we used template matching method of Intel computer vision library OpenCV with recognition speed about 3 frames per second. The test result is shown in Fig. 10.

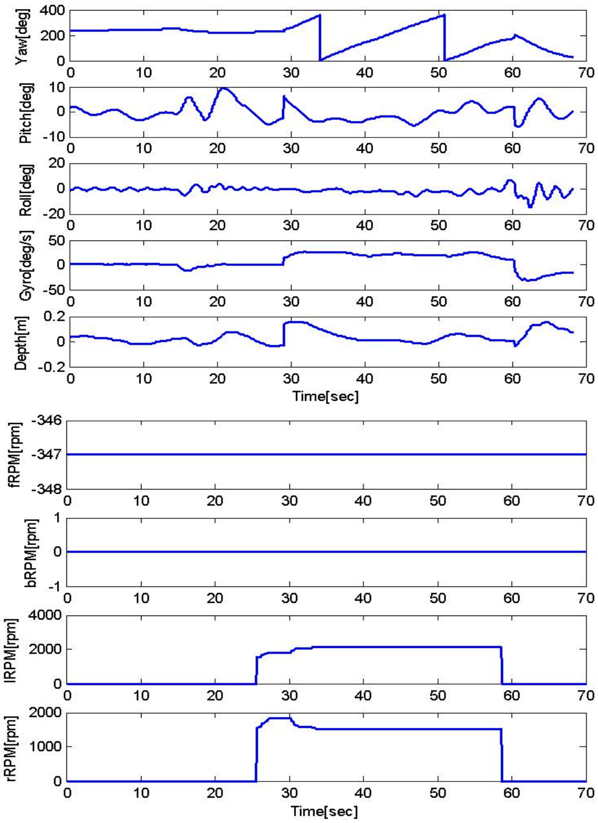

Fig. 8. Rotating motion test with right turn command.

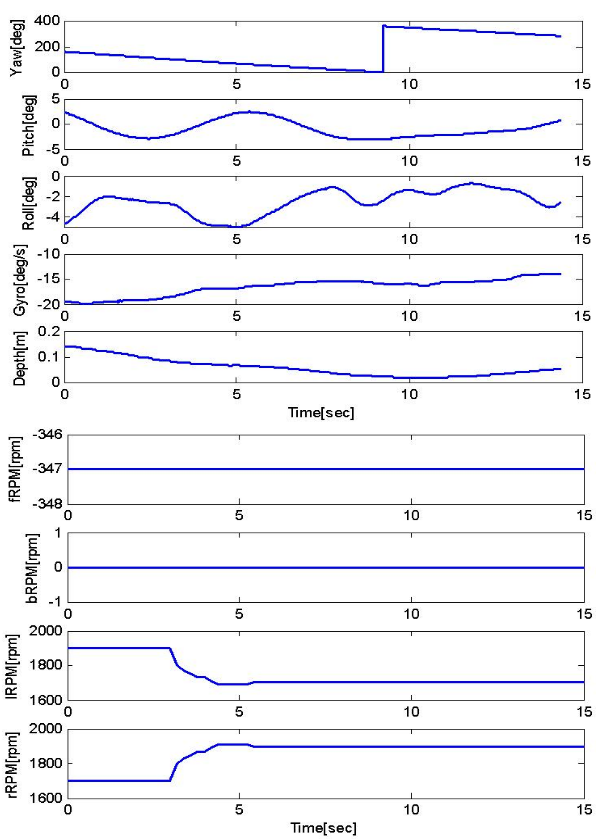

Fig. 9. Rotating motion test with left turn command.

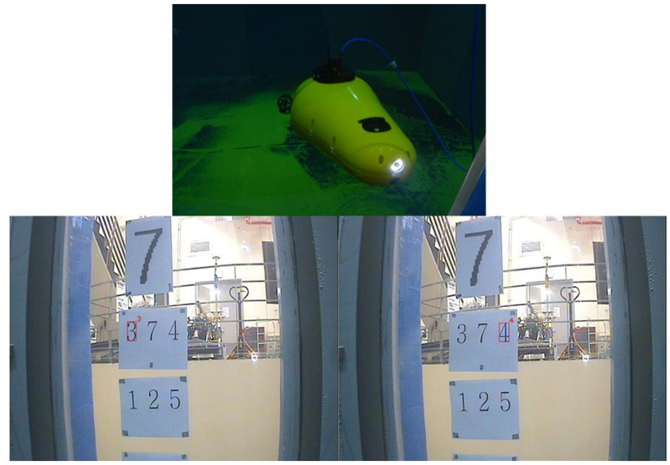

Fig. 10. Recognition of underwater number pattern.

V. SUMMARY AND FUTURE WORKS

In this paper, we introduced the P-SURO AUV which is under development in PIRO. We also summarized its first basin test which was performed in the late March. Through this test, the vehicle showed satisfactory mobility both in the vertical and horizontal plane. However, some technical problems were also reported. In the basin environment, certain sophisticated handling method may be need for some communication devices and sensors.

There are two basin tests scheduled in April. Besides solving previously mentioned technical problems, we mainly want to demonstrate sensor fusion method and inertial navigation algorithm with range sonar aiding.

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