Trends and Challenges in Unmanned Surface Vehicles (USV): From Survey to Shipping

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ABSTRACT: Autonomy and unmanned systems have evolved significantly in recent decades, becoming a key routine component for various sectors and domains as an intrinsic sign of their improvement, the ocean not being an exception. This paper shows the transition from the research concept to the commercial product and related services for Unmanned Surface Vehicles (USV). Note that it has not always been easy in most cases due to the limitations of the technology, business, and policy framework. An overview of current trends in USV technology looking for a baseline to understand the sector where some experiences of the authors are shown in this work. The analysis presented shows a multidisciplinary approach to the field. USV's capabilities and applications today include a wide range of operations and services aimed at meeting the specific needs of the maritime sector. This important consideration for USV has yet to be fully addressed, but progress is being made.

1 INTRODUCTION

All manner of "water-going" platforms have been by far the first sophisticated machines developed by humans. As a key element of exploration, commerce and war, ships have always involved engineering solutions to difficult problems and talented humans to build and operate them. For thousands of years sailors have placed their trust, and their lives, in constructions of wood, then steel, in the face of a challenging ocean. It could be said that the age of "autonomy" has been slow to come to ships. But this is changing. Nowadays there are many small and medium-size unmanned boats in routine-use, paving the way towards fully autonomous vessels as ultimate step in this sector. Many institutions, universities and companies have begun developing Unmanned Surface Vehicles (USV) aiming to cover a wide range of applications and services, evolving rapidly. With growing worldwide interest in

commercial, scientific, and military issues associated with both open-ocean and shallow waters, there has been a corresponding growth in demand for the development of more complex USV with advanced guidance, navigation, and control (GNC) functionalities. The development of fully-autonomous USV is underway aiming to minimize both human control needs and the effects to the effective and reliable operation from human errors [12].

USV are defined as unmanned vehicles which perform tasks in a wide range of environments without any human intervention with highly nonlinear dynamics. Further improvements on USV technology are expected to bring tremendous benefits, such a lower development and operation cost, improved staff safety, extended operational range, and precision and greater autonomy. Increased

flexibility in sophisticated environments and dangerous mission [4, 7, 67] is also envisaged.

With the inclusion of a more robust, commercially available and affordable navigation equipment (GPS, IMU, etc.), wireless telemetry systems, "blue" power sources and trending intelligent-analytics technologies (Artificial Intelligence, Machine/Deep learning, etc.) [47, 51, 52, 57], the applications range for USV has significantly increased and improved in key domains and sectors such as scientific research, environmental missions, ocean exploration, military uses and other applications (transportation, communication relays, refueling, unmanned aerial or unmanned underwater vehicles platform, etc.) [2, 45, 48].

This paper is organized as follows: Section 2 provides an updated overview on USV technology. Section 3 focus on autonomous vessels as evolution from USV technology in as ultimate step on maritime navigation technology [6]. Section 4 provides a description of the policy framework as key driver for autonomous maritime navigation and shipping implementation. Section 5 is addressed to review intelligent analytics methodologies in path planning and collision avoidance for USV navigation. Finally, concluding remarks are drawn in Section 6.

2 USV TECHNOLOGY. DEVELOPMENTS AND MILESTONES

Through the last two decades, several USV developments have been undertaken through public and private initiatives with diverse scope and purpose [46, 53, 79]. After clearly experimental beginnings with limited capabilities in terms autonomy, endurance, payload, power outputs, etc., in recent years significant progress has been made in all USV subsystem components (hull and structural elements, propulsion and power system, GNC, telemetry, payloads, data management and ground station). This enabled USV to become a leading commercial technology solution in several applications and services (some on a routine basis) beyond the military and research [5, 10, 26, 27, 41].

The initial reference on the path to autonomous ships is technical. The core technologies that enable unmanned vessels have come about largely due to developments in other fields [8, 15, 22, 23]. Improved USV capabilities allow to undertake missions both in coastal and open-ocean areas for long periods of time due to a more efficient power and propulsion systems based in some cases on renewable energy sources (solar, wind, waves), Fig. 1. State-of-the-art broadband telemetry systems enable remote real-time operation and decision-making by the operator. In parallel with the mechanical and electronic system architecture improvements for USVs, software advanced rapidly as well, with special focus on autonomous navigation methods and techniques in compliance and contribution to ocean digitalization and e-navigation framework initiatives.

Figure 1. Wave Glider ASV starting a mission conducted by PLOCAN

While small USV developments are usually deployed within sight of the operator there are many others that go further. Considering hull dimension and propulsion system as classification factors, several flag-ship developments through last decade have been released, highlighting Sailbuoy [21] tested as pre-commercial solution at Oceanic Platform of the Canary Islands (PLOCAN) open-ocean observatory in 2012; Wave Glider [17, 30] robust enough to complete a crossing of the Pacific Ocean from California to Australia or successfully accomplish routing transects across the Macaronesia region by PLOCAN; AutoNaut [36] performed trials at PLOCAN testy-site waters for marine mammal monitoring, see Fig. 2; C.-Enduro; the Saildrone [86] able to perform long-range missions such circumnavigate the Antarctica and ATL2MED [71] being PLOCAN an active member in the second one providing its test-site facilities for launching and initial field validations; DriX [34] with specific applications on survey-services for industry; Mayflower [50] expecting to sail between Plymouth-Cape Cod (MA, USA); Sphyrna [72] that focusses on passive acoustic monitoring applications; Data Explorer; XOCEAN XO-450 [82] for energy and seabed mapping commercial survey services; SeaTrac; Submaran-S10 [58] as hybrid concept able to both sail the ocean surface and glide the water-column as underwater vehicle.

All of them are fully or partially powered by endless ocean-energy sources. In parallel, half-way to autonomous ship concept, developments such Sea-KIT [73]; Ocean Infinity [59] have also been released for specific seabed-mapping and survey-services in industry applications at ocean-basin level worldwide. These developments, many of them already commercial, demonstrated that specialty USV could withstand the harsh ocean environment for extended periods and their software and systems were reliable enough for extended voyages and missions.

Figure 2. AutoNaut ASV trials at PLOCAN test-site facilities

3 AUTONOMOUS VESSELS: THE ULTIMATE STEP TOWARDS SHIPPING 4.0 IMPLEMENTATION

The current global trend on autonomy developments in mobility seems to be widely yet accepted by the maritime community, primarily due to budgetary issues. Up to date, autonomous and remotely operated platforms at sea have been mainly used as carriers of sensors and other measuring devices mainly addressed to oceanography, hydrography and off-shore applications in nearshore, controlled test-site areas or outside shipping routes. However, nowadays we are facing a step further towards a new paradigm associated with cyber-physical systems, big data and autonomy as part of Shipping 4.0 and Digital Ocean international trends and strategies. Efforts in transport cost reduction, the global need of minimize emissions and the demand for improving safety at sea are three base reasons on why autonomous shipping is under consideration and early stages of implementation [9, 54, 65, 66].

Under these premises, the development and future implementation of vessels as MASS (Maritime Autonomous Surface Ship) will represent an inflexion point for the paradigm shift in the industry and maritime shipping system as a whole [39, 61, 80, 81]. Therefore, for a successful and smooth settlement of MASS as well as the relevant infrastructures in the maritime sector, key aspects related to autonomous shipping and their impact on technology, regulation and societal aspects should be envisaged [1, 28, 29].

From the purely technology perspective, ships should be built with enhanced control capabilities, broadband telemetry, graphic interfaces, complex sensor payloads, etc. in order to be operated by means of remote land-based or off-shore services [40]. However, the technology replacing manning needs to re-shape the crew in terms of safety, efficiency and environmental protection. On the industry side, MASS is expected to change shipbuilding and equipment, as well as shipping protocols and port infrastructures. Industries related to high specialized technology base sectors such autonomy and automation, unmanned operations, big data, artificial intelligence, machine learning, enterprise-grade connectivity and analytics will be essential.

In what refers to global trends of autonomous vessels development, in the past decade several international projects with large investment have been (and still) conducted with Scandinavian companies and research institutions playing a leading role. Rolls Royce [69], Kongsberg, DNV GL, Norwegian University of Science and Technology (NTNU), among others, are fully involved with ambitious plans to develop a new generation of all-electric and autonomous container ships by 2022, according to projects listed in Table 1. In the same direction, other research institutions and companies are developing complementary and competing concepts to support unmanned shipping operations, coupled with specific infrastructures and services, including autonomous ports, high bandwidth telemetry, etc.

Table 1. Flagship projects to develop autonomous vessels

Project Name (Period)	Main Partner Institutions
MUNIN (2012-215)	8 EU research and industry
ReVOLT (2014-2018)	DNV GL, NTNU
AAWA (2015-2018)	Rolls Royce, DNV GL
YARA BIRKELAND (2017-2020)	KM, YARA, NTNU, DNV GL
AUTOSHIP (2019-2022)	CIAOTECH, KM, SINTEF, BV

MUNIN, ReVOLT [18], AAWA have paved the way for Yara Birkeland project [70, 85]. Yara and Kongsberg have partnered to develop the world's first fully electric container vessel, starting in 2017 working towards remote operation by 2019 and is scheduled to go fully autonomous in 2021.

Therefore, despite the rapid development of science and technology in the maritime industry, autonomous vessels indisputably need to be subject to the international regulations necessary for the vessels to operate safely across nations and even the seabed areas beyond national jurisdiction. Some regulatory aspects of manned vessels may be compatible with unmanned vessels, such as certain clauses of the International Safety Management (ISM) Code. However, there is a need for specific international regulations taking into account the characteristics of unmanned vessels as well.

4 POLICY FRAMEWORK AS KEY DRIVER FOR AUTONOMOUS MARITIME NAVIGATION AND SHIPPING IMPLEMENTATION

While technology and market push are required for any innovation to take hold, regulation aspects become a major consideration. This is especially right in the case of autonomous vessels, where certain key developments can be noted as advancing the field.

During the period of roughly 2000-2010 early work on software and algorithms to enable unmanned vessels to adhere to the COLREGs (Convention on the International Regulations for Preventing Collisions at Sea) began. The ASTM Committee launch, designed to develop technical standards for unmanned maritime vehicles, including a sub-committee for regulatory issues. This catalyzed further policy developments. The Association for Unmanned Systems International (AUVSI) began to engage the issue through their Maritime Advocacy Committee in 2011. A particular focus was informing and engaging the U.S. Navigation Safety Advisory Council (NAVSAC). This body informs the U.S. Coast Guard, the relevant regulator for U.S. Waters. Through a series of meetings this work eventually resulted, in late 2012, in a resolution offering advice on both technology solutions, such as use of the automated identification system (AIS) and policy steps, such as amendments to certain COLREGs [37].

The UK's industry group, Maritime UK, launched an effort to develop voluntary best practices for unmanned vessels, though they referred to them as maritime autonomous systems (MAS). The first version of the UK Industry Code of Practice focused mainly on technical aspects such as design and construction of MAS [25, 49]. The UK Maritime

Autonomous Systems Regulatory Working Group (MASRWG) released this first document in 2017. While the guidance in the first version of the code was for design, construction, and operation, it was heavily focused on design and manufacture. Seeing significant growth in the autonomous systems the MASRWG updated the Code of Practice to increase focus on the USV operations, with firstly guidance on skills, training and platform's registration.

A multidisciplinary group of Spanish research centers, companies and public agencies, under the coordination of DGMM (General Directorate of Marine Merchant) are joining forces since late 2020 in order to setup a working group on autonomous maritime navigation. Its main goal is to setup the right national framework to develop and operate USV and autonomous ships that currently are under development [56, 78]. PLOCAN is one of the active partners providing both test-site capabilities and the ownership of the first autonomous boat flagged in Spain [24].

Figure 3. UTEK unmanned boat tested at PLOCAN test-site

While these previous efforts were regional in focus the ultimate regulator responsible for the COLREGs is the International Maritime Organization (IMO). In 2017, following a proposal by a number of Member States, IMO's Maritime Safety Committee (MSC) agreed to include the issue on its agenda. This led to yet another name for the technology, marine autonomous surface ships (MASS). IMO agreed to start with a scoping exercise to determine how the safe, secure and environmentally sound operation of MASS might be introduced in IMO policies and rules [31–33].

Subsequently, in 2019 the MSC approved interim guidelines for MASS trials. These were intended to guide the ongoing developments and early demonstrations on larger MASS eyeing commercial scale vessels. The guidelines said that trials should be conducted to provide at least the same degree of safety, security and protection of the environment as provided by the relevant existing regulations for manned vessels. They addressed risk mitigation practices and MASS operator qualifications. Notably the guidelines also suggested that appropriate steps to ensure cyber risk management.

The next step in the IMO process is to complete their scoping exercise. This will evaluate IMO rules and policies for applicability to MASS operations, taking into account human, technology and operational factors. Of particular interest to the technology community the IMO will employ four "degrees" of autonomy for the scoping exercise

(Table 2). The IMO anticipates completing this work in 2021.

Table 2. MASS Levels of Control according to IMO in the frame of a regulatory scoping exercise from 2018.

Level	Description
1	Ships with automated processes and decision support
2	Remotely controlled ships with seafarers onboard
3	Remotely controlled ships without seafarers onboard
4	Fully autonomous ships

In Level (1) seafarers are on board to operate and control shipboard systems and functions. Some operations may be automated and at times be unsupervised but with seafarers on board ready to take control. Level (2) seafarers are available on board to take control and to operate the shipboard systems and functions. In level (3) the ship is controlled and operated from another location. There are no seafarers on board. Finally, in Level (4) the operating system of the ship is able to undertake decisions and determine actions by itself.

One of the biggest challenges in developing the technology for MASS is to demonstrate that unmanned systems are at least as safe as a manned ship system and to provide the Shore Control Centre (SCC) with adequate situation awareness. In case of emergency situations such as stranding or evasive manoeuvring, the ship systems should be remotely monitored and controlled by the operators of the SCC receiving crucial information via satellite at short time intervals (Figure 4). The SCC should also have a smart alarm system and the ability to switch to the manual control mode in case of doubt on the autonomous system [38, 63, 68].

Figure 4. USV - Shore Control Centre (SCC) at PLOCAN facilities

5 TOWARDS A SAFE JOURNEY ON AUTONOMOUS MARITIME NAVIGATION

The mission-oriented operating system (MOOS) enabled surveys for both commercial and scientific purposes to make good use of USV technology. MOOS allowed such missions to be executed in a supervisory control approach. Usually the vessel low-level control (i.e. rudder actuation and navigation path planning to pre-set waypoints) is automated while the overall behaviour is managed by an operator (Figure 5). This approach is commonly seen in USV today [11, 19, 77, 84].
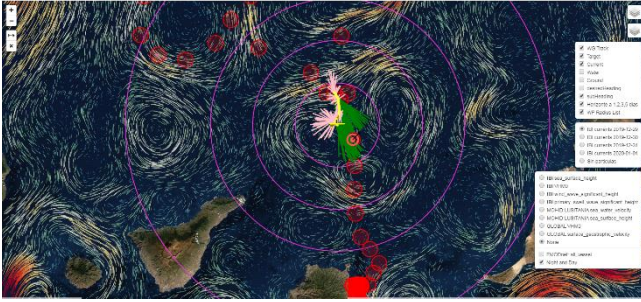
Figure 5. Graphic interface for USV remote piloting based on pre-set waypoints with overlapped path planning tools from multi-source data assimilation.

Autonomous navigation is achieved by training or programming the instrument with the stored data about its behavior in various operational scenarios. The autonomous behavior relies on intelligent analytics based on machine learning (ML) algorithms. As a major advance in ML, the deep learning (DL) approach is becoming a powerful technique for autonomy. DL methodologies are applied in various fields in the maritime industry such as detecting anomalies, ship classification, collision avoidance, risk detection of cyberattacks, navigation in ports, etc. [60]. A diverse range of methods are available in the literature for USV and MASS autonomy and their applications in maritime navigation.

All learning techniques require small to large amount of data in sophisticated format as base for algorithms to generate the working models. Hence "Data engineering" plays a crucial role in the proper functioning of these techniques that are used for autonomous navigation, and particularly in the field of ship automation. Considering the range of scenarios under which USV or MASS is exposed to, the amount of data to be engineered could escalate to 'Big Data'. Extremely important elements for their operation are the anti-collision system and the data fusion method from various sensors detecting obstacles on a programmed path aiming a reliable avoidance for a safe operation [55, 83].

Data source and storage are other key components on which the total process of ship automation is based. Considering the diverse type of data being loaded through sensors, experiments, simulation or calculation could intensify the problem of effective storage for the later stage of data cleansing and data transformation. Data engineering is the basis for the anticipated outcome expected from a model. These models are necessary in order a USV or MASS to navigate without pilot assistance.

Autonomous navigation of ship consists of various sensors to detect the navigating path, the environmental and vessel properties to determine safe travel. The successful implementation of autonomy on vessels would occur with intelligent decisions in all operational conditions. Many methods have evolved from remotely operated to full-autonomous operations in the last three decades. Table 3 shows traditional methods summarized in two categories.

Table 3. Summary of traditional methods on autonomous navigation

Classical Methods	Reactive Methods
RoadMap Building	Fuzzy Logic Controller
	Neural Network
Cell Decomposition	Neuro-Fuzzy
	Generic Algorithm
Artificial Potential Field	Particle SWARM Optimization
	Artificial Immune network

Advances in deep learning has made the approaches towards replicating these complex situations and autonomous collision avoidance [42, 62, 76] an easily achievable task in support to COLREGs [3]. A high level of recognition and situational awareness is necessary when AIS Data is combined with data from other sources. To develop a fully autonomous anomaly detection system, it should be supported with the visuals of vessel interaction at various environments to take intelligent decisions, which can be provided by the CNN algorithm.

Path planning is one of the key parameters in marine autonomous systems [13, 35, 44, 74, 75]. Its essence is to avoid obstacles and reach the target point at optimum distance and time. The effective path planning includes methods of artificial potential field, neural network [16, 64], fuzzy logic [14, 20, 43] and genetic algorithm. Most recent path planning algorithm, a deep learning approach, adopts a safety domain around each obstacle that serves to indicate the risk of collision. The algorithm uses deep reinforcement learning to reach the local target position successfully in unknown dynamic environment. Deep reinforcement learning solves the problem of dimensionality well and can process multidimensional inputs.

6 CONCLUSIONS

In this paper, a global vision of the USV sector has been shown from the experiences of the authors in PLOCAN. A detailed analysis about the present and future of this sector has been depicted. An especial emphasis has been done in showing the interdisciplinary nature of the field, involving technological, commercial and politics aspects. In particular, the new tends in artificial intelligence field, which represent a big step forward in the advance of the autonomous navigation. The technological developments presented include a multidisciplinary set of state-of-the-art: Sensors and systems for orientation, navigation, control, telemetry, propulsion, route planning, as well as specific tools for supervision and situational awareness operations, being key the inclusion of the aforementioned techniques of artificial intelligence. IMO is developing a global regulatory framework for MASS implementation in coming years. Because of that, it becomes necessary at this time to make further efforts in order to analysis this new sector.

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