Technical Report

Test plan for SWAMP maneuverability

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This technical report describes the maneuverability test plan for the autonomous surface vehicle SWAMP (Shallow Water Autonomous Multipurpose Platform), adapted from the standard maneuverability tests (IMO and ITTC). To this end, we start by describing some standard maneuverability tests of ships and then how these were adapted to the SWAMP case.

1. Standard maneuvering tests

The following paragraphs summarize the standard procedures for some types of maneuvers typically used to study vessel maneuverability (Ref. [1],[2],[3]).

1.1 Initial test condition.

Most maneuvering 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 to in IMO Resolution MSC.137(76). The test is initiated by the order to the steering system to execute the actual test.

• **turning (circle) test**, generally started with a hard over rudder angle (generally 35° starboard and port) 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 taking into account the deviations caused by the current and the wind.

<u>Turning circle tests</u>

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

• **zig-zag test** (10°/10°, 20°/20°, or modified), the first 2 overshoots should be accomplished when possible. These tests are conducted to port and starboard.

The zig-zag maneuver is obtained, starting from a straight course traveled at constant speed with the rudder at the neutral angle, bringing the rudder to a predetermined rudder angle + α0 to starboard and keeping it in this position until the ship rotates the heading by a predetermined angle + δ0 (defined as the angle between the guideline reached and the guideline held at the entrance to the maneuver and indicated as ship heading), after which the rudder is rotated to the opposite side by the same amount (- α0) 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 –δ0. The bar angles are obviously referred to the neutral bar angle. The procedure, repeated at least five times to stabilize the maneuver, test the test conditions and collect additional data, is characterized by the choice of the pair of angles (α0, δ0), and is indicated by the abbreviation α0 / δ0. Usually, even if not established by the rules, the first approach is made to starboard to verify the behavior 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 maneuvers, in order to evaluate the behavior of the ship at a medium and high rudder angle. In particular, the former is recommended because it provides particularly useful information for assessing course stability - in fact, it tests maneuverability 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 maneuvers with angles of 15° and 25°.

<u>Zig-zag or modified zig-zag tests</u>

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

• **pull-out test** by going back to the steady course rudder angle after a short execute of the rudder (some 10°) to port and starboard.

NOTE: The position and heading of the model are the most important information obtained from the free model tests; hence the accuracy of these measurements should be documented.

1.2 Vehicle data

The following parameters should be considered for all free running maneuvering model tests (Ref. [1],[2])

- scale
- model dimensions
- ratios of model to basin dimensions
- water depth
- hull configuration
- propulsion and steering arrangements

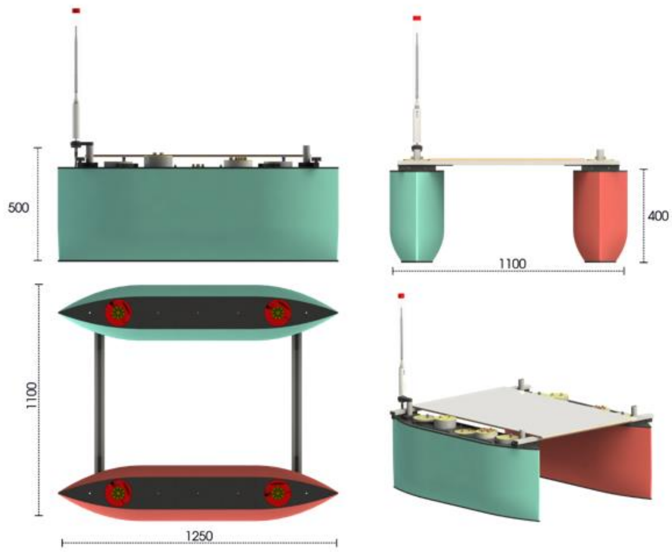
• loading condition of ship model
• model mass
• position of center of gravity of ship model
• moments of inertia of ship model

1.3 Complementary data

• Environmental conditions (wind, currents, …)
• Temperature of water measured at a depth near half of the model draught

2. SWAMP MANEUVERING TESTS

SWAMP is a non-standard surface robotic platform, characterized by small size (1.20 m x 1.1 m x 0.4 m) and low weight (< 50 kg) as shown in Figure 1. It has a double hull catamaran structure equipped with four independent modules (minions) that operate pump-jet azimuthal thrusters completely contained in the hulls. These thrusters have the characteristic of being completely steerable over 360° (Figure 2). This means that SWAMP can maneuver in very small spaces. However, this fact also implies a series of considerations on the execution of the tests and on the quantities that need to be recorded to characterize maneuverability from an ITTC point of view.



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)	

Figure 1 - SWAMP characteristics

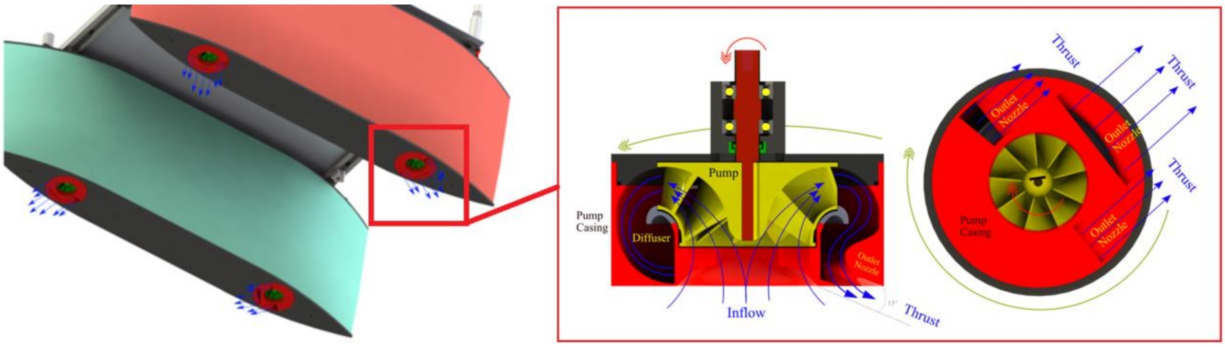


Figure 2 - Detailed view of SWAMP pump-jet azimuthal thrusters

The following table represents the list of variables required to be considered as Benchmark Data for Validation of Manoeuvring Predictions (Ref. [1],[2],[4]).

Symbol	Item	Unit
t	time	s
X	X position in earth fixed system	m
Y	Y position in earth fixed system	m
Z	Z position in earth fixed system	m
ϕ	Roll angle	degrees
θ	Pitch angle	degrees
ψ	Yaw angle	degree
u	surge velocity	m/s
v	sway velocity	m/s
w	heave velocity	m/s
p	roll rate	deg/s
q	pitch rate	deg/s
r	yaw rate	deg/s
δ	Rudder angle	deg
n	Propeller revolutions of portside propeller	rpm
T_{PS}	Thrust of portside propeller	N
T_{SB}	Thrust of starboard side propeller	N
Q_{PS}	Torque of portside propeller	Nm
Q_{SB}	Torque of starboard side propeller	Nm

Table 1 - List of variables required to be considered as Benchmark Data for Validation of Manoeuvring Predictions

1. The trajectory (X,Y) and time histories of heave z, angular motions $(\phi,\theta,\psi-\psi_c)$, dimensional velocities for 6DOF motions (u,v,w,p,q,r), rudder angle δ, thrust coefficient T and torque coefficient Q for each propeller and propeller rate of revolution n [rpm] after the ship was released (t = t0), should be submitted.
2. The ship position or trajectory should be given in an Earth-fixed coordinate system with X pointing North, Y pointing East, and Z pointing downward as shown in Figure 3. This XY axis system remains horizontal in the earth. The ship was released at (X0, Y0) when t = t0 . The roll angle (φ) is positive for pushing starboard into the water, pitch (θ) is positive for bow up position and yaw angle (ψ) is positive for bow turned to starboard. The reported trajectory

is dimensional and angular motions should be reported in degrees. The angular velocities should be reported in degree second. The reported yaw angle should be the deviation of yaw angle respect to the target yaw i.e. $\psi-\psi C$.

3. All velocities for 6DOF motions (u, v, w, p, q, r) should be reported in ship-fixed coordinate system with x axis positive toward bow, y axis positive toward starboard and z axis positive downward. This xyz axis system rotates with the ship in yaw but not pitch and roll, i.e., remains horizontal in the earth. It is a so-called “yawed-only reference system”. Given this convention, the reported velocities are:

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = \begin{pmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} p \\ q \\ r \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} \quad (2)$$

In Equation (2), the unit of p, q, r, $\dot{\phi}$, $\dot{\theta}$ and $\dot{\psi}$ is [deg/s].

4. Rudder angle (δ) is positive when trailing edge moves to portside.
5. The thrust T and torque Q for each propeller should be reported in shaft coordinate system with x axis positive toward the engine. Values are given dimensional
6. All motions should be reported at O. The origin is located on O which is located at midships.

The Earth-fixed coordinate system and all the variables are illustrated in Figure 3. The origin is located on O. The time t=0 is the time when the steering starts. The initial direction of the model is the direction of X-axis. Initial conditions at t = 0 are: X0=0, Y0=0, u=U0, δ=δ0 (which is the neutral rudder angle).

There is a right-handed earth-fixed coordinate system x0y0z0, and a horizontally moving right-handed body-fixed coordinate system xyz. The body-fixed coordinate system has its origin in O (midship), and the xy plane moves with the ship. The heading angle is defined as the angle between X- and x0-axis. u and v are the velocity components in x and y direction. The hull drift angle will be defined as β=atan(-v/u), and the total velocity U=√(u2+v2).

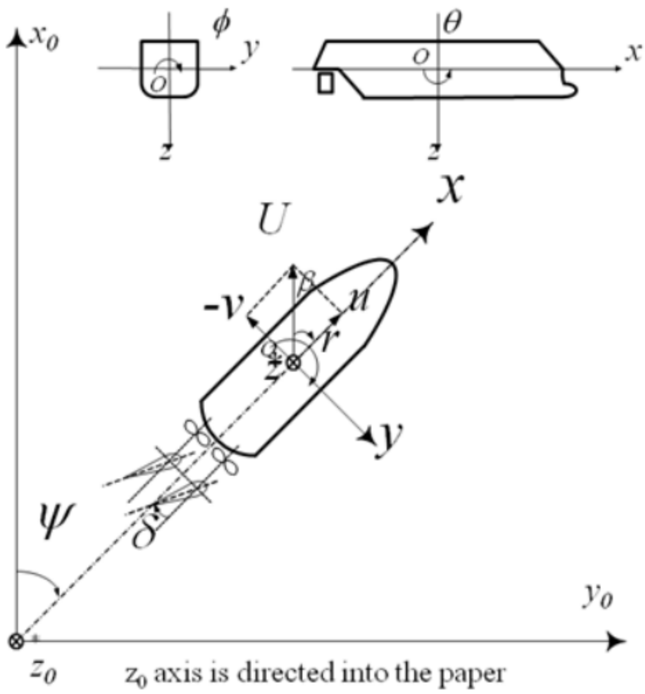


Figure 3- Illustration of the sign convention of the earth-fixed and body-fixed coordinate system

By comparing what is required by the standard procedures mentioned above with the quantities recorded and/or calculated in the case of SWAMP, the main difference to be underlined is that in the case of SWAMP there is no rudder angle (because there is no rudder) but there will be an azimuth angle value set on each module that controls the pump-jet azimuthal thrusters.

Starting from Table 1, a new table (Table 2) adapted to the SWAMP case was created, containing: the names of the variables required by the ITTC procedures followed by the name of our variables in the SWAMP telemetry, the standard name (if present in the CF convention otherwise is left empty), the type of variable (calculated, physically measured or set), the unit of measurement and any notes/comments .

Note: as described above, SWAMP has four independent modules (minions) that operate pump-jet azimuthal thrusters. They are identified according to their position inside the hulls: Front Right (FR), Front Left (FL), Rear Right (RR) and Rear Left (RL).

So in the table 2, XX represents the possible combinations of minions: XX = FR, FL, RR, RL

Name	**Telemetry name**	**Standard name**	**coverage_content_type**	**Unit**	**Note**
date		date	measured		Format ISO 8601
time	gpstime	time	measured		
latitude		latitude	measured	degree N	
longitude		longitude	measured	degree E	
X Position in earth fixed	xgps	projection_x_coordinate	calculated	m	

system					
Y Position in earth fixed system	ygps	projection_y_coordinate	calculated	m	
Z Position in earth fixed system	-				not present
horizontalAccuracy			measured	m	Provided by GPS
llhPositionValidFlags			measured	-	0/1 - not valid/valid
roll	phiIMU	platform_roll	measured	degree	
pitch	thetaIMU	platform_pitch	measured	degree	
yaw	psiIMU	platform_yaw	measured	degree	
surge velocity	platform_yaw	platform_surge_rate_fore	calculated	m s-1	
sway velocity	platform_roll	platform_sway_rate_starboard	calculated	m s-1	
heave velocity	-	platform_heave_rate_down			not present
speedAccuracy			measured	m s-1	
headingAccuracy			measured	degree	
nedVelocityValidFlags			measured	-	0/1 - not valid/valid
roll rate	asvMeas.pIMU.value	platform_roll_rate	measured	degree s-1	
pitch rate	asvMeas.qIMU.value	platform_pitch_rate	measured	degree s-1	
yaw rate	asvMeas.rIMU.value	platform_yaw_rate	measured	degree s-1	
surge_acceleration		platform_surge_acceleration_fore	measured	m s-2	
sway_acceleration		platform_sway_acceleration_starboard	measured	m s-2	
heave_acceleration		platform_heave_acceleration_down	measured	m s-2	
azimuth_angle_reference			set value	degree	
XX_azimuth_angle	XX_azimuthMotorAngle		measured	degree	This is the variable that can be assimilated to the "Rudder angle" in the case of the

					ship. There are four values, one for each minion.
thruster_speed_reference			set value	rpm	
XX_thruster_speed	XX_thrustMotorSpeed		measured	rpm	There are four values, one for each minion.
XX_thruster_force	-		calculated	N	It must be calculated and added to the telemetry for each minion
XX_thruster_current	-		calculated	Nm	It must be calculated and added to the telemetry for each minion starting from the thrust current value

Table 2 - List of variables adapted from Table 1 considering the SWAMP telemetry variables

2.1 Test plan and automatic execution of the operations

The tests for SWAMP maneuverability were conducted during a first test session in September 2022 at the Venice arsenal.

The wind and current conditions were not optimal for carrying out the tests, but they were nevertheless executed to validate the data acquisition procedures and to verify that all the required variables were correctly recorded by the system and present in the SWAMP telemetry. For this reason, the data collected are of little significance from the point of view of maneuverability analyses (Figure 4), but they are of fundamental importance for testing and validating the system and the acquisition chain in preparation for conducting further tests in an automated manner, when the environmental conditions are optimal.

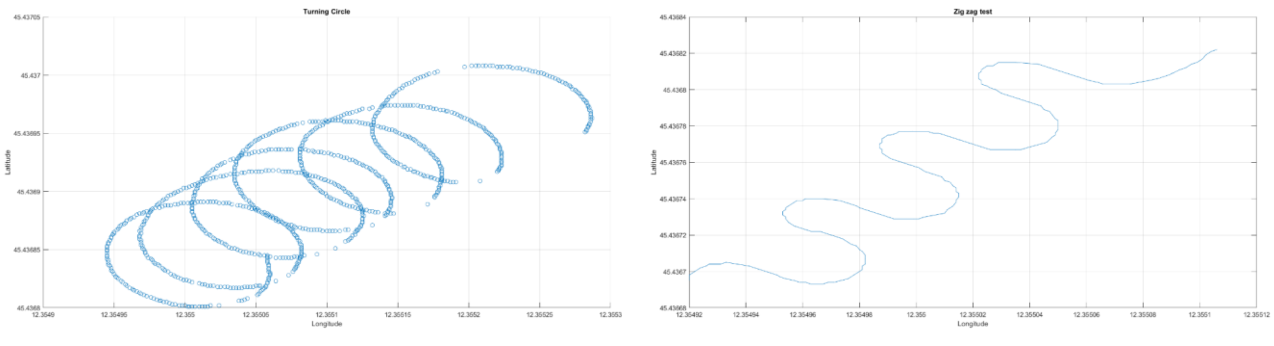


Figure 4 – Example of data acquired during the Turning circle test (left) and Zig-zag test (right).

2.1.1 Type of test and set values

The following tables summarize the values set during the turning circle tests (Table 3) and the zig-zag test (Table 4). In the case of turning circle, each trial ended with a pull out maneuver.

Type of test	Parameters	
	Azimuth angle (degree)	Thruster Speed (rpm)
Turning circle (540°) **+ Pull out**	±10°	400/600/800/1000/1200/1400/1600
(Performed at the end of Turning Circle)	±15°	400/600/800/1000/1200/1400/1600
	±20°	400/600/800/1000/1200/1400/1600
	±25°	400/600/800/1000/1200/1400/1600
	±30°	400/600/800/1000/1200/1400/1600
	±40°	400/600/800/1000/1200/1400/1600
	±50°	400/600/800/1000/1200/1400/1600
	±60°	400/600/800/1000/1200/1400/1600

Table 3 - Turning circle and pull out: combinations of values for Azimuth angles and thruster speed set during the test

Type of test	Parameters	
	Azimuth angle / Heading (degree)	Thruster Speed (rpm)
Zig-zag	10°/10°	400/600/800/1000/1200/1400/1600
(6 angle changes for each test)	15°/15°	400/600/800/1000/1200/1400/1600
	20°/20°	400/600/800/1000/1200/1400/1600
	25°/25°	400/600/800/1000/1200/1400/1600
	30°/30°	400/600/800/1000/1200/1400/1600
	40°/40°	400/600/800/1000/1200/1400/1600
	50°/50°	400/600/800/1000/1200/1400/1600
	60°/60°	400/600/800/1000/1200/1400/1600

Table 4 – Zig-zag: combinations of values for Azimuth angles/Heading and thruster speed set during the test

2.1.2 Automatic execution of maneuvers tests

For the execution of the tests, which require the combination of all the values contained in Tables 3 and 4, it was decided to automatize the sequence of instructions and the relative saving of the output files.

Two configuration files were created (one for the Turning circle and one for the Zig-zag) containing the list of operations with the parameters and the values of each parameter. These configuration files were used by the SWAMP GNC system to perform maneuvers automatically and sequentially.

A special section “Maneuvers” was also added to the SWAMP interface (Figure 5) containing three buttons which respectively allow the start, pause or resume of the maneuverability tests.

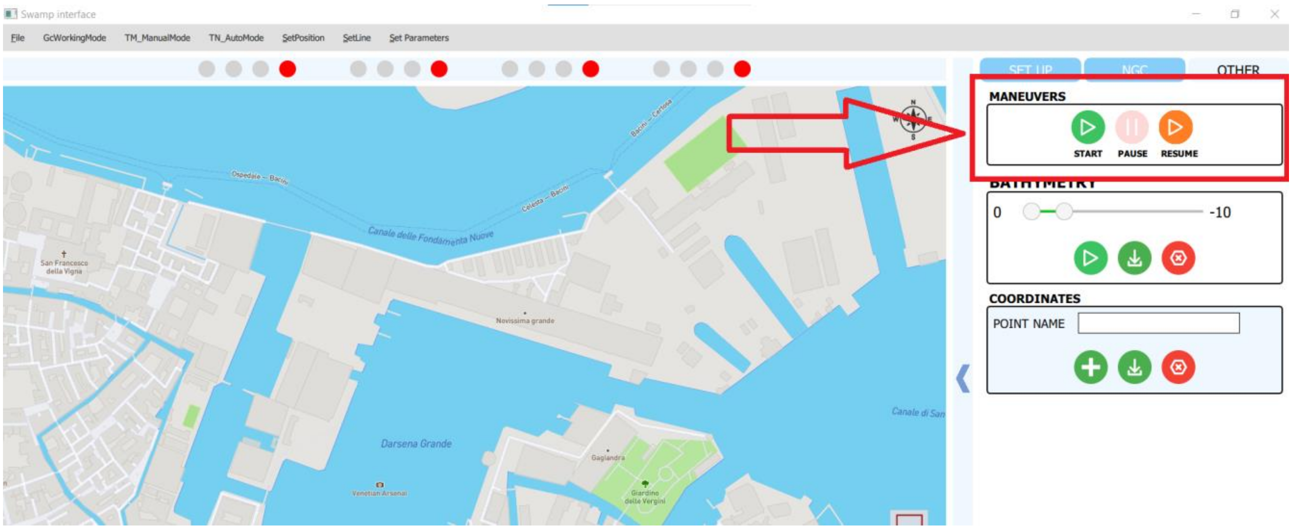


Figure 5 - Section of the SWAMP interface to manage the automatic execution of the maneuvering tests

2.1.3 File naming convention

Data coming from each test listed above should be registered in a separate file. The proposed file naming convention is the following one:

date_time_vehicleName_TestType_parametersValues.csv

where:

- date and time are expressed using the ISO8601 standard (date YYYYMMDD and time hhmmss)
- vehicleName indicates the platform used for the test (e.g. SWAMP, PROTEUS_ROV, PROTEUS_USSV, etc…)
- testType is one of the standard maneuvering tests recognized by the IMO (turningCircle, ZigZag, pull out, etc…)
- parametersValues are the value used during the test (azimuth angle, rpm, etc…)

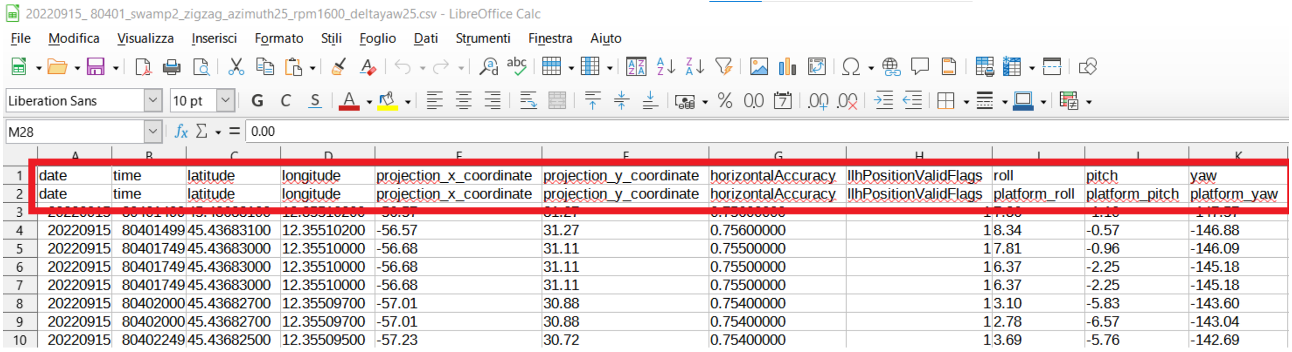
The file format is a comma-separated values (.CSV) file that is a delimited text file that uses a comma to separate values. Each line of the file is a data record.

Example:

20220912_113010_swamp2_turningCircle_azimuth15_rpm20.csv

As we need to be able to give a custom name to each variable in the log, but also a pointer to the standard variable, the .csv file has the first two rows containing two headers (Figure 6): the first header line contains the custom name as listed in the SWAMP telemetry, the second one contains the long_name of the standard variable that it refers to (following the CF convention [5], if possible).

This structure was chosen to be in a format that makes file management easier from a FAIR point of view and that allows us to create NetCDF files containing global metadata and variables metadata in a quick and structured way, as described in [6].



	A	B	C	D	E	F	G	H	I	J	K
1	date	time	latitude	longitude	projection_x_coordinate	projection_y_coordinate	horizontalAccuracy	llhPositionValidFlags	roll	pitch	yaw
2	date	time	latitude	longitude	projection_x_coordinate	projection_y_coordinate	horizontalAccuracy	llhPositionValidFlags	platform_roll	platform_pitch	platform_yaw
3	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4	20220915	80401499	45.43683100	12.35510200	-56.57	31.27	0.75600000	1	8.34	-0.57	-146.88
5	20220915	80401749	45.43683000	12.35510000	-56.68	31.11	0.75500000	1	7.81	-0.96	-146.09
6	20220915	80401749	45.43683000	12.35510000	-56.68	31.11	0.75500000	1	6.37	-2.25	-145.18
7	20220915	80401749	45.43683000	12.35510000	-56.68	31.11	0.75500000	1	6.37	-2.25	-145.18
8	20220915	80402000	45.43682700	12.35509700	-57.01	30.88	0.75400000	1	3.10	-5.83	-143.60
9	20220915	80402000	45.43682700	12.35509700	-57.01	30.88	0.75400000	1	2.78	-6.57	-143.04
10	20220915	80402249	45.43682500	12.35509500	-57.23	30.72	0.75400000	1	3.69	-5.76	-142.69

Figure 6 – Example of .csv file obtained at the end of zig-zag test. The red box shows the first two rows containing two headers the first header line contains the custom name as listed in the SWAMP telemetry, the second one contains the long_name of the standard variable that it refers to (following the CF convention)

References:

[1] https://ittc.info/media/1890/75-02-06-01.pdf

[2] https://www.ittc.info/media/8091/75-02-06-05.pdf

[3]http://unina.stidue.net/Universita'%20di%20Trieste/Ingegneria%20Industriale%20e%20dell'Informazione/Biot/2%20Lezioni%20di%20Allestimento%20Navale%20NO/Cap.2%20-%20La%20manovrabilit%E0%20della%20nave.pdf

[4] http://simman2020.kr/contents/test_case_5.2.php

[5]https://cfconventions.org/Data/cf-standard-names/current/build/cf-standard-name-table.html

[6]https://corradomotta.github.io/FAIR-Data-in-Marine-Robotics/html/index.html