U-SWATH: An innovative USV design towards the extended ship

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Synopsis

Maritime sector is facing a fast increasing in combining innovative aspects with marine operations especially for what regards cooperative operations and environmental monitoring and protection. In this scenario CNR-INM developed a large size innovative Unmanned Marine Vehicle (UMV) named U-SWATH (Unmanned Small-waterplane-area twin hull). The vehicle was studied for extending the unmanned marine operations both cooperating with a mother ship or with other unmanned vehicle like UAV (Unmanned Aerial Vehicle) and UUV (Unmanned Underwater Vehicle) also by providing launch, recovery and reload systems for these vehicles. Characterised by a modular structure, U-SWATH is expressly addressed to multi-purpose applications that include sampling and monitoring of environmental parameters in coastal, protected and dangerous waters,seabed mapping and monitoring, chemical-biological on-board analysis, first emergency monitoring for oil-spill, patrolling and civil protection, testing of new technologies and tools.
The use of high-tech like U-SWATH is nowadays considered a need for both ordinary and uncommon operations at sea. The envision for U-SWATH is to enhance precision in data collection and increase their spatial resolution with a reduction of the costs of the surveys.
For this reason a SWATH non-conventional design was chosen to ensure excellent seakeeping and good efficiency thus increasing the time and precision of the surveys. To increase the flexibility of U-SWATH each of the two submersible hulls is composed of modular and interchangeable elements that can be outfitted with different payloads, equipment, propulsive or manoeuvring elements. An innovative navigation and guidance control was studied in combination with a propulsion layout based on new azimuthal thrusters to increase the survey ability and the cooperation abilities.

Keywords: USV, Marine Robotics, SWATH, Modularity, Expandable robotics, Extended Ship

1 Introduction

In the last years robotics is progressively expanding and modifying mankinds ability to explore and monitor oceans and coastal areas. Autonomous Underwater Vehicles (AUVs, for short) are now a common tool for executing geophysical and environmental surveys, monitoring and exploration. A recent overview of their contribution to the advancement of marine geosciences is, for instance, given in Wynn et al. (2014). On the other hand, although with the limitations due to the lack of rules for operations, the growing worldwide interest in commercial, scientific, and military issues associated with both oceans and shallow waters, has pushed a corresponding growth in demand for the development of Unmanned Surface Vehicles (USVs, for short) as reported in Liu et al. (2016). In particular, the natural role of USVs as communication relays between the air environment of electro-magnetic waves and the underwater world of acoustic propagation allows the development of networked systems integrating satellite and heterogeneous air, surface and underwater unmanned vehicles as discussed in Pinto et al. (2017).
At the same time, the maritime industry considers automated and autonomous ships one of the key technologies of the future (Rødseth and Burmeister (2012)). This requires an increasing level of integration between the ship system and a dedicated land ICT infrastructure which should be devoted, among other things, to the management of operation logistics, storage and access to the vast amount of heterogeneous data collected, and supervision and control of on-board subsystems. Unmanned ships, as foreseen for Yara-Birkeland (2018), will operate between a small number of pre-defined ports, either in liner mode or as part of an industrial shipping system.

Authors' Biographies

Gabriele Bruzzone is Senior Researcher at CNR he is the head of the Field and Interaction Robotics research group of CNR-INM. His research activity focuses on the design, development and test at field of real-time hardware and software architectures for the control of complex robotic systems (manipulators, tele-operated and autonomous, underwater and surface marine vehicles, aerial and terrestrial ones).
Angelo Odetti is Research fellow at CNR-ISSIA, PhD student at DITEN-UNIGE. Marine Engineer and Naval Architect with a background in Air cushion technology research, is designer of the general layout and of structural and naval components of UMVs.
Marco Bibuli, Ph.D. is researcher at CNR-INM focusing his research activity on advanced navigation, guidance and control systems for autonomous marine platforms, as well as mission control and supervision systems for marine robots' autonomy enhancement.
Massimo Caccia former director of CNR-ISSIA focuses his research interests on UMV navigation, guidance and control algorithms as well as mobile robots for ship structure inspection. He is involved on a huge number of EC and Italian National projects.
Emilio Fortunato Campana is director of DIITET department at CNR. Former director of CNR-INSEAN and award-winning researcher his research mainly focuses on Simulation Based Design and Numerical Optimization, Wave Breaking and Vorticity Free-surface interaction and Ship hydrodynamics.
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In this framework, the Blue Italian Growth Technology Cluster identified Shipbuilding and Marine Robotics as a development trajectory for the integration of naval engineering, ICT and robotics know-how in order to pursue the strategic vision of developing intelligent/autonomous ships, submarines and ocean structures, extended in space and time with cooperative autonomous heterogeneous unmanned vehicles, covering the three segments of marine robotics: underwater, surface and aerial.
This RD&I vision relies on the results of the Italian Ritmare Flagship Project (2015) coordinated by CNR (Consiglio Nazionale delle Ricerche), where INM (Institute of Marine Engineering) researchers designed and developed a new generation of unmanned underwater and surface vehicles. In particular U-SWATH, namely Unmanned Small-waterplane-area twin hull, vessel was designed to support marine science and cooperative robotics research operating in coastal areas. The high costs associated with the use of research oceanographic vessels and the maturity of the unmanned surface vehicles (USV) suggested the possibility of developing a system for monitoring coastal areas based on modular and cooperative robotics.
Autonomous marine vehicles greatly increase the performance of the surveys since the high automation coupled with control and guidance algorithms and the multiple proprioceptive and exteroceptive sensors present on the vehicle allow to increase the precision of analysis like bathymetry, object detection, sampling resolution etc., the reduction of execution times and also to carry out specific operations in protected, difficult or dangerous environment as shown by Bruzzone et al. (2018).

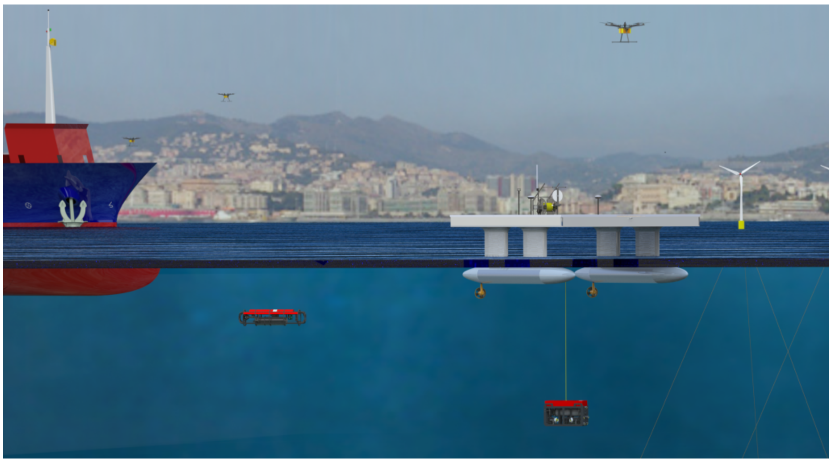

Figure 1: U-SWATH in a CNR extended ship vision

2 Robot description

U-SWATH aim is working in coastal monitoring with a wide range of possible applications like patrolling, water quality monitoring, bathymetric analysis, biological areas monitoring with analysis of chemical and physical properties, first emergency in water pollution such as oil spills, monitoring and recovery of cultural heritage on the sea floor. U-SWATH is designed to integrate skills in naval engineering, ICT and robotics and other innovative aspects at Italian National Research Council. U-SWATH is an Unmanned Surface Vehicle designed to work both in coastal and inland waters to carry out surveillance, monitoring and sampling operations. One of its main purposes is to be used as a test-bed for research and technological development activities in areas such as: naval architecture, robotics, marine sciences, material technologies and research on innovative power systems.
The vehicle, completely designed when this article was written, is under construction at the present stage.
The cutting-edge aspects that characterize the project are the SWATH design and the extended capabilities of the entire robotic system. The non-conventional hull design is optimized to ensure a unique seakeeping (higher operation capability) and a reduced resistance (higher endurance). This configuration guarantees excellent transversal stability, as well as satisfying the need for modularity of such an application.
The SWATH hulls are composed of modular and interchangeable elements that can be outfitted with different payloads, equipment, propulsive or manoeuvring elements. The main propulsion system is based on the development of azimuthal thrusters to combine good manoeuvrability, innovative guidance controls, propulsive performance (reduced installed power) and low noise with consequent higher efficiency in measurements and surveys. If compared to the existing vessels, the USV unit is characterised by large dimensions (5 m long, 2.5 m wide, 1.5 m high, 1.4 t displacement) where a wide and flat deck (approx 15 sq m) connecting the hulls represent the key element. The deck not only allows for the use of a system of alternative power generation systems but also to work in cooperation with other smaller unmanned vehicles. Thanks to these peculiarities, U-SWATH has an increased survey

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ability extending the acquisition of environmental data to the water column from free-surface to the sea floor. For its modular nature U-SWATH will become the basis for prototype testing of new materials, motors, propulsion systems, energy generation systems, propellers, control surfaces etc. .
The U-SWATH concept is the basis for the future development of extended autonomous ships for this reason it is studied to be embarked on an oceanographic vessel. In turn the vehicle was designed for hosting the launch and recovery systems for surface (USV) [2 Length, 2 m Breadth, 150 kg Weight], underwater (AUV / ROV) [2.5 m Length, 1 m Breadth, 0.5 m Height, 150 kg Weight] or aerial (UAV) [2m Length, 2m Breadth, 15 kg Weight] vehicles and /or on-board autonomous laboratory for in situ bio-chemical measurements.

3 U-SWATH hull and layout

U-SWATH is an autonomous surface vehicle belonging to the category of Small Waterplane Area Twin Hull. Technically, a SWATH is a type of a catamaran designed to minimize the hull volume at sea's surface (where wave energy is located) thus offering exceptional stability in a wide range of sea states. These characteristics are greater than any other monohull ship or catamaran. The SWATH displacement is placed beneath the waves and this allows to maintain a quasi-horizontal position in wave heights up to the distance between the hulls and the platform substantially reducing the ship's motions.
Although the adoption of SWATH technology was already theorised in USV by Brizzolara et al. (2011) and used by other research groups in smaller USV like Beck et al. (2008), U-SWATH is the first medium-size USV using the SWATH technology for multi-purpose scopes including cooperation and marsupial robotics activities.
The SWATH hull remains under the water surface and the benefits of this technology are minimal resistance and maximum sea-worthiness. This submersible twin-hull ship design minimizes hull cross section area at the sea's surface making the vehicle very stable in water. The minimisation of hull cross section area is related to wave generation with a consequent reduction of energy consumption and an increase in survey time.
The two U-SWATH submersible hulls are connected to the upper platform by a twin narrow struts each. The choice of this kind of design arises from three main necessities: power reduction, better use of underwater instrumentation and cooperation ability.
Reduction of resistance is important for the increase of mission endurance and hence survey time and of payload capacity, the less the power consumption the more the payload capacity. For the purpose of hull optimization U-SWATH hull was simulated by means of numerical simulation tools as in Zaghi et al. (2015) both in fresh water and salt water conditions in compliance with ITTC standards.
Different types of simulations were made both in steady state and unsteady state with wave resistance analysis. Among these simulations some took into consideration the second twin-hull (for the interference factor analysis) and the propulsion system. Constructive interference was recorded around 4.5kn. As expected, the wave resistance is relevant. Both for complete and demi SWATH configurations the wave pattern plays a crucial role for the hull design optimization.
In table 1 the hydrostatic characteristics of U-SWATH are shown. Even if the small variation of restoring hydrodynamic contribution could not guarantee a perfect sea-keeping for vertical motions, the excellent transversal stability, even in high seas and at high speeds allows an optimal use of underwater mapping instruments. The increased roll stability of the vehicle allows for a more precise and stable management of underwater sensors (especially acoustic ones) that is a well known problem in acoustic mapping as shown in Alkan (2003) and Sakib (2017). The layover due to vehicle rolling can be highly reduced and inappropriate data with large rolling angles can be lowered to a minimum.
The stability of U-SWATH also allows for a better cooperation between an autonomous mother ship and smaller

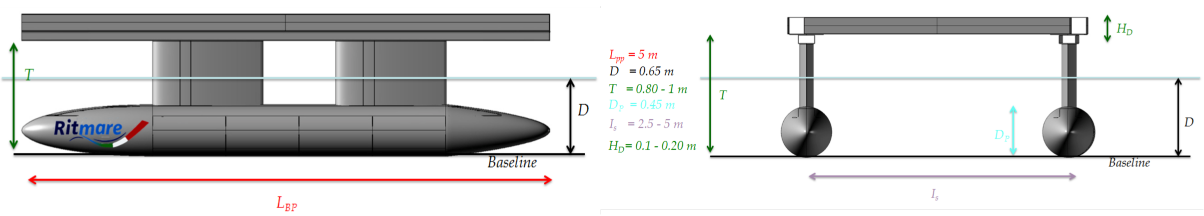

Figure 2: U-SWATH Hull measures

UMVs and UAVs. Moving towards the extended ship this is a key element. The foreseen environmental conditions limit of U-SWATH is Beaufort Scale 5. U-SWATH with its 5 m in length and 4 m in breadth is considered a large dimension vehicle if compared to existing civil USVs.
The maximum weight of the vehicle is around 1400 kg, of which 600 of payload. All these characteristics allows

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to host a launch and recovery system for cooperation between the U-SWATH and other vehicles. This can be done with autonomous launching and recovering of a Remotely Operated Vehicle (ROV) or an Autonomous Underwater Vehicle (AUV) that can be recovered on-board. The operations can be extended to air by creating a large docking area for Unmanned Aerial Vehicles (UAV) landing and take-off.
Moving to this direction U-SWATH can become the mother vehicle in the extended ship concept or can become the extension of an extended huge ship.

Table 1: U-SWATH, Unmanned Small Waterplane Twin Hull characteristics

Hydrostatic Characteristics		
Displacement	[Kg]	1400
D	[m]	0.65
LCB	[m]	2525
TCB	[m]	1250
VCB	[m]	0.246
Wetted Surface	[m^2]	14.750
Waterplane Area	[m^2]	0.371
BMT	[m]	0.427
BML	[m]	0.130

4 Modular Design

Following the trend of modular robotics like P2-ROV (Odetti et al. (2017b)) and e-URoPe (Odetti et al. (2017a)) developed at CNR the design of U-SWATH is thought modular extending this concept to larger robotic systems. Its large size places U-SWATH in the category of autonomous boats and ensure a high degree of modularity, a large number of possible payloads with the capacity of working even with high sea states. Each of the submersible hulls, connected to the bridge via two vertical foil struts one in the bow and the other in the stern, is composed of a main supporting girder and various interchangeable modules. Each hull is divided into 6 separate and independent modules, 4 central elements and two ogive shaped elements at bow and stern. Every module is waterproof, has its own dedicated electric power and can be modified and/or changed to be outfitted with different payloads, equipment, propulsive or manoeuvring elements, as shown in Figure 3. This is a way to satisfy the need for modularity for the submersible parts.
U-SWATH is mainly made of anodized aluminium but all the non-structural parts are made of plastics. The two

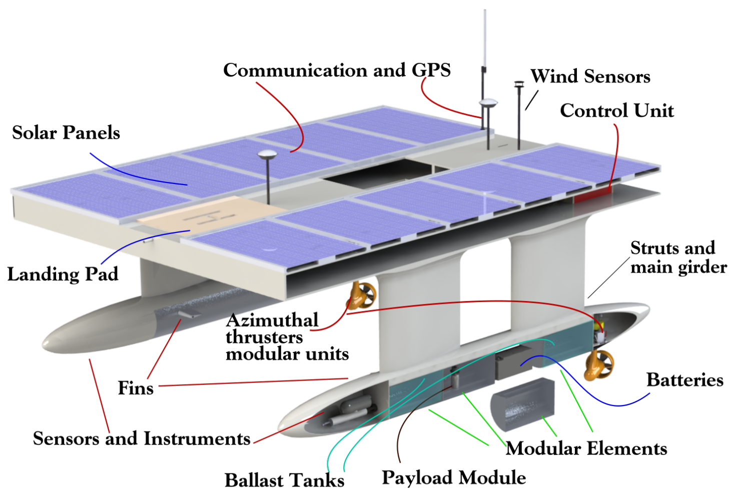

Figure 3: U-SWATH General Layout

vertical struts of each hull are connected to an upper longitudinal girder that forms a reticular structure (composed by transversal and longitudinal elements) that connects the two hulls and creates the main bridge. The wide space resulting from this structure is occupied by a flat deck constituted by a rectangular watertight box with an exposed

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horizontal area of approximately 15 m^2. On the resulting bridge solar panels are positioned supplying power to the batteries and in the future it will be possible to accommodate a solar sail.
The whole U-SWATH is intended to be modular thus also the intelligent core of the vehicle, contained in a plastic canister positioned inside the box-shaped anodized aluminium deck, was designed for offering the possibility to interact with various and different payloads. For this reason the electronic core communicates and interacts with the manifold sensors and actuators already installed on the vehicle and others that could be installed in the underwater modules or on the bridge (navigation and control systems, communication, survey sensors and other instrumentation).
The propulsion of U-SWATH is based on two new azimuthal thrusters especially developed for U-SWATH and installed in the stern module.
Four automatic ballast tanks located inside 4 modules, 2 per hull, will be used for the balancing of depth and trim.
As mentioned in Section 2 The vehicle is mainly designed for different purposes: monitoring of waters, chemical-biological analysis, emergency and patrolling. The wide space present on-board either underwater inside the modular hulls and on top and under the box bridge make U-SWATH a suitable multi-purpose platform where researchers of CNR and other institutions will be able to perform their experiments: e.g. a laboratory for bio-chemical measurements, for testing of new materials, motors, propulsion systems, stabilizing control surfaces, optical and electromagnetic instruments, new sensors or study of hydrodynamic noise.
The possibility of hosting other devices for the extraction of energy from wind and waves and currents will also be evaluated.
It is from these needs that U-SWATH originates, trying to improve and increase the adoption of large vehicles for autonomous surveys, services and research.
The U-SWATH modular payload concept arises from the requirement of multitasking and reconfigurability. For this reason even the propulsion system is modular as well as the ballast tanks and the battery modules, thanks the above mentioned peculiarities in the future it will be possible to modify the actual configuration and enhance the vehicle's layout.

5 Propulsion system

The new propulsion unit for U-SWATH was designed and developed by CNR-INM and is placed underneath the stern modules as shown in Figure 3. It is composed of two azimuthal thrusters used for both thrust and manoeuvring with a pod that can rotate 360^o around a vertical axis (azimuth) allowing a higher degree of manoeuvrability than a fixed propeller and rudder system. The podded system, standing underneath the hull, works in undisturbed free-stream thus increasing the efficiency.
The propulsion unit is similar in the concept to the ABB Group's Azipod Berchiche et al. (2017) where an electric motor is fitted in a pod, connected directly to the propeller without gears.
Each thruster electromechanics consists of a 48V brushless main motor (1 kW at 1400 rpm) especially designed for the U-SWATH application. This is positioned inside the pod with its corresponding stainless steel casing. The upper mechanics and supports, the azimuth motor and the electronics of control are all embedded in the system and contained inside the stern module thus constituting a real unique module.
The azimuth motor is a stepper motor with integrated electronics, encoder and driver. Its high torque is used

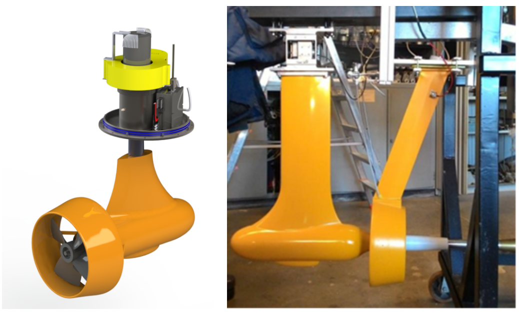

Figure 4: U-SWATH Propulsion unit and test rig

for manoeuvring the motor and its casing constructed with a Naca wing profile rudder. A slip-ring on top of the vertical shaft guarantees the electrical connection through the continuous rotation of the propulsion unit.
As mentioned before we have two different operational speed, the transfer speed is 3 m/s and the operative speed is 1 m/s.

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The azimuthal ducted propeller was designed at free running condition, through numerical models. The prototype performance was measured in different layouts and testing conditions through open water tests in calm water and at zero yaw angle as reported in Santic et al. (2017b).
The azimuthal ducted podded propulsion system was considered as the best choice. Such a configuration ensures safety (preventing propeller damages in shallow water condition), efficiency, reduced noise and is satisfactory in terms of the enhanced manoeuvring capabilities required. The adoption of a nozzle around the propeller increases performances at low speeds (here, 1 m/s).
A two stage design process was applied. An empirical model was used to define the base ducted propeller configuration, whereas a modified version was identified through the application of a hybrid RANS/BEM model for modified geometries at the design point as shown in Santic et al. (2017a). The chosen propeller is the INSEAN E1648 model with a P/D=1.1 inside the 1922d0 nozzle derived from the Wageningen Ka4-70 in nozzle 19A Kuiper (1992).
A complete description of the experimental activity can be found in Santic et al. (2017b) where it is shown the complete propulsion unit test by means of open water tests in calm water and zero yaw angle; the experimental set-up, enabled the measure of the single load contribution which provides the total thrust and torque.

6 Power and electronics

The planned typical duration of the missions (shown in table 2) that can be carried out by U-SWATH with just the batteries power supply is estimated to be 8 hours with a maximum speed is 3 m/s for transfers, while it is foreseen a speed of 1 m/s or even less during the phases of monitoring and measurement. The operative sea state limit of U-SWATH is foreseen in Beaufort Scale 5, higher sea states operations will be checked in field tests. To keep the safety at an high level the on-board electric power maximum tension is kept under 48 V. Power is supplied by a system of eight 12 V and 70 Ah batteries that are positioned inside one module per hull and can be recharged by an endothermic generator before the mission and by a system of 48 V solar panels placed on the surface of the bridge during the mission. The solar panels have a total exposed area of 15 m^2 and are characterised by a 200 W/m^2 power density that can generate up to 3.5 kWh.

Table 2: U-SWATH type mission

V	time	P_{eff}	P_{users}	P_{tot}	Ah at 48 V
$[m/s]$	$[h]$	$[kW]$	$[kW]$	$[kWh]$	Ah
3	1	2,0	0,1	2,0	42
1	6	0,1	0,1	1,1	24
3	1	2,0	0,1	2,0	42

This is important because the power consumption of U-SWATH at maximum speed is around 2.3 kWh thus implying that solar panels, in good weather condition can provide power to the entire system greatly increasing the survey time.
Every single underwater module's payload has its own dedicated power and communication guaranteed by a series of LANs and 48 V cables that are redistributed inside each module in relation to the power and communication needs.
The control system of U-SWATH is installed in a waterproof box located inside the bridge and it is based on a SBC (Single Board Computer) and two PC/104 modules providing digital input/output, analog input, analog output and serial input/output respectively. All these I/O channels permit the SBC to communicate and interact with the manifold sensors and actuators already installed on the vehicle and others that could be installed at a later time. The sensors that will be initially mounted on board U-SWATH and used for basic navigation are: compass, GPS, Inertial measurement unit (IMU) and altimeter. Further expansions, foreseen in a near future, will provide: a multi-beam sonar, a side-scan sonar, a RADAR and a LIDAR for obstacle detection and collision avoidance, a Doppler Velocity Log for the measurement of speed and a very precise Fiber Optic Gyrocompass. The box inside the bridge also contains the DC-DC converters used for powering the control system and a wired Ethernet link used by the control system for communicating with the data acquisition and control systems of the equipment that will be located on the modules placed on the hulls. As far as the communication systems are concerned, U-SWATH is equipped with two Wi-Fi Ethernet links working at 2.4 GHz and with a maximum range of 1 km using omnidirectional antennas. One Wi-Fi communication channel is devoted to send commands to and to receive telemetry data from a remote operator, the other Wi-Fi channel is made available for the payloads. An additional radio channel at a lower frequency (169 MHz) and narrow bandwidth but with a longer operating range (10 km maximum using omnidirectional antennas) is used as a security link. Also an acoustic modem is to be installed on board for communicating and positioning of underwater equipment (e.g. ROVs, AUVs, moorings, etc.) Finally, an

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Ethernet IP camera with a video stream that will be sent through the Wi-Fi Ethernet link is mounted in the bow for allowing First Person View (FPV) and remote piloting. Some additional IP camera can be mounted both laterally and in the stern either for facilitating manoeuvring operations or for observing the surrounding environment. Also Underwater cameras can be installed.

7 Guidance and Control strategies

Combined guidance and control strategies for the autonomous navigation of U-SWATH are based on the final aim of autonomous shipping. The capabilities of U-SWATH have to be migrated and adapted towards the reliable and safe control of commercial-like unmanned vessel, that are taking place thanks to a number of technological research projects. The employment of the SWATH technology combined with Azimuthal propulsion, requires robust guidance techniques to provide precise and reliable motion control during navigation. For U-SWATH a dual-loop guidance and control scheme able to provide advanced navigation capabilities was studied. In particular, the inner control loop, devoted to the actuation of the azimuthal thrusters, allows the tracking of reference course angle (namely the autopilot). Such a control loop is characterized by a modified PID regulation scheme, where a novel adaptive derivative component is inserted in order to improve the convergence curve towards the required course reference. The outer guidance loop, based on Lyapunov/virtual-target approach, allows the vessel to track generic desired paths, thus enhancing the autonomous navigation capabilities also in constrained environments.

8 Results

The resulting characteristics of U-SWATH are shown in table 3

Table 3: U-SWATH, Unmanned Small Waterplane Twin Hull characteristics

Main Characteristics			**Power and Electronics**		
Length L	$[m]$	5.0	Rated Power	$[kW]$	2.5
Breadth B	$[m]$	4.0	Endurance at full load	$[h]$	8
Height H	$[m]$	1.5	Batteries 12 V, 70 Ah	nr	8
Weight	$[kg]$	1400	Solar Panels	15 m^2	200 W/m^2
Maximum Draft	$[m]$	0.75			
Rated Speed	$[m/s]$	3			
Azimuthal Thrusters	nr	2			
Propulsion Unit Thrust	$[N]$	250			
Propulsion Unit speed	$[rpm]$	1400			
Basic Payload			**Additional Payload**		
Double antenna GPS	Trimble		Echo Sounder	Tritech	
LED Lights	nr 4		CTD Probe	Idronaut	
Ethernet Cameras	nr 3		Fiber Optic Gyro(FOR)		
Doppler Velocity Log (DVL)	Teledyne		LIDAR		
IMU	Microstrain		LARS		
Wind Direction Sensor	WindSonic				

9 Conclusions and further research

This article is intended to show the steps that led to the development of U-SWATH. It is an Unmanned Surface Vehicle, able to work both in coastal and inland waters to carry out surveillance, monitoring and sampling operations and one of its main purposes is to be used as a test-bed for research and technological development activities in areas such as: naval architecture, robotics, marine sciences, material technologies and research on innovative power systems. U-SWATH is developed to show how the marine robotic technology is mature to be applied to bigger and heavier systems that will become useful to substantially reduce the costs of surveys by increasing their quality and efficiency.

The vehicle, completely designed when this article was written, is currently under construction. Future steps of the project foresee the assembly, the model identification with PMM, in the presence of waves and the validation at field of hydrodynamics. Following steps will include tests of the boat at Nemi Lake with its identification and control implementation. The future challenges, expressed in the present article, include cooperation with UxVs, installation on-board of sensors and systems and the mapping of various environments.

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