Procedures for Manoeuvrability Characterization: From Ships to Marine Robots

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Abstract

The work aims at presenting an extension of the ITTC standard procedures, employed for the identification of vessel characteristics and performance, towards marine robotic platforms. An automatic system for the execution of standard manoeuvring procedures is exploited to perform an autonomous data gathering and system identification. Execution of zig-zag, turning circle and pull-out manoeuvres are described and experimental data are reported with respect to the employment of the SWAMP ASV. A subsequent data analysis is performed to obtain a dynamic model that can be exploited for motion estimation and synthesis/adaptation of control schemes.

1. Introduction

The International Towing Tank Conference (ITTC) has developed, starting from the International Maritime Organisation (IMO) manoeuvring criteria, *IMO (2002)*, a set of manoeuvring guidelines for ships designed to provide a standard method for assessing their manoeuvrability in various conditions. The ITTC procedures, *ITTC (2021a, 2017a,b)* for detailed reference, include these manoeuvre tests:

- Turning (circle): the purpose is to measure the ship's manoeuvring spaces, to evaluate both its ability to change course and its ability to carry out emergency manoeuvres to avoid a collision.
- Zig-zag: this manoeuvre tests a ship's ability to change direction quickly while maintaining a steady speed.
- Direct/reverse spiral: this test allows the steering diagram to be plotted by points in order to test ship's dynamic stability.
- Pull-out: this test allows to evaluate the ship's ability to disengage from the evolution
- Stopping: the manoeuvre is performed to test the ability of the vessel to stop in order to avoid collision with an obstacle in its path.

The ITTC manoeuvres are used by ship designers and builders to evaluate the manoeuvrability of new ship designs and by ship operators to evaluate the manoeuvrability of their ships in specific operating conditions, *SIMMAN (2020)*.

In recent years, there has been an increasing interest in the application of ITTC manoeuvres to marine robots, such as Autonomous Surface Vessels (ASVs), Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs). These marine robots are used in a variety of applications, including oceanography, hydrography, surveillance, and search and rescue.

The use of ITTC manoeuvres for marine robots has several advantages. First, they provide a standard method for evaluating the manoeuvrability of marine robots in various conditions. Second, they can be used to optimize the design of marine robots for specific applications. Finally, they can be used to evaluate the performance of marine robots in real-world conditions. In particular, bearing in mind the future vision of marine robots operating in daily maritime traffic, it is crucial to identify the operational capabilities and limitation in order to guarantee a safe and efficient environment where autonomous agents and manned vessels can coexist.

There are also several challenges that must be overcome in order to extend the ITTC principles to the evaluation of marine robots' manoeuvrability. One challenge is that the ITTC manoeuvres were developed for ships, which have different characteristics than marine robots. For example, ships have a large displacement and a deep draft, while marine robots are typically smaller and have a much shallower draft. Another challenge is that the ITTC manoeuvres were developed for manned ships and models, while marine robots are typically operated remotely or autonomously, using specific NGC (navigation, guidance and control) algorithms. The essential challenge for marine robots, when it comes to integrating ITTC procedures, lies in the lack of vehicle classification and absence of guidelines, which instead are established for traditional ship hulls. In marine engineering and naval architecture hulls are divided in hulls families or systematic series, each series is derived from a mother hull. For every hull of each family there are known features, among which geometry, propulsive performance and characteristics. No such thing exists for marine robotic vehicles. Creating this base knowledge is the main challenge of manoeuvrability standardisation in marine robotics.

In the case of autonomous underwater vehicles (AUV) operating throughout the water column, specific ITTC procedures were developed to identify the characteristics of vertical motion, *ITTC (2021b)*. Autonomous surface vehicles (ASV), on the other hand, can be considered "small vessels", therefore the ITTC procedures can be applied directly to such autonomous platforms, with appropriate adaptations related to the specificities of this type of robotic vehicles.

The aim of this paper is to describe the development of automated procedures allowing the "fast" identification of the manoeuvring capabilities of the specific autonomous agent; the term "fast" refers to the fact that the overall procedure can be executed within minutes to hours, depending on the resolution and degree of accuracy that the operator intends to cover over the operational span of the vehicle as opposed to days (weeks) normally required for such characterisation for traditional ships (military vessels).

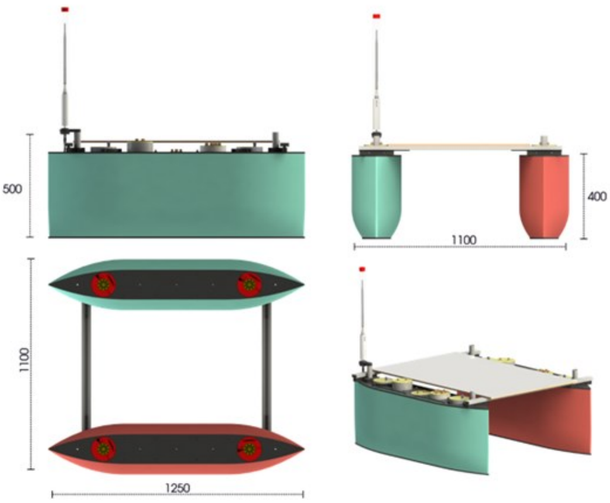
Thanks to the intelligence onboard the autonomous vehicle, the system can automatically execute the sequence of required manoeuvres for providing the estimation of navigation performance. The presented work starts with the migration of the standardized ITTC procedures to ASVs in order to assess the feasibility of such manoeuvres and, in case, adapt or add further procedures to characterize different/non-conventional hulls and thrust configurations.

2. Robotic Platforms Today

Autonomous marine platforms currently rely on consolidated technology; although new materials, alternative hulls and propulsion concepts and innovative control systems are still pacing the design of brand-new prototypes, the industrial sector has exponentially increased the production of commercial autonomous vessels. Then marine robotic fleet designed and built by CNR-INM are shown in Fig.1.

Fig.1: Different robotic platforms designed by CNR-INM: ASV SWAMP (left), ROV/AUV Proteus (centre), ROV/AUV e-URoPe (right)

The ASV SWAMP (Shallow Water Autonomous Multipurpose Platform), Fig.2, *Odetti et al. (2020), Bibuli et al. (2022)*, is an autonomous catamaran with double-ended hulls, providing increased stability, smaller draft with higher payload. SWAMP is characterised by enhanced manoeuvring in narrow space and shallow water thanks to the bespoken thrusters flushed with the hull. Achieving good stability was the main driver in the choice of the catamaran shape since payload elements, like sonars used for mapping the sea bottom, request for stable platform with minimised motions. The need for a wide payload area suitable for modularity and re-configurability, *Pellegrini et al. (2023),* shaped the design of SWAMP. The main idea behind the choice of double-ended hull was the possibility of coupling this solution with the adoption of four azimuth thrusters to be adequately manoeuvrable also in restricted and perturbed waters. Modularity was one of the main ideas behind the design of this autonomous surface vessel. Every hull is composed of various transverse sections of lightweight foam whose number or shape may be modified in function of the actual needs. In this way, the geometry geometry of the hull may be modified to increase the volume and reduce the immersion or to augment stability or to reduce the drag or in function of other operational requests. This concept also allows thinking of the hull as a modular structure where propulsion units, batteries in a various number, sensors and payloads may be positioned or removed from the hull. The vehicle is constituted by the two mono-hull vehicles and the two connection bars. Payload like winches, samplers, sensors, landing pads, etc.; can be installed on the payload deck. The final weight of the entire catamaran structure is 35 kg.



Type:	Double Ended Catamaran	
Overall Length	[mm]	1230
Minimum Breadth	[mm]	700
Maximum Breadth	[mm]	1250
Distance Between Hulls	[mm]	800
Construction Height	[mm]	500
Maximum Draft	[mm]	150
Light Weight	[kg]	35
Maximum Weight	[kg]	60
Buoyancy Reserve	[kg]	70
Propulsion Unit Thrust	[N]	12.5
Propulsion Units	nr	4
Autonomy at maximum power	[h]	2
Operating Speed	[m/s]	1
Maximum Speed	[m/s]	1.6
Mean Energy Consumption	[Wh]	400
Voltage	[V]	44,4
Single Battery	[Ah]	13
Number of batteries	nr	2
Communication	Wifi - Radio	
Steering Ability	DP	
NGC Sensors	2 x (GPS, AHRS, Camera)	

Fig.2: ASV SWAMP general layout with measures

3. Automated ITTC Manoeuvres Execution

This section describes the manoeuvrability test plan for the autonomous surface vehicle SWAMP, adapted from the standard manoeuvrability tests (IMO and ITTC). To this end, some standard manoeuvrability tests of ships and how these were adapted to the SWAMP case, *Ferretti et al. (2022),* are described in the following.

Most manoeuvring tests start from a straight course condition with as steady as possible values of heading, speed, rpm, and rudder angle or corresponding (pod angle, water-jet steering nozzle angle, etc.). Straight-line speed runs should be carried out in order to find the propeller rpm corresponding to the desired test speed. The most common tests are those referred in IMO Resolution MSC.137(76). The test is initiated by the order to the steering system to execute the actual test.

The procedure reported in the following has to be suitably adapted to the specific autonomous platforms since, for instance, they refer to rudder angles, but the ASV SWAMP is equipped with azimuth thrusters and no rudder is present; thus, in this case, the rudder angle is considered as the azimuth angle applied symmetrically to each thruster pod. The value of the propeller rpm has, for the SWAMP platform, to be intended as the revolution rate of each thruster pump.

The innovative contribution of this work is the completely automated execution of the manoeuvre set, that is autonomously managed by the control architecture onboard the robot. The manoeuvre list, with the specific parameter settings e.g. rpm, azimuth angles, number of circles, etc.; are pre-compiled by the operator and fed to the system. Additional information such as the georeferenced center of the operational area and the main north-referenced direction for the platform motion (in particular for the zig-zag manoeuvres) are also defined. Thanks to the latter information set, the automatic system can compute a number of waypoints that the platform will track prior to each manoeuvre, in order to execute each manoeuvre always at the same (practically) identical initial conditions. In particular, the system executes the following set of operations in preparation of each manoeuvre:

1. The vehicle moves to the initial waypoint, the "entrance" of the operational area;
2. The vehicle moves to a second waypoint in order to get aligned along the main direction of the manoeuvre (the orientation of the zig-zag motion or the tangent line to enter into the turning circle);
3. The vehicle moves to a third waypoint (on the same line connecting the first and second waypoints), setting the intended rpm/speed required for the specific manoeuvre;
4. The manoeuvre execution is activated;
5. If zig-zag – the manoeuvre is ended when 3 complete oscillations (3 on starboard side and 3 on port side) are achieved.
   If turning-circle – the manoeuvre is ended when 3 complete turns are achieved;
6. Only for turning-circle – when the turning is completed, a pull-out manoeuvre is commanded, requiring the platform to proceed at constant rpm and zero rudder/azimuth angle for 30 seconds;
7. The manoeuvre is completed and the related data are logged. If other manoeuvres are scheduled, the execution loop starts again, otherwise the automatic procedure is completed and the vehicle will stop standing by for further commands from the operator.

3.1 Turning circle and Pull-out test

The Turning Circle (TC) test is generally started with a hard over rudder angle (generally 35° starboard and portside) and finished by a pull-out by putting the rudder back to neutral angle after completing the turning test, i.e.; after reaching a steady yaw rate. The ship is kept on the circular path for at least one and a half turns (540°), but it is better if at least two turns (720°) are covered, so that the recorded values can be corrected considering the deviations caused by the current and the wind.

For the TC tests, the following parameters should especially be taken into account:

- initial forward speed(s) u
- initial propeller rate(s) of rotations n
- ordered steering device angles δ

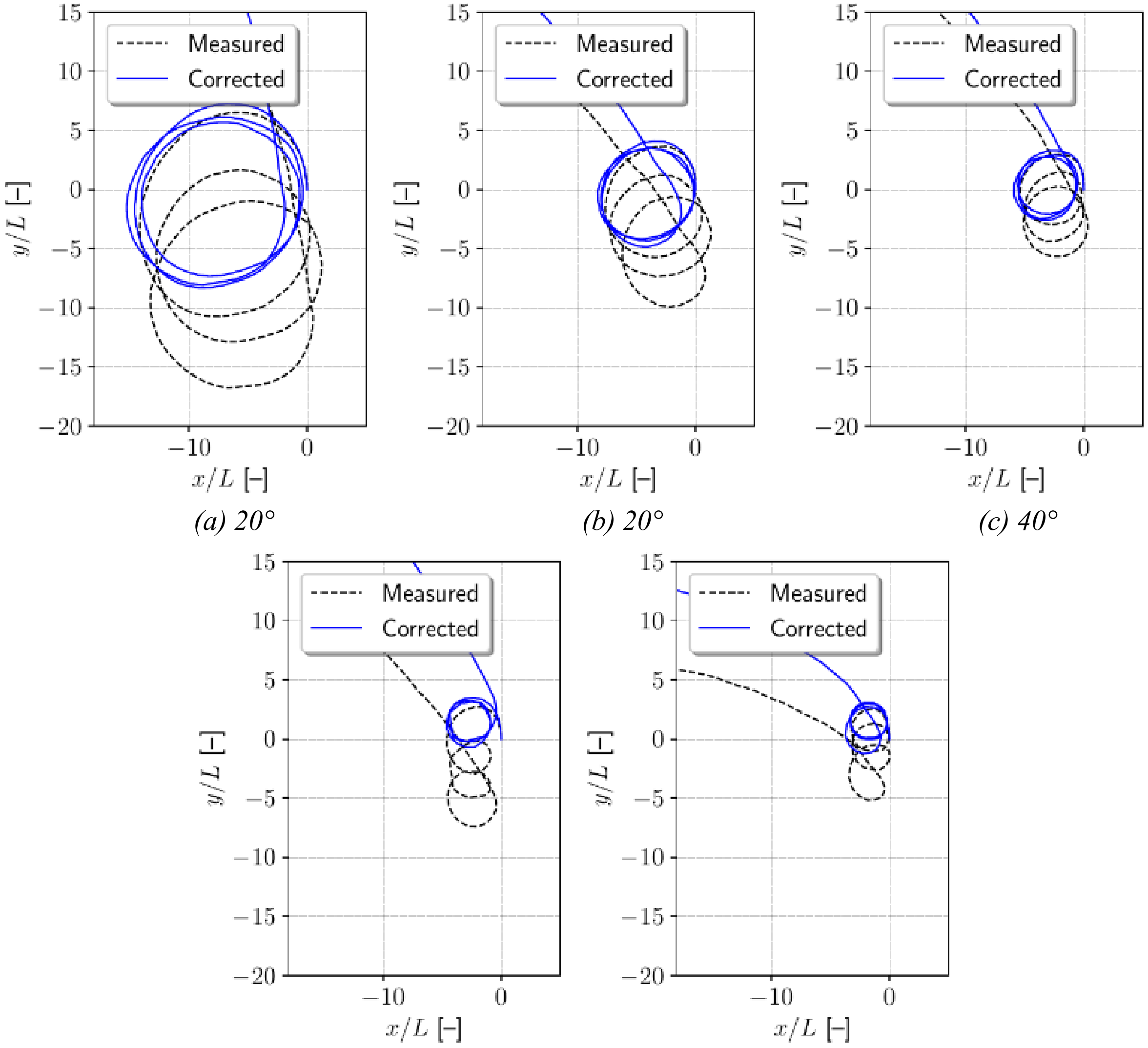
The values set during the turning circle tests are summarized in Table I; each trial ends with a pull-out manoeuvre.

Table I: Turning circle and pull out: combinations of azimuth angles and thruster speed during test

Azimuth angle	**Thruster speed**
±20°	1200/1600 rpm
±30°	1600 rpm
±40°	1600 rpm
±50°	1600 rpm
±60°	1600 rpm

(*) TC test correspond to 3x360° + pull out

Fig.3 reports the normalized vehicle position (x/L and y/L) plot during the execution of a set of port side turning circle tests at 1600 rpm, corresponding to about a U = 1 m/s. The motion of the circles centre (measured data), thus indicating the presence of sea current or wind, that has been estimated to correct the data and identify the ideal (but not perfect) manoeuvre in calm water, allowing insight of the manoeuvrability behaviour of the model, e.g.; Fig.4 shows the tactical diameter (TD) as a function of the azimuth angle δ, including the expected value (EV) and the standard deviation (SD) over three turns.



(a) 20° *(b) 20°* *(c) 40°*

(d) 50° *(e) 60°*

Fig.3: Example of data acquired (measured) and corrected (due to sea current) during port side turning circle test at 1600 rpm varying the azimuth angle

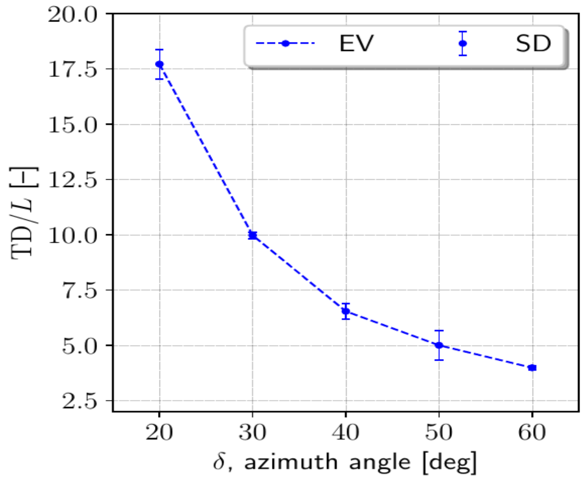


Fig.4: Tactical diameter TD as function of azimuth angle for port side turning circle test at 1600 rpm

At the end of each TC test, a Pull-out manoeuvre is executed by going back to the steady course rudder angle after a short execute of the rudder (some 10°) to port and starboard side.

With a deeper look into the turning-circle data, as well as in the pull-out manoeuvre, it is possible to notice a biased motion on the port side of the vehicle, Fig.3. This behaviour highlights an asymmetry in the platform configuration, resulting in a corrupted motion characteristic.

3.2 Zig-zag test

The first two overshoots should be accomplished when possible. These tests are conducted to port and starboard. The zig-zag (ZZ) manoeuvre is obtained, starting from a straight course travelled at constant speed with the rudder at the neutral angle, bringing the rudder to a predetermined rudder angle $+\alpha_0$ to starboard and keeping it in this position until the ship rotates the heading by a predetermined angle $+\delta_0$ (defined as the angle between the guideline reached and the guideline held at the entrance to the manoeuvre and indicated as ship heading), after which the rudder is rotated to the opposite side by the same amount ($-\alpha_0$) and leave it in this position until the ship responds to the rudder with a heading variation, again measured with respect to the straight-line entry course, equal to $-\delta_0$. The bar angles are obviously referred to the neutral bar angle. The procedure, repeated at least five times to stabilize the manoeuvre, test the test conditions and collect additional data, is characterized by the choice of the two angles (α_0, δ_0), and is indicated by the abbreviation α_0/δ_0. Usually, even if not established by the rules, the first approach is made to starboard to verify the behaviour of the ship to the need to disengage from another ship that crosses in the opposite direction. The IMO has standardized 10°/10° and 20°/20° zig-zag manoeuvres, to evaluate the behaviour of the ship at a medium and high rudder angle. In particular, the former is recommended because it provides useful information for assessing course stability. It tests manoeuvrability for medium-small rudder and turn angles, closer to the usual course control angles. For large ships, it is also recommended to carry out the zig-zag manoeuvres with angles of 15° and 25°.

The modified zig-zag manoeuvre test is used to express course-keeping qualities in conditions like actual operations characterized by small heading changes and rudder values. The test procedure for a modified zig-zag manoeuvre is the same as for zig-zag manoeuvre, but the execute heading angle is chosen to be as small as 1°, the rudder angle being 5° or 10°, *ITTC (2017b).*

Following parameters should especially be taken into account:

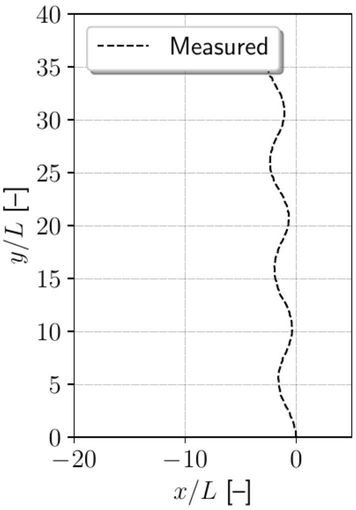
- initial forward speed(s) u
- initial propeller rate(s) of rotations n
- ordered steering device angles δ and heading angle ψ (δ/ψ, i.e.; 10°/10° or 20°/20°)
- turning speed of steering device

The values set during the zig-zag tests are summarized in Table II. Fig.4 shows an example of normalized ship trajectories conditional to azimuth angle at 1600 rpm. For the same test set, the thruster heading (mean value of the four thrusters) is compared to the yaw angle in Fig.5, providing an insight of the ZZ overshoots.

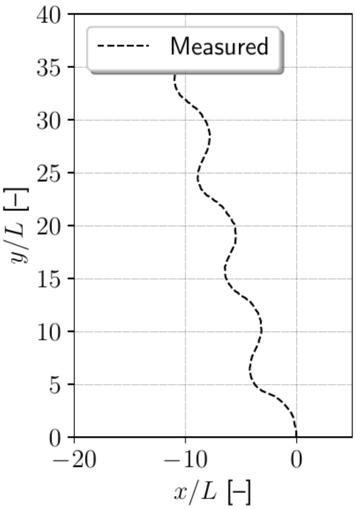
Table II: Zig-zag test: combinations of values for azimuth angles/heading and thruster speed

Azimuth angle / Heading [deg]	**Thruster speed**
10°/10°	800/1000/1200/1400/1600 rpm
15°/15°	800/1000/1200/1400/1600 rpm
20°/20°	800/1000/1200/1400/1600 rpm
25°/25°	800/1000/1200/1400/1600 rpm
30°/30°	800/1000/1200/1400/1600 rpm
40°/40°	800/1000/1200/1400/1600 rpm
50°/50°	800/1000/1200/1400/1600 rpm
60°/60°	800/1000/1200/1400/1600 rpm

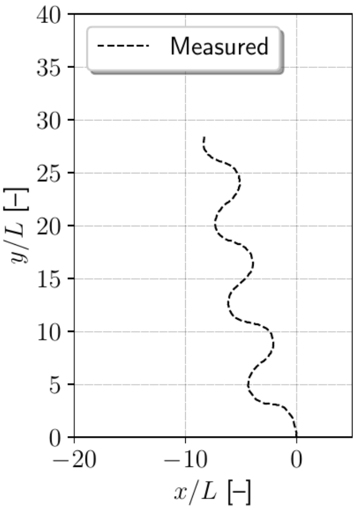
(*) 6 angle changes for each test



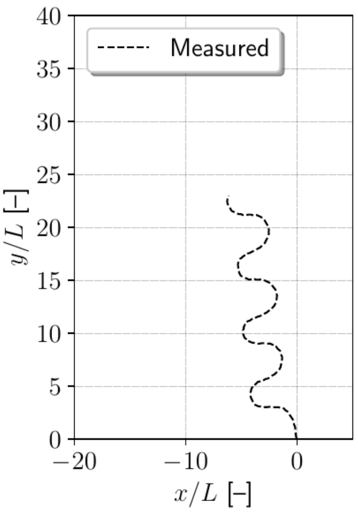
(a) 20°



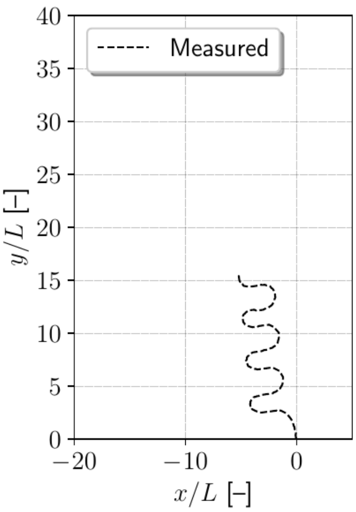
(b) 30°



(c) 40°

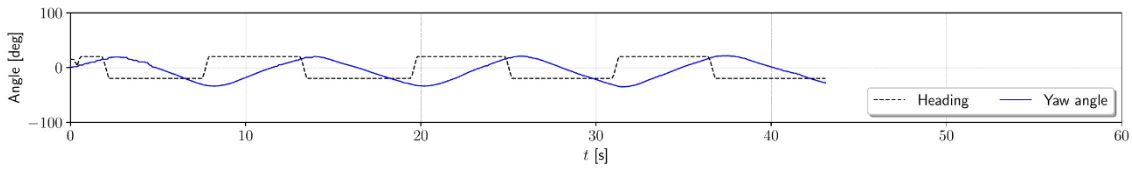


(d) 50°

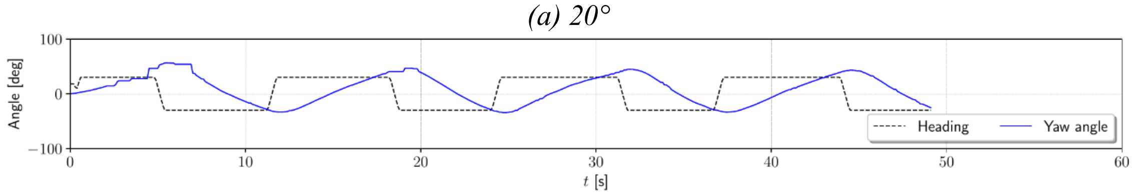


(e) 60°

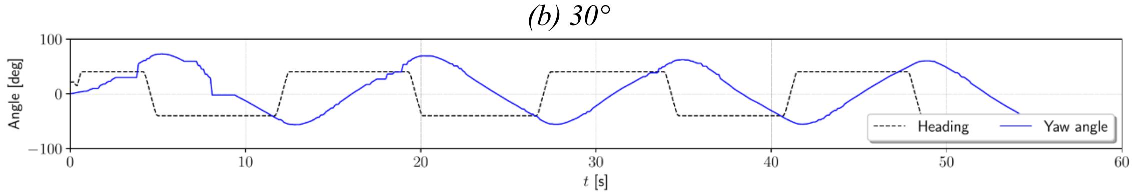
Fig.4: Example of data acquired (measured) zig-zag test at 1600 rpm varying the azimuth angle



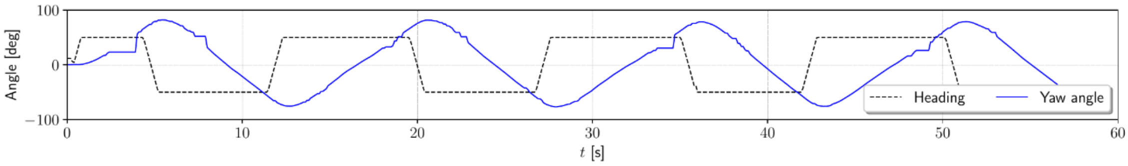
(a) 20°



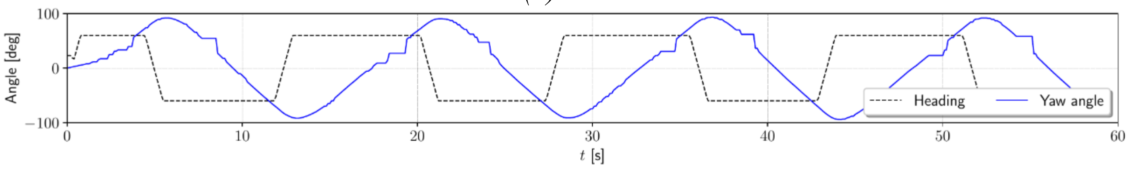
(b) 30°



(c) 40°



(d) 50°



(e) 60°

Fig.5: Example of data acquired during a zig-zag test: thruster heading vs yaw angle at 1600 rpm

6. Data analysis

A practical dynamic model of the platform has been derived from the acquired data. The form of the model is the one usually employed for control design purpose and described as follows:

$$I_r\, \dot{r} = k_r\, r\ +\ c_{r_u}\, r\, |u| + c_{r_v}\, r\, |v| + b_r\, \delta \qquad (1)$$

r is the yaw-rate, u and v the surge and sway velocities, δ the azimuth angle, I_r the moment of inertia, k_r the linear drag term, c_{r_u} and c_{r_v} the cross-velocity drag terms, and b_r the input interface term.

Since the moment of inertia is known and equal to 7.58 Kg/m^2, it is possible to estimate the unknown drag and input interface terms through a left pseudo-inversion operation:

$$\frac{1}{I_r}\begin{bmatrix} k_r \\ c_{r_u} \\ c_{r_v} \\ b_r \end{bmatrix} = \begin{bmatrix} \underline{r} & \underline{r}\,|\underline{u}| & \underline{r}\,|\underline{v}| & \underline{\delta} \end{bmatrix}^{\#} \underline{\dot{r}} \qquad (2)$$

where the underlined terms represent the measurement vectors. The four terms have the following values reported in Table III.

Table III: Values of the dynamic model parameters

k_r	-13.5227
c_{r_u}	7.2526
c_{r_v}	2.6854
b_r	3.9683

The calculated parameters are then used to estimate the dynamic behaviour of the platform by integrating over the time the dynamic equation (1). This procedure has been performed both for the zig-zag manoeuvre, the result is depicted in Fig.6, and for the turning circle followed by the pull-out phase, reported in Fig.7. In both the experiments it is possible to notice the superimposition of the estimated signal with respect to the actual measure.

The model identified can be furtherly employed for the synthesis of guidance and control loops, where possible deviation of the parameter values from the actual ones (due to changing operational conditions and measurement errors) can be mitigated by means of adaptive control schemes, as for instance reported in *Bibuli et al. (2020)*.

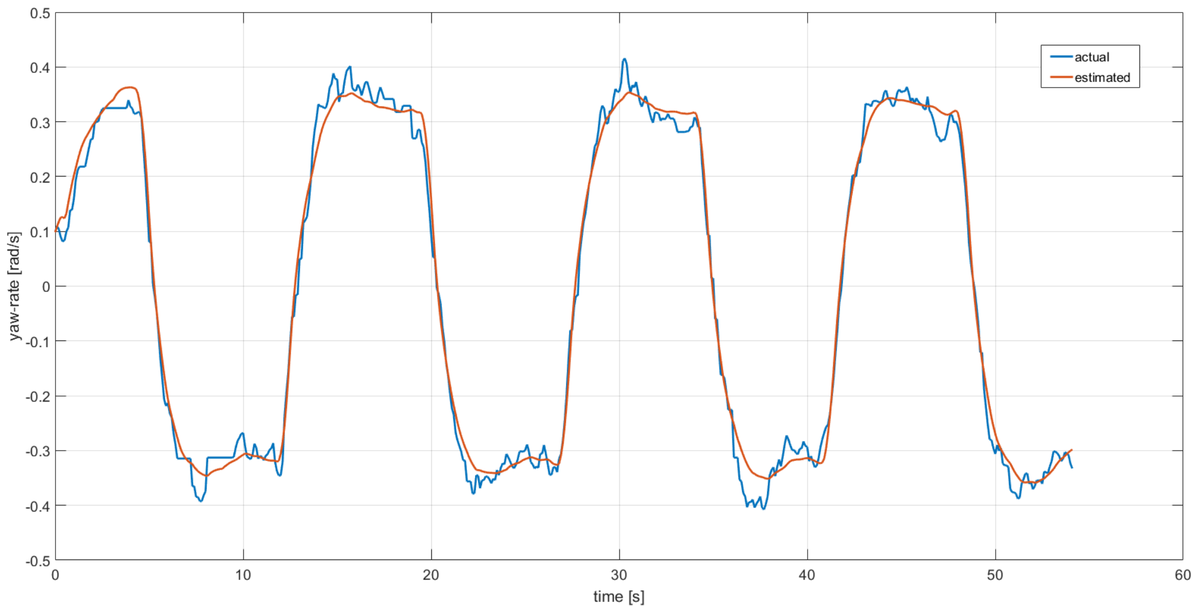


Fig.6: Platform motion estimation during the zig-zag manoeuvre

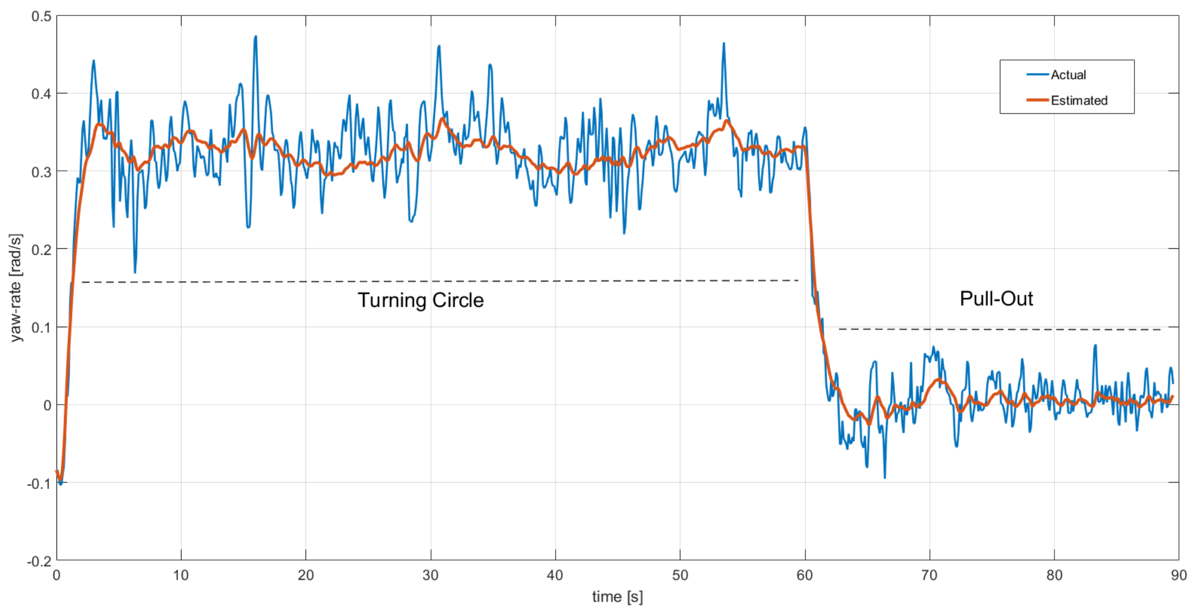


Fig.7: Platform motion estimation during the turning circle manoeuvre

7. Conclusions

The ITTC manoeuvres are a valuable tool for evaluating the manoeuvrability of ships, and there is growing interest in extending these manoeuvres to marine robots. However, there are several challenges that must be overcome in order to extend the ITTC manoeuvres to marine robots, such as the differences in characteristics and operation between ships and marine robots.

Extending such process to autonomous robotic platforms allows the automatic execution of the manoeuvring procedures in a repeatable and consistent framework, allowing a fast identification of the main characteristics of the platform, including the self-adaptation of navigation, guidance and control schemes. Such a fast procedure is of great support in marine robots exploitation, since their payload and configuration can significantly change over time because of the specific operational requirements.

This work represents a first step in the direction of standardisation of ship procedures with the aim of including robotic technology in the framework of marine traffic regulation, in the future view of collaborative manned and unmanned vessel cooperating together.

Acknowledgements

The authors wish to thank Giorgio Bruzzone, Mauro Giacopelli and Edoardo Spirandelli (CNR-INM/Genoa) for their fundamental contribution to SWAMP design and development. This work is developed within the framework of the National Recovery and Resilience Plan (NRRP), RAISE-Robotics and AI for Socioeconomic Empowerment.

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