ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline (Draft)

UV Full Scale Manoeuvring Trials

7.5	Process Control
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UV Full Scale Manoeuvring Trials

1. PURPOSE OF GUIDELINE

This guideline provides assistance when performing full scale trials to determine the manoeuvring characteristics of an UV (Underwater Vehicle), but the present version focuses on the behaviour of an AUV (Autonomous Underwater Vehicle) as a reaction to rudder, elevator, and other control device actions.

2. RECOMMENDED PROCEDURES FOR MANOEUVRING TRIALS

2.1 Overview

For operation purpose, the tests should cover following qualities:

inherent dynamic stability,
course- keeping ability (both in horizontal and vertical plane),
initial turning/heading(yaw)-changing ability,
heading(yaw) checking ability,
initial diving/depth-changing ability,
pitch checking ability,
turning ability (both in horizontal and vertical plane),
acceleration/deceleration ability,
heading(yaw)-keeping ability
depth-keeping ability,
position-keeping ability,
waypoints tracking ability,
path tracking ability.

Table 1 shows a total of 12 manoeuvring tests recommended in this guideline, providing the AUV handling characteristics checked by each test.

Furthermore, recommendations are formulated for operation purposes, including the operation near the water surface or near the bottom and the operation at low speed.

Test procedures should document trials in a way which is compatible with both AUV design and scientific purpose (e.g. validation of predicted manoeuvres).

An adequate AUV control system would be necessary to carry out the full scale trials.

2.2 Trial Conditions

2.2.1 Environmental Restrictions

Manoeuvrability of an AUV is affected by the ocean environment. Therefore, the trial site should be located in waters of adequate depth with low current and tidal influence as possible, and manoeuvring trials should be performed in the calmest possible weather conditions. It is recommended that

1. the test must be executed in open water, far away from banks and ship traffic;
2. the operating depth should be determined so that the water surface, the bottom and the wind do not affect the manoeuvrability of an AUV;
3. the maximum sea state should be chosen taking into account the AUV's characteristics such as AUV speed, AUV displacement, control force, etc.;
4. the maximum current speed should be chosen taking into account the AUV's characteristics such as AUV speed, AUV displacement, control force, etc.

Table 1: Recommended Manoeuvring Tests for AUV

Type of Test		Manoeuvrability to be checked
1	Turning Circle Test	7
2	Horizontal Zig-zag Test	3,4,9
3	Heading Control Test	2,3,4,9
4	Vertical Zig-zag Test	5,6,10
5	Depth Control Test/Meander Test	2,5,6,10
6	Helical/Spiral Manoeuvring Test	1,2
7	Acceleration/Deceleration Test	8
8	Docking Test	2,11,12
9	Waypoints Tracking Test	2,12
10	Path Tracking Test	2,13
11	Advanced Speed Test	1
12	Rudder Deflection Test	1

(*) 1. inherent dynamic stability,
2. course- keeping ability (both in horizontal and vertical plane),
3. initial turning/heading (yaw)-changing ability,
4. heading (yaw) checking ability,
5. initial diving/depth-changing ability,
6. pitch checking ability,
7. turning ability (both in horizontal and vertical plane),
8. acceleration/deceleration ability,
9. heading (yaw)-keeping ability
10. depth-keeping ability,
11. position-keeping ability,
12. waypoints tracking ability,
13. path tracking ability.

2.2.2 AUV Operational Conditions

It is recommended that the trials are to be carried out with the AUV in a normal operational condition. Depending on the test and its purpose, some tests should be conducted in a non-normal operational condition.

2.2.3 AUV Initial Conditions

Before the execution of the relevant manoeuvre, the AUV must have run at constant speed or thruster setting with minimum rate of change in 6 DOF (degrees of freedom) motion (steady course). The AUV must also be required to keep a steady heading and depth by its control system.

The manoeuvrability of an AUV is affected by the initial conditions. Therefore, before carrying out the manoeuvring test, the initial conditions of AUV should be recorded in the test, such as:

- initial speed,
- initial position,
- initial depth,
- initial heading(yaw) angle,
- initial pitch angle,
- initial rudder angle,
- initial elevator(fin) angle,
- initial propeller(thruster) rpm,
- etc.

2.3 Test procedures and parameters to be obtained

2.3.1 Turning Circle Test

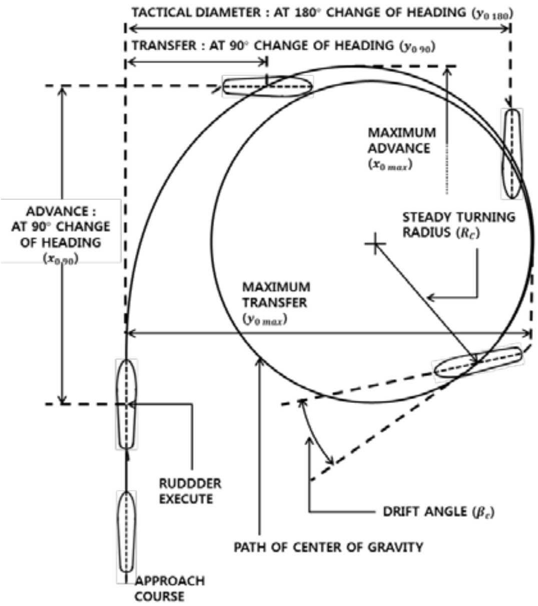

Figure 1 Turning circle: definitions

A turning circle test is a manoeuvre in which the vehicle enters turning motion starting at a constant speed and constant depth (in a horizontal plane). The test is performed by deflecting the rudders to a predefined angle and holding it still resulting in the vehicle entering a circular path. A turning circle of at least 540 degrees is necessary to determine the main parameters of this trial. Whenever possible, turning circle tests at low or half design speed should be performed as well.

The turning radius, turning speed, and rate of turn are characteristics of a particular turning path. The vehicle controller allows the user to set a desired radius of turn and to control the rudder angles and speeds for a desired turning.

The essential information referred to the midship to be obtained from this manoeuvre consists of (see Figure 1):

- tactical diameter,
- advance,
- transfer,
- turning speed,
- time to change heading by 90 degrees,
- time to change heading by 180 degrees,
- time to change heading by 270 degrees.

The first three of these may be presented in non-dimensional form by dividing their values by the AUV's overall length.

2.3.2 Horizontal Zig-Zag Test

The zig-zag test is conducted to check the horizontal manoeuvring property of an AUV at a constant speed and constant depth. The zig-zag test is obtained by reversing the rudder (wing and control surface) alternately by δ degrees to either side at a deviation ψ from the initial course. After a steady approach the rudder is put over to starboard (first execute). When the heading is ψ degrees off the initial course, the rudder is reversed to the same angle to port (second execute).

After counter rudder has been applied, the AUV initially continues yawing in the original direction with decreasing yaw rate until it changes sign, so that the ship eventually yaws to port in response to the rudder. When the heading is ψ degrees off the course port, the rudder is reversed again to starboard (third execute). This process continues until a total of 3 rudder executes have been completed.

Hence, a zig-zag test is determined by the combination of the values of change of heading Ψ and rudder angle, and is denoted δ/ψ. Common values for these parameters are 5/5, 10/10 and 20/20. However, other combinations could be applied.

The manoeuvres are to be executed at constant propeller (thruster) rpm.

Zig-zag manoeuvres must be carried out starting with rudder to both starboard and to port, in order to identify the environmental effects (e.g. current) and asymmetric behaviour of the vehicle.

For a first simple analysis of the results, characteristic steering values defined in Figure 2 can be used.

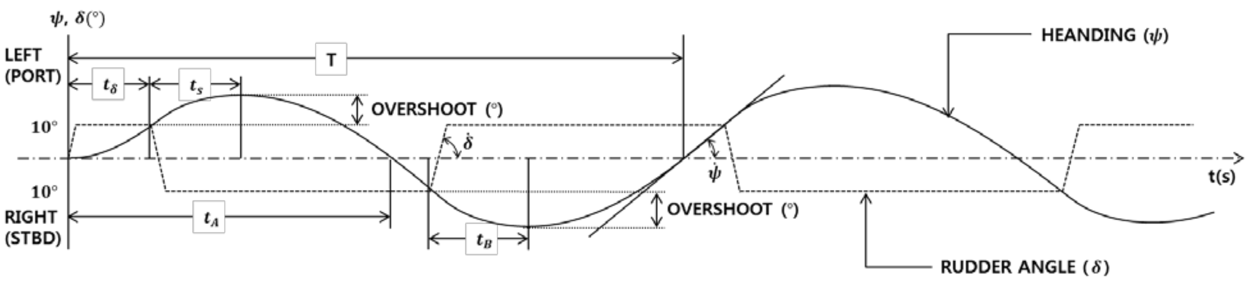

Figure 2. Time trace of zig-zag test parameters

Results of zig-zag tests are defined as follows**:**

Initial turning time t_δ (s): the time from the instant the rudder is put at the outset of the manoeuvre (first execute) until the heading is Ψ degrees off the initial course. At this instant the rudder is reversed to the opposite side (second execute).

Execute heading angle (degrees): heading Ψ at which the rudder is reversed.

Overshoot angle (degrees): the angle through which the ship continues to turn in the original direction after the application of counter rudder. The first and second overshoot angles correspond to the maximum heading angle reached after the second and third execute, respectively.

Time to check yaw (t_S, t_B) (s): the time between the rudder execute and the time of the maximum heading change in the original direction.

Heading ψ (degrees): the course deviation from the straight initial course.

Reach t_A (s): the time between the first execute and the instant when the AUV's heading is zero after the second execute.

Time of a complete cycle T (s): the time between the first execute and the instant when the AUV's heading is zero after the third execute.

If the rudder cannot be controlled manually, the Horizontal Zig-Zag Test is performed analogously as described in section 2.3.4 for the Vertical Zig-Zag Control Test.

2.3.3 Heading Control Test

The heading control test is conducted to check the performance of the AUV controller at a constant speed and constant depth in the horizontal plane. The heading control test is obtained by controlling the rudder angle which is determined by the error between the desired heading and the current heading to follow the desired heading.

When the desired heading is a step function, the overshoot, rise time, and steady error should be characteristics of the heading control test, as illustrated in Figure 3.

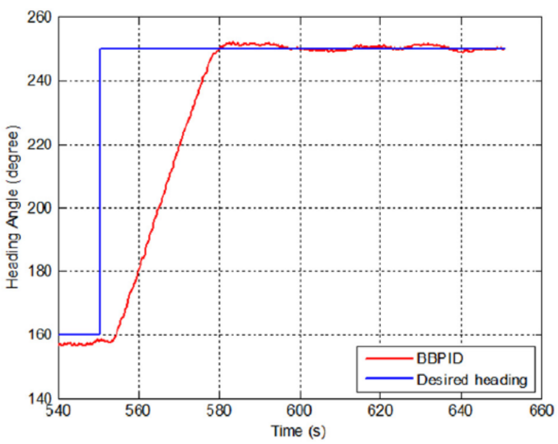

Figure. 3 Heading Control Test (Wan et al. (2018))

2.3.4 Vertical Zig-Zag Control Test

The Vertical Zig-Zag Control Test assesses the vehicle's manoeuvrability in the vertical plane, providing an idea of its ability to perform emergency manoeuvres to avoid collision to the seabed, as well as to submerged or floating structures, for instance.

The AUV is kept at a steady depth, at the "starting depth" set point, before the manoeuvre begins. Then, the vehicle is commanded to submerge, using a controller to set a constant pitch value. When the vehicle reaches a pre-defined depth, the pitch set point changes its signal (keeping the same magnitude). The AUV emerges, keeping its pitch angle until it reaches the other pre-defined depth, when the next diving manoeuvre should start by imposing the next change to the pitch set point. The vehicle, therefore, is supposed to execute an oscillating manoeuvre in the vertical plane. Figure 4 shows an example of the vertical zig-zag test.

The following variables should be recorded: starting depth, minimum depth set point, maximum depth set point, elevator angle, pitch angle, depth, AUV speed.

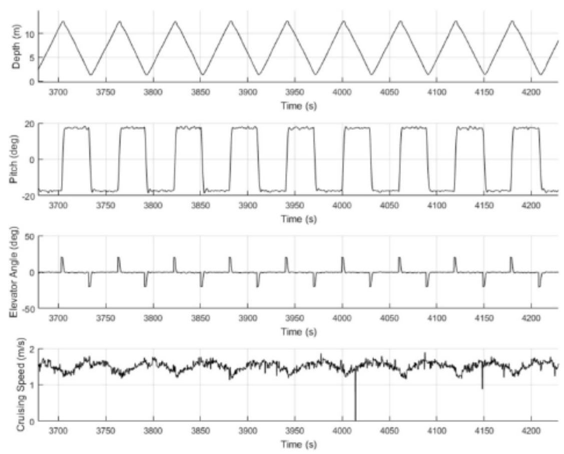

Figure 4 Vertical Zig-Zag Manoeuvre (Freire et al. (2018))

From the test, the next results can be measured:

- Initial Diving Time: the time from the instant the first pitch set point is imposed to the pitch controller to the time the pitch angle first reaches this set point value.
- First Overshoot depth: the depth through which the AUV continues in the first diving manoeuvre after the input of the second pitch set point to the controller.
- Second Overshoot depth: the depth through which the AUV continues in the first emerging manoeuvre after the input of the third pitch set point to the controller.
- Time to check the first maximum set point depth: the time between the input of the first pitch set point and the time when the first maximum se point depth is reached.
- Reach at diving: the time between the input of the first pitch setpoint and the time at the end of the first diving manoeuvre.
- Time to reach the first emerging: the time between the input of the second pitch setpoint to the controller and the time the AUV´s pitch reached this value.

All parameters should be compared to the correspondent values measured in next cycles.

These manoeuvres can be carried out at 5/-5, 10/-10, and 15/-15 degrees, or other combinations depending on the AUV application.

2.3.5 Depth Control Test

The depth control or meander test is conducted to check the performance of the AUV controller at a constant speed in the vertical plane. The depth control test is obtained by controlling the elevator (plane, fin) angle which is determined by the error between the desired depth and the current depth to follow the desired depth. It should be necessary to control the pitch motion in order to stably follow the desired depth because heave motion and the pitch motion are coupled.

When the desired depth is a step function, the overshoot, rise time, and steady error should be characteristics of the depth control test. Figure 5 shows an example of the depth control test.

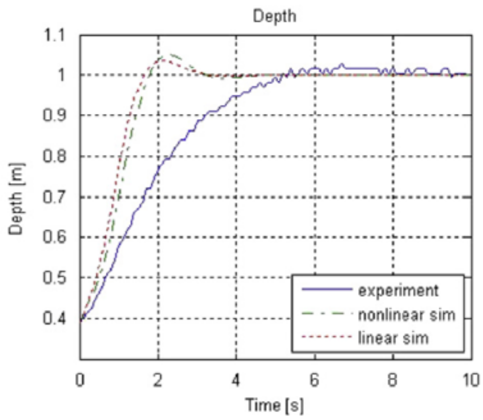

Figure 5 Depth Control Test (Jun et al. (2009))

2.3.6 Helical/Spiral Manoeuvring Test

Helical/Spiral manoeuvres are applied to assess the manoeuvring property in 6 DOF (degrees of freedom) motion of the AUV in a horizontal and vertical plane. The helix manoeuvre is not a standard manoeuvre but was designed to excite all six degrees of freedom. A 3D motion in which the vehicle spiralled down in circles was considered to excite all 6 DOF. Figure 6 shows an example of the helix manoeuvre test.

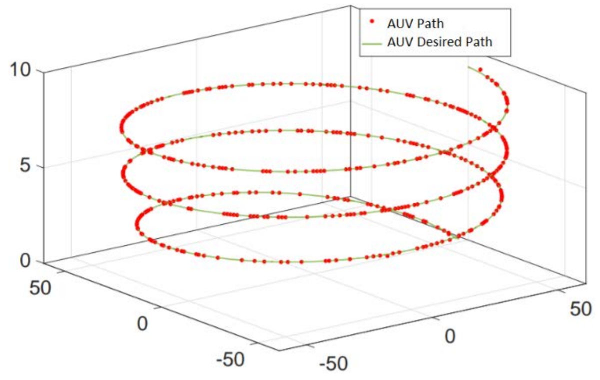

Figure 6 Helical/Spiral Manoeuvring Test (Ramirez et al. (2019))

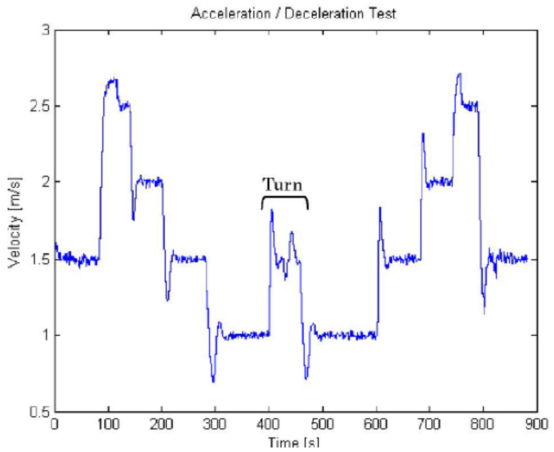

Figure 7 Acceleration/Deceleration Test (Issac et al. (2007))

2.3.7 Acceleration/Deceleration Test

An acceleration test is performed by increasing the speed of the vehicle from rest or from ahead speed to a higher ahead speed. A deceleration test is performed by decreasing the speed of the vehicle from ahead speed to a lower speed or until the vehicle comes to a rest. The test is performed at a constant depth.

An AUV is often designed to be slightly positively buoyant. For this reason, it should be difficult or impossible to keep the vehicle at rest at depth because the vehicle slowly rises to the surface. To overcome these above difficulties, it should be decided to do the test by changing the speed from a lower to higher value for acceleration and vice-versa for deceleration while the vehicle follows a straight-line path at any depth. Figure 7 shows an example of such test.

2.3.8 Docking Test

The docking test is conducted to verify the approach algorithm and system validity for underwater docking. A docking test should be performed using an image processing method and vision guidance to discriminate an underwater dock.

The docking test is obtained by controlling the rudder angle and elevator angle which are determined by the position error between the docking position and the current vehicle position to move the docking position.

When the docking control test is performed, the position error between the docking position and the current position are the characteristic results of the docking test. The control force which is determined using the position error should also be one of the characteristic results of the docking test. Figure 8 shows an example of the docking test.

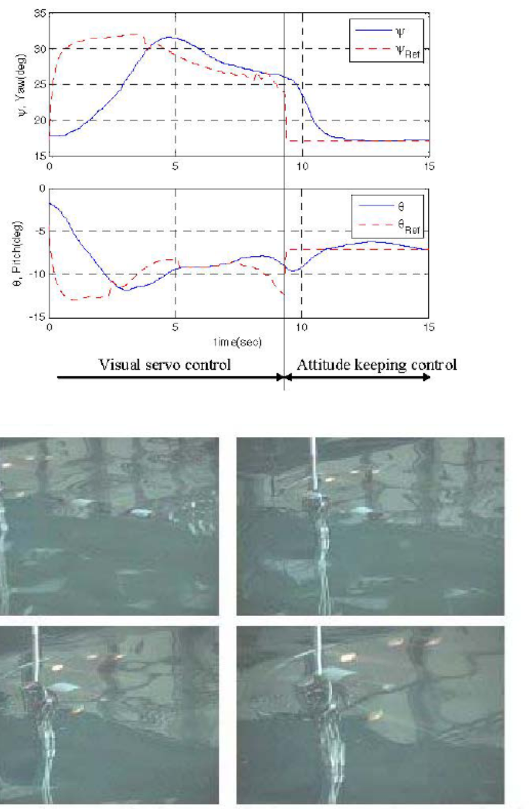

Figure 8 Docking Test (Park et al. (2007))

2.3.9 Waypoints Tracking Test

The waypoints tracking test is conducted to check the performance of the AUV controller in a horizontal plane. When the waypoints tracking test is to be made, the depth and speed should be kept constant by using the control system.

The waypoints tracking test is obtained by controlling the rudder angle which is determined by the position error between the waypoint position and the current vehicle position to move the waypoint. It may be necessary to pre-record the position of waypoints in the vehicle.

When the waypoints tracking test is performed, the position error between the waypoint position and the current position are the characteristic results of the waypoints tracking test. The control force which is determined using the position error should also be one of the characteristic results of the waypoints tracking test. Figure 9 shows an example of the waypoints tracking test.

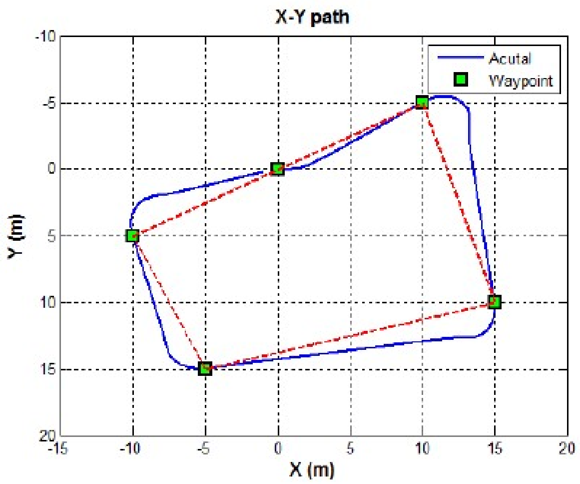

Figure 9 Waypoints Tracking Test (Ko et al. (2013))

2.3.10 Path Tracking Test

The path tracking test is conducted to check the performance of the AUV controller in a horizontal plane. When the path tracking test is to be made, the depth and speed should be kept constant by using control system.

The path tracking test is obtained by controlling the rudder angle which is determined by the path error between the desired path and the current vehicle path to follow the desired path. It may be necessary to pre-record the desired path in the vehicle in the test.

When the path tracking test is performed, the path error between the desired path (the desired trajectory) and the current path (the actual trajectory) is the characteristic results of the path tracking test. The control force which is determined using the pass error should also be one of the characteristic results of the path tracking test. Figure 10 shows an example of the path tracking test.

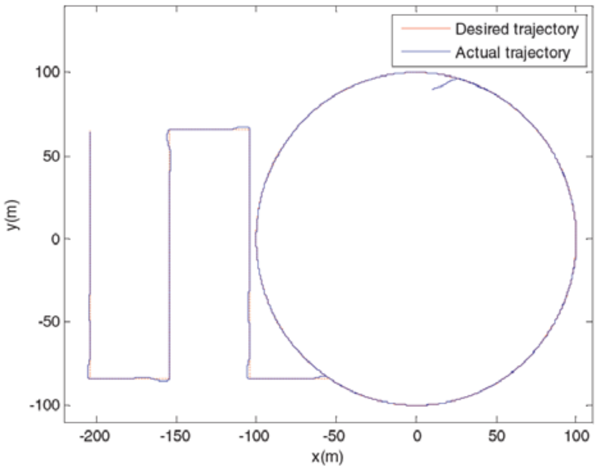

Figure 10 Path Tracking Test (Zhou et al. (2018))

2.3.11 Parameters to be obtained

In each test, the parameters appropriate for the test object should be measured and documented by adequate instrumentation from at least the following parameters:

- initial speed, position (or trajectory),
- speed,
- depth,
- yaw(heading) and yaw rate,
- pitch and pitch rate,
- rudder angle (or horizontal control force),
- elevator angle (or vertical control force),
- propeller (or thruster) rpm,
- desired depth,
- desired heading,
- desired pitch,
- current position and desired docking position,
- current position and desired waypoint positions,
- current path and desired path.

3. DATA ACQUISITION SYSTEM

3.1 General

During the different trials, the data has to be measured and recorded from the start of the approach run until the end of the manoeuvring trial.

Data should be acquired by a computer-based system because almost all the manoeuvring trials require time history data. The system should be able to collect, record and process real-time trial data of all measured parameters. The data acquisition system is installed in the AUV hull and the communication system should be used to communicate the acquired data with the surface or other vehicles using wireless LAN, R/F modem or acoustic modem. A real time communication is not mandatory since the control logic is commonly uploaded to the AUV.

The data sampling rate should be determined so that the acquired data can sufficiently indicate the characteristic of the AUV. A minimal sampling rate of 5 Hz is recommended. The sampling rate should be at least twice the filter frequency according to the sampling theory.

3.2 Instrumentation

3.2.1 Overview

This section presents specific procedures and necessary equipment for the instrumentation of full-scale manoeuvring trials. A general procedure on the calibration of the instruments can be found on the ITTC Procedure 7.5-01-03-01 Uncertainty Analysis: Instrument Calibration (ITTC, 2014).

3.2.2 AUV position

The position of the AUV should be measured by adequate instrumentation. The velocity and orientation of the AUV are usually measured by Doppler Velocity Log (DVL). DVL is an acoustic sensor which can measure the vehicle's velocity relative to the water or sea bottom through emitting signal to the bottom of the sea and using Doppler shift of the returned signals when the vehicle is submerged. The position should be measured using electronic tracking or DGPS while the AUV is on the surface.

3.2.3 AUV motions

The motions should be measured by adequate instrumentation. The AHRS (Attitude Heading Reference System) supplies information on the 3-axis angular velocities, 3-axis acceleration, 2-axis inclination, and heading angle to the control system. The yaw and pitch angles could be measured using AHRS. Inertial navigation system (INS) could be also used to measure horizontal position and velocity through integrating the linear accelerations and angular velocities.

3.2.4 AUV depth

The depth should be measured by adequate instrumentation such as pressure sensor.

3.2.5 Control parameters

Rudder and elevator angle should be measured by adequate instrumentation (e.g. angular potentiometer) installed on the rudder or AUV hull.

Propeller and thruster shaft rpm should be measured by adequate instrumentation (e.g. angular potentiometer) installed on the AUV hull.

3.3 AUV Parameters

Following AUV related parameters should be documented:

- AUV type;
- Principal dimensions and Inertial parameters (*Length, Diameter, Mass, Cruising and maximum Velocity, Diving Depth, etc*);
- Lateral/longitudinal projected area;
- Rudder/ elevator type;
- Number of rudders/elevators;
- Rudder/ elevator area;
- Rudder/ elevator angle;
- Propeller/thruster type;
- Propeller/thruster diameter and pitch;
- Number of propellers/thrusters and turning direction of each propeller/thruster;
- Battery or power supply type;
- Auto-pilot / control parameters;
- Propeller position;
- Thruster power;
- Battery volume;
- Payload information.

3.4 Initial Conditions

The following data is to be clearly recorded for each trial:

- Date / Time;
- Area of trial;
- Initial approach speed, heading, pitch, and depth of AUV;
- AUV's loading condition (weight, longitudinal centre of gravity and transverse metacentric height);
- Radii of gyration;
- Water depth;
- Environmental conditions, including
  - Current speed and relative direction;
  - Wind relative speed and direction;
  - Sea state.

4. COMPOSITION OF THE AUV

4.1 Overview

An AUV is generally composed of a mechanical system, a communication system and a control system. Its mechanical system includes the hull structure, the thruster and control device(s). Its communication system, which enables it to communicate with surface or other vehicles, includes wired and wireless LAN and a R/F modem and/or acoustic modem. Its control system includes a computer, electrical interface boards, sensors and software.

4.2 Mechanical System

The hull size of AUV is constrained by the space for the on-board instruments, and the hull shape is constrained by the AUV's hydrodynamic characteristics. The instruments (sensors, control devices, etc) constituting mechanical system are different according to the operation purpose of AUV. Therefore, if possible, it is recommended to show the hull structure and the general arrangement in order to increase the understanding of the mechanical system, see for instance Fig. 11.

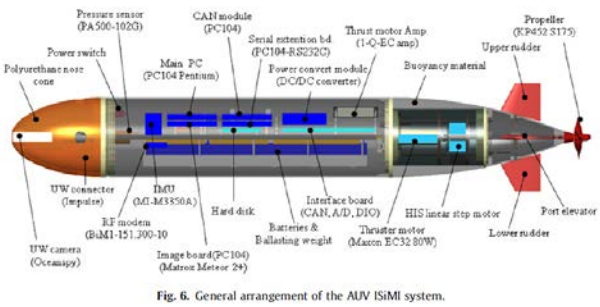

Figure 11 General arrangement (Jun et al. (2009))

4.3 Communication System

Although an AUV is capable of autonomous operations, it is often advantageous to maintain contact with the vehicle from the surface. If possible, it is recommended to show the architecture of the communication system in order to increase the understanding of the communication system.

When the communication system is used in the trial, following related information should be explained:

- Communication interface;
- Communication network;
- Communication strategy;
- Transmitter type and specification (Bandwidth, data rate, output, protocol).

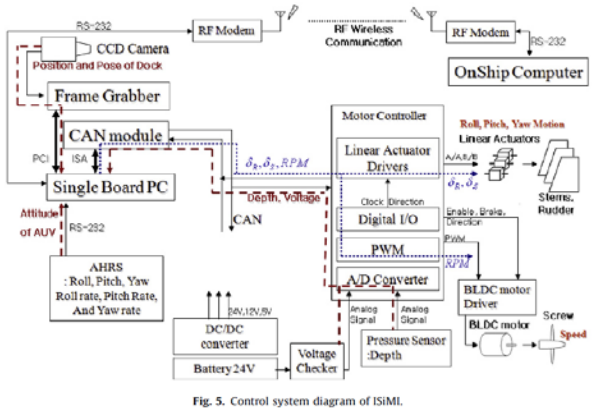

Figure 12 Control system diagram including communication system (Jun et al. (2009))

4.4 Control System

In the case of an AUV, in contrast to a manned surface ship, a control system for controlling the AUV's motion is indispensably required in order to achieve the operation purpose of AUV. If possible, it is recommended to show the diagram and software architecture of the control system in order to increase the understanding of the control system.

It is also recommended to explain the control system used in the trial, and the following related information should be explained:

- Control algorithm or methodology;
- Determination of control input or force;
- Feedback sensor signals;
- Sensors and its characteristics;
- Control actuator and its characteristics;
- Control system block diagram.

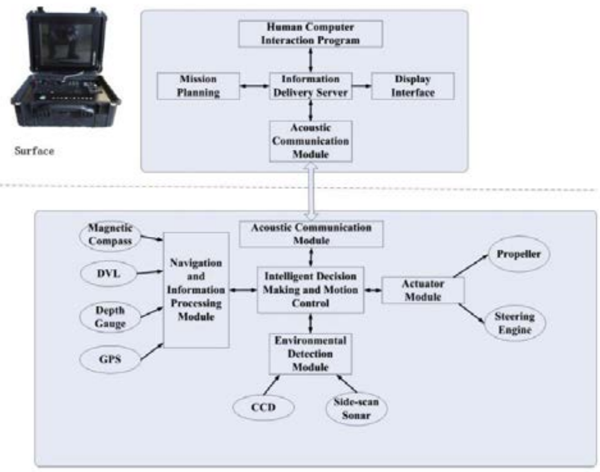

Figure 13 Software architecture of the control system (Zhang et al. (2018))

5. DATA ANALYSIS

5.1 Correlation between Numerical Simulations and Full Scale Trials

If the full scale trials are to be compared to numerical simulations, the sensor signals which are used in the numerical simulations must be properly defined according to the sensor signals of the AUV in the full scale trials.

It is also important to check if the control force and its characteristics are equivalent in numerical simulations and full-scale trials.

5.2 Uncertainty Analysis

5.2.1 General

Trial data uncertainty analysis should be carried out to assess the level of confidence in the trial results and to provide the statistics associated with AUV trial measurements.

For the uncertainty analysis of AUV position and speed, shaft rpm and torque, reference can be made to the uncertainty analysis section of the Final Report and Recommendations to the 23rd ITTC - The Specialist Committee on Speed and Powering Trials (ITTC, 2002).

The effect of errors in rudder angle or control device setting on the manoeuvre is difficult to assess through conventional uncertainty analysis. It is recommended to make use of simulation techniques for this purpose, for instance the method described in the ITTC procedure 7.5-02-06-05, Uncertainty Analysis for Free Running Model Tests.

5.2.2 Correction due to Environment

The environmental conditions such as current can significantly affect the AUV's manoeuvrability. For particular trials close to the sea surface, the wave elevation will also be a disturbance. IMO Resolution MSC.137(76) (2002) suggests a method to account for environmental effects. It could also be a reference to full scale trials test of AUV.

5.2.3 Correction due to AUV Initial Conditions

When the trials are performed, the AUV's manoeuvrability can be affected by the initial condition of the AUV. In general, initial speed, position, depth, and heading angle affect the determination of control input and the trial results.

It is also important to keep the initial conditions constant in the full scale trials in order to ensure the reliability of test results.

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