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Design and Development of an Onshore Testing System for Autonomous Underwater Vehicle

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Abstract—**Through and comprehensive tests are essential to ensure complete stability and reliability of autonomous underwater vehicle. Due to the high-cost and risk of the field test of underwater vehicle, onshore testing is needed. This paper presents the design and development of an onshore testing system for autonomous underwater vehicle; system architecture, workflow, implementation of key subsystems and some experimental results are described. Resort the onshore testing system, the performance of the vehicle can be tested comprehensively in a laboratory environment.**

Keywords—onshore testing; all-hardware-in-the-loop simulation; autonomous underwater vehicle; load simulation; signal simulation

I. INTRODUCTION

Autonomous underwater vehicle (AUV) is an underwater robot with the ability to operate and carry out missions without manual inputs, tethers or remote control [1]. AUV has great value and general applicability in scientific, commercial and military fields. Typically, AUV operates in a complex and severe underwater environment, using its own power supply and make decisions according to the input from onboard sensors only. Without any human in the loop, AUV must be able to execute complex missions correctly, and handle unexpected scenarios [2]. Therefore, AUV must be stable and reliable functionally, electrically and mechanically in order to accomplish the missions successfully. Hence, through and comprehensive tests are necessary to ensure complete stability and reliability of AUV.

Because of the special operating environment, field tests of AUV must be carried out on the lake or at sea, which can be a hard, time consuming and sometimes high-risk task [3]. Thus, more and more researchers focusing on seeking solutions to the onshore testing of AUVs. Simulation is an important tool for the development of equipment and robots, and was widely used in the verification of underwater vehicles [4,5]. Simulation tools can help to test and validate control laws and software architecture, and to detect preliminary inconsistencies within the scenario [6]. In addition, simulation technologies reduce the required human resources; decrease the number of necessary real experiments, and the time spent. However, most of the existing underwater vehicle simulation systems are digital simulation systems or hardware-in-the-loop simulation systems, which can only be used for the verification of a certain part of the underwater vehicle, such as control algorithms [7], controller and so on. With the digital simulation system or hardware-in-the-loop simulation system can't achieve the through and comprehensive tests of underwater vehicles.

To cover the shortage of digital simulation system and hardware-in-the-loop simulation system, an all-hardware-in-the-loop simulation technology was proposed [8]. In present research, an onshore testing system for AUV was developed based on this technology. The onshore testing system was designed according to the notion of testing the AUV in a laboratory environment. Based on all-hardware-in-the-loop simulation technology, the onshore testing system takes the entire AUV into simulation process; therefore the performance of the vehicle can be tested comprehensively.

In this paper, the design and development of an onshore testing system for a portable AUV was presented. The onshore testing system architecture, workflow and the implementation of some key subsystems are described. Some experimental results was discussed to illustrate the specifications and performance of the onshore testing system.

II. ONSHORE TESTING SYSTEM ARCHITECTURE

The onshore testing system presented in this paper is designed for the onshore testing of a portable AUV, named Explorer-100, which was built by the Shenyang Institute of Automation, Chinese Academy of Sciences, to meet the requirements of fast, flexible, and low cost [9,10]. The Explorer-100 AUV is equipped with a fixed pitch propeller to provide thrust, an X-shaped fins to control yaw and pitch of the AUV, an attitude and heading reference system (AHRS) to measure attitude of the AUV, a depth gauge to gauge real time depth of the AUV, a Doppler velocity log (DVL) to detect surge speed of the AUV and a GPS modular to obtain real time position of the vehicle when floating on the water.

According to configuration of the Explorer-100 AUV ,the architecture of the onshore testing system is designed as shown in Fig. 1, which includes the real Explorer-100 AUV and a series of subsystems, such as visual simulation system, ocean environment model, AUV dynamic model, communication modular, management modular, thruster load simulator, rudder load simulator, three-axle turntable, depth

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signals simulator, DVL signals simulator, satellite positioning signals simulator and so on.

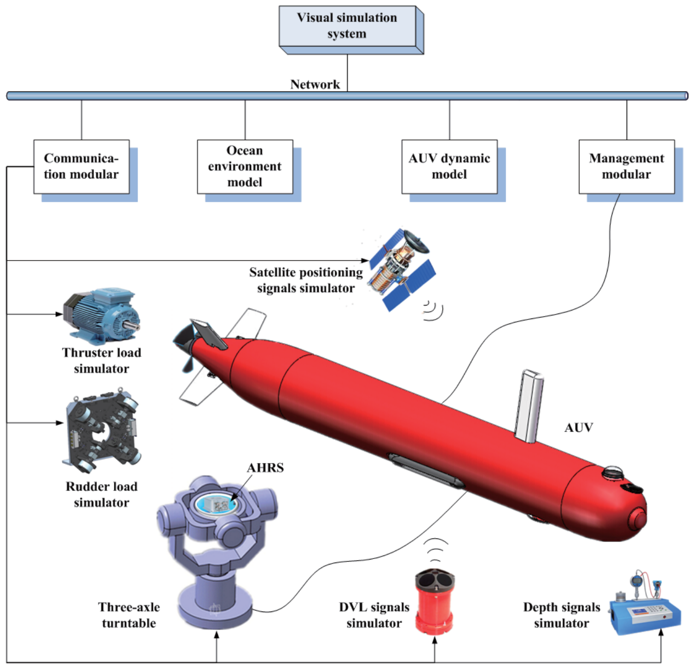

Fig. 1. Architecture of the onshore testing system for Explorer-100 AUV

III. DYNAMIC MODEL OF EXPLORER-100 AUV

A. Coordinates and Notations

In order to describe the motion of the underwater vehicle and build its nonlinear mathematical model, a special reference frame must be established. Based on the recommendations of International Towing Tank Conference and Society of Naval Architects and Marine Engineers, there are two reference frames widely used in the published literature of underwater vehicles, as illustrated in Fig. 2. Nomenclatures and notations associated with those reference frames are defined as follows [11].

- $E-\xi\eta\zeta$: are earth-fixed coordinates.
- $E-xyz$: are body-fixed coordinates.
- u,v,w : is surge, sway and heave speed of the vehicle.
- ξ,η,ζ : the positions of the vehicle with respect to the earth fixed coordinates.
- Φ,Θ,Ψ : the orientations of the vehicle with respect to the earth fixed coordinates.
- p,q,r : the rotation velocities of the vehicle with respect to the body fixed coordinates.
- X,Y,Z : the total forces acting on the vehicle with respect to the body fixed coordinates.
- K,M,N : the moments acting on vehicles with respect to the body fixed coordinates.

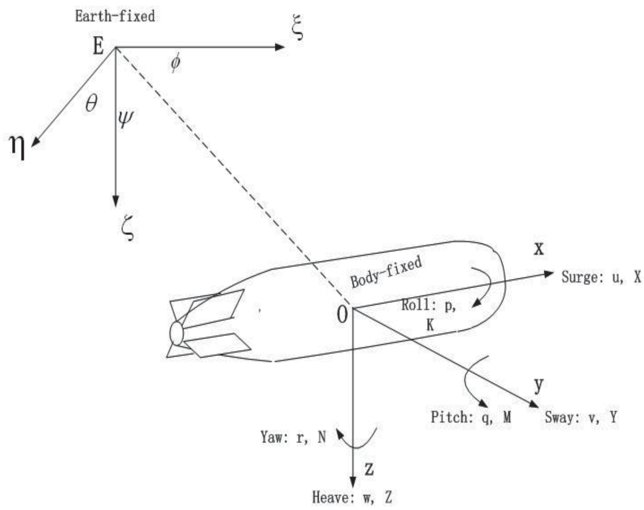

Fig. 2. Coordinates system for Explorer-100 AUV

B. Dynamic Model of Explorer-100 AUV

Like most underwater vehicle, the Explorer-100 AUV was designed can stabilize roll angle itself. The X-shaped fins symmetry in x and z axis are used to control yaw and pitch of the AUV, just the same as rudder and elevator for traditional submarines. The mapping from rudder and elevator angles to fin angles can be described as in (1) [12, 13]:

$$\begin{cases} \delta_1 = \delta_4 = -\dfrac{\sqrt{2}}{2}(\delta_e + \delta_r) \\ \delta_2 = \delta_3 = \dfrac{\sqrt{2}}{2}(\delta_e - \delta_r) \end{cases} \tag{1}$$

Where δ_1 the left-upper fin angle of the Explorer-100 AUV, δ_2 is the right-upper fin angle, δ_3 is the left-lower fin angle, δ_4 is the right-lower fin angle, δ_r is the rudder angle of traditional submarine, δ_e is the elevator angle of traditional submarine.

As described in [13], the six-degree of freedom nonlinear equation of the Explorer-100 AUV can be described as follows:

$$\begin{aligned} & m\dot{u} + mz_g\dot{q} - my_g\dot{r} = X_{HS} + X_{uau}u|u| + X_u u \\ & + X_{vv}v^2 + (mx_g + X_{qq})q^2 + (mx_g + X_{rr})r^2 \\ & + (m + X_{vr})vr + (-m + X_{wq})wq + (-my_g)pq \\ & + (-mz_g)pr + X_{uauae}u|u||\delta_e| + X_{uauar}u|u||\delta_r| \\ & + X_{uauaer}u|u|\delta_e|\delta_r| + X_{porp}n_{prop} \end{aligned} \tag{2}$$

$$\begin{aligned} & m\dot{v} - mz_g\dot{p} + mx_g\dot{r} = Y_{HS} + Y_{vav}v|v| + Y_{uv}uv \\ & + (-m + Y_{ur})ur + (m)wp + (my_g)p^2 \\ & + (-mx_g)pq + (-mz_g)qr + (my_g)r^2 \\ & + Y_{uaur}u|u|\delta_r + Y_{uauaer}u|u||\delta_e|\delta_r \end{aligned} \tag{3}$$

$$
\begin{aligned}
& m\dot{w}+my_g\dot{p}-mx_g\dot{q}=Z_{HS}+Z_{waw}w|w|+Z_{vv}v^2 \\
& +Z_{uw}uw+(m+Z_{uq})uq+Z_{qaq}q|q|+(-m)vp \\
& +(mz_g)p^2+(-mx_g)pr+(mz_g)q^2+(-my_g)qr \\
& +Z_{uaue}u|u|\delta_e+Z_{uauear}u|u|\delta_e|\delta_r|
\end{aligned} \tag{4}
$$

$$
\begin{aligned}
& -mz_g\dot{v}+my_g\dot{w}+I_{xx}\dot{p}-I_{xy}\dot{q}-I_{xz}\dot{r}=K_{HS} \\
& +K_{uv}uv+(mz_g+K_{ur})ur+(my_g)uq+(-my_g)vp \\
& +(-mz_g)wp+(I_{xz})pq+(-I_{xy})pr+(I_{yz})q^2 \\
& +(I_{yy}-I_{zz})qr+(-I_{yz})r^2+K_{vav}v|v|+K_{vap}v|p| \\
& +K_p p+K_{prop}n_{prop}
\end{aligned} \tag{5}
$$

$$
\begin{aligned}
& mz_g\dot{u}-mx_g\dot{w}-I_{xy}\dot{p}+I_{yy}\dot{q}-I_{yz}\dot{r}=M_{HS} \\
& +M_{uw}uw+M_{uu}u^2+M_{vv}v^2+(-mx_g+M_{uq})uq \\
& +(mx_g)vp+(mz_g)vr+(-mz_g)wq+(-I_{xz})p^2 \\
& +(-I_{yz})pq+(I_{zz}-I_{xx})pr+(I_{xy})qr+(I_{xz})r^2 \\
& +M_{uaue}u|u|\delta_e+M_{uauear}u|u|\delta_e|\delta_r|
\end{aligned} \tag{6}
$$

$$
\begin{aligned}
& -my_g\dot{u}+mx_g\dot{v}-I_{xz}\dot{p}-I_{yz}\dot{q}+I_{zz}\dot{r}=N_{HS} \\
& +N_{uv}uv+(-mx_g+N_{ur})ur+(-my_g)vr \\
& +(mx_g)wp+(my_g)wq+(I_{xy})p^2+(I_{xx}-I_{yy})pq \\
& +I_{yz}pr+(-I_{xy})q^2+(-I_{xz})qr \\
& +N_{uaur}u|u|\delta_r+N_{uauaer}u|u||\delta_e|\delta_r
\end{aligned} \tag{7}
$$

In dynamic model (2) ~ (7), rudder angle δ_r and elevator angle δ_e can be solved from fins angle δ_1, δ_2, δ_3 and δ_4 based on (1). n_{prop} is rotation speed of the propeller of the Explorer-100 AUV.

IV. Workflow of the Onshore Testing System

Workflow of the onshore testing system is depicted in Fig. 3. During onshore testing, the Explorer-100 AUV operates just the same as it was cruising underwater. The onshore testing system simulate real operating environment of the AUV, such as motion simulation, real time attitude simulation, depth gauge signal simulation, DVL signal simulation, satellite positioning devices signal simulation, thruster load simulation, rudders load simulation and so on.

A. Motion simulation

As described in (2) ~ (7), when the dynamic model parameters of the Explorer-100 AUV are known, the motion information of the next time step can be calculated based on current moment motion information, ocean environment information, real time fins angle and real time propeller rotation speed. During onshore testing, ocean environment information can be obtained from ocean environment model, real time fins angle and propeller rotation speed were measured by rudder load simulator and thruster load simulator respectively, just as shown in Fig. 3.

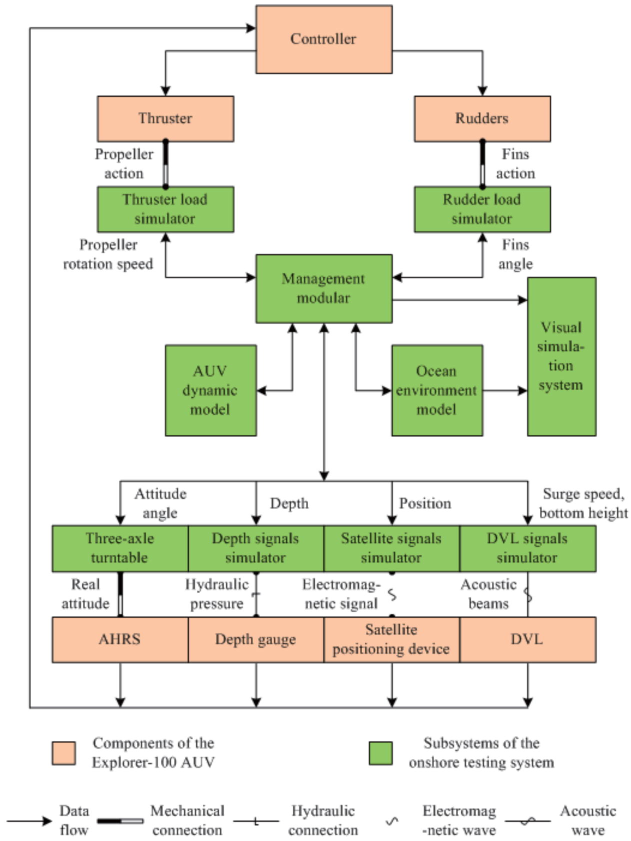

Fig. 3. Workflow of the onshore testing system for Explorer-100 AUV

B. System Workflow

When onshore testing starts, the motion state of Explorer-100 AUV, ocean environment information, and other initial conditions and parameters will be initialized based on the setting situation. The AUV operates to execute its mission, thruster and rudders act according to instructions of the controller. Then, motion information of the next time step can be calculated based on AUV dynamic model, thruster information, rudder angle, ocean environment information and other information.

After obtained the motion information such as linear velocities, angular velocities, attitude angles, depth and horizontal position, the simulate of real operating environment of the AUV begins.

Three-axle turntable operates according to the calculated angular velocities and attitude angles, rotate the AHRS of the AUV to simulate the change of attitude. Real time thruster load and rudder load will be calculated based on thruster load model and rudder load model, load torques will be applied to AUV thruster and rudders by thruster load simulator and rudder load simulator respectively. Hydraulic pressure corresponding to current depth will be generated by depth signal simulator and applied to the depth gauge of AUV. Acoustic beams contain current linear velocity information will be generated by DVL signals simulator. Electromagnetic signals identical to the signals of satellite positioning systems will be generated by satellite positioning signals simulator.

At the same time, the Explorer-100 AUV operates in the simulated environment, acquire information from onboard sensors and equipments, and make control instructions according to its control algorithms. Then, actuators such as thruster and rudders act according to those instructions, and the next simulation process begins.

V. REALIZATION OF THE ONSHORE TESTING SYSTEM

A. Thruster load simulator

Thruster load simulator of the onshore testing system is a passive torque servo system which exerts load torque on the AUV thruster, and measure real time propeller rotation speed of the AUV.

Framework of the thruster load simulator is shown in Fig. 4, which include servo motor, servo motor driver, torque-speed sensor, signal acquisition system, thruster load simulator control unit, couplings and so on. The servo motor and servo motor driver is used to provide thruster load torque, the torque-speed sensor and signal acquisition system is utilized to measure the load torque exert on the thruster motor and rotation speed of the thruster motor. The thruster load simulator is shown in Fig. 5.

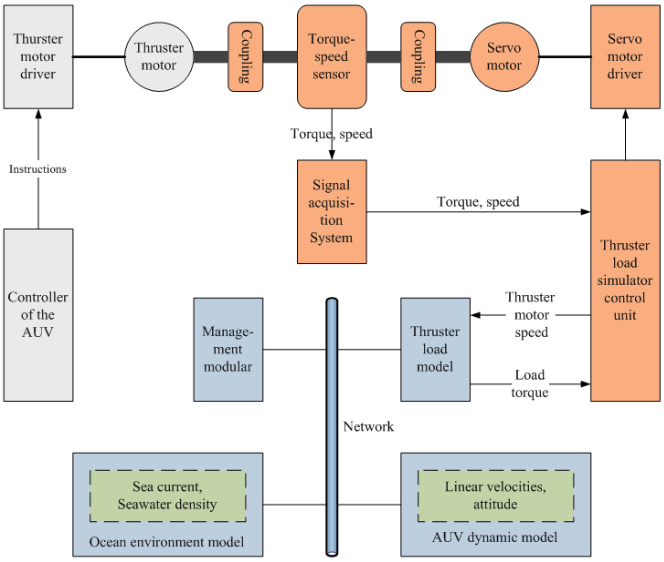

Fig. 4. Framwork of the thruster load simulator

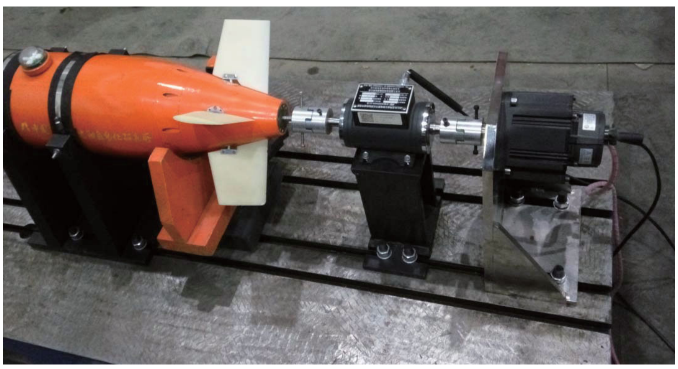

Fig. 5. The thruster load simulator

B. Rudder laod simulator

Rudder load simulator consists of four sets of passive torque servo system, the arrangement of the four sets of passive torque servo system is also X-shaped to ensure each fin of the Explorer-100 AUV and each set of passive torque servo system share a common shaft.

The framework of one set of passive torque servo system in the rudder load simulator is illustrated in Fig. 6. As shown in Fig.6, the passive torque servo system in the rudder load simulator consists of a torque motor and a torque motor driver, a torque sensor and a signal regulator, a photoelectric encoder and a pulse counter, a rudder load simulator control system and some mechanical devices. When operating, the torque motor provide rudder load torque exert to the steering gear of the AUV. The torque sensor measure real time load torque exert on the steering gear, the photoelectric encoder measure real time fins angle of the AUV. In order to acquire high accurate rudder load torque, a control diagram consist of torque control loop, current control loop and surplus torque compensation loop is designed. Experimental result of one set of passive torque servo system in the rudder load simulator is shown in Fig. 7.

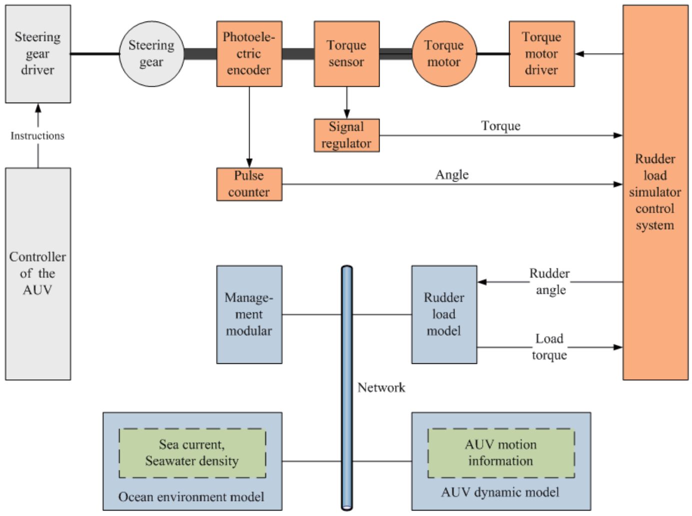

Fig. 6. Framework of the rudder load simulator

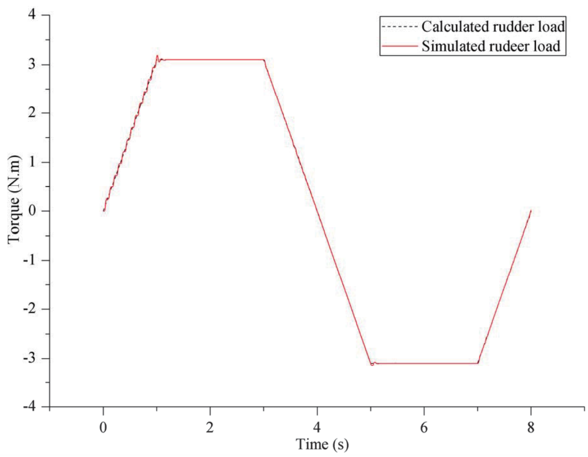

Fig. 7. Experimental result of the rudder load simulator

C. *Other Subsystems*

In the onshore testing system, three-axle turntable serves as a mount of AHRS of the Explorer-100 AUV. When the turntable revolves, the AHRS revolves together with the turntable, thus simulate the attitude change of the AUV. Depth signals simulator is actually a pressure generating device connected to the depth gauge of the AUV by a flexible pipe. When operation, the depth signals simulator generate a hydraulic pressure stressing the depth gauge, simulate the water pressure corresponding to the depth of the AUV. DVL signals simulator is an acoustics system sends acoustics beams to the DVL of the AUV, the acoustics beams generate by the DVL signals simulator contains information of surge speed and bottom height of the AUV, these information were calculated in motion simulation process. Satellite positioning signals simulator generates electromagnetic signals identical to the signals of satellite positioning systems such as the GPS. With the satellite positioning signals simulator, satellite positioning device on the AUV can get position information obtained from the motion simulation process.

D. *Onshore Testing System Specifications*

The whole onshore testing system is illustrated in Fig. 8. Key parameters of the onshore testing system and related specifications of the Explorer-100 AUV are listed in Table 1.

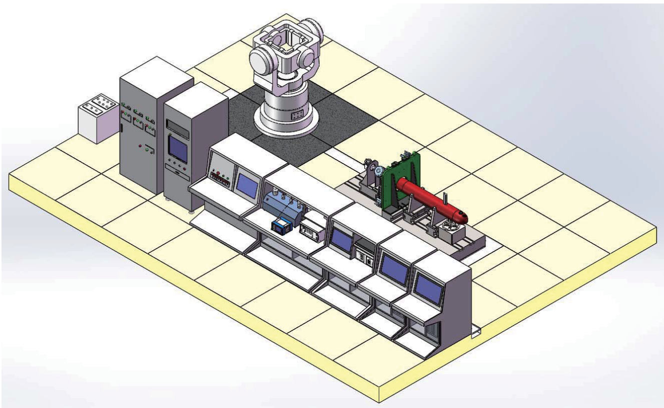

Fig. 8. Onshore testing system for the Explorer-100 AUV

TABLE. 1 SPECIFICATIONS OF THE ONSHORE TESTING SYSTEM

Onshore testing system		Explorer-100 AUV
Thruster load simulator	Load simulation: 5 N.m @ ±0.4%F.S Speed measuring: 2000r/min @ ±0.4%F.S	Max thruster motor torque: 2N.m Max thruster motor speed: 1000r/min
Rudder load simulator	Load simulation: 3 N.m @ ±0.5%F.S Rudder angle measuring: 360° @ ±0.1°	Max steering gear torque: 2.84 N.m Max rudder angle: 40°
Depth signals simulator	Hydraulic pressure output: 4 MPa @ ±0.05%F.S	Operating depth: 100m
Three-axle turntable	Angular control: 360°@± 0.003°	Attitude measuring accuracy: 0.5°

VI. CONCLUSION

An onshore testing system based on all-hardware-in-the-loop simulation technology was proposed. The onshore testing system architecture, workflow, design of subsystems such as the thruster load system simulator and rudder load simulator was described. Unlike traditional digital simulation system or hardware-in-the-loop simulation system, the onshore testing system takes the entire AUV into simulation process. Resort the onshore testing system, the performance of the AUV can be tested comprehensively in a laboratory environment.

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